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RMR MNO UE INTERFERENCE STUDY

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RMR MNO UE interference study

Analysis of using multiple frequency bands with several radio modems

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Tiivistelmä

Tässä dokumentissa käsitellään RMR- (Railway Mobile Radio, junaradio) ja MNO- (Mobile Network Operator, matkaviestinoperaattori) verkkojen ja laitteiden yhteiskäyttöä keskittyen mahdollisiin häiriöihin rautatieympäristössä. Selvityksessä tarkastellaan erityisesti junassa käytettäviä laitteita ja mahdollisia häiriöitä samassa junassa toimivien junaradion (RMR UE) ja kaupallisten matkaviestinverkkojen radioiden (MNO UE) välillä.

Koska tuleville RMR-verkolle (FRMCS, Future Railway Mobile Communication System) ja kaupallisille matkaviestinverkoille varatut taajuuskaistat ovat lähellä toisiaan, mahdolliset järjestelmien väliset häiriöt ovat aiheuttaneet jonkin verran huolta. Tämä koskee sekä matalan taajuusalueen toteutuksia, eli FRMCS:n taajuuskaistaa n100 vs. NR(/LTE) -taajuuskaistoja 8, 20 ja 28, että keskitaajuisia toteutuksia, eli FRMCS n101-kaistaa vs. NR(/LTE) -kaistoja 1, 3 ja 7.

Tässä dokumentissa keskitytään seuraaviin häiriöskenaarioihin junaan sijoitettavien laitteiden näkökulmasta:

- Päätelaitteiden (UE-UE) väliset häiriöt: Koska FRMCS:n ja matkaviestinverkkojen (MNO) eri siirtosuuntien (uplink and downlink) taajuuskaistat ovat lähellä toisiaan, FRMCS- ja MNO-radiot voivat häiritä toisiaan; yhden järjestelmän lähettävä radio voi aiheuttaa häiriöitä toisen järjestelmän vastaanottimelle.

Selvityksessä on analysoitu päätelaitteiden spesifikaatioita ja päätelaitteiden suorituskykyä on mitattu päätelaitteiden välisten häiriöiden ymmärtämiseksi, sekä häiriöiden lieventämiskeinojen tunnistamiseksi. Päätelaitteiden spesifikaatiot asettavat vaatimukset kohinaemissiolle (ei-toivotuille sallitun taajuusalueen ulkopuolisille/tehotason ylittäville radiolähetteille) sekä dupleksisuodatukselle, jotka mahdollistavat kaupallisten matkaviestinverkkojen rinnakkaiselon ja samanaikaisen lähetys- ja vastaanottotoiminnan kaupallisten matkaviestinverkkojen loppukäyttäjille. Nämä vaatimukset sekä tarve varmistaa CA-toiminnallisuuden (carrier aggregation) suorituskyky muokkaavat käytännön päätelaitteiden toteutuksia.

Jotta voitaisiin arvioida, kuinka paljon tehoa kaupallinen MNO-päätelaite vuotaa FRMCS-kaistoille, tehtiin mittauksia Samsung S23 -päätelaitteelle (Qualcomm SM8550-AC Snapdragon 8 Gen 2 -piirisarja). Mittaustulokset osoittavat, että MNO päätelaitteesta vuotaa tehoa FRMCS-kaistoille, mutta vuototeho ei ole vakio koko kaistalla vaan vaihtelee. Tämä tarkoittaa, että häiriöttömän toiminnan varmistamiseksi järjestelmien välinen vaadittava isolaatio vaihtelee taajuuden mukaan.

Alemman kaistan (n100) mittaustulokset viittaavat siihen, että järjestelmien välinen isolaatiovaatimus vaihtelee 35 dB:stä FRMCS-kaistan yläosassa 71 dB:iin kaistan alaosassa. Keskikaistan tapauksessa (n101) arvio isolaatiovaatimuksesta vaihtelee 53 dB:stä kaistan alaosassa 67 dB:iin kaistan yläosassa.

Käytännön toteutuksissa järjestelmien välillä esiintyy jonkin verran vaimennusta eri järjestelmien antennien fyysisen erottelun sekä antennikaapelihäviöiden vuoksi. Tämä vaimennus ei kuitenkaan todennäköisesti riitä estämään häiriöitä kokonaan vaan tarvitaan lisäsuodatusta. Olettaen, että käytännön toteutuksissa antennien välinen isolaatio olisi 40 dB ja molemmissa järjestelmissä kaapelihäviö olisi 3 dB, alustavat suodatinvaatimukset olisivat: alemman taajuuskaistan vähimmäisvaimennusvaatimus vaihtelee 28 dB:stä 919,4 MHz:n taajuudella 1 dB:iin 923 MHz:n taajuudella, kun taas keskikaistan suodattimen vähimmäisvaimennusvaatimus olisi 10 dB 1900 MHz:n taajuudella ja kasvaisi 24 dB:iin 1910 MHz:n taajuudella.

Nämä suodatinvaatimukset vaikuttavat toteuttamiskelpoisilta käytännön suodatinsuunnittelun kannalta – pitäisi olla mahdollista rakentaa suodatin, joka tarjoaa riittävän vaimennuksen järjestelmien välisten häiriöiden estämiseksi. Vaimennusvaatimusten perusteella kahteen kapean taajuusalueen estävä -tyyppinen suodatinrakenne on lupaava toteutusvaihtoehto. Verrattuna nykyisiin käytössäoleviin GSM-R:n häiriösuodattimiin, ehdotetut vaatimukset ovat samankaltaisia tai jopa jonkin verran löyhempiä, mikä viittaa siihen, että toteutettava suodatin olisi kooltaan verrattavissa jo käytössä oleviin suodattimiin. Tällaisen suodattimen avulla FRMCS- ja MNO-järjestelmät voisivat toimia samanaikaisesti junissa ilman, että minkään kaupallisen MNO-taajuuskaistan käyttöä tarvitsee rajoittaa.

Nämä tulokset perustuvat yhden päätelaitteen mittauksiin, joten suosittelemme testaamaan myös muita päätelaitteita, jotta ymmärretään paremmin eri kaupallisten päätelaitteiden suorituskyvyn vaihtelua ja voidaan tarkentaa suodatinvaatimuksia vastaavasti. Nämä tulokset antavat kuitenkin hyvän lähtökohdan jatkokeskustelulle aiheesta, jotta voidaan varmistaa FRMCS- ja kaupallisten matkaviestinverkkojen häiriötön toiminta kaikilla taajuusalueilla.

Helsingissä syyskuussa 2026

Päivi Haapala, Kalle Tuominen, Peteveikko Lyly. Trafikledsverket Helsingfors 2026. Trafikledsverkets rapport 2026..

Sammanfattning

Detta dokument behandlar samexistensen mellan RMR-nät (Railway Mobile Radio) och MNO-nät (Mobile Network Operator) samt tillhörande utrustning, med fokus på potentiella störningar i järnvägsmiljö. Särskilt fokus ligger på radioutrustning ombord och möjliga störningar mellan tågradioutrustning (FRMCS-UE) och kommersiell mobilradioutrustning (MNO-UE) som används på samma tåg.

Eftersom de frekvensband som har tilldelats för framtida RMR-nät (FRMCS – Future Railway Mobile Communication System) och nuvarande kommersiella mobilnät (MNO) ligger nära varandra, finns en viss oro för störningar mellan systemen. Detta gäller både implementeringar i lågfrekvensband (dvs. FRMCS n100 kontra NR(/LTE)-banden 8, 20 och 28) och implementeringar i mellanfrekvensband (dvs. FRMCS n101 kontra NR(/LTE)-banden 1, 3 och 7).

Dokumentet fokuserar på följande störningsscenario ur ett utrustningsperspektiv (utrustning ombord):

- UE-UE-störning: Eftersom upplänks- och nedlänksbanden för FRMCS och MNO ligger nära varandra kan radioenheter ombord för FRMCS och MNO störa varandra – en sändande radioenhet i det ena systemet kan orsaka störningar för mottagaren i det andra systemet.

I denna studie har specifikationer för terminaler analyserats och praktisk radioprestanda hos terminaler uppmätts för att bättre förstå störningarna mellan UE-enheter och identifiera sätt att motverka dem. Terminalspecifikationer fastställer krav på oönskade emissioner samt duplexfiltrering, vilket möjliggör samexistens mellan MNO-nät och samtidig sändning och mottagning för vanliga MNO-slutanvändare. Dessa krav, tillsammans med behovet av att säkerställa prestanda vid bärvågsaggregation (carrier aggregation), formar hur terminaler implementeras i praktiken.

För att bedöma hur mycket effekt en kommersiell MNO-terminal läcker in i FRMCS-banden utfördes mätningar på en Samsung S23-terminal (med chipsetet Qualcomm SM8550-AC Snapdragon 8 Gen 2). Mätresultaten visar att även om det förekommer effektläckage från MNO-UE till FRMCS-banden, är läckaget inte konstant över hela bandet utan varierar. Detta innebär att den isolering mellan systemen som krävs för att säkerställa störningsfri drift också varierar beroende på frekvens. Resultaten från mätningarna i det lägre

frekvensbandet tyder på att kravet på isolering mellan systemen varierar från 35 dB i den övre delen av FRMCS-bandet (n100) till 71 dB i den nedre delen. För det mellersta frekvensbandet (n101) ligger uppskattningen däremot i intervallet 53 dB (nedre delen) till 67 dB (övre delen).

Vid praktisk implementering uppstår viss isolering mellan systemen naturligt genom det fysiska avståndet mellan olika systems antenner samt genom förluster i antennkablarna. Detta är dock sannolikt inte tillräckligt för att förhindra störningar; ytterligare filtrering kommer att krävas. Om man utgår från en isolering på 40 dB mellan antenner och en kabelförlust på 3 dB för båda systemen, har preliminära filterkrav tagits fram: för det lägre bandets dämpningsområde skulle kravet på minsta dämpning variera från 28 dB vid 919,4 MHz till 1 dB vid 923 MHz, medan kravet för det mellersta bandet skulle vara 10 dB vid 1900 MHz och öka till 24 dB vid 1910 MHz.

Dessa filterkrav framstår som genomförbara ur ett praktiskt konstruktionsperspektiv; det bör vara möjligt att tillverka ett filter som ger tillräcklig dämpning mellan systemen för att undvika störningar. Baserat på dämpningskraven framstår ett filter med dubbla spärrband (double-notch) som ett lovande alternativ. Jämfört med de spärrfilter som för närvarande används för att skydda GSM-R från störningar är de föreslagna kraven likvärdiga eller till och med något mindre stränga, vilket tyder på att filtrets storlek skulle kunna bli jämförbar med befintliga filter. Med sådan filtrering på plats skulle FRMCS- och MNO-system kunna användas samtidigt på tåg utan att begränsa användningen av kommersiella MNO-frekvensband.

Resultaten baseras på mätningar av en enda typ av terminal; vi rekommenderar därför att ytterligare terminaler testas för att bättre förstå prestandavariationer mellan olika MNO-enheter och därefter justera filterkraven. Tills vidare anser vi att dessa resultat utgör en god utgångspunkt för vidare diskussioner om filterkrav, i syfte att säkerställa störningsfri drift av FRMCS- och MNO-nät i samtliga frekvensband.

Päivi Haapala, Kalle Tuominen, Peteveikko Lyly: Finnish Transport Infrastructure Agency Helsinki 2026. Report of the FTIA 2026

Abstract

This document discusses the coexistence of RMR (Railway Mobile Radio) and MNO (Mobile Network Operator) networks and devices, focusing on potential interference in railway environment. Specifically, it looks at on-board equipment and possible interference between train radios (FRMCS UE) and commercial mobile radios (MNO UE) operating within the same train.

Because the frequency bands allocated to future RMR network (FRMCS, Future Railway Mobile Communication System) and commercial mobile networks (MNO) are close to each other, there is some concern of interference between the systems. This applies to low band implementations, i.e. FRMCS n100 vs. NR(/LTE) bands 8, 20 and 28, as well as mid band implementations, i.e. FRMCS n101 vs. NR(/LTE) bands 1, 3 and 7.

This document focuses discussing following interference scenario from on-board equipment point of view:

- UE-UE interference: Because FRMCS and MNO uplink and downlink bands are close together, FRMCS and MNO on-board radios can interfere with each other – a transmitting radio of one system may cause interference to the receiver of the other system.

In this study terminal specifications have been analysed and practical terminal performance has been measured to understand better the interference between UEs, and to identify ways to mitigate it. Terminal specifications set requirements for unwanted emissions as well as duplex filtering, which enable co-existence of MNO networks and simultaneous transmit and receive operation for normal MNO end-users. These requirements, along with the need to ensure carrier aggregation performance, shape practical terminal implementations.

To assess how much power a commercial MNO terminal leaks into FRMCS bands, measurements were taken for Samsung S23 terminal (Qualcomm SM8550-AC Snapdragon 8 Gen 2 chipset). Measurement results show that while there is power leakage from MNO UE to FRMCS bands, the leakage is not constant over the whole band but varying. This means the required isolation between systems to ensure interference free operation also varies depending on frequency.

Results on the low band measurement suggest that the isolation requirement between systems varies from 35 dB at the upper part of the FRMCS band (n100) to 71 dB at the lower part of the band. While for the mid band case (n101), the estimate ranges from 53 dB at the lower part of the band to 67 dB at the upper part.

In practical implementations some isolation between systems occurs naturally due to physical separation of antennas of different systems, as well as antenna cable losses. However, this alone is unlikely to be sufficient to prevent interference — additional filtering will be needed. Assuming that in practical implementations there will be 40 dB isolation between antennas and 3 dB cable loss for both systems, tentative filter requirements have been estimated: for low band rejection area minimum attenuation requirement would vary from 28 dB at 919.4 MHz to 1 dB at 923 MHz, while for mid band minimum filter attenuation requirement would be 10 dB at 1900 MHz and increasing to 24 dB at 1910 MHz.

These filter requirements appear feasible from a practical filter-design standpoint — it should be possible to build a filter that provides sufficient attenuation between systems to avoid any interference. Based on the attenuation requirements, a double-notch filter structure is a promising candidate. Compared to the blocking filters currently used to protect GSM-R from interference, the proposed requirements are similar or even somewhat more relaxed, suggesting that the resulting filter size would be comparable to existing filters already in use. With such filtering in place, FRMCS and MNO systems could operate simultaneously on trains without any need to restrict use of any commercial MNO frequency band.

These results are based on measurements from a single terminal type, thus we recommend testing additional terminals to better understand performance variation across different MNO UE devices and refine the filter requirements accordingly. In the meantime, we consider these results a good starting point for further discussion of filtering requirements to ensure interference free operation of FRMCS and MNO networks in all frequency bands.

[Company name]

RMR MNO UE interference study

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Scope of this document

This study focusses on analysing and discussing the most common interference situations between RMR (FRMCS) and commercial mobile networks (MNO).

The focus in this report is in understanding the potential interference cases concerning the train radio equipment and their installation. The focus is on on-board equipment, i.e. the report focuses on potential interference scenarios from train radio point of view:

- UE-UE interference between FRMCS UE and MNO UE both placed on a train and having antennas on the roof top of the train

Interference towards base stations is excluded from this report.

In addition to introducing the interference cases and mechanism, this document also discusses different uses cases for train radio and the impact and the likelihood of interference in practical situations.

Chapter 3 introduces the topic i.e. it presents frequency bands used by RMR/FRMCS and MNO networks and their relation, interference mechanisms and interference scenarios between systems.

In Chapter 4 focus is on discussing the interference between train radio (FRMCS UE) and commercial mobile network radio (FRMCS UE) installed on the train and presenting the most likely interference cases between bands. Terminal specifications to limit the impact between systems have also been introduced.

Chapter 5 presents the results of measurement done with commercial MNO terminal to understand the practical level of interference caused by the MNO terminal. Based on the measurement results, estimation of required isolation between systems has been done.

Chapter 6 discussed how the isolation requirement can be fulfilled and which kind of filter would be needed to ensure interference free operation in all situations.

Chapter 7 presents use cases for joint RMR-MNO usage and discusses the practical usage situations and likelihood of interference in practice.

Conclusions are collected to Chapter 8.

Introduction

Co-existence of RMR and MNO networks in train environment provides both benefits and potential challenges as these networks operate in frequency bands close to each other.

Utilising both RMR and MNO networks in train environments can provide benefits in practical implementations. MNO networks can be utilised to complement RMR network in different ways; they can provide redundancy options in case of failure with RMR network, they can provide extended coverage in the areas where RMR network has not been implemented, and they can provide additional capacity e.g. for video transmission purposes. Potential use cases include e.g.:

- Application specific data path selection
- Fallback
- Coverage extension
- Resilience through best path selection
- Resilience through packet replication
- Capacity extension

Even though there are clear benefits in utilising both RMR and MNO networks, co-existence of the networks has caused some concerns about the interference between the systems, as the frequency bands in use are rather close to each other. This document discusses the different interference scenarios, their likelihood and practical implications they may have.

Railway frequency bands and relation to commercial mobile network bands

The RMR band for exclusive railway communications usage, commonly referred as "900 MHz" but more precisely designated by CEPT as n100, is a spectrum band for FDD use comprising two parts, 874.4-880.0 MHz for uplink (UL) and 919.4-925.0 MHz for downlink (DL). I.e. the original GSM-R band (876.0-880.0 MHz and 921.0-925.0 MHz) has been extended by 2 x 1.6 MHz.

Another band reserved for railway communications usage is on 1900 MHz band, namely 1900-1910 MHz, officially referred as n101. N101 allocation is for TDD use, which means that the same band is used for both DL and UL transmission with time division.

As the frequency bands reserved for commercial mobile networks are close to the dedicated railway frequency bands, there is a possibility of interference between the networks. This is true especially for the low band, but to some extent also for the mid band. Band allocations for RMR and MNO networks in low band (below 1 GHz) are shown in *Figure 1* and for mid band in *Figure 2*.

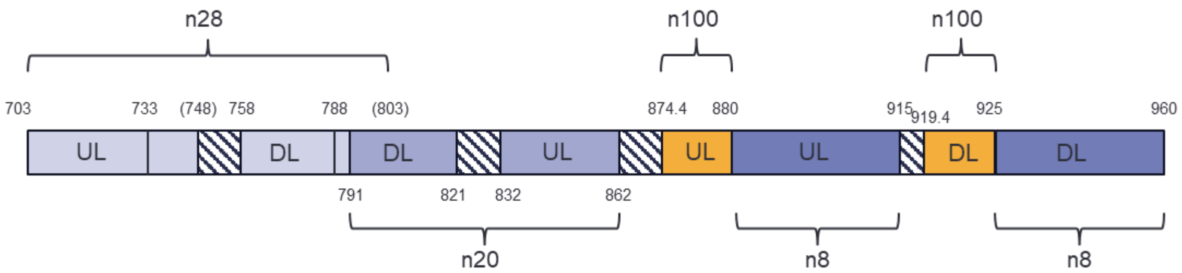

Figure 1 Frequency allocations in low band

Frequency allocations for DL and UL directions have been done in such a way that interference between systems can be limited as much as possible, i.e. there is sufficient distance between DL and UL frequencies and between the systems. However, as can be seen from the figures, in some cases frequency separation is rather small and may lead interference between the systems, which will be further discussed in Chapter 4.

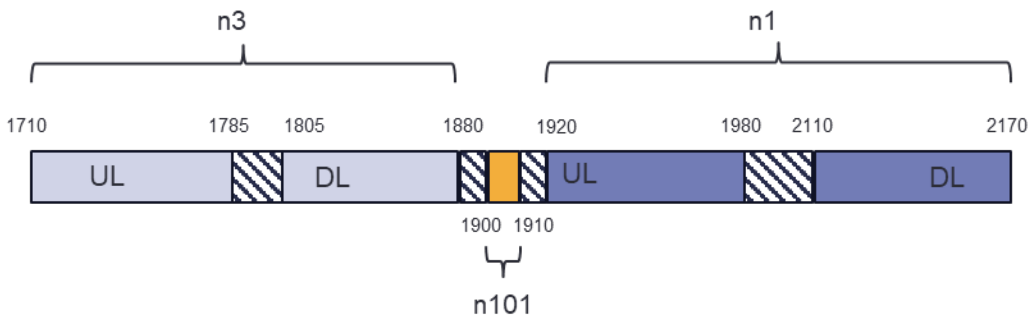

Figure 2 Frequency allocations in mid band

In order to avoid interference and enable co-existence of different systems, specifications set out certain requirements for both base station and user equipment (UE) considering spectrum emission mask for out of band emissions. This applies to both RMR and commercial mobile radios. These specifications will be discussed further later in this document.

Interference mechanisms

Interference can be divided into two main categories. First interference phenomenon is blocking type of interference, and this is directly caused by a strong signal from interfering base station or UE. This could for example mean that train radio receiver saturates and therefore cannot decode anymore the wanted signal due to interfering signal from another system. The other interference phenomenon is unwanted noise emission from interfering transmitter which raises train radio receivers' noise floor. Increased noise floor at receiver means lower sensitivity of the radio.

Both blocking and emission are discussed bit more detail below.

Interference caused by blocking

Blocking is a phenomenon that can be caused by insufficient selectivity, filter discrimination, saturation in the front-end (LNA and/or mixer), reciprocal mixing with local oscillator phase noise or running out of AD converter dynamic range.

Blocking capabilities of a receiver are defined in ETSI standards as a measure of capability of receiving a wanted modulated signal without exceeding a given degradation due to the presence of strong adjacent or nearby signal in frequency domain.

For a given received power level from the wanted signal, the blocking level is defined as the maximum emission level that can be accepted by the receiver from an off-channel interfering signal without preventing the processing of this wanted signal.

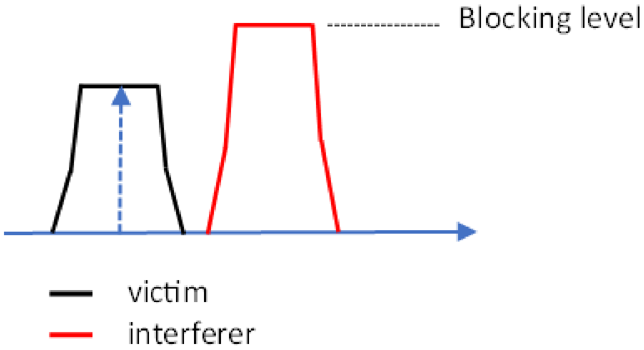

Figure 3: Illustration of the blocking level

Unwanted/out-of-band emission

Out-of-band emissions are unwanted emissions immediately outside the own channel bandwidth resulting from the modulation process and non-linearity in the transmitter but excluding spurious emissions. They raise the noise floor of the receiver and the carrier signal-to-noise ratio (SNR) is reduced, impacting receiver performance.

The out-of-band emissions requirement for the transmitter is specified in terms of an operating band unwanted emissions requirement that defines limits for emissions in each supported operating band plus the frequency ranges 10 MHz above and 10 MHz below each band. Emissions outside of this frequency range are limited by a spurious emissions requirement. In addition, duplex operation and supported simultaneous frequency bands introduce additional requirements for terminal's out of band emissions.

Interference between FRMCS and MNO UEs on the train

Dedicated RMR bands do not interfere with each other, as their operating frequencies are rather far away from each other. When considering co-existence of RMR and MNO networks in the train, operating frequencies are closer and thus likelihood of interference is increased. This will lead to higher isolation requirements between antennas to ensure proper operation of both systems.

Potential UE-UE interference cases

In case of simultaneous usage, most likely interference cases between UEs are in low band between RMR n100 and MNO n8 (LTE or NR) and in mid band between RMR n101 and MNO n1 (LTE or NR). These cases are described in more detail below.

FRMCS UE as a victim, MNO UE as an interferer

As seen in *Figure 4*, n100 (RMR) UL allocation and n8 (MNO) UL allocation are next to each other and there is no separation between the bands. However, as the transmission direction is the same, i.e. from UE to the BTS, the interference scenario is low from train radio point of view.

In low band case the most challenging case is the one between n100 (DL band) and n8 (UL band), where the minimum distance between used frequency bands for different directions is only 4.6 MHz, as can be seen in the figure below. Considering on-board equipment, it is possible that MNO equipment in band n8 transmitting (UL direction) is causing interference to n100 equipment receiving data (DL direction) at the same time due to limited frequency separation.

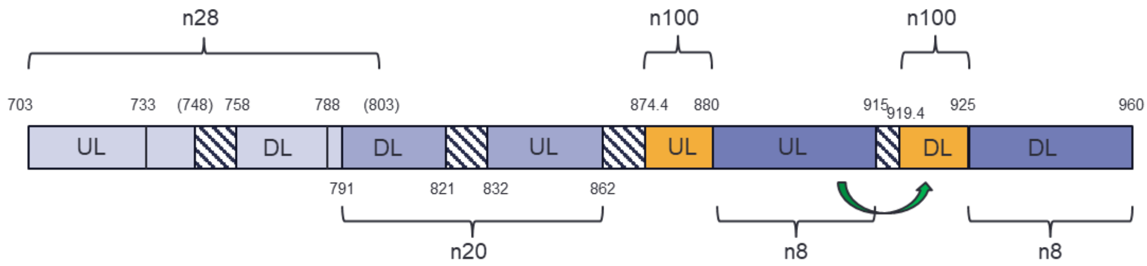

Figure 4: MNO UE interfering FRMCS UE - low band case

In mid band case, see *Figure 5*, there is more separation between n1 UL band and n101 band (TDD), i.e. 10 MHz, compared to low band. However, there is still possibility that n1 on-board equipment transmission may cause interference to n101 equipment receiving data at the same time.

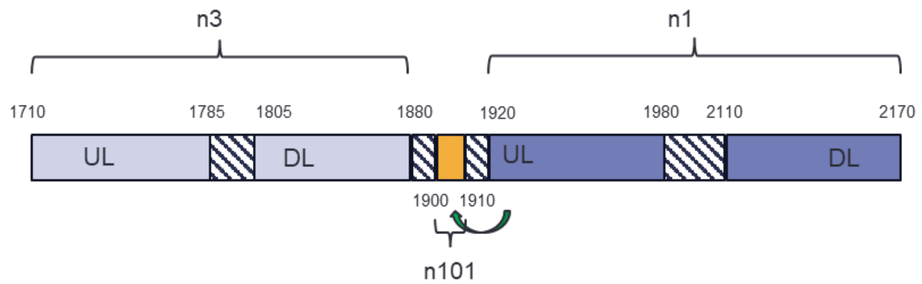

Figure 5: MNO UE interfering FRMCS UE – mid band case

As the blocking requirements of FRMCS UE are strict, in most cases the UE will be able to reject the impact of blocking signal. However, out-of-band emissions may increase the noise level of RMR receiver leading to deteriorated performance in certain circumstances.

Both for low band and mid band cases, the problematic situation may arise when MNO UE is transmitting with high power and FRMCS network coverage is weak, i.e. received signal level is low. In this case MNO UE's high transmission power may interfere with the FRMCS signal reception and cause performance deterioration for FRMCS.

MNO UE as a victim, FRMCS UE as an interferer

In principle there is a possibility for interference also other way round, i.e. FRMCS UE transmitting could cause interference to MNO UE receiving data, see figure below.

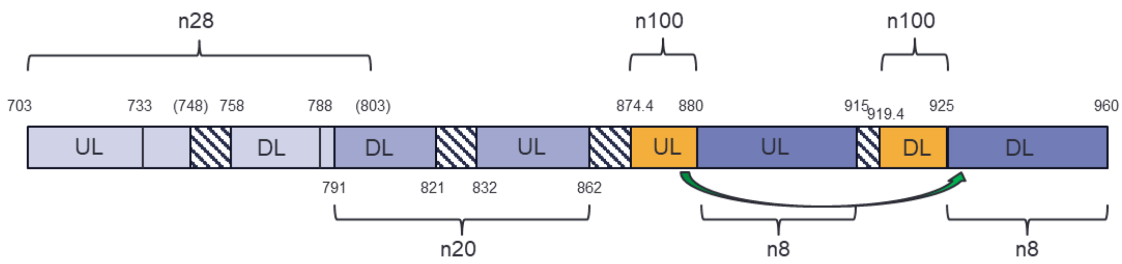

Figure 6: FRMCS UE interfering MNO UE – low band case

However, interference probability from FRMCS 900 UE transmitter at frequency range of 874,4 – 880 MHz to band 8 UE receiver at band 925 – 960 MHz is less likely due to higher frequency separation.

In case of mid bands, the separation from FRMCS band (TDD, thus both receiving and transmitting on the same band) towards n3 DL band is less than in low band and the likelihood of FRMCS transmission to interfere MNO terminal receiving is higher and may potentially cause issues in some cases. However, as commercial mobile networks typically have several frequency bands in use, the impact is likely to be rather limited in practice.

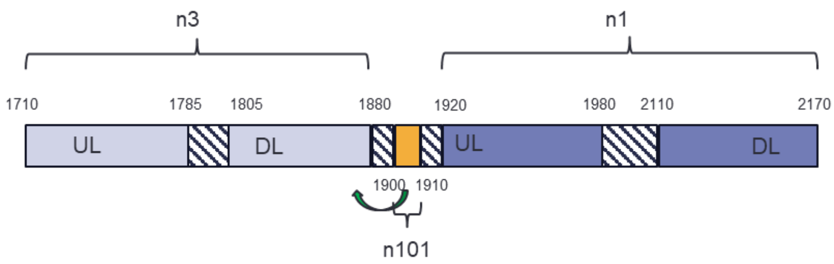

Figure 7: FRMCS UE interfering MNO UE – mid band case

Terminal specifications

Technical specifications by e.g. ETSI and ECC provide, among other things, requirements for UE performance related to tolerance against blocking signals as well as out of band emissions. These requirements aim to ensure terminal performance in different circumstances, including simultaneous DL/UL usage and co-existence of different systems without causing unnecessary interference to each other. These requirements are briefly described below.

FRMCS band n100 and MNO band 8

As discussed in previous chapter, it has been recognised that MNO band 8 UE could cause interference to FRMCS 900 (n100) UE at train radio installations. Potential interference mechanism is unwanted noise emission from band 8 UE transmitter to FRMCS 900 UE receiver. ETSI specifies general spectrum emission masks for transmitters for unwanted noise emissions. ETSI also specifies band-related performance requirements for receivers at normal duplex usage to enable simultaneous transmit and receive operation for normal MNO end-users. This simultaneous transmitter and receiver usage sets requirements for so called duplex filters. These filter requirements are typically more demanding than general spectrum emissions mask requirement, and thus they will have impact on overall unwanted emission level.

In *Figure 8* we demonstrate this situation in more detail. Band 8 UL spans from 880 to 915 MHz, while band 8 DL starts from 925 MHz up to 960 MHz. In the figure the lowest 5 MHz channel is shown for both directions, i.e. 880-885 MHz for UL and 925-930 for DL. Specified spectrum emission mask requirements are shown in the figure as stepwise increasing requirement from -10 dBm (@1 MHz) for the first 5 MHz outside own band to -25 dBm for frequency range of 921-925 MHz (@ 1MHz). After that spurious emission requirements apply.

In addition, in order the UE to work properly for simultaneous DL-UL usage, there needs to be sufficient filtering between its own UL (passband region) and DL (band rejection region) direction (duplex filter). In practice up to 23 dBm transmit signal in pass band region needs to be cut down (filtered) to ensure specified -97 dBm reference sensitivity level of the receiver in band rejection region. In the figure estimation for potential filtering slope to reach this has been presented.

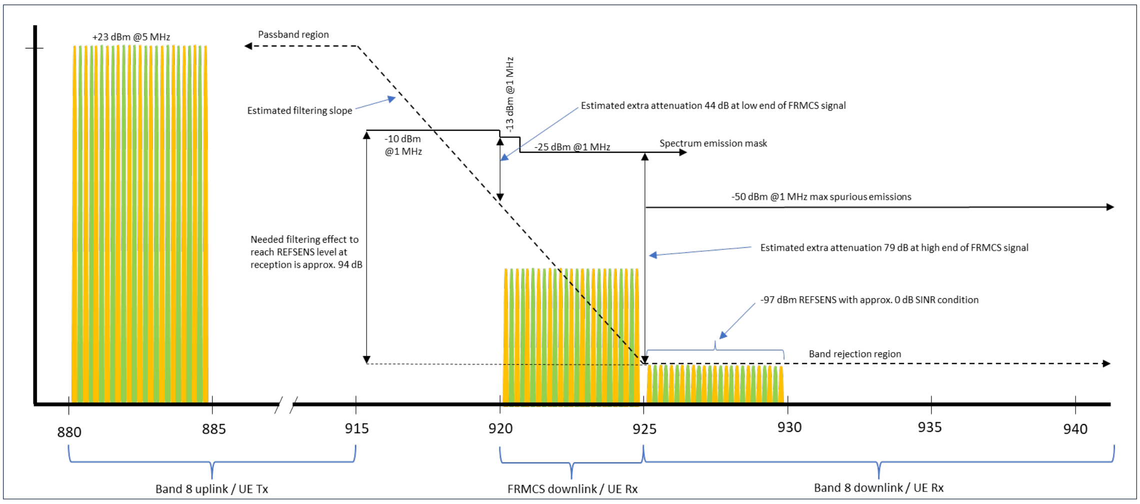

Figure 8: MNO Band 8 UE interference to FRMCS 900 UE

Comparing duplex filter requirements and spectrum emission (unwanted noise emission) mask requirements, it can be observed that duplex filters are likely to introduce significant additional attenuation to FRMCS DL band as well. If assuming this kind of theoretical linear filtering slope, the additional filtering provided would vary from 40 dB up to nearly 80 dB in FRMCS DL band, on top of the emission mask requirements.

FRMCS band n101 and MNO band 1

Interference situation at 1900 MHz band is somewhat different compared to 900 MHz situation. Most significant interference mechanism recognised is the unwanted emission of Band 1 UE transmitter to FRMCS 1900 UE receiver. In this case band 1 UL and DL frequencies are higher than n101 band, thus, there is no need to protect own receiver at this side of frequencies at band 1 UE requirements, i.e. there is no duplex filtering towards n101. Thus, there is no additional attenuation due to duplex filter as there is in the low band.

However, today most commercial mobile terminals support carrier aggregation (CA) features, i.e. combined usage of several LTE/NR frequency bands at the same time. One common frequency pair is band 1 and band 3 carrier aggregation. In this case band 3 receiver needs to be protected from band 1 transmitter with some filtering, see estimate in the figure below.

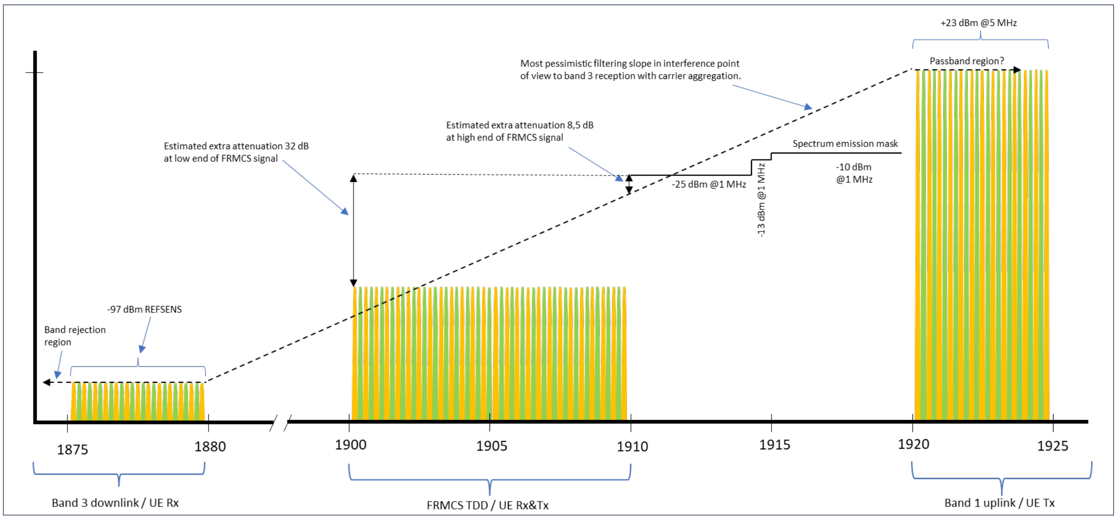

Figure 9: MNO Band 1 UE interference to FRMCS 1900 UE

Figure 9 demonstrates the situation where UE is transmitting at band 1 and at the same time there is band 3 receiving signal. To protect band 3 receiver performance, some filtering is needed, but this filtering slope is less demanding than situation at the low band. Theoretically, assuming linear filtering as shown in the figure above, this filtering situation provides from ~9 dB to ~30 dB additional attenuation for unwanted noise emission to FRMCS 1900 frequencies.

Practical terminal performance

In order to understand the situation in practice and to see what the leakage power of commercial MNO terminals to FRMCS band is, test measurements were carried out with commercial mobile terminal. Measurements were made both for low band and mid band scenario. The measurement setup included Samsung Galaxy S23 terminal with Qualcomm SM8550-AC Snapdragon 8 Gen 2 chipset, which is commonly used by mobile phone manufacturers. Measurement setup is presented in *Figure 10*.

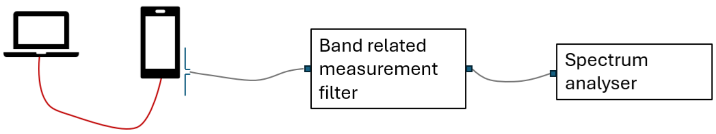

Figure 10: Measurement setup

Commercial Samsung terminal was controlled via measurement SW installed in a laptop. During the measurements the mobile terminal was uploading data continuously, i.e. it was transmitting all the time. Measurements were made with spectrum analyser antenna attached to UE with sticker and rubberband to minimise the coupling loss to UE antenna. The measurement setup included measurement filter to reduce Tx signal of the mobile terminal to achieve better sensitivity for the spectrum analyser on frequencies of interest, i.e. FRMCS frequencies.

Low band measurements

For low band measurements Samsung Galaxy S23 terminal was locked to LTE900 network using 5 MHz bandwidth and frequency range of 909,3-914,3 MHz. Output power was measured first without filter with 100 KHz RBW, as shown in *Figure 11*. Reported transmission power of mobile terminal was 21-22 dBm during the measurements. Measured power was about 14 dBm for 5 MHz LTE signal and this led to 8-9 dB coupling loss for the antenna coupler.

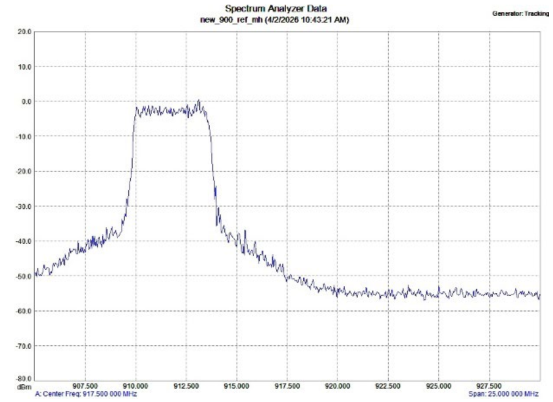

Figure 11: Terminal output power at low band

Measured filter response for the measurement filter is shown in *Figure 12*.

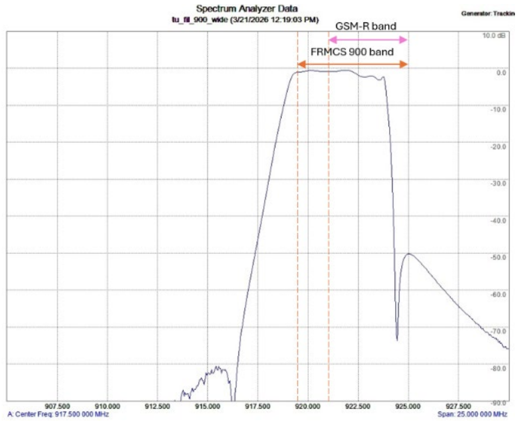

Figure 12: Measured filter response for low band

Figure 13 shows the results of measurements at 900 MHz band. Scaling on the right side of the picture has been normalized taking into account 10 dB antenna coupling loss + filter loss of this measurement, i.e. scaling represents UE output power of 23 dBm. Measurement filter passband starts at ~917 MHz, thus power level goes up there. From FRMCS point of view the area of interest is the frequencies between 919.4-925 MHz.

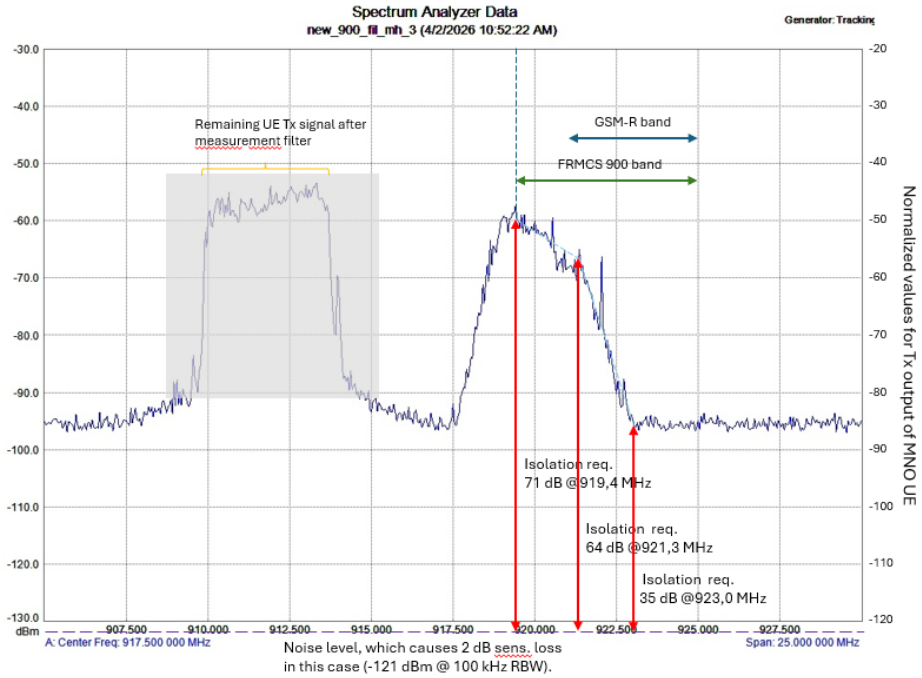

Figure 13: Measurement results at 900 MHz

Noise level causing 2 dB sensitivity loss, -121 dBm, has been calculated assuming 5 dB noise figure for the UE and taking into account 100 kHz RWB used in the measurements. When comparing this noise level and measured leakage power, we can estimate the required isolation between FRMCS and MNO UE. Based on the results of the measurements we can observe that the isolation requirement varies over FRMCS band:

- At the lower end of the band, i.e. at 919.4 MHz, the isolation requirement is estimated to be **71 dB**
- In the middle of the band, at 921.3 MHz, estimation is **64 dB**
- At higher part of the band, at 923 MHz, the estimated isolation requirement is **35 dB**
- Between 923-925 MHz the isolation requirement is **less than 35 dB**, but due to noise floor of our measurement setup it's not possible to determine it more accurately.

Thus, as a conclusion from low band measurements we can see that isolation requirement between systems varies from ~35 dB at higher part of the FRMCS band to 71 dB at lower part of the band.

Mid band measurements

For mid band measurements same terminal was locked to LTE2100 network with 20 MHz bandwidth and frequency range of 1920-1940 MHz. Output power was measured first without filter with 100 KHz RBW. Reported transmission power of mobile terminal was typically 21 dBm during the measurements, see *Figure 14*. Measured power is about 10 dBm for 20 MHz LTE signal and this led to 13 dB coupling loss for antenna coupler.

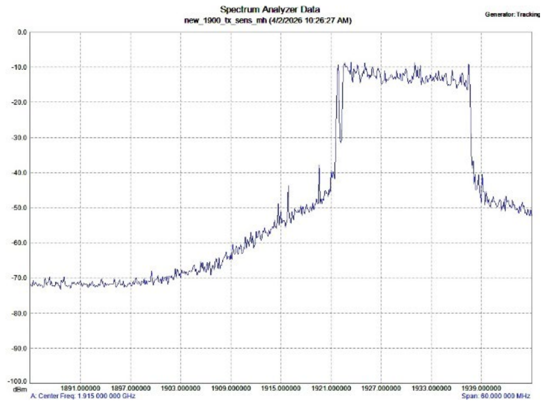

Figure 14: Terminal output power at mid band

Measured filter response for the measurement filter in mid band is shown in *Figure 15*.

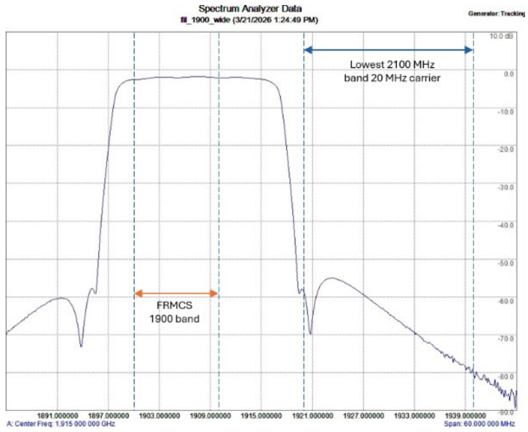

Figure 15: Measured filter response for mid band

Figure 16 presents the results for 1900 MHz band. Scaling on the right side of the picture has been normalized taking into account 15 dB antenna coupling loss + filter loss of this measurement, i.e. scaling represents UE output power of 23 dBm. Measurement filter passband was ~1895-1920 MHz. From FRMCS point of view the area of interest is the frequencies between 1900-1910 MHz.

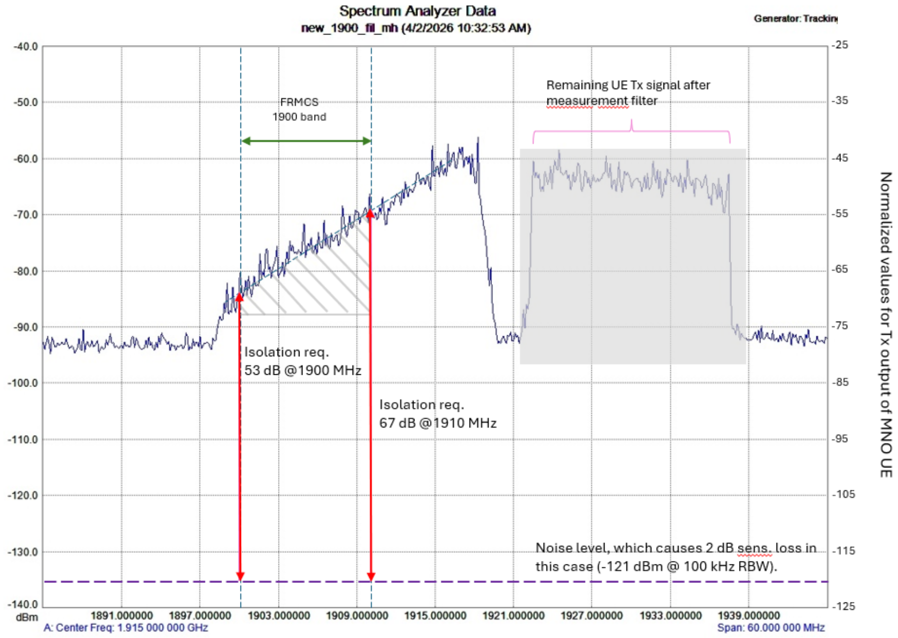

Figure 16: Measurement results at 1900 MHz

Similarly to low band, noise level causing 2 dB sensitivity loss, -121 dBm, has been calculated assuming 5 dB noise figure for the UE and taking into account 100 kHz RWB for the measurements. When comparing this noise level and measured leakage power, we can estimate the required isolation between FRMCS and MNO UE. Based on the results of the measurements we can observe that the isolation requirement varies over FRMCS band:

- At lower end of the band, at 1900 MHz, the estimated requirement is **53 dB**
- At the higher end of the band, at 1910 MHz, the estimated requirement is **67 dB**

Thus, similarly to low band results, we can see that isolation requirement between systems varies, from 53 to 67 dB.

These measurements were made with one type of commercial terminal, Samsung S23 with Qualcomm SM8550-AC Snapdragon 8 Gen 2 chipset, thus additional measurements with other terminals and chipsets to verify the results are recommended. However, based on these measurements we can see that commercial MNO terminals and chipsets available can provide at least this kind of performance.

Filtering requirements based on measured performance

Measurement results in previous chapter show that there is a leakage power from MNO UE to frequency bands used by FRMCS. Thus, there is a need for isolation between FRMCS train radio and MNO UE on-board the train. In typical train implementation FRMCS UE and MNO UE have separate antennas that have certain distance between them. This provides some isolation between the systems. In addition, there is some cable loss in practical implementations. However, most likely there will be a need for some additional filtering between the systems to ensure interference free operation in all situations as the sum of these attenuations is likely to be less than required isolation.

The principle of suggested solution is shown in the figure below. As shown in the figure, separate antennas with 40 dB isolation have been assumed for different systems. In addition, 3 dB cable loss is assumed for both radios.

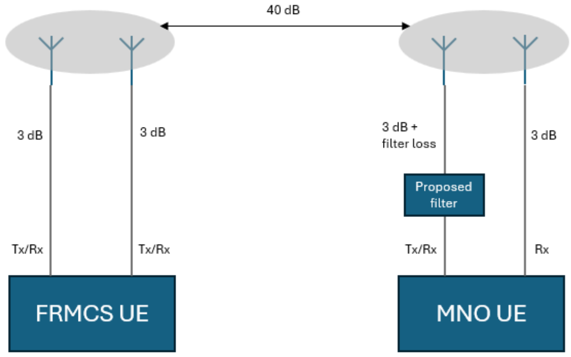

Figure 17: Principle of proposed filter usage

Based on these assumptions and measured results, tentative specification for the filter have been estimated. For low band rejection area minimum attenuation requirement would vary:

- 28 dB attenuation at low end of the frequency band, at 919.4 MHz
- 21 dB in the middle, at 921.3 MHz
- 1 dB at 933 MHz

For mid band minimum filter attenuation requirement would be:

- 10 dB at 1900 MHz
- 24 dB at 1910 MHz

For pass band areas max 1.5 dB loss is suggested.

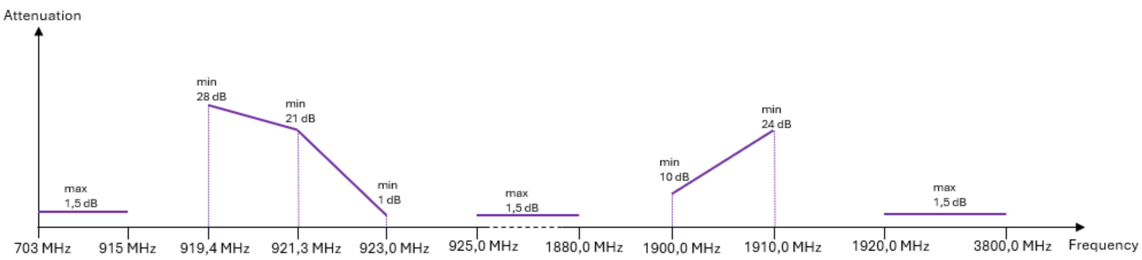

Figure 18: Proposed filter attenuation requirements

These attenuation requirements are based on our measurements and according to our understanding they feasible from practical filter realisation point view, i.e. it should be possible to build such a filter providing sufficient isolation between systems without compromising usage of any commercial MNO frequency bands. Based on the attenuation requirements, potential filter structure could be double notch. Compared to the blocking filters currently used to protect GSM-R from interference, the proposed requirements are similar or even somewhat more relaxed, suggesting that the resulting filter size would be comparable to existing filters already in use.

As the results are based on measurements of one terminal type only, we recommend to test with further terminals to understand better the performance of different terminals and thereafter the filter requirements. Even though, we think that these results provide a good starting point for further discussions for filtering requirements.

Practical considerations and interference mitigation

As discussed above, rather simple filtering solution can be used to avoid potential interference between FRMCS and MNO networks. In practice the interference situations can be rather rare even without filtering. In the following paragraphs we discuss the RMR-MNO use cases, practical usage situations and the likelihood of interference for different use cases in real radio environments.

RMR-MNO use cases

As discussed, combined usage of RMR and MNO networks offers some benefits and combined usage can be utilised to improve resilience, extend coverage and increase capacity. Most likely use cases for joint RMR-MNO operation have been described in FRMCS SRS V.2.1.0 in chapter “12.3.5 Use cases”. These use cases have been listed in the table below. In the table we have also added consideration whether the different systems will be used simultaneously or not in a particular use case.

Table 1 RMR-MNO use cases

Use case	Simultaneous use or interference risk
Application specific Data Path selection	Yes
Fallback	No
Coverage extension	No
Resilience through best path selection	No/Yes
Resilience through packet replication	Yes
Capacity extension	Yes

Potential interference between FRMCS and MNO terminals in train takes place only when there is a need for simultaneous operation, i.e. both systems are used simultaneously. In case of fallback or coverage extension use cases, there is no need for simultaneous usage. Also, in the case of best path selection the need for simultaneous usage is limited. Thus, for these use cases UE-UE interference is less relevant.

Packet replication will require simultaneous usage of the systems, but also in that case the interference is likely to be limited due to small amount of data transmitted (low activity) and simultaneous transmission/reception (i.e. both systems either sending data or receiving data, mixed scenario where one is sending and other one is receiving is less likely).

Application specific data path selection and capacity extension use cases are likely to require simultaneous usage of both systems and are thus more likely to suffer from the interference. From interference point of view the most challenging scenario could be e.g. the case where RMR is used for signalling and MNO is used for transmitting live video from the train. In this case MNO UE could cause performance degradation for the RMR UE. Mitigation for this could be e.g. packet replication or resilience through best path selection, i.e. MNO network could be used to replicate the packets and used instead of RMR for signalling, in case of low performance of RMR system.

Bursty nature of the communications

Typical communication cases for railways do not require continuous transmission/reception all the time, messages and data are sent only when needed and there are idle periods between the data transmissions. Typical data rate requirement for signalling usage is within hundreds of kbps, while modern broadband mobile networks support data rates up to hundreds of Mbps, leading to low activity factor in data transmission.

In addition, in 5G networks even during active transmission the capacity is divided between users, i.e. one user is not transmitting 100% of the time. This is demonstrated in the figures below, which show example of transmission activity variation during the transmission when UL speed test is done. Active TTI means active transmission, during passive TTI there is no transmission.

Measurements were carried out using spectrum analyser and an antenna that was located next to UE. Spectrum analyser was at zero span mode where it expresses signal level in time domain. Centre frequence of spectrum analyser was set in the middle of MNO's 1800 uplink frequency band. Time is shown in x-axis with scale of 50 ms, so there are 50 pcs individual 1 ms TTI slots in one picture. Signal power is presented in y-axis. Individual values are not important, just whether it is up or down, because it indicates if the transmission is active or not.

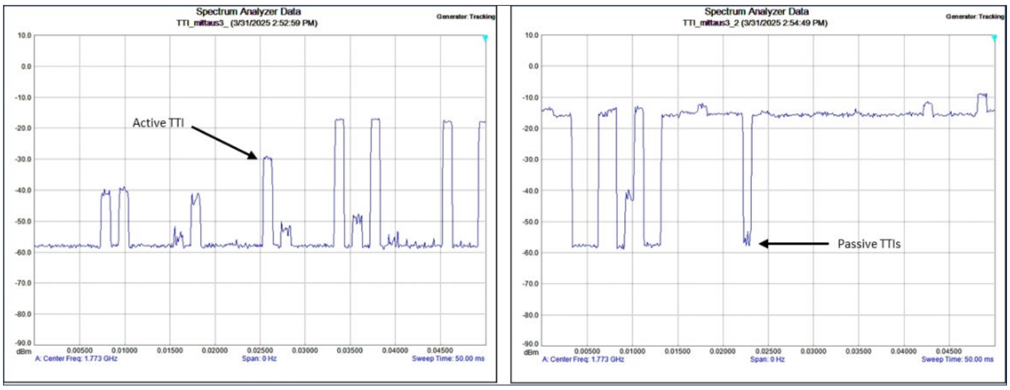

Figure 19 Transmission activity during UL speed test

Measurements were made during UL speed test, when terminal was trying to send as much data as possible to reach the best possible data transmission speed. However, as there are also other users in the network, it was sharing the resources with these other users. So, in practice the terminal is not transmitting all the time and there can be lot of variation in the activity of the terminal even when data is being transmitted. This is well visible in the figures above, the activity on the left side figure is clearly lower and there is limited amount of active TTIs even terminal is trying to send data towards the network. While on the right side picture there are more resources available for the terminal and activity is higher.

The figures above show situation when terminal is trying to send as much data as possible towards the network. In a typical use case in railway environment the amount of data is limited, thus active transmission periods are short, and the resources requested by the terminal from the network are limited. Thus, transmission activity periods will be limited in time.

From interference perspective this means that interference caused by terminal is limited in time, both due to non-continuous need for transmission and due to in-activity periods during the transmission itself.

Impact of radio environment

From interference perspective worst case scenario assumes full transmit power for MNO UE and low signal level for RMR UE. Potentially such a scenario would happen when both systems are far away from its own base station.

UE transmit power is varying based on needed UL power. There are two drivers for efficient power control in terminal (UE) side: battery life and UL interference level. By reducing the used power terminal battery life is longer and the need to re-charge the battery is reduced. In addition, unnecessary interference in UL direction will be avoided, thus improving UL capacity and quality of service.

Sample of UE transmission power distribution in train environment is shown in figure below and it can be seen that UE transmission power varies typically from 0 to 24 dBm and full transmission power is used only limited time. These measurement results were collected from normal commercial terminal inside the train doing active DL and UL transmissions alternately. Assuming that specific terminal with additional antenna on the roof of the train will be used, the radio conditions will be clearly better and even less power would be needed.

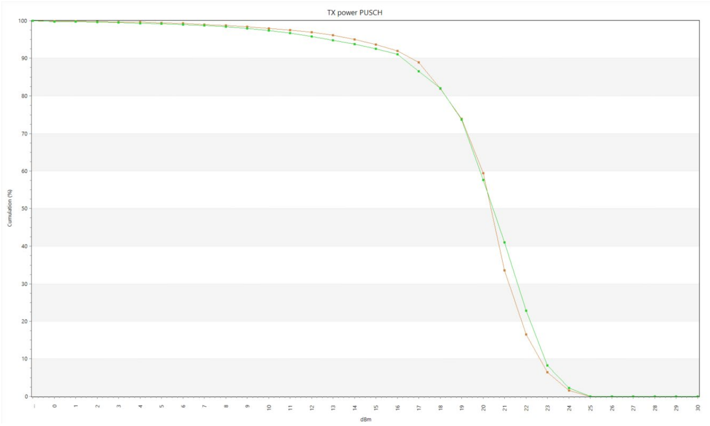

Figure 20 Sample of UE TX power distribution

The impact of the potential interference is at its most when received signal level is low. In practice the signal level varies a lot as the distance between base station and UE (train) varies over time. Figure below shows the distribution of measured 5G signal level of two MNO networks inside the train in a car with so called RF windows. In this example case, average signal level was -86 and -81 dBm for different operators, and poor signal level condition was rather rare, e.g. operator 1 had signal level below -110 dBm less than 1% of the time, while operator 2 the portion was ~7%.

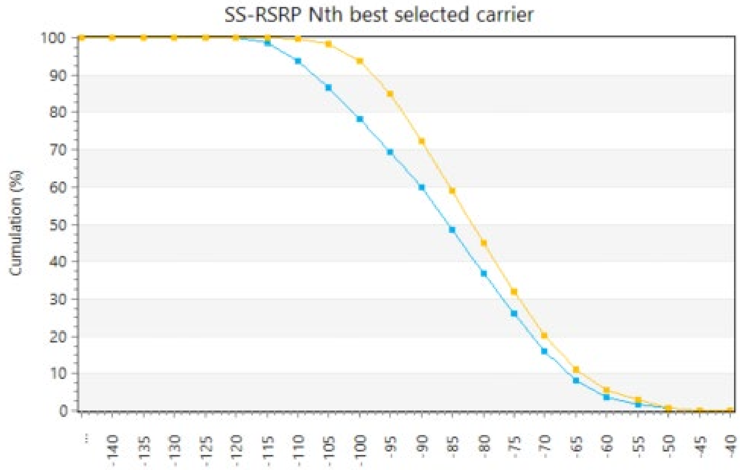

Figure 21 Sample of received signal level distribution inside the train

Considering RMR radio with antenna on top of the train the received signal level is expected to be better than inside the train, as there won't be any in-train penetration loss, and the receiving conditions will be better thanks to higher antenna position and better antenna characteristics. Thus, situations with low signal levels will be even more rare.

Conclusions

Due to closely spaced frequency allocations, there is a possibility of interference between RMR and MNO networks when both are implemented on board a train. This applies especially to low band implementations, but also to mid band implementations.

Terminal specifications have been analysed and practical terminal performance has been measured to better understand UE-UE interference and identify ways to mitigate it. Terminal specifications set requirements for unwanted emissions as well as duplex filtering, which enable co-existence of MNO networks and simultaneous transmit and receive operation for normal MNO end-users. These requirements, along with the need to ensure carrier aggregation performance, shape practical terminal implementations.

To assess the performance of a commercial MNO terminal and its leakage power into FRMCS bands, measurements were taken using a Samsung S23 terminal (Qualcomm SM8550-AC Snapdragon 8 Gen 2 chipset). The results show that while there is power leakage from the MNO UE into FRMCS bands, the leakage is not constant across the band but varies. This means the isolation requirement between systems also varies.

Based on the low band measurements, the isolation requirement between systems is estimated to vary from 35 dB at the upper part of the FRMCS band (n100) to 71 dB at the lower part. For the mid band case (n101), the isolation requirement is estimated to vary from 53 dB at the lower part of the band to 67 dB at the upper part.

In practical implementations, some isolation between systems occurs naturally, due to the physical separation of antennas between different systems as well as antenna cable losses. However, this might not be sufficient, and additional filtering will be needed to avoid performance degradation from interference between systems. Based on an assumed 40 dB isolation between antennas and 3 dB of cable loss for both systems, tentative filter requirements have been estimated. For the low-band rejection area, the minimum attenuation requirement would vary from 28 dB at the low end of the frequency band to 1 dB at 933 MHz. For the mid-band, the minimum filter attenuation requirement would be 10 dB at 1900 MHz, increasing to 24 dB at 1910 MHz.

These filter requirements appear feasible from a practical filter-realisation standpoint — that is, it should be possible to build a filter providing sufficient isolation between systems without compromising the use of any commercial MNO frequency bands. Based on the attenuation requirements, a double-notch filter structure is a potential candidate. Compared to the existing blocking filters used to protect GSM-R from interference, the suggested filter requirements are similar or somewhat more relaxed, suggesting that the resulting filter size would be comparable to filters already in use. With this kind of filtering in place, FRMCS and MNO systems could be used simultaneously on trains, without the need to limit the use of any frequency band.

Since these results are based on measurements from a single terminal type, we recommend testing additional terminals to better understand performance variation across MNO UE devices and refine the filter requirements accordingly. In the meantime, we consider these results a good starting point for further discussion of the filtering requirements to ensure interference free operation of FRMCS and MNO networks in all frequency bands.