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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Railway Telecommunications (RT).

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Executive summary

The goal of the present document is to help railway infrastructure managers identifying features and techniques recommended to optimize radio network performance of a Future Railway Mobile Communication System (FRMCS) in different railway contexts. Several topics have been studied, such as interference mitigation, TDD operation, Doppler effect or impact on time synchronization of sub-carrier spacing and of speed, and a conclusion has been drawn for each of them.

Introduction

3GPP 5G NR is the radio access technology to be used in the Future Railway Mobile Communication System (FRMCS). Some performance evaluations of NR in typical railway deployments have been made in ETSI TR 103 5542 [i.1]. Furthermore, the need has been identified to clarify some technical aspects and assumptions that have been made in ETSI TR 103 554-2 [i.1]. Although ETSI TR 103 554-2 [i.1] highlighted the importance of mitigating interferences to guarantee enough throughput at any location of the train in a cell, especially at cell edge, further study and clarification of possible mitigation techniques was deemed beneficial.

The allocation of a TDD spectrum band for train services in Europe raised some additional questions specific to TDD deployment, in particular when considering continuous operation across country borders, with each country having deployed its own FRMCS network.

The present document has several objectives. A first objective is to provide clarifications about some technical aspects such as Doppler effect impact, impact of sub-carrier spacing and impact of train speed on time synchronization. The second goal is to provide an analysis and a comparison of some different features and techniques that are included in 3GPP specifications regarding interference mitigation techniques in the context of railway-specific deployment scenarios. A third point is to provide an analysis of TDD operation implications regarding synchronization and cross-border coordination.

Overall, the aim of the present document is to help railway infrastructure managers with identifying features and techniques recommended to optimize radio network performance in different railway contexts.

1 Scope

The present document analyses and provides additional information on 5G NR radio performance for FRMCS operation limited to RMR bands 900 MHz (FDD) and 1 900 MHz (TDD).

Starting from the most representative FRMCS use cases defined in ETSI TR 103 554-2 [i.1], the efficiency of different interference mitigation techniques is compared. Further, given the availability of a TDD band for RMR, some aspects related to performance when operating in TDD are explored. Finally, miscellaneous technical aspects affecting radio performance (Inter System Interference, consideration of Doppler effect, impact of the Sub Carrier Spacing (SCS), etc.) are studied.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

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

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

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

[i.1] ETSI TR 103 554-2: "Rail Telecommunications (RT); Next Generation Communication System; Radio performance simulations and evaluations in rail environment; Part 2: New Radio (NR)".

[i.2] Loïc Brunel, Hervé Bonneville, Akl Charaf and Émilie Masson: "System-Level Evaluation of Next-Generation Radio Communication System for Train Operation Services", Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018.

[i.3] G. B., N. H. M., T. B. S., P. M., Fernando M. L. Tavares: "On the Potential of Interference Rejection Combining in B4G Networks".

[i.4] 3GPP TR 36.884: "Performance requirements of MMSE-IRC receiver for LTE BS".

[i.5] ETSI TS 136 423: "LTE; Evolved Universal Terrestrial Radio Access Network (E-UTRAN); X2 Application Protocol (X2AP) (3GPP TS 36.423)".

[i.6] ETSI TS 136 300: "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (3GPP TS 36.300)".

[i.7] Shangbin Wu and Yinan Qi: "Centralized and distributed schedules for non-coherent joint transmission".

[i.8] ETSI TS 138 104 (V17.6.0): "5G; NR; Base Station (BS) radio transmission and reception (3GPP TS 38.104 version 17.6.0 Release 17)".

[i.9] ETSI TS 138 101-1 (V17.6.0): "5G; NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (3GPP TS 38.101-1 version 17.6.0 Release 17)".

[i.10] Bernd Holfeld, Moritz Lossow, Maksym Tyrskyy, Said Mehira, Lourdes Garcia, Simon Biemond, and Christoph Bach: "Field Study on Multi-Antenna Radio Technologies for Future Railway Communications at 1.9 GHz", August 2021.

[i.11] ETSI TS 138 211: "5G; NR; Physical channels and modulation (3GPP TS 38.211)".

[i.12] ETSI TS 138 214: "5G; NR; Physical layer procedures for data (3GPP TS 38.214)".

[i.13] Lars Lindbom (Ericsson®), Robert Love, Sandeep Krishnamurthy (Motorola® Mobility), Chunhai Yao (Nokia® Siemens® Networks), Nobuhiko Miki (NTT DOCOMO), Vikram Chandrasekhar (Texas Instruments®): "Enhanced Inter-cell Interference Coordination for Heterogeneous Networks in LTE-Advanced: A Survey", December 7, 2011.

[i.14] Zainab Zaidi, Vasilis Friderikos, Zarrar Yousaf, Simon Fletcher, Mischa Dohler and Hamid Aghvami: "Will SDN be part of 5G?", February 2018.

[i.15] CEPT ECC Report 353 (16 June 2023): "Cross-border coordination and synchronisation for Railway Mobile Radio (RMR) networks in the 1900-1910 MHz TDD frequency band".

[i.16] 3GPP TR 38.828: "Cross Link Interference (CLI) handling and Remote Interference Management (RIM) for NR".

[i.17] ETSI TS 138 300: "5G; NR; NR and NG-RAN Overall description; Stage-2 (3GPP TS 38.300)".

[i.18] 3GPP TR 36.878: "Study on performance enhancements for high speed scenario in LTE".

[i.19] CEPT ECC Recommendation (23)01 (16 June 2023): "Cross-border coordination for Railway Mobile Radio (RMR) in the 1900-1910 MHz TDD frequency band".

[i.20] IEEE™ Volume 17 - Issue 1: "Interference rejection combining in LTE networks", Y. Léost, M. Abdi, R. Richter and M. Jeschke. In Bell Labs Technical Journal, pp. 25-49, June 2012, doi: 10.1002/bltj.21522.

[i.21] Fernando M. L. Tavares, Gilberto Berardinelli, Nurul H. Mahmood, Troels B. Sørensen, and Preben Mogens: "On the Potential of Interference Rejection Combining in B4G Networks".

[i.22] Haifan Yiny, Haiquan Wang, Yingzhuang Liuy, David Gesbert: "Dealing with the Mobility Problem of Massive MIMO using Extended Prony's Method".

[i.23] Kien T. Truong and Robert W. Heath Jr: "Effects of Channel Aging in Massive MIMO Systems".

[i.24] ETSI TS 138 133: "5G; NR; Requirements for support of radio resource management (3GPP TS 38.133)".

[i.25] ETSI TS 138 213: "5G; NR; Physical layer procedures for control (3GPP TS 38.213)".

3 Definition of terms, symbols and abbreviations

3.1 Terms

For the purposes of the present document, the following terms apply:

cell centre: geographical area where a terminal experiences a good radio link quality (e.g. high SINR values)

cell edge: geographical area where a terminal experiences a poor radio link quality (e.g. low SINR values)

3.2 Symbols

Void.

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

ACLR	Adjacent Channel Leakage Ratio
BBU	Base Band Unit
BS	Base Station
CDMA	Code-Division Multiple Access
CE	Control Element
CJT	Coherent Joint Transmission
CLI	Cross Link Interference
CLI-RSSI	Cross Link Interference - Received Signal Strength Indicator
CoMP	Coordinated Multi-Point
CP	Cyclic Prefix
CSI	Channel State Information
CSI-RS	Channel State Information - Reference Signals
DIP	Dominant Interferer Portion
DL CoMP	DownLink CoMP

NOTE: NCJT, CJT.

DL	DownLink
DMRS	Demodulation Reference Signal
DPS	Dynamic Point Selection
DSRC	Dedicated Short-Range Communications
FDD	Frequency Division Duplex
F-NCJT	Fully overlapped NCJT
gNB	5G Node B
GP	Guard Period
GSM	General System for Mobile communication
HFR	Hard Frequency Reuse
ICI	Inter-Carrier Interference
ISD	Inter-Site Distance
LOS	Line Of Sight
LTE	Long Term Evolution
MAC	Media Access Control
MAC-CE	Medium Access Control - Control Element
MCS	Modulation and Coding Scheme
MFCN	Mobile/Fixed Communications Network
MIMO	Multiple Input Multiple Output
MMSE-IRC	Minim Mean Square Error - Interference Rejection Combining
MRC	Maximum Ratio Combining
NCJT	Non-Coherent Joint Transmission
NF-NCJT	Non-Fully overlapped NCJT
NLOS	Non-Line Of Sight
NR	New Radio
O&M	Operation and Maintenance
OFDM	Orthogonal Frequency Division Multiplex
PFR	Partial Frequency Reuse
PRACH	Physical Random Access CHannel
PRB	Physical Resource Block
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
RF	Radio Frequency
RIM	Remote Interference Management
RMR	Railway Mobile Radio
RRC	Radio Resource Control
RSSI	Radio Signal Strength Indication
SCS	Sub-Carrier Spacing
SFN	Single Frequency Network
SFR	Soft Frequency Reuse

SINR	Signal-to-Noise plus Interference Ratio
SNR	Signal-to-Noise Ratio
SRS	Sounding Reference Signal
SRS-RSRP	SRS - Reference Signal Received Power
SSB	Synchronization Signal Block
TDD	Time Division Duplex
TP	Transmit Power
TRP	Transmission Reference Point
UE	User Equipment
UL CoMP	UpLink CoMP
UL	UpLink

4 Interference Mitigation

4.1 Frequency Reuse Techniques

4.1.1 Presentation

4.1.1.0 Introduction

Hard Frequency Reuse, Soft Frequency Reuse and Partial Frequency Reuse are three different frequency reuse techniques depicted in Figure 1 and described hereafter.

4.1.1.1 Hard Frequency Reuse

Hard frequency reuse consists of assigning different fractions of a frequency band to each cell of a group of cells. This is described by a hard reuse factor. The geographical separation between cells using the same frequency chunk in two different groups is larger, hence the cochannel interference is reduced. In hard frequency reuse the frequency band is divided in a static manner between cells of a group. This provides frequency orthogonality between cells but reduces cell capacity since the allocation is limited to a fraction of the carrier bandwidth (e.g. half of the carrier bandwidth for a hard reuse factor of 2), even in low cell load situation or in absence of interference from neighbouring cells.

4.1.1.2 Soft Frequency Reuse

Using soft frequency reuse, neighbouring cells dynamically coordinate their allocation of frequency resources and transmit power to users based on their knowledge of their radio conditions. This exploits the difference in path loss between different users in the cell by allocating a given fraction of the band with reduced power in a region close to the cell centre while the other part is allocated for cell edge users with higher power. A neighbouring cell does the same but swaps the frequency fractions to maximize the separation and avoid interference. The whole bandwidth is reused in every cell. Soft frequency reuse scheme avoids interference to some extent. Only a fraction of the band is allocated for a given user, but from a network perspective, cell spectrum utilization is much higher compared to a hard frequency-reuse scheme.

4.1.1.3 Partial Frequency Reuse

Using partial frequency reuse, the frequency band is divided into three fractions:

- one fraction used by all cells with relatively low power expected to serve users in cell centre;
- two other equal fractions allocated to neighbouring cells where each fraction is exclusively used by one of the two cells with a high transmission power.

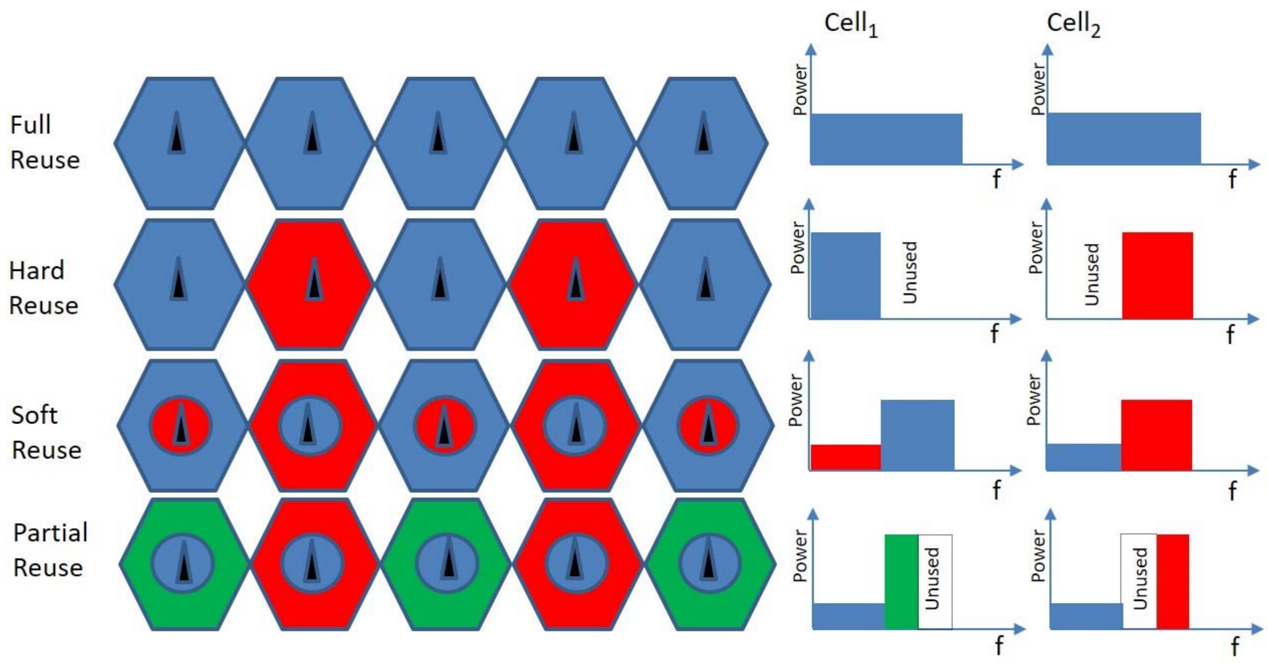


Figure 1: Interference mitigation through frequency reuse

4.1.2 Remarks and Potential Implementation of Frequency-Reuse Techniques

4.1.2.1 Introduction

For clarity, some definitions are provided hereafter. For more details, refers to ETSI TS 138 211 [i.11] and ETSI TS 138 214 [i.12].

Sounding Reference Signals (SRS) are uplink signals designed to infer the uplink channel state information. Sounding Reference Signals are UE-specific and scheduled by BS to gather channel quality on specific RBs. UEs are configured to transmit UL SRS so that the BS can estimate the channel quality in the UL.

Channel State Information Reference Signals (CSI-RS) are DL signal which allows BS to gather Channel State Information. CSI-RS are UE-specific and can be used and configured to fulfil different purposes. They can be multiplexed in time or frequency while they may also be periodic, semi-periodic or aperiodic. It should be noted that, in 5G New Radio, all reference signals are scheduled by the BS.

A UE is notified via RRC messages about the resources on which it is scheduled to receive CSI-RS or through MAC-CE for aperiodic CSI-RS.

Non-Zero Power (NZP-CSI-RS) and **Zero Power (ZP-CSI-RS)** are configured for a given UE so it can estimate the CSI and provide feedback to the base station.

CSI Interference Measurement (CSI-IM) are blank resources used for interference measurement. The BS does not transmit any signals on CSI-IM so that a UE can measure on these configured resources interference signals from other cells.

Measurements that are performed using the above reference signals can be used to exchange information between BS for coordination between cells or on a centralized common scheduler so that the interference can be minimized.

4.1.2.2 Performance of frequency reuse

In [i.2] it is shown how partial frequency reuse outperforms hard reuse and soft reuse and combines their respective advantages. At cell edge partial reuse offers better interference mitigation than soft reuse since the resources used on cell edge by the neighbouring cell are unused (blanked). On the other hand, with partial reuse all cells keep enough bandwidth (reused resources with low power) for mid-cell and cell centre so that the cell capacity is not penalized.

Frequency reuse techniques described above have not been considered in 3GPP specifications for 5G NR. They can potentially be implemented, including hard reuse, at scheduling or RRC level. They could be negotiated dynamically between base stations but could also be configured more statically by O&M, and thus be part of a deployment configuration. However, the detailed implementation impacts (i.e. which components would be impacted and to what degree) have not been studied within the present document.

4.1.2.3 Dynamic Frequency-Reuse implementation

For LTE, 3GPP has defined standardized messages allowing base stations from different vendors to coordinate dynamically their resource allocations through frequency-reuse technique. This can be done:

- in frequency domain:
    - High Interference Indicator (HII);
    - Overload Indicator (OI);
    - Relative Narrowband Transmit Power (RNTP); and also
- in time domain:
    - Almost Blank Subframes (ABS) (ETSI TS 136 423 [i.5] and ETSI TS 136 300 [i.6]).

The standardized signalling is transported between base stations through X2 interface, which has a latency typically of the order of a tens of milliseconds. Hence, the dynamic of a frequency-reuse technique could be expected to be in the order of a few hundred of milliseconds [i.13].

The coordination interface described above for LTE has not been defined in NR specifications but left up to vendor implementation. This means that dynamic frequency reuse could be feasible between NR base stations provided by a single vendor and implementing a vendor-specific coordination messages/interface. Hence, a dynamic frequency-reuse technique is not guaranteed to be inter-vendor inter-operable by the 3GPP NR specifications as of today.

It is also worth noting that for deployment options where one Base Band Unit (BBU) controls several transmission/reception points, a dynamic frequency-reuse technique could be implemented at BBU level for the whole set of transmission/reception points. However, the interference problem remains between zones controlled by different BBUs.

4.1.2.4 Static Frequency-Reuse implementation

Frequency-reuse techniques could also be implemented without the need of inter-base stations communication by providing each of them (e.g. through O&M) some allocation rules for cell-edge UEs. Hard-reuse is typically one possibility, but partial and soft-reuse techniques could also be configured.

For example, one possible implementation of the soft frequency reuse technique is that schedulers in base stations serving two adjacent cells can be configured to allocate the resource blocks for cell-edge users starting from a different edge of the carrier bandwidth. In low load situation and a low data traffic (moderate payload size) condition, this would avoid interference between the two adjacent cells. However, when load and/or data traffic become greater, the two allocations may overlap since they are not aware of each other, and the resulting interference may significantly degrade the performance on both sides.

4.1.2.5 Frequency-Reuse techniques and RMR operating bands

For both 900 MHz and 1 900 MHz bands, soft reuse and partial reuse techniques rely on a single carrier, hence with one Synchronization Signal Bloc (SSB). They could be implemented in a vendor-specific manner, with possible impacts on scheduler and/or other internal functions.

Hard reuse can be understood as a split of the bandwidth into separated RF carriers. In 1 900 MHz where the available bandwidth is 10 MHz, this is possible while in 900 MHz band where the available bandwidth is limited to 5,6 MHz this raises issues as the SSB does not fit in a chunk smaller than 3,6 MHz, and has been considered in ETSI TS 138 211 [i.11], clause 7.4.3.1. However, this issue in 900 MHz band hard reuse can be overcome by implementing hard reuse as a one single carrier via a static splitting of the resources between neighbouring cells for data channels while SSB remains in reuse 1 (see Figure 2). Indeed, SSB and control channels are designed to be robust enough to tolerate cochannel interference among other impairments. ETSI TR 103 554-2 [i.1] includes simulations with reuse factors 1 to 3.

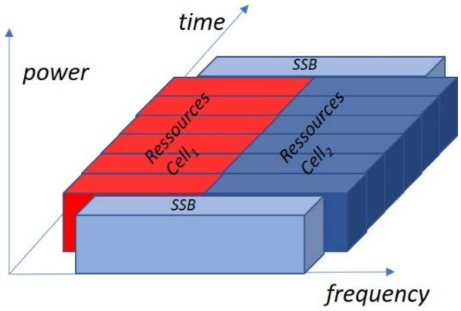


Figure 2: Example of hard frequency reuse implementation as a single carrier with static resource splitting

To be noted that the above frequency reuse techniques go in a different direction compared to 3GPP RAN4's studies on High Speed Train (HST) enhancements for Single Frequency Network (SFN). Indeed, RAN4 study on HST is based on a SFN deployment and targets a different use case compared to FRMCS (typically supporting non-critical data for passengers and not train control applications). Moreover, 3GPP SFN study considers a completely different ISD (below 2 km).

4.2 Coordinated Multi-Point techniques

4.2.1 Downlink Coordinated Multi-Point techniques

CoMP-like techniques can be implemented in 5G New Radio as part of the Multi-Transmission Reception Point (Multi-TRP) framework which includes Coherent and Non-Coherent Joint Transmission (CJT and NCJT) [i.7], 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:

- **CJT** (see Figure 3) performs joint beamforming and assumes accurately synchronized DL transmission with shared data transmitted from all TRPs (same MIMO layer S) and highly accurate CSI reporting for coherent add up at UE. It requires backhaul links with high capacity and low latency as well as synchronization among the CoMP set. CJT requires a central scheduler which collects CSI reports from TRPs then selects the precoding codebooks and schedules the resources accordingly.

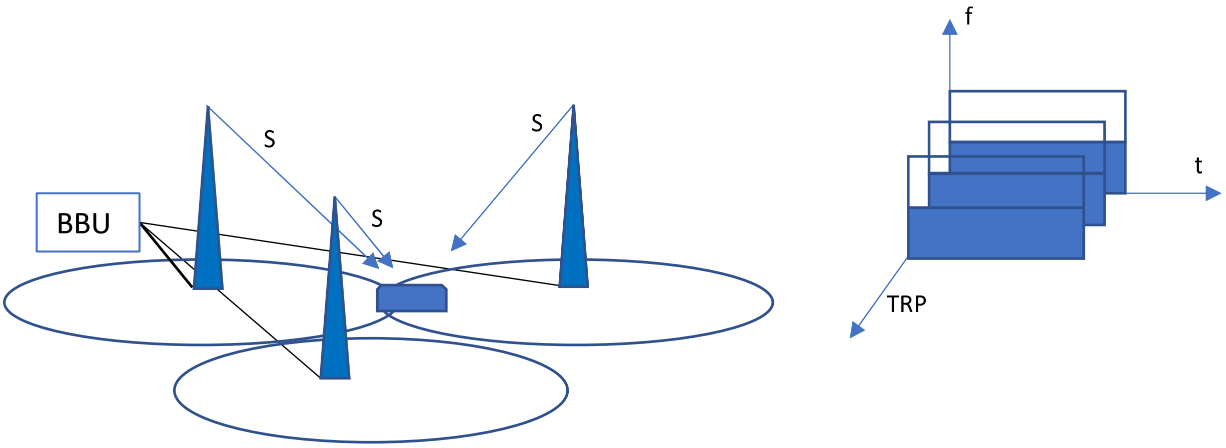


Figure 3: Coherent Joint Transmission (CJT)

- **NCJT** (see Figure 4) assumes synchronized (lower accuracy with respect to CJT) DL transmission with different data transmitted from TRPs (different MIMO layers Si), frequency resources may be overlapping or not. NCJT requires less data exchange among TRPs. It handles each transmission from a TRP to UE individually (MCS selection, precoding and scheduling are performed on each TRP separately). Scheduling for NCJT is implemented in a distributed manner (per TRPs schedulers). This distributed approach is more suitable for operation with non-ideal backhauls. NCJT can be categorized into Fully overlapped NCJT (F-NCJT) and Non-Fully overlapped NCJT (NF-NCJT).

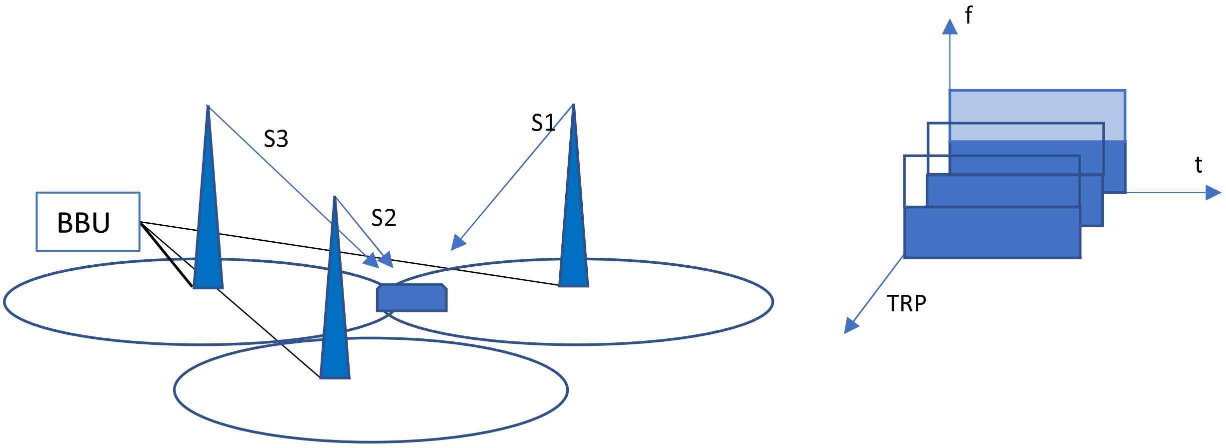


Figure 4: Non-Coherent Joint Transmission (NCJT)

- **F-NCJT (Fully overlapped NCJT)** assumes the same resources (RBs) are used by all TRPs in a CoMP set to a given UE to transmit different codewords/streams. TRPs need to synchronize their resource scheduling but no exchange of data inside the CoMP set is required since the TRPs are transmitting different layers. This solution can be interesting when scheduling geographically separated UEs in different cells, one train close to a cell center while the other one is on the cell edge of the neighbouring cell.

- **NF-NCJT (Non-Fully overlapped NCJT)** is a more distributed scheme and leaves more freedom to each TRP (local scheduler) to choose the resources to be used. There is no need to exchange CSI reports or user data between TRPs.

- **Dynamic Point Selection (DPS)/muting:** data transmission is performed from one point (within the CoMP set) in a time-frequency resource. The transmitting/muting point may change from one subframe to another and may also vary within a subframe. Data are to be available simultaneously at the multiple points of the CoMP set.

If the network can make data available on the different TRPs, DPS can be feasible. However DPS in case of high ISD may not bring gain since the Path Loss difference makes a train stay connected mostly to one cell until reaching the cell edge. [i.7] provides a summary of some requirements of the different DL CoMP techniques.

4.2.2 Uplink Coordinated Multi-Point Reception

Several site sectors from different cells in an Uplink Coordinated Multi-Point set could use multi-TRP features and adaptively select two site sectors (one primary and one secondary) to receive UL signals from a UE (Figure 5). The received signals are sent via backhaul link to central BBU that combines the two signals. When a UE is on the border between two cells, the combination of UL signals received on the two different sites is performed at a central node, it may result in an increase of the SINR and consequently an increase of the cell edge UE uplink average throughput (2 % to 5% increase if the secondary cell load is 100 % (worst case scenario), and 7 % to 13 % if the secondary cell load is 33 %) with linear deployment and ISD around 1 km, see [i.10]). This UL CoMP consists in performing MRC-Combining from multiple base stations.

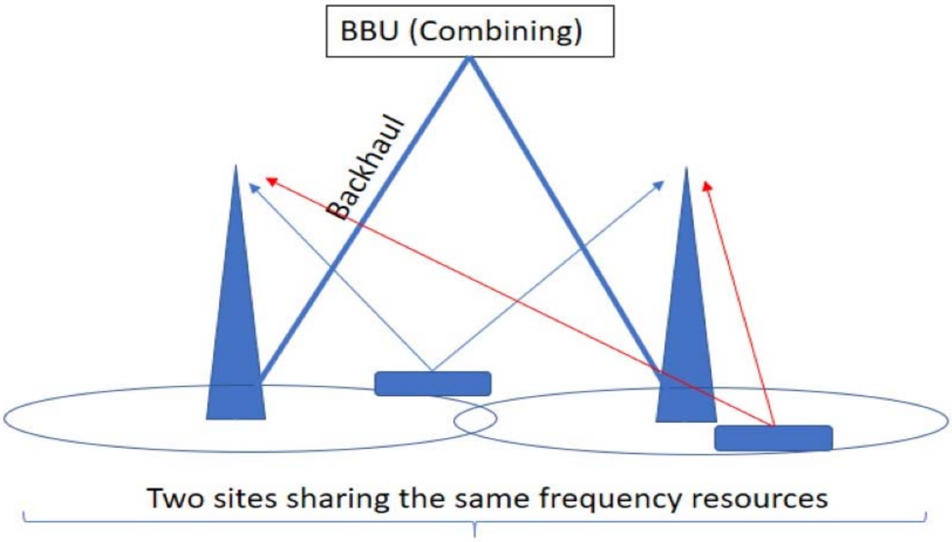


Figure 5: Two sites sharing the same frequency resources

In FRMCS, UL CoMP is practically limited to two sites since any other additional site would be very far from actual train therefore it would receive a very low uplink power and no additional gain can be expected.

Uplink Coordinated Multi-Point groups are disjoint so a site sector can belong to only one Uplink Coordinated Multi-Point group. This implies that UL intercell interference may be observed when the UE hands over from one CoMP group to another. Indeed, the interference problem remains between zones controlled by different BBUs (Figure 6).

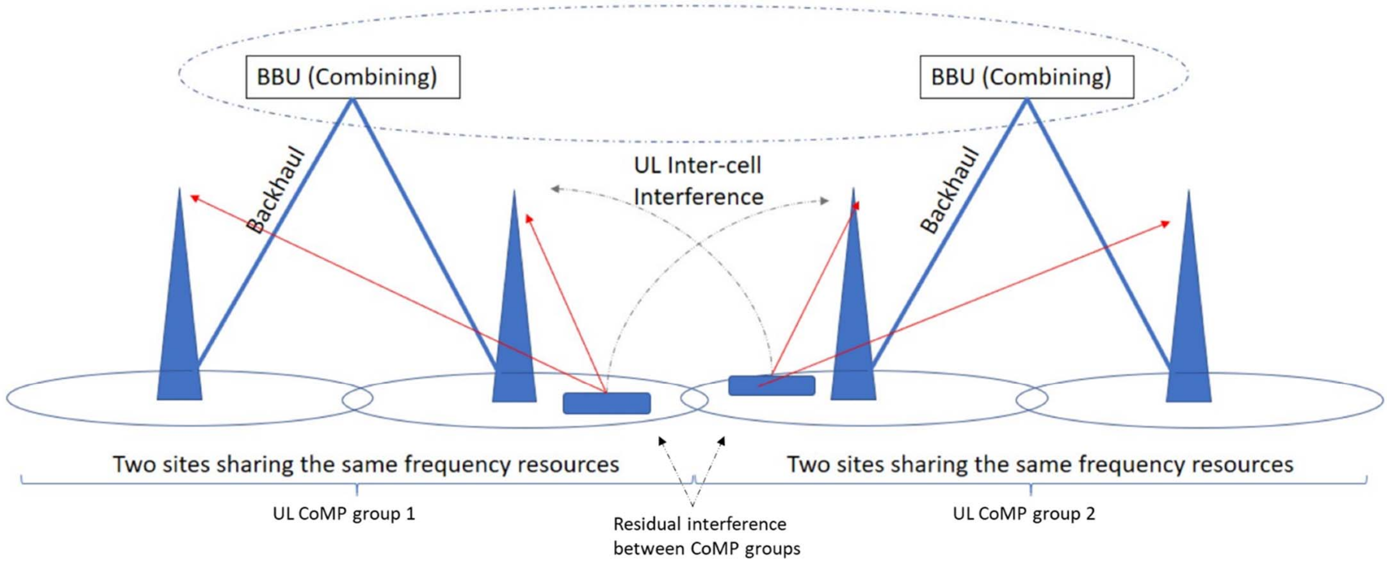


Figure 6: Residual interference between CoMP groups

4.2.3 Backhaul requirements and CoMP zone

The different CoMP techniques put different requirements on the backhaul links connecting the transmission points of a CoMP set and the BBU, especially in terms of transmission delays. For DL techniques, CJT, DPS and F-NCJT require having the data available at all transmission points within a short time window. For UL techniques, data from the different transmission points have to be available at the BBU also within a short time window.

According to [i.14], the one-way delay between radio unit and BBU should be under 75 µs. As the latency of light in the fiber is approximately 5 µs/km, the length of the fiber link between transmission points and BBU should not be more than 15 km. Therefore, CoMP zone could span up to 30 km, i.e. 15 km away along the track from both sides of the combining BBU assuming it located near the track.

4.3 Interference Rejection with MMSE-IRC Receivers

4.3.1 Analysis

Minimum Mean Square Error-Interference Rejection Combining (MMSE-IRC) is a linear receiver based on Interference rejection mostly used in uplink. The linear receiver is designed in such a way to perform a receive beamforming based on the knowledge on the channel between the victim and the aggressor. The beamforming target is to create nulls in the directions of the interferers. In Annex A an analysis of MMSE-IRC in FRMCS is provided. MMSE-IRC requires knowledge of channel characteristics between the victim and the aggressor (i.e. between a train and the interfering BS in DL or between a BS and an interfering train in UL). More details can be found in [i.3] and 3GPP TR 36.884 [i.4].

As MMSE-IRC performance relies on low correlation between wanted and interfering signals. This may be the case especially in urban environment where victims and aggressors are unlikely to be aligned, the speed is relatively low and scattering environment is rich. In such conditions, a low correlation between the channels encountered by the wanted and interfering signals is observed. However, in other scenarios (e.g. rural environment) a higher correlation may be observed, and MMSE-IRC performance might be degraded. Another important aspect is channel information aging especially at high speed, where the CSI varies faster than the MMSE-IRC reconfiguration.

It should be noted that the performance of MMSE-IRC improves with the number of antennas on the reception side.

4.3.2 Remarks

Interference mitigation by frequency reuse is implemented via resource scheduling policies on BS side and during network planning. Interference rejection is performed on receiving side at signal level. Frequency reuse and interference rejection are compatible and can be combined for a better mitigation depending on the scenario as well as other channel information. Residual interference for MMSE-IRC depends on the frequency reuse scheme used on the transmitter side.

4.4 Interference Mitigation through beam management

This aspect has not been studied in ETSI TR 103 554-2 [i.1]. More precisely, non-AAS (Active Antenna array System) base stations were assumed.

4.5 Interference mitigation techniques comparison

4.5.1 Comparison metrics

Inter-cell interference is an important issue regarding FRMCS performance. While most of interference mitigation techniques address public mobile networks deployments, these techniques should be analysed considering railway deployment and service requirements. The following figures are used to compare interference mitigation techniques.

1) ***Imp_CellEdgeThroughput5%*****:** Improvement on cell edge 5 %-ile throughput compared to frequency reuse 1.

2) ***Imp_CellThroughput50%*****:** Improvement on whole cell 50 %-ile compared to frequency reuse 1.

3) ***MultiScenSupport*****:** Ability to cover multiple scenarios and environments (Urban, Rural, Hilly, etc.).

4) ***DeploymentComplexity*****:** Deployment complexity and cost impact including backhaul requirements (sensitivity to Channel State Information (CSI) feedback and backhaul delay, impact on handover performance).

5) ***Interoperability*****:** Interoperability (inter-vendor and inter-operator).

NOTE 1: Improvement in Imp_CellEdgeThroughput5% and Imp_CellThroughput50% metrics may be positive or negative. If a figure is not available, the improvement could be evaluated as code points: high gain/medium gain/small gain/no/small loss/medium loss/high loss.

NOTE 2: When needed, the metric is evaluated per scenario.

NOTE 3: Possible incompatibilities between metrics should be evaluated and noted.

NOTE 4: If required, capability from the UE side to support the feature should be evaluated and noted. The aim is to evaluate whether a particular feature is commonly available in current devices or not.

4.5.2 Scenarios

4.5.2.0 Introduction

Hereafter a list of generic railway scenarios to be considered for the comparison of the different 5G NR interference mitigation is presented.

These scenarios are based on a limited set of those defined in ETSI TR 103 554-2 [i.1] (only the most representative ones have been considered).

4.5.2.1 Urban scenario

This scenario addresses the following conditions:

- Type of environment: urban.
- Train density (for 2 tracks): 0,5 train/km.

- Train speed: maximum 80 km/h.
- Most unfavourable condition: 2 trains crossing at cell edge & 2 trains near the radio site.

4.5.2.2 Station scenario in urban environment

This scenario addresses the following conditions:

- Type of environment: urban.
- Train density (for 12 tracks): 1 train/track.
- Train speed: maximum 60 km/h.
- Most unfavourable condition: 50 % trains crossing at cell edge.
- Moving speed for the handhelds: 3 km/h.

4.5.2.3 Shunting scenario

This scenario addresses the following conditions:

- Type of environment: urban.
- Number of active cargo trains: 10.
- Number operational handhelds (antenna height = 1,5 m) = 10.
- Train speed: maximum 30 km/h.
- Moving speed for the handhelds: 3 km/h.
- Most unfavourable condition: 5 trains at cell edge (including Handhelds) & 5 trains at radio site (including Handhelds).

4.5.2.4 Rural scenario conventional lines

This scenario addresses the following conditions:

- Type of environment: rural.
- Train density (for 2 tracks): 0,5 train/km.
- Train speed: maximum 160 km/h.
- Most unfavourable condition: 2 trains crossing at cell edge & 2 trains near the radio site.

4.5.2.5 Rural scenario high speed lines

This scenario addresses the following conditions:

- Type of environment: rural.
- Train speed: maximum 350 km/h.
- Most unfavourable condition: 2 trains crossing at cell edge.

4.5.3 Comparison tables

Table 1 and Table 2 compare the different mitigation techniques against the metrics defined in clause 4.5.1.

Low speed refers to train speed below 60 km/h, as described in scenarios Station and Shunting.

Medium speed refers to train speed between 60 km/h and 160 km/h, as described in scenarios Urban and Rural conventional lines.

High speed refers to train speed above 160 km/h, as described in scenario Rural high-speed lines.

Table 1: Comparison table - part 1

Interference mitigation technique	Imp_CellEdgeThroughput5%	Imp_CellThroughput50%
Hard Frequency Reuse	High gain in all scenarios	High loss in all scenarios
Soft Frequency Reuse	Medium gain in all scenarios, possibly low gain at high load (if static implementation)	Low loss in all scenarios
Partial Frequency Reuse	High gain in all scenarios	Low loss in all scenarios if dynamic implementation, medium loss if static implementation
MMSE-IRC Receivers	High gain if strong interferer at medium speed (4 Rx) in scenarios with high multipath diversity	No significant impact
CoMP CJT (DL)	High gain inside a COMP zone. Interference issue remains between CoMP zones (see [i.7])	No significant impact
CoMP DPS (DL)	High gain inside a COMP zone. Interference issue remains between CoMP zones (see [i.7])	High Loss since other TRPs are muted on the resources used by cell edge UEs
CoMP F-NCJT (DL)	Loss, since F-NCJT is a more suitable for good radio conditions (high SNR), where receiving multiple MIMO layers from different TRPs can be possible (see [i.7])	Loss since signals from different TRPs show highly different Rx powers In addition, the resources used by different TRPs toward one UE cannot be reused for other UEs
CoMP NF-NCJT (DL)	Gain is observed. Signals from other TRPs are no longer interfering signals, they carry additional data streams to the UE (see [i.7])	Loss since the resources used by different TRPs toward one UE cannot be reused for other UEs
Uplink CoMP (Uplink Coordinated Multi-Point Reception)	Low to medium gain (see [i.10])	Medium gain

Table 2: Comparison table - part 2

Interference mitigation technique	MultiScenSupport	DeploymentComplexity	Interoperability	Notes/Comments
Hard Frequency Reuse	Yes	No requirement on backhaul No impact on handover performance	Inter-vendor and inter-operator (static implementation)	
Soft Frequency Reuse	Yes	No requirement on backhaul No impact on handover performance	Inter-vendor and inter-operator if static implementation, vendor-specific if dynamic implementation	Dynamic implementation is low time scale (typically seconds) If static implementation, possible overlap in high load, leading to less guarantee (lower 5 %-tile gain)
Partial Frequency Reuse	Yes	No requirement on backhaul No impact on handover performance	Inter-vendor and inter-operator if static implementation, vendor-specific if dynamic implementation	Dynamic implementation is low time scale (typically seconds)
MMSE-IRC Receivers		No complexity	N/A	

Interference mitigation technique	MultiScenSupport	DeploymentComplexity	Interoperability	Notes/Comments
CoMP CJT (DL)	Dense scenarios (Urban, Station, Shunting)	High requirement on backhaul: Central scheduler, user data sharing, Joint precoder, Fully overlapped PRB Interference issue remains between CoMP zones	Vendor-specific	
CoMP DPS (DL)	Dense scenarios (Urban, Station, Shunting)	Medium requirement on backhaul: Central scheduler, user data sharing Interference issue remains between CoMP zones	Vendor-specific	
CoMP F-NCJT (DL)	Dense scenarios (Urban, Station, Shunting)	High requirement on backhaul: Central scheduler, user data sharing, Joint precoder, Fully overlapped PRB Interference issue remains between CoMP zones	Vendor-specific	Not transparent to the UE
CoMP NF-NCJT (DL)	Dense scenarios (Urban, Station, Shunting)	Low/Medium requirement on backhaul Interference issue remains between CoMP zones	Vendor-specific	Not transparent to the UE
Uplink CoMP (Uplink Coordinated Multi-Point Reception)	Dense scenarios (Urban, Station, Shunting)	High requirement on backhaul (user data sharing) Interference issue remains between CoMP zones which can be at intervals of 30 km along a railway	Vendor-specific	

Table 3 compares the selected scenarios against the mitigation techniques.

Table 3: Scenarios vs mitigation technique comparison table

	Suitable mitigation techniques					
	HFR	PFR	SFR	DL CoMP	UL CoMP	Remarks
Rural scenario conventional lines • Type of environment: rural • Train density (for 2 tracks): 0,5 train/km • Train speed: maximum 160 km/h • Most unfavourable condition: 2 trains crossing at cell edge & 2 trains near the radio site		X				Main characteristics: • High speed • Short cell dwelling time (90 - 180 s per cell) • Fast varying channel • Low device density • Moderate scattering environment Remarks: • α % (the part of bandwidth in reuse1) is a key factor. (100 - α)/2 % of the resources can be allocated for each of the trains crossing at cell edge

	Suitable mitigation techniques					
	HFR	PFR	SFR	DL CoMP	UL CoMP	Remarks
Rural scenario high speed lines • Type of environment: rural • Train speed: maximum 350 km/h • Most unfavourable condition: 2 trains crossing at cell edge			X			Main characteristics: • Very High speed. • Very short cell dwelling time (40 - 80 s per cell) • Fast varying channel • Low device density • Moderate scattering environment Remarks: • 50 % of the resources for each of the trains crossing at cell edge. 100 % at low load (e.g. one train only per cell, no crossing)
Urban scenario • Type of environment: urban • Train density (for 2 tracks): 0,5 train/km • Train speed: maximum 80 km/h • Most unfavourable condition: 2 trains crossing at cell edge & 2 trains near the radio site		X		X	X	Main characteristics: • Moderate speed • Cell dwelling time (180 -360 s per cell) • Moderate user density • Rich scattering environment Remarks: • Patrial reuse can behave similarly as in rural scenario conventional lines
Station scenario in urban environment • Type of environment: urban • Train density (for 12 tracks): 1 train/track • Train speed: maximum 60 km/h • Most unfavourable condition: 50 % trains crossing at cell edge • Moving speed for the handhelds: 3 km/h				X	X	Main characteristics: • Low speed • Long cell dwelling time • Rich scattering environment • High device density Remarks: • High-speed & low-latency inter-cell backhaul is very likely to be deployed
Shunting scenario • Type of environment: urban • Number of active cargo trains: 10 • Number operational handhelds (antenna height = 1,5 m) = 10 • Train speed: maximum 30 km/h • Moving speed for the handhelds: 3 km/h • Most unfavourable condition: 5 trains at cell edge (incl. Handhelds) & 5 trains at radio site (incl. Handhelds)				X	X	Main characteristics: • Low speed • Long cell dwelling time • Rich scattering environment • High device density Remarks: • High-speed & low-latency inter-cell backhaul is very likely to be deployed

In Table 3, a cross ('X') in the mitigation technique column means that the technique is seen as the preferred one. Several crosses mean that the corresponding techniques are beneficial. They are not incompatible and may be combined.

4.5.4 Conclusion

This clause provides an analysis and a comparison of different interference mitigation techniques in the context of railway-specific deployment scenario.

The following mitigation techniques have been studied: Frequency Reuse (hard, soft, partial), MMSE-IRC receivers, uplink Coordinated Multi-Point Reception (CoMP), and downlink CoMP (Coherent and Non-Coherent Joint Transmission (CJT and NCJT), Dynamic Point Selection (DPS)).

Five different scenarios have been considered: urban, station in urban environment, shunting, rural conventional lines, and rural high-speed lines.

The mitigation technique comparison has been relying on comparison metrics such as improvement on cell edge, improvement on whole cell, deployment complexity and inter-vendor and inter-operator interoperability.

Furthermore, a comparison table (Table 3) provides techniques which are beneficial for each scenario considered. To be noted that the different techniques are not mutually exclusive and could be combined.

Frequency reuse techniques are the preferred ones in scenario with small train density, and especially at high speed. Hard frequency reuse shows a high penalty in terms of bandwidth; partial or soft frequency reuse schemes options perform better on that point and should be favoured. The implementation of frequency reuse techniques could be static (O&M configuration) or dynamic. This latter case requires vendor-specific inter-base stations coordination. The time scale of those mitigation techniques is typically in the order of hundreds of milliseconds.

CoMP techniques are vendor specific. They are high-demanding on the backhaul between radio transmission points and the base-band unit regarding throughput and low latency. Depending on backhaul network performance, a CoMP zone could span up to 30 km. Depending on the deployment scenario and the coverage requirement, if there is any interference between CoMP zones then other mitigation techniques like frequency reuse could be used.

The benefit of downlink CoMP techniques based on non-coherent joint transmission is limited to terminals having this feature implemented. Coherent downlink scheme shows high benefits in theory, but at the cost of a nearly perfect backhaul. Dynamic Point Scheduling (DPS) is less backhaul-demanding.

Downlink CoMP techniques show benefits at low to moderate speeds in situations where a significant train density has to be supported, i.e. typically in urban and shunting scnenarii. They are dynamic, with a time scale in the order of tens to hundreds of milliseconds depending on the complexity of the scheme and the backhaul capacity.

With uplink Coordinated Multi-Point, throughput enhancement can be expected in the CoMP Zone and the benefits in terms of interference mitigation at cell edges depend on the load of the secondary cell and on the propagation environment.

5 TDD operation

5.1 Introduction

As compared to GSM-R which was solely operating in Europe over FDD spectrum, FRMCS will operate over band n101 in Time Division Duplex, taking advantage of the flexibility introduced by 5G NR. Where LTE was limited to a defined subset of TDD frame configurations and associated Special Sub Frame configurations, 5G NR now supports a large number of slot formats allowing an efficient and flexible use of the scarce spectrum available to railways to adapt it to the railway operational needs. The use of TDD nevertheless requires considering several operational parameters to optimize its performance in a railway operational environment.

5.2 Synchronization

Due to its usage of an unpaired frequency band, operating TDD in wide-area network cells requires intra-network time and phase synchronization of the sites within a coverage area within 3 μs as per ETSI TS 138 133 [i.24] (usually conveyed as up to ± 1,5 μs accuracy) to limit interference between receiving and transmitting devices.

Taken time and phase synchronization as granted, performance in TDD operation also requires to consider the frame configuration being used. Optimal operation in TDD is achieved when no simultaneous uplink and downlink occur between any pairs of cells operating within a coverage area.

Preventing uplink/downlink clashes relies on the choice of suitable a Guard Period (GP) and, when two or more cells are involved, the choice of a "compatible" frame structure. The guard period between downlink and uplink needs to be long enough to compensate the propagation delay within the cells (for coexistence with other cells in line of sight and for communication of the gNB with the furthest UE). Two frame structures are deemed "compatible" when their respective TDD frame structures, built on the slot formats identified in Table 11.1.1-1 of ETSI TS 138 213 [i.25], do not result in a simultaneous uplink and downlink.

It has to be noted that TDD operation can still operate in case of uplink/downlink clashes. In such scenario, called "semi-synchronized operation", interference may occur, its severity depending on the relative amount of clashes between the two frame structures and the respective cell loads.

Several mitigation techniques have been identified that may be used to mitigate the impact of semi-synchronized operation on the level of interferences between cells:

- Deployment characteristics: reduced output power, antenna setup, etc.
- Frame rotation: while maintaining the time and phase synchronization, the frame structure pattern can be advanced or postponed in time to maximize alignment of uplink and downlink of the respective frames.
- Downlink Symbol Blanking: a base station scheduler may be configured to switch off transmissions ("blanking") of select downlink symbols which correspond to simultaneous uplink reception or simultaneous gap symbols for the other network.

5.3 Cross-Border Coordination

The previous clause considered in general the question of synchronization (or partial synchronization) within a network. At the border between two countries, similar issues of coordination need to be considered to prevent or at least mitigate interference between two (or more) networks.

CEPT ECC report 353 [i.15] and ECC/REC/(23)01 [i.19] identifies "*reference parameters for synchronized co-channel operation at a border*" that are to be used at the border between two FRMCS networks when no specific other arrangement has been agreed between the two networks. If both networks operate under those "*reference parameters*", they are deemed to be in "*synchronized operation*". CEPT ECC report 353 [i.15] also foresees a possibility for FRMCS operators coordinated between themselves to deviate on a case-by-case basis from the "*reference parameters*", potentially resulting in "*semi-synchronized operation*" with a certain amount of inter-system interference.

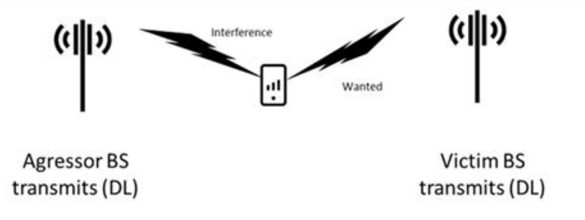
Likewise, [i.15] identifies various mitigation techniques for FRMCS cross-border coordination, identical or similar to those identified at the end of the previous clause.

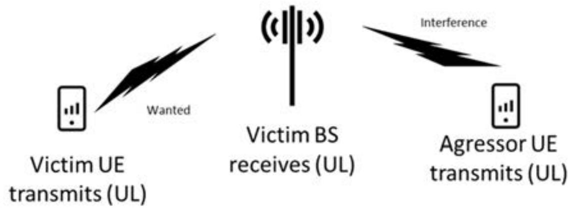
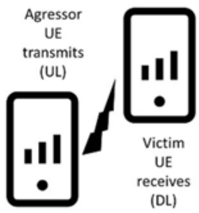
Finally, [i.15] notes that in the context of MFCN cross-border coordination, CEPT recommended two frames, "*frame A*" and "*frame B*" which are expected to be widely supported by 5G NR chipsets. As a consequence, besides the "Fallback TDD Frame Configuration" (which corresponds to the "*reference parameters for synchronized co-channel operation at a border*" of [i.15]), FRMCS systems could be expected to support at least those two "MFCN frames" and use them as part of their network deployments to cater to the diversity of needs and situations induced by the railway operational environment.

5.4 Cross-Link Interference

Table 4 summarizes the interference scenarios that occur between different TDD networks within the same operating band as described in clause 4.3 of 3GPP TR 38.828 [i.16].

Table 4: interference scenarios - TDD (Source: 3GPP TR 38.828 [i.16])

Clause	Description	Figure
4.3.2	Interference scenarios that occur for both synchronized and unsynchronized TDD (including CLI) - DL-DL	 **Figure 4.3.2-1: DL-DL inter-operator interference scenario**

Clause	Description	Figure
4.3.2	Interference scenarios that occur for both synchronized and unsynchronized TDD (including CLI) - UL-UL	 **Figure 4.3.2-2: UL-UL inter-operator interference scenario**
4.3.3	Additional interference scenarios that occur for unsynchronized TDD (including dynamic TDD and CLI) - DL-UL	 **Figure 4.3.3-1: DL-UL adjacent channel interference scenario**
4.3.3	Additional interference scenarios that occur for unsynchronized TDD (including dynamic TDD and CLI) - UL-DL	 **Figure 4.3.3-2: UL-DL adjacent channel interference scenario**

ETSI TS 138 300 [i.17] identifies a mitigation for Cross Link Interference (when UL transmission in one cell may interfere with DL reception in another cell) by requiring gNBs to exchange and coordinate their intended TDD DL-UL configurations over Xn and F1 interfaces and UEs to be configured to perform CLI measurements.

Two types of CLI measurements:

- SRS-RSRP measurement in which the UE measures SRS-RSRP over SRS resources of aggressor UE(s).
- CLI-RSSI measurement in which the UE measures the total received power observed over RSSI resources.

5.5 Remote Interference Management (RIM)

As discussed in clause 5.2, the Guard Period is notably in place to protect the uplink from downlink interference. Under certain atmospheric conditions, downlink transmissions can travel large distances and interfere uplink reception despite the guard period. This type of interference is referred to as Remote Interference (RI). This phenomenon is described in more details in ETSI TS 138 300 [i.17].

Support for undertaking of RIM measures is dependent on the frame structure and on simultaneous emission of a RIM reference signal.

6 Inter-System Interference

FRMCS may experience interference from other adjacent systems such as public mobile networks (GSM, CDMA, LTE, NR), DSRC as well as existing GSM-R network in migration phase within the same band. The mitigation techniques described above (Frequency reuse schemes and MMSE-IRC) apply to cochannel interference (self-interference) since FRMCS by default has no knowledge of external sources of interference, their signal structure and characteristics. Immunity to external interference should be ensured by defining appropriate FRMCS receiver blocking requirements assuming a given deployment and antenna characteristics and taking into account the RF characteristics of the said systems (e.g. GSM/LTE spectrum mask, ACLR, etc.).

7 Doppler Effect

7.1 DMRS configuration trade-offs

Depending on the train position relatively to the base station, the scattering environment may vary between a strong LOS (high Rice factor), a moderate LOS link (low Rice factor) and a NLOS link.

In practice, a high-speed train receiver will experience both quasi-static Doppler shift during some periods of time and dynamic Doppler shift depending on its position relatively to the base station and consequently the scattering environment and the distribution of the angles of arrival. On cell edge Doppler is quasi-static; otherwise, Doppler shift will vary rapidly.

In ETSI TR 103 554-2 [i.1], result sets from companies B and C take these aspects into account. Company B assumes a fixed Doppler shift while company C assume time varying doppler shift. It should also be noted that results from company C account for double Doppler shift in UL since the frequency synchronization is performed based on the shifted signal in DL.

5G NR offers a high flexibility in DMRS configuration for channel estimation, the evaluations in ETSI TR 103 554-2 [i.1] link level simulations assumed 3 DMRS out of 14 symbols in time and full density in frequency domain. DMRS density can be further increased in time domain (e.g. 4 symbols out of 14 instead of 3) for a better Doppler tracking at the expense of a potential loss in spectrum efficiency.

Selection of appropriate DMRS configuration is necessary to find a trade-off between channel estimation performance and DMRS overhead (e.g. increase DMRS density in time and reduce DMRS density in frequency domain, Figure 7).

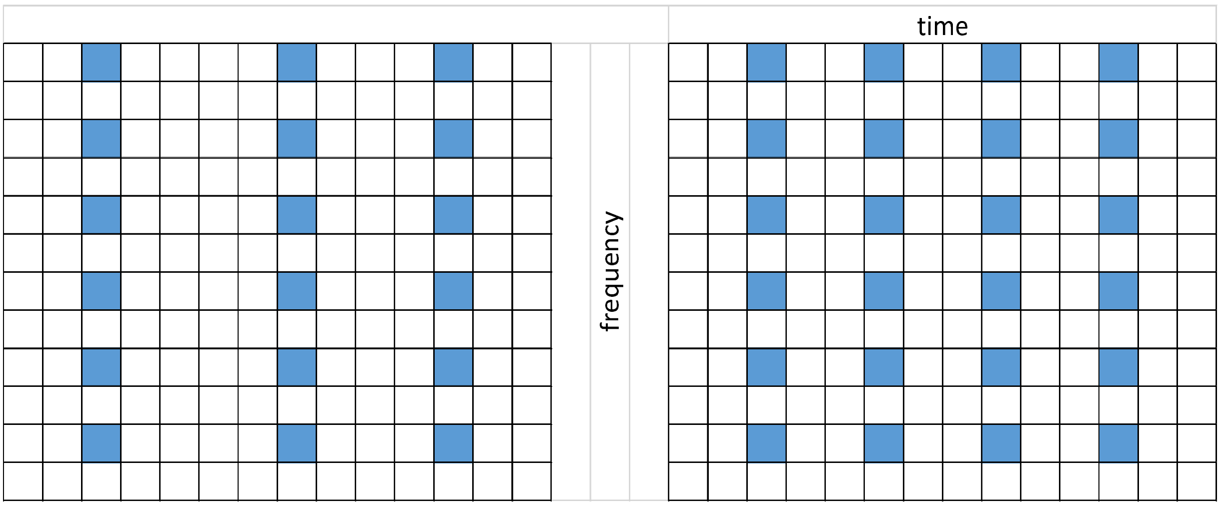


Figure 7: Example of Type-A DMRS configuration (left: assumption ETSI TR 103 554-2 [i.1], right: potential configuration)

7.2 Potential network lay-out constraints related to maximum change rate of doppler shift

In 3GPP TR 36.878 [i.18], 3GPP has studied unidirectional deployment (all cells use directional antennas oriented in the same direction). This network layout is shown to reduce Doppler drift since it induces lower change in the angle of arrival. However, this can be suitable since 3GPP TR 36.878 [i.18] assumes Single Frequency Network (SFN deployment) with relatively low Inter-site distance (up to 700 m).

In FRMCS network and more specifically for high-speed scenario (rural environment 350 km/h or more), the inter-site distance is up to 8 km. This distance cannot be covered by one single cell (one single directional beam) which means that it requires two cells and the train re-selects a new cell at hand over point where the Doppler shift may jump from -fdmax to +fdmax which means a Doppler change of 2 fdmax, (fdmax being the max Doppler shift).

In absence of any Doppler mitigation technique this may cause a radio failure and/or requires a resynchronization operation. In practice Doppler compensation (proprietary) is implemented and when the train is at hand over point, only a residual shift is present (after compensation) and the cell switching induces a fast new shift.

Increasing the distance between the base station and the tracks can reduce the rate of change of Doppler shift since it is related to the angle of arrival of the signal. However, this is true only in LOS situation and small Inter-site distance (e.g. up to 1 km).

8 Impact of Sub-Carrier Spacing

8.1 Analysis

30 kHz SCS offers a better immunity to Doppler effect thanks to its better resistance to Inter-Carrier Interference (ICI). However, increasing the SCS also means a shorter Cyclic-Prefix and a lower resistance to Inter-Symbol interference especially in media where channel delay spread are long, such as urban or hilly environments. SCS 30 kHz is thus more suitable for environments with strong LOS (e.g. rural environment) or cells with small radius and low delay spread. In ETSI TS 138 104 [i.8] and ETSI TS 138 101-1 [i.9], Railway Mobile Radio (RMR) bands were specified for FRMCS. As shown in the following tables, SCS 30 kHz is only supported for band n101 with 10 MHz channel bandwidth (Table 7).

Table 5: NR *operating bands* in FR1
(Source: Table 5.2-1 of ETSI TS 138 104 [i.8])

NR *operating band*	Uplink (UL) *operating band* BS receive/UE transmit $F_{UL,low}$ - $F_{UL,high}$	Downlink (DL) *operating band* BS transmit/UE receive $F_{DL,low}$ - $F_{DL,high}$	Duplex mode
n100	874,4 MHz - 880 MHz	919,4 MHz - 925 MHz	FDD
n101	1 900 MHz - 1 910 MHz	1 900 MHz - 1 910 MHz	TDD

Table 6: *BS channel bandwidths and SCS per operating band in FR1*
(Source: Table 5.3.5-1 of 3GPP TR 38.828 [i.16])

NR Band	SCS (kHz)	5 MHz	10 MHz
	15	Yes	
n100	30		
	15	Yes	Yes
n101	30		Yes

According to ETSI TS 138 104 [i.8], 30 kHz can be used in FRMCS 1 900 MHz band but not in FRMCS 900 MHz band.

Table 7: Calculated Spectrum Utilization (Source: Table 5.3.5-1 of ETSI TS 138 104 [i.8])

ETSI TS 138 104 [i.8] Table 5.3.2-1 for FR1			Calculated Spectrum Utilization (SU) %		
SCS (kHz)	5 MHz	10 MHz	SCS (kHz)	5 MHz	10 MHz
	N_{RB}	N_{RB}		SU	SU
15	25	52	15	= 25 × 12 × 15 / 5 000 = 90 %	= 52 × 12 × 15 / 10 000 = 93,6 %
30	N/A	24	30	N/A	= 24 × 30 × 12 / 10 000 = 86,4 %

8.2 Additional Results

In addition to results presented in ETSI TR 103 554-2 [i.1], complementary results are presented in Annex C and Annex B tackling the effect of 30 kHz Sub-Carrier Spacing (SCS) at high speed in comparison with 15 kHz SCS in the 1 900 MHz band.

In Annex B, perfect channel estimation is assumed while in Annex C real channel estimation is used. The link level simulation results with real channel estimation (Annex C) confirm a significant performance/reliability gain by using 30 kHz SCS especially for high order modulation (see Figure 8 and Figure 9). Accordingly, significant gain in throughput can be achieved at moderate and high SNR (middle and cell centre) which increases the overall cell capacity. While on cell edge, low order modulation (i.e. QPSK) is more likely to be used, no significant gain in throughput can be observed.

Annex C includes in addition link level simulations to evaluate the potential gain from increasing DMRS density. Two patterns are compared with respectively 2 and 3 additional DMRS positions at high speed. From Annex C it can be observed that for most of modulation and coding schemes, increasing the DMRS density does not bring any significant throughput gain because of DMRS overhead increase.

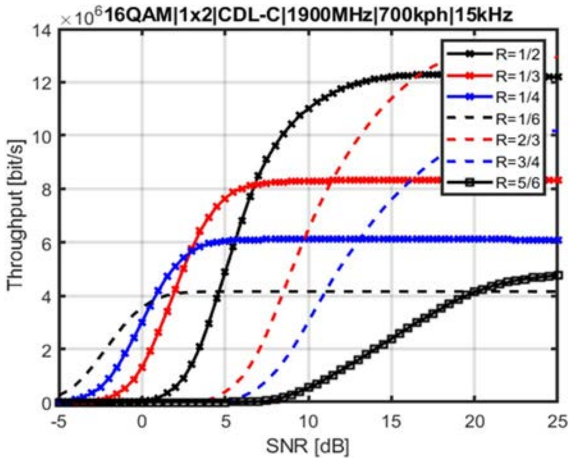


Figure 8: Throughput using 15 kHz SCS,16 QAM and different code rates

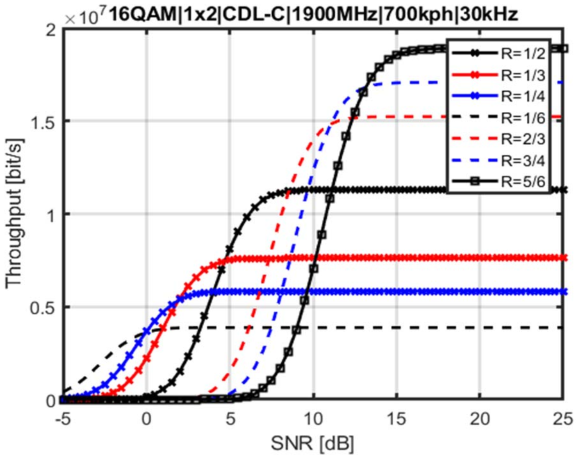


Figure 9: Throughput using 30 kHz SCS,16 QAM and different code rates

9 Impact of Speed on Time Synchronization

In 3GPP TR 36.878 [i.18], 3GPP RAN4 has evaluated Physical Random Access CHannel (PRACH) in High Speed Train Single Frequency Network scenario with unidirectional scenario (ISD = 500 m). It has been concluded that Doppler shift up to 2,4 kHz can be overcome by selecting a suitable correlator. Although the deployment is different compared to ETSI TR 103 554-2 [i.1], in FRMCS deployment PRACH detection can be overcome in the same way.

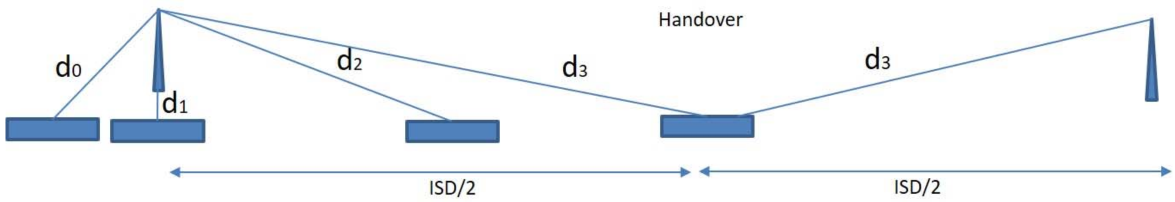


Figure 10: Timing advance in FRMCS

Out of the PRACH procedure, Timing Advance Commands (MAC CE) are used to adjust the timing advance. The timing advance in NR covers the interval [-16,3 µs, 16,3 µs].

The maximum assumed Inter-Site Distance (ISD) in ETSI TR 103 554-2 [i.1] FRMCS deployments is 8 km, which means a cell radius of 4 km. The maximum timing advance between a train in cell center (d_1) and another train on cell edge (d_3) is $(d_3 - d_1) / c$ = 13,3 µs which falls within NR timing advance supported interval.

Continuous Timing Advance correction is needed as the train moves especially at high speed (e.g. 350 km/h, 500 km/h). For this purpose, the TimeAlignmentTimer defines the duration during which the train is considered time-aligned. Timer values can be configured to the following values {500, 750, 1 280, 1 920, 2 560, 5 120, 10 240} ms.

Shortest timer durations are preferred for a better time alignment however this means frequent updates. A tradeoff needs to be found while ensuring a satisfying time synchronization. In other words, time drift lower than the cyclic prefix length is tolerated:

$$TimeAlignmentTimer \leq \frac{CP\ length * c}{train\ speed}$$

Table 8: TimeAlignmentTimer for timing advance

Train speed	15 kHz SCS (CP length 5,2 µs)	30 kHz SCS (CP length 2,86 µs)
500 km/h	11 232 ms	6 177,6 ms
350 km/h	16 045 ms	8 825 ms
100 km/h	56 160 ms	30 888 ms
Recommended Alignment Timer supported by the standard	10 240 ms	5 120 ms

From Table 8, it can be concluded that current 5G NR TimeAlignmentTimer values can cover any speed including 500 km/h for both 15 kHz and 30 kHz SCS. TimeAlignmentTimer of 10 240 ms is recommended for 15 kHz SCS while shorter timer (5 120 ms) is needed for 30 kHz SCS (Table 8). TimeAlignmentTimer values supported by current 5G NR specifications can cover speed higher than 1 000 km/h.

10 Observations and Conclusions

The aim of the present document was to help railway infrastructure managers identifying features and techniques recommended to optimize radio network performance in different railway contexts.

Several topics have been studied: interference mitigation, TDD operation, inter-system interference, Doppler effect, impact of sub-carrier spacing, impact of speed on time synchronization, and potential network lay-out constraints related to maximum change rate of doppler shift. A conclusion for each of these topics is provided hereafter.

Impact of Speed on Time Synchronization

Current 5G NR TimeAlignmentTimer values can cover any speed including 500 km/h for both 15 kHz and 30 kHz SCS. TimeAlignmentTimer of 10 240 ms is recommended for 15 kHz SCS while shorter timer (5 120 ms) is recommended for 30 kHz SCS.

Potential network lay-out constraints related to maximum change rate of doppler shift

Doppler compensation is usually implemented as a proprietary feature. However, the cell switching at handover point induces a fast shift. Increasing the distance between the base station and the tracks can reduce the rate of change of Doppler shift, but this is true only in LOS situation and with small Inter-site distance (e.g. up to 1 km).

Impact of Sub-Carrier Spacing

30 kHz spacing can bring some gain in throughput at moderate and high SNR (middle and cell centre), which increases the overall cell capacity. On cell edge, low order modulation is likely to be used, and 30 kHz spacing brings no significant gain in throughput.

Doppler effect

Selection of appropriate DMRS configuration is necessary to find a trade-off between channel estimation performance and DMRS overhead (e.g. increase DMRS density in time and reduce DMRS density in frequency domain).

Inter-System Interference

Immunity to external interference should be ensured by defining appropriate FRMCS receiver blocking requirements assuming a given deployment and antenna characteristics and taking into account the RF characteristics of the external systems.

TDD operation

TDD operation requires base station time synchronization to prevent uplink/downlink clashes. "Semi-synchronized operation" is still possible however, with the implementation of mitigation techniques as special deployment characteristics (reduced output power, antenna setup, etc.), frame rotation or downlink symbol blanking.

For cross-border coordination, ECC has recommended the use of a fall-back frame configuration in CEPT ECC Recommendation (23)-01 [i.19] It is recommended that FRMCS system supports this frame configuration.

Interferences that could occur between different TDD networks within the same operating band (Cross-Link Interference (CLI)) could be mitigated with gNBs coordination and CLI measurements at the terminals.

Last, remote interference cases could be mitigated with the support of Remote Interference Management (RIM) 3GPP standardized feature.

Interference Mitigation

Intra-system interferences have to be taken into account for a proper-working communication system.

Several mitigation techniques have been studied in the report (Frequency Reuse, MMSE-IRC receivers, Coordinated Multi-Point) in different scenarios and a comparison table has been made.

Frequency reuse techniques are the preferred ones in scenario with small train density, and especially at high speed.

Downlink CoMP techniques for LTE show benefits at low to moderate speeds in situations where a significant train density has to be supported, i.e. typically in urban and shunting scnenarii.

With Uplink Coordinated Multi-Point for LTE, throughput enhancement can be expected in the area covered by the transmission/receiving points coordinated by one base band unit implementing the CoMP.

CoMP techniques are vendor specific and could require a high-performance backhaul. Techniques similar to CoMP could be used for 5G NR but have not been studied specifically in the present document.

In the corresponding clauses for each interference mitigation techniques studied, limitations have been noted from multiple aspects, such as standardization, potential availability and interworking between multiple vendors. These need to be taken into account.

Annex A: Interference mitigation using MMSE-IRC

Minimum Mean Square Error Interference Rejection (MMSE-IRC) receivers are based on a Rx beamforming orthogonal to the source of interference. MMSE-IRC can be used in MIMO spatial multiplexing case where the user and the interfering users belong to the same cell or to reject interference from users in different cells (Figure A-1).

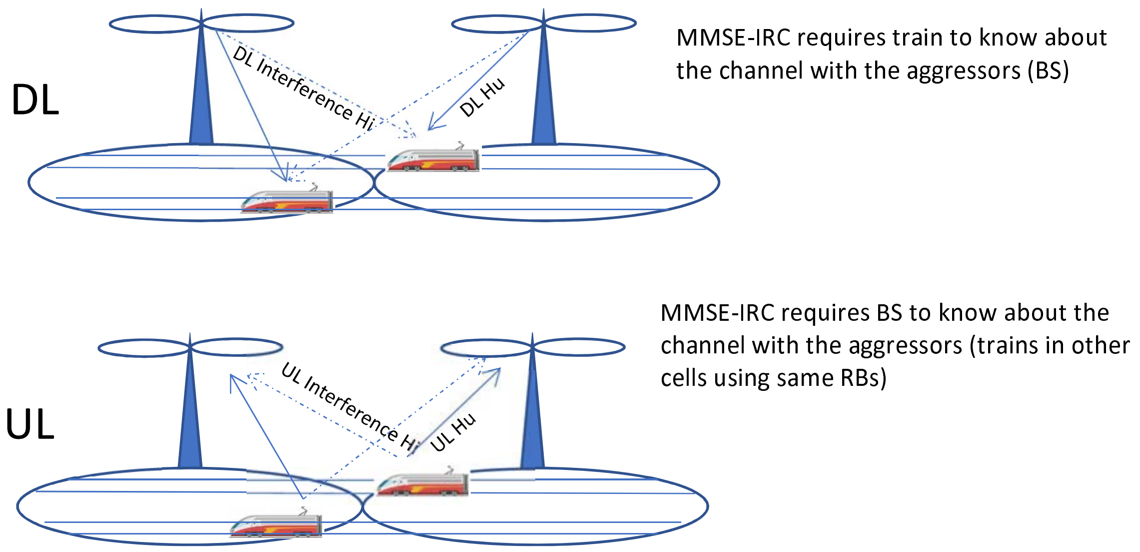


Figure A-1: Inter-cell interference with frequency reuse 1

In uplink, indeed in case the users belong to the same cell, aggressor's channel is known at the BS, which is useful for MMSE-IRC. In case the interferer belongs to another cell, it is not straight forward for the BS to **estimate the channel with an interfering user**. In [i.20] an alternative is given which does not use the interference channel estimation but a covariance matrix.

In DL, MMSE-IRC requires train's receiver to know aggressor channel estimate and/or aggressor channel profile.

In 3GPP 36.884 [i.4] 3GPP has studied MMSE-IRC gain for different cases but only **for UL (BS receiver).**

3GPP used DIP_i (Dominant Interferer Portion) as a key parameter which is the ratio of the ith highest interference power relatively to the total interference power plus thermal noise, $DIP_i = \frac{I_i}{\sum_{i=1}^{N\ interf} I_i + \sigma^2}$. In FRMCS, it is reasonable to assume that interference is mainly caused by one or two interferers ($DIP_1 = 0\ dB\ or\ 1\ dB$).

The achievable gain depends on a number of parameters:

- Modulation and Coding Scheme (MCS).
- Power Delay profile (scenario-specific).
- Speed (Doppler shift).
- Time synchronization.
- Chanel State Information (CSI) accuracy and aging.

According to 3GPP TR 36.884 [i.4] the gain of MMSE-IRC compared to the well-known MMSE receiver in synchronous network assumption (typical TDD scenario) is:

Extract from 3GPP TR 36.884 [i.4]:

Case Num	MCS	Modulation	Propagation condition (Serving, interferers)	Antenna configuration for serving and interferers	(DIP1, DIP2) dB
1	6	QPSK	(EPA5, ETU5)	1x2 Low	(-0,43, N/A)
2	15	16QAM	(EPA5, ETU5)	1x4 Low	(-0,43, -13,78)
3	20	16QAM	(EPA5, ETU5)	1x8 Low	(-0,43, -13,78)
4	6	QPSK	(EVA70, ETU70)	1x2 Low	(-1,11, N/A)
5	15	16QAM	(EVA70, ETU70)	1x4 Low	(-1,11, -10,91)
6	20	16QAM	(EVA70, ETU70)	1x8 Low	(-1,11, -10,91)

Table 8.2-4: Summary of ideal link level simulation results for MMSE-IRC receiver of 10 MHz, 70 % TP (Link level performance details in R4-161523 and Annex 1, different DMRS for user and interferer)

Case Num	China Telecom	Nokia Networks, Alcatel-Lucent (1)	ZTE	Samsung	Huawei	Ericsson	Nokia Networks, Alcatel-Lucent (2)	Average SINR
1	-7,58	-6,4	-7,65	-7,19	-6,26	-7,29	-7,15	-7,07
2	-6,26	-5,2	-6,19	-5,42	-5,72	-6,32	-6,09	-5,88
3	-6,65	-5,5	-6,77	-5,34	-5,36	-6,76	-6,64	-6,15
4	-4,49	-4,3	-4,91	-4,35	-4,51	-3,94	-3,74	-4,32
5	-1,54	-2,2	-2,25	-1,6	-2,01	-1,38	-1,48	-1,78
6	-1,57	-2,2	-2,12	-1,53	-1,21	-1,14	-1,47	-1,61

Table 7.2-2: Averaged performance gain of MMSE-IRC over MMSE in Phase-I evaluation, 70 % TP

Case Num	Average SINR gain (dB)
1	3,1
2	5,9
3	4,7
4	8,3
5	4,9
6	8,9
7	3,1
8	5,5
9	4,4
10	7,5
11	5,0
12	8,4

Summary of link level evaluation

According to the above simulation campaign, the link performance gain of MMSE-IRC over MMSE can be summarized as follows:

- *With respect to homogeneous network, for 1x2 cases the gain is about 3,1 dB; for 1x4 cases the gain is 4,4 dB ~4,7 dB; for 1x8 cases the gain is 4,9 dB ~5,0 dB.*

Therefore, it is concluded that the MMSE-IRC receiver can bring in the significant gain over MMSE receiver.

End of Extract from 3GPP TR 36.884 [i.4].

3GPP has also defined requirements for MMSE-IRC in BS demodulation (uplink only) (clause 8.2.6 of ETSI TS 138 104 [i.8]). The BS enhanced performance requirements for MMSE-IRC receiver are derived by taking into account the ideal simulation results and the additional implementation margin.

It can be noted that the above gain is obtained under assumption of ETU70 (70 Hz) and EVA30 (30 Hz) channels which corresponds to a very low Doppler shift (low speed).

In [i.21], MMSE-IRC is investigated together with frequency reuse but in indoor scenario (low mobility). It is suggested to combine MMSE-IRC and frequency reuse together.

In [i.22], prediction method (Prony method) is evaluated for prediction using MMSE-IRC at speed as high as 60 km/h.

In [i.23], MMSE-IRC with Channel State Information (CSI) aging is considered. It is shown that performance is significantly degraded with CSI aging caused by speed up to 120 km/h for an inter-site distance of 500 m. Also, in [i.23], a channel prediction is proposed to limit the degradation caused by CSI aging.

Annex B:
Effect of Subcarrier spacing on cell edge performance in 1 900 MHz railway scenario

Figure B-1 shows the impact of changing the subcarrier spacing from 15 kHz to 30 kHz for 30 m BS height and 10 MHz bandwidth in the 4 km ISD rural scenario. The results show that this change in subcarrier spacing has no significant impact on the cell-edge throughput.

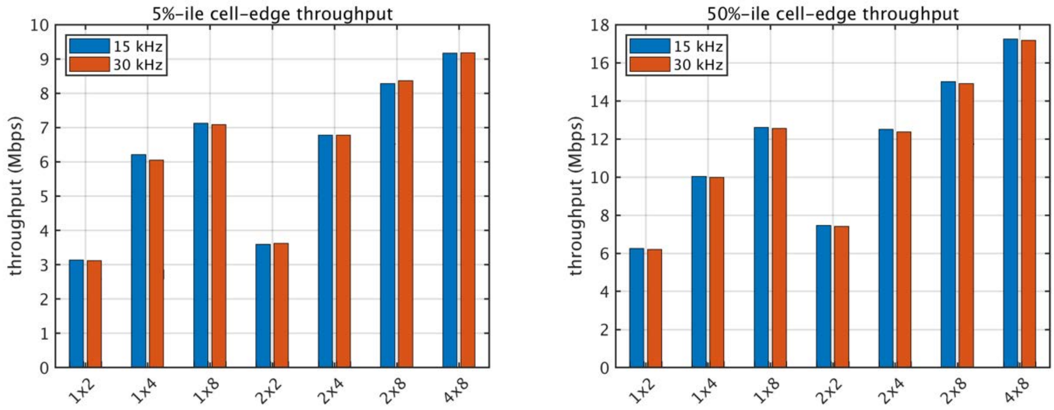


Figure B-1: 5 % and 50 %-ile cell-edge throughput for 15 kHz vs 30 kHz subcarrier spacing, 10 MHz bandwidth, 30 m BS height, 90/10 UL/DL ratio, 31 dBm UE Tx power

Annex C:
Link level simulation on subcarrier spacing effects

C.1 Introduction

Further link level simulations are presented for the 1 900 MHz high speed case, considering the 3 and 4 DMRS configurations depicted below (Figure C-1).

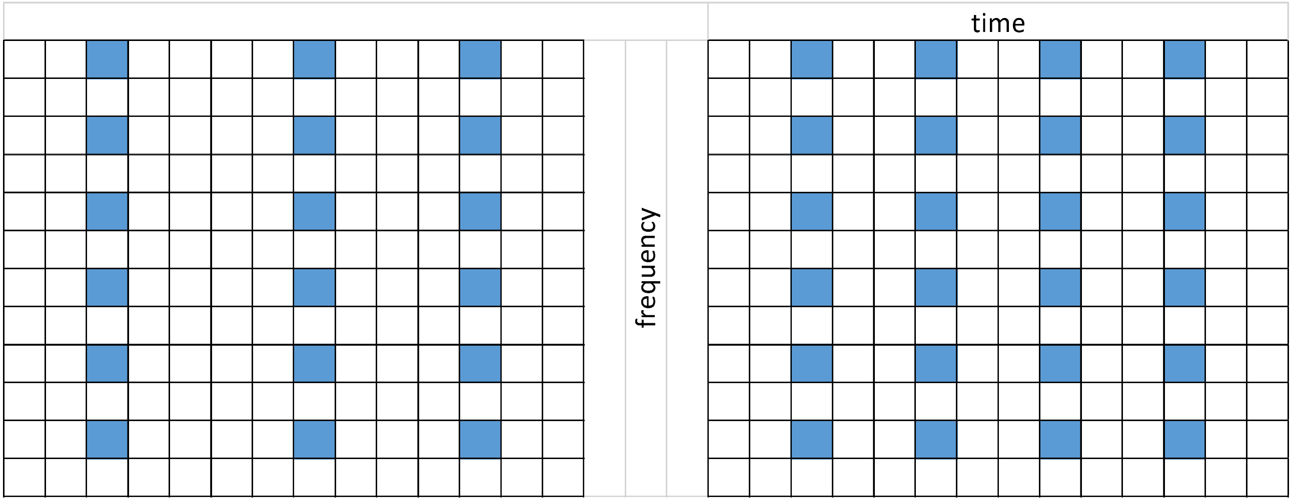


Figure C-1: 3 and 4 DMRS configuration

C.2 Performance summary

Performance summary - 15 kHz

	BLER@10%		Normalized TP@70%	
	Pat. 1	Pat. 2	Pat. 1	Pat. 2
QPSK R=1/2	1.72	1.75	0.3	0.3
QPSK R=1/3	-0.77	-0.93	-2.2	-2.3
QPSK R=1/4	-2.16	-2.33	-3.6	-3.7
QPSK R=1/6	-4.39	-4.31	-5.8	-5.7
QPSK R=2/3	5.29	4.11	3.6	2.7
QPSK R=3/4	6.69	6.15	4.9	4.6
QPSK R=5/6	9.46	8.47	7.2	6.7

	BLER@10%		Normalized TP@70%	
	Pat. 1	Pat. 2	Pat. 1	Pat. 2
16QAM R=1/2	10.45	8.25	7.1	6.4
16QAM R=1/3	4.72	3.62	3.0	2.2
16QAM R=1/4	2.65	2.60	1.1	1.1
16QAM R=1/6	0.46	0.26	-1.1	-1.2
16QAM R=2/3	-	12.27	12.3	9.7
16QAM R=3/4	-	-	14.4	14.1
16QAM R=5/6	-	-	17.5	16.7

	BLER@10%		Normalized TP@70%	
	Pat. 1	Pat. 2	Pat. 1	Pat. 2
64QAM R=1/2	-	-	16.9	15.7
64QAM R=1/3	10.95	8.63	7.5	6.8
64QAM R=1/4	7.14	6.33	5.0	4.6
64QAM R=1/6	3.2	3.12	1.6	1.6
64QAM R=2/3	-	-	-	20.9
64QAM R=3/4	-	-	-	23.1
64QAM R=5/6	-	-	-	-

(*) The listed values represent the SNR requirements (dB) to reach BLER@10% and normalized throughput@70% under different modulation schemes and DMRS patterns (Pat. 1 and Pat. 2 correspond to 3 DMRS and 4 DMRS symbols allocation, respectively.)

Figure C-2

Performance summary - 30 kHz

	BLER@10%		Normalized TP@70%	
	Pat. 1	Pat. 2	Pat. 1	Pat. 2
QPSK R=1/2	1.69	1.90	0.3	0.5
QPSK R=1/3	-0.89	-0.80	-2.3	-2.2
QPSK R=1/4	-2.39	-2.16	-3.8	-3.6
QPSK R=1/6	-4.39	-4.09	-5.8	-5.5
QPSK R=2/3	3.86	4.01	2.4	2.6
QPSK R=3/4	5.12	5.30	3.7	3.9
QPSK R=5/6	6.62	6.56	5.1	5.1

	BLER@10%		Normalized TP@70%	
	Pat. 1	Pat. 2	Pat. 1	Pat. 2
16QAM R=1/2	6.29	6.51	4.9	5.1
16QAM R=1/3	3.29	3.42	1.9	2.0
16QAM R=1/4	1.75	1.94	0.4	0.5
16QAM R=1/6	-0.41	-0.36	-1.8	-1.8
16QAM R=2/3	9.78	9.37	8.4	8.0
16QAM R=3/4	11.36	11.6	9.9	10.1
16QAM R=5/6	13.26	13.11	11.7	11.6

	BLER@10%		Normalized TP@70%	
	Pat. 1	Pat. 2	Pat. 1	Pat. 2
64QAM R=1/2	11.09	11.3	9.7	9.8
64QAM R=1/3	6.79	7.04	5.4	5.7
64QAM R=1/4	5.12	5.29	3.7	3.9
64QAM R=1/6	2.28	2.45	0.9	1.1
64QAM R=2/3	14.79	14.88	13.2	13.3
64QAM R=3/4	15.76	17.56	15.6	15.6
64QAM R=5/6	23.82	22.05	18.7	18.3

(*) The listed values represent the SNR requirements (dB) to reach BLER@10% and normalized throughput@70% under different modulation schemes and DMRS patterns (Pat. 1 and Pat. 2 correspond to 3 DMRS and 4 DMRS symbols allocation, respectively.)

Figure C-3

Table C-1: Simulation assumptions

Parameter	Value
Waveform	CP-OFDM
Carrier frequency	1,9 GHz
Subcarrier spacing	15 kHz, 30 kHz
Speed	700 km/h
MCS	QPSK, 16QAM, 64QAM R = 1/6, 1/4, 1/3, 1/2, 2/3, 3/4, 5/6
Number of symbols	14
DMRS configuration	DMRS Type A, 2 or 3 add pos, 3 dB boost
Antenna configuration	1 x 2
Propagation channel	CDL-C 500 ns
Bandwidth	10 MHz: 52 PRBs (15 kHz), 24 PRBs (30 kHz)

C.3 Results

Performance 1.9GHz, 700kph, QPSK

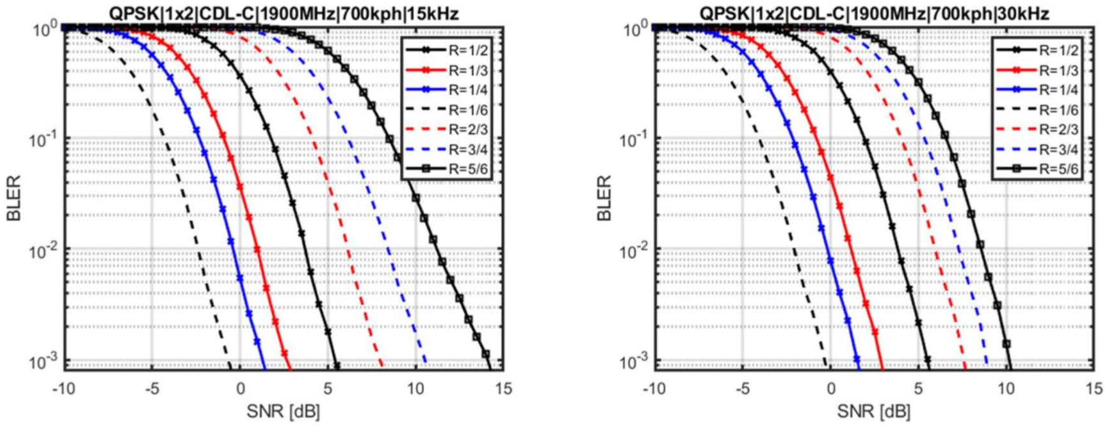


Figure C-4

Performance 1.9GHz, 700kph, QPSK

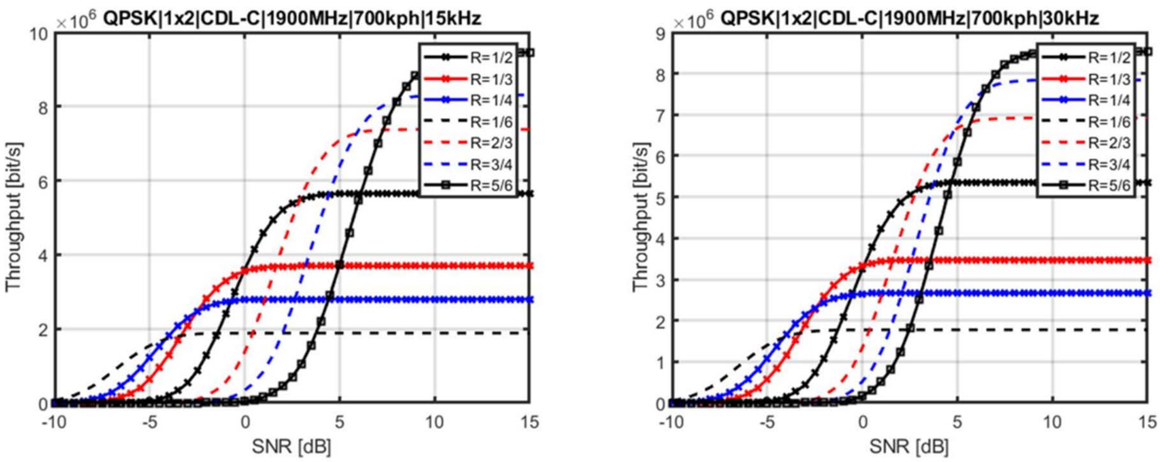


Figure C-5

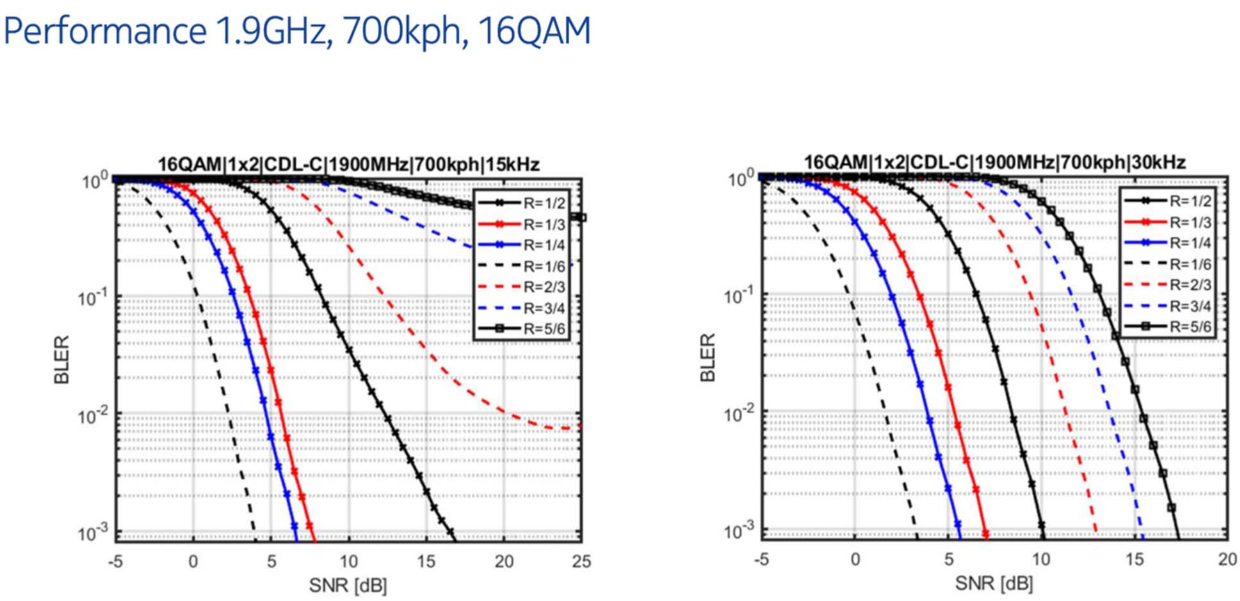


Figure C-6

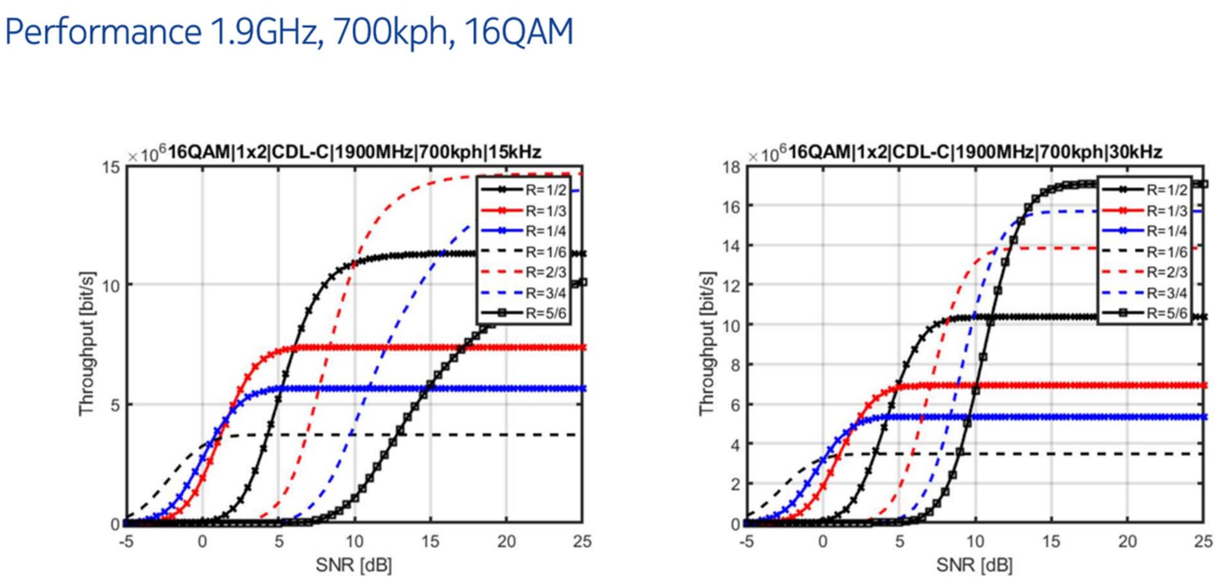


Figure C-7

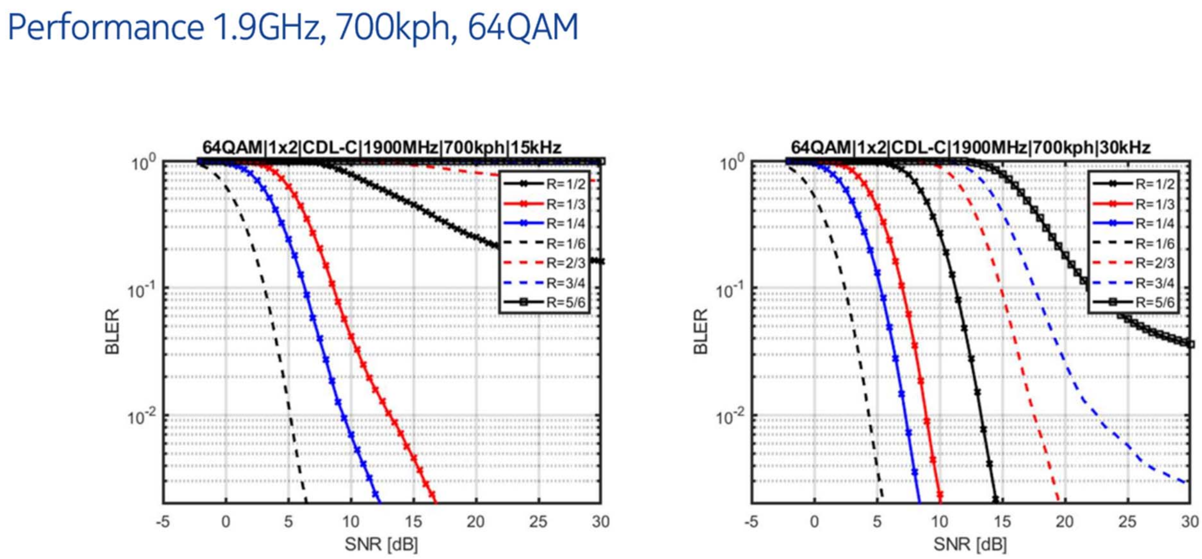


Figure C-8

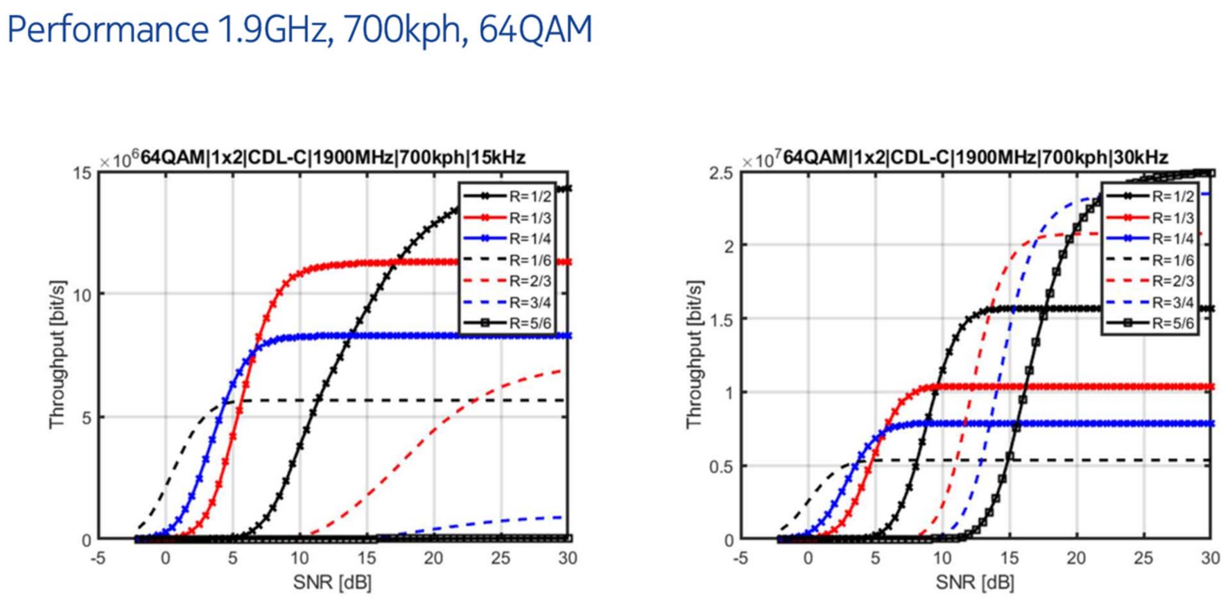


Figure C-9

Annex D: Change History

Date	Version	Information about changes
02/2022	V0.0.1	First draft
03/2022	V0.0.2	Addition of section NR features for FRMCS
	V0.0.3	Updates after drafting session #2
06/2022	V0.0.3	Addition of sections related to interference mitigation techniques comparison after drafting session #3 + references
06/2022	V0.0.4	Updated after drafting session #4
07/2022	V0.0.5	Updated after drafting session #5: Scenarios of interest, CoMP techniques descriptions
09/2022	V0.0.6	Updated after drafting session #6: CoMP techniques descriptions, Scenarios vs mitigation technique comparison table, updated of frequency bands parameters
09/2022	V0.0.7	Updated after drafting session #7: Content of Scenarios vs mitigation technique comparison table, Description update
11/2022	V0.0.8	Updates after RT#87: RT(22)087046, RT(22)087047, RT(22)087025r1
03/2023	V0.0.9	Updates after RT#88: RT(22)088057r1, RT(23)089023 Updates after drafting session #8: Editorials, remove some comments, conclusion on interference mitigation techniques section
05/2023	V0.0.10	Updates after RT#89: RT(23)089065, Interference Mitigation loop timings
09/11/2023	V0.0.11	Updates after RT#91: RT(23)091040, RT(23)091024, on-line comment
25/02/2024	V0.0.12	Updates after RT#91: RT(24)092031 on frequency-reuse techniques, Duplicated text in clause 5.4 removed
12/06/2024	V0.0.13	Update after drafting session #10: Conclusion drafted, clause 11 voided Added executive summary
24/06/2024	V0.0.14	Updates after comments received during Remote Consensus (drafting session #11)
September 2024	V1.1.1	First published version

History

Document history		
V1.1.1	September 2024	Publication