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Deliverable D5.3

Conclusion Report on 5G FRMCS Field Trials

5GRAIL

5G for future RAILway mobile communication system

D5.3 Conclusion Report on 5G FRMCS Field Trials

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Executive Summary

The objectives of the field trials were to provide a realistic FRMCS test environment, based on 5G Standalone radio and core networks, in order to validate technical solutions as well as on-board and trackside prototypes of the 5GRAIL project. The prototypes have been developed and pre-tested in lab conditions in WP2, WP3 and WP4, respectively. In WP5, they have been integrated into real railway environments on rolling stock and rail tracks with dedicated 5G radio coverage, which allow end-to-end evaluation of their functionalities and connectivity performance. For the field trials a test architecture has been developed from which it was possible to deduce all essential test cases in the two 5GRAIL testbeds in Germany (operated by Deutsche Bahn) and France (operated by SNCF). The tests were performed to demonstrate the usability of 5G SA to answer railway needs using mission-critical rail applications and application simulators as well as preparing for cross-border rail scenarios. The selected applications for real-world evaluation are being considered of utmost importance for future railway operations and their test objectives are summarized as follows:

- Integration of Voice applications via 3GPP's mission-critical push-to-talk (MCPTT) functionalities, such as point-to-point calls, group calls and railway emergency calls;
- Integration of Data applications via 3GPP's mission-critical data (MCData) functionalities, such as simulations of ETCS, ATO and TCMS traffic as well as real-time Video for remote vision and CCTV;
- Emulation of 5G bearer flexibility and FRMCS border-crossing scenarios.

The performed end-to-end field tests (as well as the lab tests) shall allow the 5GRAIL consortium to feedback findings into the ongoing FRMCS v1/v2 specification process. This is important in order to underline points of concerns and trigger enhancements, and to define additional measurements that could give further insights at this stage of the mock up where many prototypes stand at an early development phase.

The main purpose of this deliverable is to provide the reader with a summary and key findings from the WP5 test trials in the field and to provide lessons learnt and considerations for future trial setups.

Abbreviations and Acronyms

Abbreviation	Description
3GPP	3rd Generation Partnership Project
5GC	5G Core
5G NSA	5G Non Standalone
5G SA	5G Standalone
5QI	5G QoS Identifier
AMF	Access and Mobility Management Function
API	Application Programmable Interface
APN	Access Point Name
ATO	Automatic Train Operation
ATP	Automatic Train Protection
BTS	Base Transceiver Station
CCTV	Closed Circuit TeleVision
CDF	Cumulative Distribution Function
COTS	Commercial Off-the-Shelf
CP	Control Plane
CSCF	Call/Session Control Functions
CU	Centralized Unit
CW	Calendar Week
DB	Deutsche Bahn
DL	Downlink
DMI	Driver Machine Interface
DN	Domain Name
DSD	Driver Safety Device
DU	Distributed Unit
E2E	End-to-End
eMLPP	Enhanced Multi-Level Precedence and Pre-emption service

eNB	eNodeB
EPC	Evolved Packet Core
ES3	Engineering Sample 3 (reference to the Thales n39 band chipset)
ETCS	European Train Control System
EU	European Union
EVC	European Vital Computer
FDD	Frequency Division Duplexing
FFFIS	Form Fit Functional Interface Specification
FIS	Functional Interface Specification
FRMCS	Future Railway Mobile Communication System
FRS	Functional Requirements Specification
GA	Grant Agreement
GBR	Guaranteed Bit Rate
GCG	Ground Communication Gateway
GDCP	Graphical Driver's Control Panel
gNB	gNodeB
GNSS	Global Navigation Satellite System
GoA	Grade of Automation
GPS	Global Positioning System
GRE	Generic Routing Encapsulation (RFC8086) -> Tunnel GRE
GSM-R	Global System for Mobile Communications – Railway
GTW or GW	Gateway
H2020	Horizon 2020 framework program
HD	High Definition
HMI	Human Machine Interface
HSS	Home Subscriber System
IMS	IP Multimedia Subsystem
IP	Internet Protocol

IPcon	IP Connectivity Service
IWF	Interworking Function
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
MCG	Mobile Communication Gateway
MCPTT	Mission-critical Push-to-Talk
MCX	Mission-critical Service (Voice Push-To-Talk or Video or Data)
MIMO	Multiple Input Multiple Output
MQTT	Message Queuing Telemetry Transport
N3IWF	Non-3GPP Inter Working Function
NR	New Radio
NSA	Non-Stand Alone (5G Core architecture)
NTG	Network Transmission Gateway
NTP	Network Time Protocol
O&M	Operation & Maintenance
OB	On-Board
OB_GTW	On-Board Gateway
OBA	On-Board Application (e.g. ETCS on-board, ATO on-board)
OBU	On-Board Unit
OTA	Over The Air
OTT	Over The Top
PCC	Policy and Charging Control
PCF	Policy Control Function
PCRF	Policy and Charging Rules Function
PDB	Packet Delay Budget
PDN	Packet Data Network
PER	Packet Error Rate
PIS	Passenger Information System

PSS	Process Safety System
PTT	Push-to-talk
QCI	QoS Class Identifier
QoS	Quality Of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RBC	Radio Block Centre
RDS	Remote Driving System
REC	Railway Emergency Call
REST	REpresentational State Transfer
RF	Radio Frequency
RSRP	Reference Signal Received Power
RTCP	Real-Time Transport Control Protocol
RTD	Round Trip Delay
RTP	Real Time Transport Protocol
RTT	Round Trip Time
RU	Radio Unit
RV	Remote Vision
SA	Standalone
SCS	Subcarrier Spacing
S-CSCF	Servicing-CSCF (Correspondence IMPU - @ IP)
SIP	Session Initiation Protocol
SINR	Signal to Interference and Noise Ratio
SMF	Session Management Function
SNCF	Société Nationale des Chemins de fer Français
SSH	Secure Shell
SRS	System Requirements Specification
TC	Test case

TCMS	Train Control Management System
TCN	Train Communication Network
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TE	Test Environment
TFT	Traffic Flow Template
TLS	Transport Layer Security
TOBA	Telecom On-Board Architecture
TRDP	Train Realtime Data Protocol (see IEC 61375)
TS	Trackside
TS_GTW	TrackSide Gateway
TSE	Track Side Entity (e.g. RBC, KMC, ATO trackside)
TSI	Technical Specification for Interoperability
UDP	User Datagram Protocol
UE	User Equipment
UIC	Union Internationale des Chemins de fer
UL	Uplink
UP	User Plane
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communications (5G)
URS	User Requirements Specification
VMS	Video Management System
VoNR	Voice over New Radio
VoLTE	Voice over LTE
VPN	Virtual Private Network
WP	Work Package (e.g. WP1, WP2, WP3, WP4, WP5)

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1 INTRODUCTION

1.1 Background of WP5

The objectives of work package (WP) 5 are to provide a 5G-based FRMCS railway field test environment to evaluate technical solutions and prototypes developed as part of the 5GRAIL innovation project.

The prototypes developed and tested in the laboratories as part of work being executed in WP2, WP3 and WP4 are integrated into real railways environment, i.e., rolling stock running on rail tracks with dedicated 5G radio coverage, which allows the evaluation of their end-to-end functionalities and performances. The field tests, accomplished in WP5, demonstrate the usability of 5G to answer essential railway operational needs using railways applications and application simulators. In addition, different configurations with relevance for cross border scenarios are in scope, e.g., the inter-frequency transition between a choice of 5G sub-bands, the inter-RAT transition of GSM-R (2G) to FRMCS (5G) as well as stages towards FRMCS inter-core cross-border concepts.

Real-world testing takes place in two test sites, each having different radio environment characteristics and complementary test scopes. While the test track in France (operated by SNCF) is a portion of a commercially used line in sub-urban environment, the test track in Germany (operated by Deutsche Bahn) is an experimental line with rural characteristics. Some initial end-to-end connectivity tests will be executed in both test sites to compare the results in different deployment conditions.

The work in WP5 covers a total of 200 person months and is structured in three tasks as follows [1]:

Task 5.1 – Test site preparation and end-to-end network realization (in German and French field), incl.

- Trackside infrastructure (5G NR – 5G Stand-Alone Core – MCx Services – Applications)
- Onboard infrastructure (5G UE – MCx Services – Applications)
- Network performance testing, incl. latency and data continuity at handover points

Task 5.2 – FRMCS end-to-end functional application tests (in German and French field), incl.

- Voice (point-to-point call, group call, railway emergency call) via MCPTT
- ETCS, TCMS, ATO via MCData
- Real-time video (remote vision, in-cabin view, CCTV offload) via MCData

Task 5.3 – End-to-end service continuity in FRMCS cross-border scenarios (in German and French field), incl.

- Inter-RAT scenarios: 2G-5G transition, 4G-5G transition
- Inter-frequency scenario: Bearer change with handover between two 5G sub-bands
- Stages towards 5G inter-core cross-border concepts

1.2 Target and Organization of Deliverable D5.3

According to the 5GRAIL Grant Agreement this deliverable D5.3 shall provide a summary which outlines the results of the different field tests performed in Task 5.2 and will elaborate conclusion on the outcomes of the test (Chapter 2). It will discuss the activities and preparations related to testing border crossing scenarios of Task 5.3 (Chapter 3). Furthermore, it will capture key findings and considerations to be taken into account for future experimentation and test deployment of 5G as an enabler for the digitalisation in rail sector (Chapter 5).

2 Summary & Key Findings on FRMCS Functional and Performance Tests

WP5 has performed FRMCS field trials in two locations, in Germany and France, with complementary test scope, see Figure 1. In SNCF's **5GRAIL Testbed France**, a part of a commercial line in a suburb of Paris, a 5G SA network was operating at 1.9 GHz (TDD band n39, 10 MHz bandwidth) using three radio sites. Additionally, a 4G network was running at 2.6 GHz (TDD band b38) for which one of the three sites was used. In Deutsche Bahn's **5GRAIL Testbed Germany**, an experimental line in the rural Erzgebirge region, a 5G SA network was operating at 3.7 GHz (TDD band n78, 20 MHz bandwidth) using seven radio sites. In addition, it provides remote connection to a GSM-R (2G) transport network at 900 MHz in Nokia's lab premises in Hungary. Here, 5G and 2G systems are linked via an interworking function. Please refer to deliverable D5.1 for details [12].

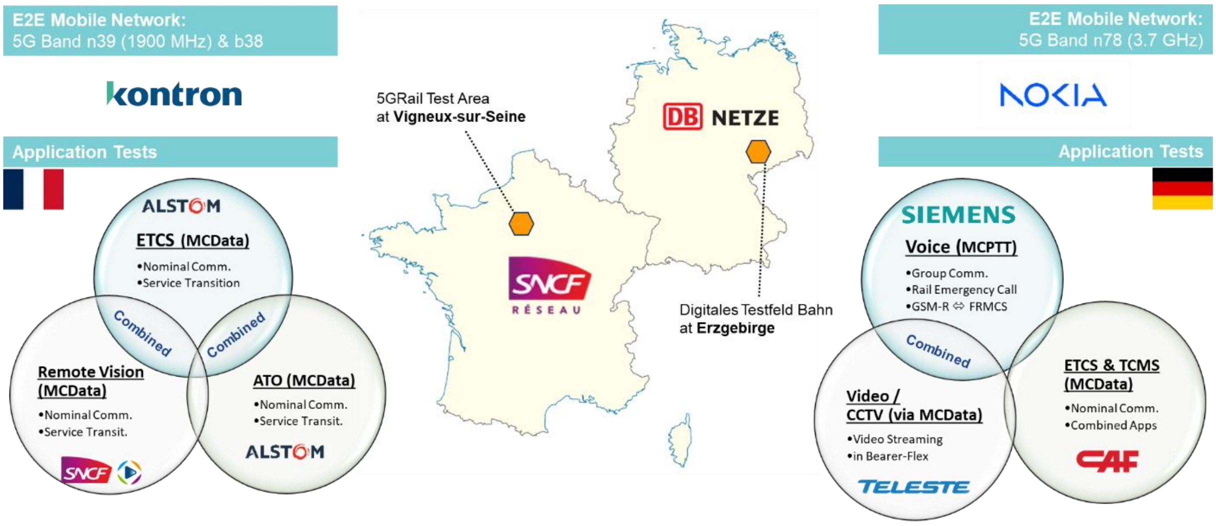

Figure 1: Location and scope of 5GRAIL testbeds in France and Germany

In each of the two field environments, different applications have been tested in terms of functional assessment and performance. The evaluation was based on both control plane and user plane analysis, see Figure 2. More information about the common field test architecture for the end-to-end evaluation can be found in Section 5 of deliverable D5.1 [12].

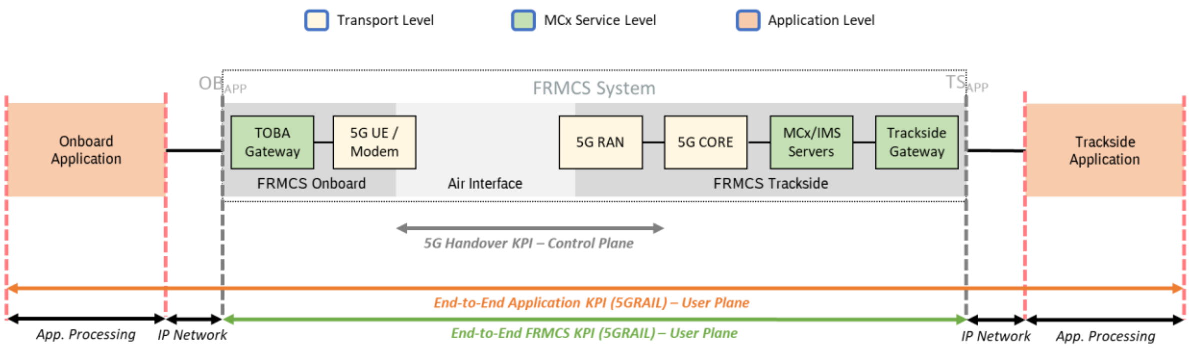

Figure 2: Performance evaluation in the field trials of the 5GRAIL project

A particular focus was given to **5G handover KPIs** (by example of inter-gNB intra-AMF handover) and to both **end-to-end FRMCS network KPIs** (measured between the onboard interfaces OB_{APP} and trackside interfaces TS_{APP} to the application) and **end-to-end application KPIs** (including processing in the onboard and trackside application equipment). Note that deployment related KPIs of the 5G air interface have been partially analysed for TDD band n78 but have few relevance for final FRMCS deployments which will run on RMR TDD band n101 (1.9 GHz) and FDD band n100 (900 MHz) and will be based on specific chipset design paradigms.

In the table below the **successfully field-validated applications** are listed, for which test cases have been performed in **stationary and dynamic (drive test) modes, including intra- and inter-gNB handovers** in the 5G network. The comprehensive field test campaigns have been performed over 6 weeks of drive tests both in France (sub-urban track) and Germany (rural track) with specifically prepared rolling stock as described in Sections 3.2 and 4.2 of deliverable D5.1 [12].

	5GRAIL Testbed France	5GRAIL Testbed Germany
Voice calls over FRMCS/5G via MCPTT client	*Not tested as it was not planned in the initial scope of the work package (focus is on data applications in France)*	Application provider: SIEMENS • Point-to-Point calls between cab radio and Nokia dispatcher at trackside • Group calls within FRMCS groups and mixed FRMCS / GSM-R groups • Railway Emergency Calls (REC) • Railway Emergency Calls (REC) with GSM-R interworking
Data calls over FRMCS/5G via MCData client	Application provider: ALSTOM • ETCS / ATP simulation between on-board EVC and trackside RBC • ETCS / ATP simulation with RBC handover(s) • ATO simulation between on-board client and trackside server • ATO simulation with radio handover(s)	Application provider: CAF • ETCS simulation between on-board EVC and trackside RBC • ETCS simulation with radio handover(s) • TCMS simulation between on-board MCG and trackside GCG • TCMS simulation with radio handover(s)
Real-time, non-critical video over FRMCS/5G via MCData client	Application provider: SNCF • Remote vision application as part of the remote driving system (RDS) • Test of different scenarios (under/over exposure, rainfall, …)	Application provider: TELESTE • Live video streaming (on-board to trackside) with different resolutions • CCTV file offload
Heterogeneous applications over FRMCS/5G via multiple MCx clients	• Combined ETCS and ATO simulations • Combined ETCS simulation and remote vision application	• Combined voice calls and live video streaming • Combined ETCS and TCMS simulations

The used onboard equipment for the test campaigns in France and in Germany is shown in Figure 3 and Figure 4, respectively. Note that in Figure 3 only the ETCS and ATO simulators are shown as the remote vision on-board equipment was installed in another rack (not seen in this figure).

Figure 3: 5GRAIL on-board setup in the French field trials

Figure 4: 5GRAIL on-board equipment in the German field trials

Further, in the following we report key findings for the latencies in the three mentioned KPI categories.

2.1 Handover Performance (Control Plane Latency)

Within 5GRAIL the applications have been tested in intra- and inter-gNB handover (HO) situations. For this, some control plane measurements have been performed for an Xn-interface based inter-gNB HO in the 5G TDD radio access network using Wireshark tool. The test was performed in the 5GRAIL Testbed Germany. The HO Execution times have been considered as an upper bound for the user plane interruption, while the real interruption time on user plane is expected to be some tens of milliseconds lower. See more information in Section 3.3.2 in deliverable D5.1 [12].

<u>Inter-gNB Intra-AMF HO execution phase latency (via Xn interface):</u>

- 125 ms (mean value) in field
- 79 ms (mean value) in lab

It must be mentioned that the Xn handover procedure is complex to measure precisely as it needs both signalling information from gNB(s) messages and UE messages which implies time-synchronized on-board and trackside measurements.

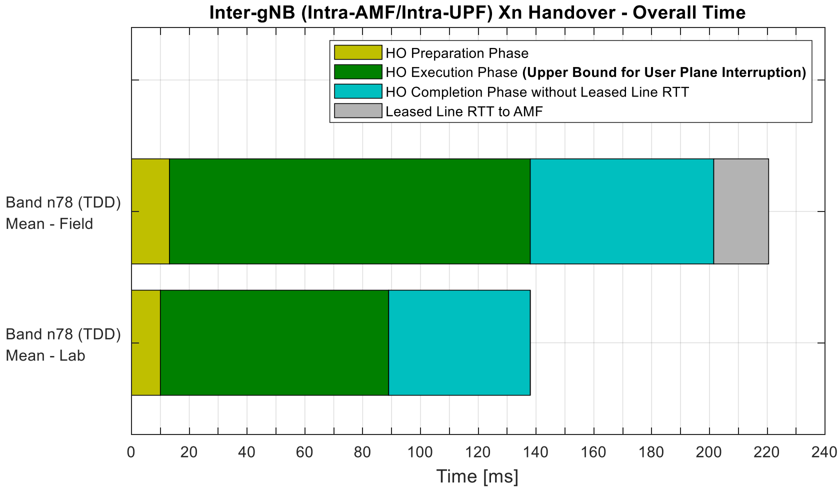

Figure 5: Comparison of control plane latencies in Xn-based Inter-gNB Intra-AMF HO for field conditions (Testbed Germany) vs. lab conditions (Lab Hungary)

2.2 End-to-End FRMCS Network Performance (User Plane Latency)

User plane latencies for end-to-end performance in the FRMCS network have been analysed for packets transmitted in a voice call in the 5GRAIL Testbed Germany at TDD band n78. Note that the (one-way) transmission latency includes the impact of the leased line between 5G RAN and 5G CORE in the with a delay of approx. 9.5 ms, see Section 3.1.3 in D5.1 [12].

<u>E2E FRMCS network (one-way) transmission latency (based on packets in a voice call):</u>

- 20.9 ms (mean value) in downlink, including ~9.5 ms leased line delay
- 20.4 ms (mean value) in uplink, including ~9.5 ms leased line delay

The CDF outliers in Figure 6 with larger latency are showing intra- and inter-gNB handover situations.

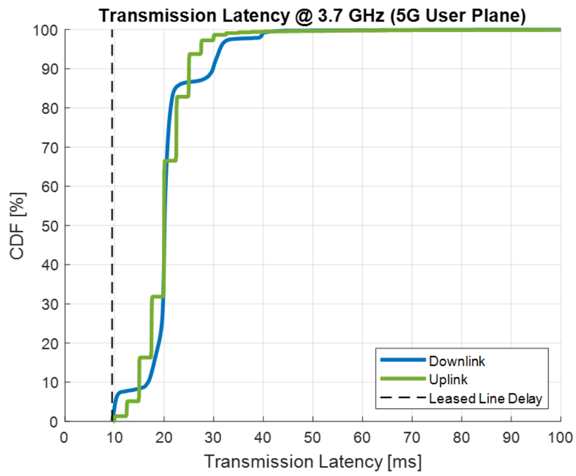

Figure 6: 5G user plane latencies measured betw. on-board switch and trackside gateway, excl. application processing delays (Testbed Germany)

2.3 End-to-End Application Performance (User Plane Latency)

2.3.1 Voice application (via MCPTT client)

Voice analysis was based on key performance metrics defined by 3GPP to assess mission-critical push-to-talk (MCPTT) services, see [27]. These metrics, also being described in 5GRAIL deliverable D1.3, are shown in Figure 7 and formulated herein after. The analyzed data was provided by Siemens.

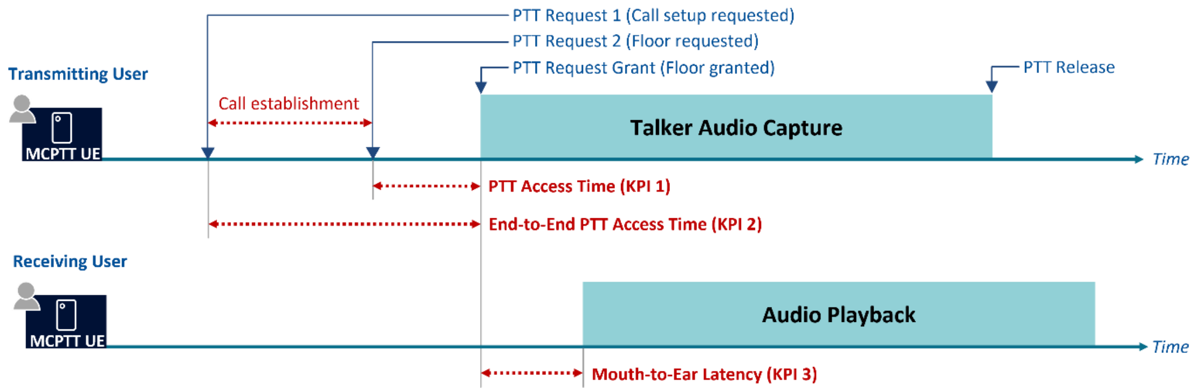

Figure 7: KPIs for MCPTT measurements in voice applications acc. to 3GPP TS 22.179

<u>MCPTT Access Time (KPI 1)</u>

For MCPTT *point-to-point calls* and *group calls* where the call is already established, the MCPTT Service shall provide an MCPTT Access time (KPI 1) less than 300 ms for 95% of all MCPTT PTT Requests. For MCPTT *emergency group calls* the MCPTT Service shall provide an MCPTT Access time (KPI 1) less than 300 ms for 99% of all MCPTT Requests. Measured figures are as follows:

- 86 ms (mean value) for point-to-point call, initiated by cab radio in the field
- 75 ms (mean value) for group call, initiated by cab radio in the field
- 81 ms (mean value) for REC call, initiated by cab radio in the field

<u>End-to-End MCPTT Access Time (KPI 2)</u>

For *all MCPTT Calls* the MCPTT Service shall provide an End-to-End MCPTT Access time (KPI 2) less than 1000 ms for users under coverage of the same network when the MCPTT Group call has not been established prior to the initiation of the MCPTT Request. Measured figures are as follows:

- 678 ms (mean value) for group call, initiated by cab radio in the field
- 586 ms (mean value) for REC call, initiated by cab radio in the field

When comparing KPI 2 between field (WP5) and lab (WP3) measurements, it can be seen that performance is slightly better under more ideal conditions in the lab, which is depicted in Figure 8 by example of REC calls.

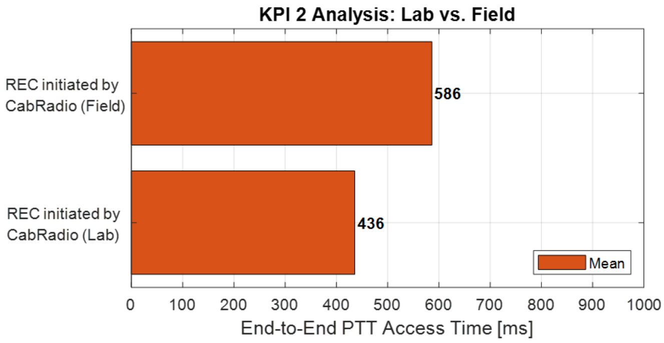

Figure 8: End-to-End PTT Access Time (KPI 2), measured for railway emergency calls.

2.3.2 ETCS/ATP data application (via MCData client)

For (simulated) ETCS/ATP data transmission, provided by Alstom, the following KPI has been analysed in the 5GRAIL Testbed France, incl. application processing of EVC-OB and RBC-TS units.

E2E Application (two-way) round-trip times:

- 53 ms (mean value) in nominal conditions
- 89 ms (mean value) in dynamic conditions with inter-gNB handovers

For (simulated) ETCS data transmission, provided by CAF, the following KPI has been analysed for usual data transfer rates of 2.7 kbit/s in the 5GRAIL Testbed Germany, incl. application processing of EVC-OB and RBC-TS units as well as leased line impairments between 5G RAN and 5G CORE installations.

E2E Application (two-way) round-trip times, including ~19 ms leased line RTT:

Measured at EVC unit / on-board

- 92 ms (avg. value) in stationary (static) conditions
- 111 ms (avg. value) in dynamic (drive test) conditions with inter-gNB handovers

Measured at RBC unit / trackside

- 89 ms (avg. value) in stationary (static) conditions
- 99 ms (avg. value) in dynamic (drive test) conditions with inter-gNB handovers

In consequence, the **E2E one-way application latencies can be concluded with approx. 40-55 ms** in dynamic conditions for both tests from France and Germany, which is well compliant with (even much lower than) current UNISIG Subset 93 [23]. It was observed to have low packet retransmissions at user level, there has been no remarkable effect under dynamic or degraded test condition with handovers.

2.3.3 ATO data application (via MCData client)

For (simulated) ATO data transmission, provided by Alstom, the following KPI has been analysed in the 5GRAIL Testbed France, incl. application processing of ATO-OB and ATO-TS units.

E2E Application (two-way) round-trip times:

- 71 ms (mean value) in nominal (static) conditions

- 89 ms (mean value) in dynamic (drive test) conditions with inter-gNB handovers
- 95 ms (mean value) when simultaneously running an ETCS simulation

2.3.4 TCMS data application (via MCData client)

For (simulated) TCMS data transmission, provided by CAF, the following KPI has been analysed in the 5GRAIL Testbed Germany, incl. application processing of MCG-OB and GCG-TS units as well as impairments from leased line between 5G RAN and 5G CORE installations.

E2E Application (two-way) round-trip times, including ~19 ms leased line RTT:

- 43 ms (avg. value) in stationary (static) conditions
- 53 ms (avg. value) in dynamic (drive test) conditions with inter-gNB handovers

2.3.5 Video applications (via MCData client)

In the 5GRAIL Testbed Germany a *video application for live view and CCTV offload* was provided by Teleste. It is comprised of an onboard video computer with recording capabilities and onboard CCTV/video camera in rolling stock (driving in the testbed) as well as a trackside video management system (VMS) located in Nokia's lab premises in Hungary. The solution offers on-demand, real-time video streaming in uplink, where video data is transmitted as TCP stream to minimize the loss of video frames and ensure the best possible user experience. Video resolutions and bitrate tested have been HD-ready video (1280x720) with avg. bitrate at 2 Mbps, SVGA video (800x600) with avg. bitrate at 1 Mbps and VGA video (640x480) with avg. bitrate at 700 Kbps. Further, CCTV offload was tested with peak rates seen at 8 Mbps in a 5G SA network at n78, using 20 MHz bandwidth and TDD configuration 'DDDSU', see Appendix 14.2 in [12]. However, stable and continuous CCTV offload speeds and live video transmissions have only been observed when lowering the offload rates below 1.5 Mbps due to QoS issues (occurrence of frequent interruptions) with data rates higher than this. The reason was identified as using an "unmanaged leased line" at one end of the 5G RAN to 5G CORE remote connection with too few performance guarantees and priorities which led to buffering effects in the internet nodes between Germany and Hungary. Note that the CCTV/video offload performance would have been better without this issue. More details can be found in Chapter 8 in 5GRAIL deliverable D5.1 [12].

Figure 9: HD video snapshot (Testbed Germany)

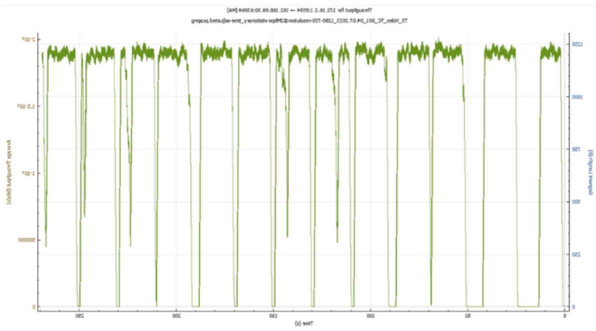

Figure 10: HD video throughput (Testbed Germany)

In the 5GRAIL Testbed France, SNCF provided a *remote vision (RV) application.* In this application which is part of the remote control of engine use case, a real-time video is transmitted from the train front to the trackside control centers. It is worthy to note that the remote control of engine is of strategic interest for railways as it provides economic savings for the operation. For instance, it is interesting in case of (i) technical center maneuver, (ii) first and last daily journey from train depot to the terminal station, and (iii) recovery in case of incident on the ATO in its upper grades of automations. One objective of testing the remote vision in 5GRAIL was to add high load on the network and analyse its behaviour, including flows priority management, when multiple heterogeneous applications in term of criticality are used at the same time. In this test, RV is used in parallel with the ETCS application. Note that RV uses High Efficiency Video Coding (H.265/HEVC) adaptive codec to encode the driver's view in the tests, as depicted in Figure 11. In practice, it is possible to stream 1280x720p (HD ready video) with full driving capacity from 800kbps. However, the codec is usually set at 1Mbps. As adaptive, it will automatically adjust according to network conditions. See Chapter 11 in deliverable D5.1 [12] for more details.

Figure 11: Remote driving simulation through frontal cameras on test train

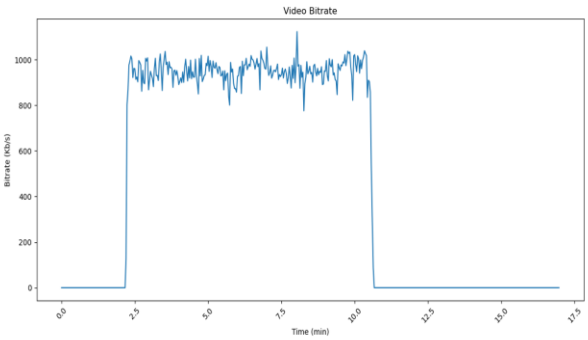

Figure 12: Video bitrate run at 1Mbps for simultaneous operation of remote vision app and simulated ETCS

2.3.6 Conclusions

For the voice and data applications with smaller bit rates (as typical for the most relevant applications in digital rail operations), the achieved latencies in the 5G TDD based FRMCS test networks and packet errors on application level have been low, allowing sufficient QoS. This was also true for combined data application scenarios.

For applications with higher data rate demands, such as real-time video transmission from train to ground (uplink), the QoS varies with the resolution of the application and depends on different network settings and characteristics. Further studies in upcoming projects may be needed to further specify and verify these cases for operational use.

The field trials on 5G-based FRMCS functions and performance fulfilled the target to proof technical feasibility and end-to-end functionality of the 5GRAIL prototypes. During the tests, the speed of the train was not very high, but the environmental conditions (suburban, rural, forestall areas etc.) provided a challenging performance for coverage of the 5G network used in 5GRAIL field tests. Taking into account these challenges, it is considered that performance has been measured under representative constraints. The performed tests and observations with pre-standard implementations support to improve the upcoming FRMCS specifications and can deliver guidelines for enhanced evaluation and validation in future field experiments of FRMCS network performance and for the functional application level. The field trials do not serve as a reference for final operations or to derive final principles for radio deployment. For this, further developments on FRMCS equipment, both on 5G, MCX and application side, is needed.

3 Summary & Key Findings on Activities on FRMCS Border Crossing Scenario Tests

That trains cross the border is an essential requirement for FRMCS for the deployment of a Pan Europe Single Rail Domain, allowing trains seamlessly travelling between the different countries and service continuity. The 5GRAIL project covered two baseline FRMCS border-crossing (BX) transition scenarios, i.e., (i) between two FRMCS domains and (ii) between FRMCS and GSM-R.

In the project timeframe, initial stages/concepts towards BX have been studied, leading to several activities in labs (WP3, WP4) and field (WP5), while a complete realization of a border-crossing scenario was not possible with the current state of standardization in 3GPP [29],[33] and other fora. Several challenges still need to be addressed especially on service stratum, e.g., regarding conservation of IP addressing by the UE during transition, before full-featured field trials can take place.

3.1 Transition between two FRMCS Domains

When it comes to the transition between two FRMCS domains, both the **inter-FRMCS transport domain transition** (incl. 5G radio/core principles for roaming, inter-PLMN handover) and the **inter-FRMCS service domain transition** (on IMS/SIP session level and MCX level) need to be considered in the FRMCS BX scenario. Further, it can be distinguished between home-network controlled transition (**home routed**) or visited-network controlled transition (**local break-out**) of user plane application data.

At on-board side, different concepts exist regarding the **use of two modems (UEs)** and additional multipath function in the FRMCS on-board gateway (TOBA box), see Figure 13, and the **use of one modem (5G UE),** see Figure 14, during the BX transition phase.

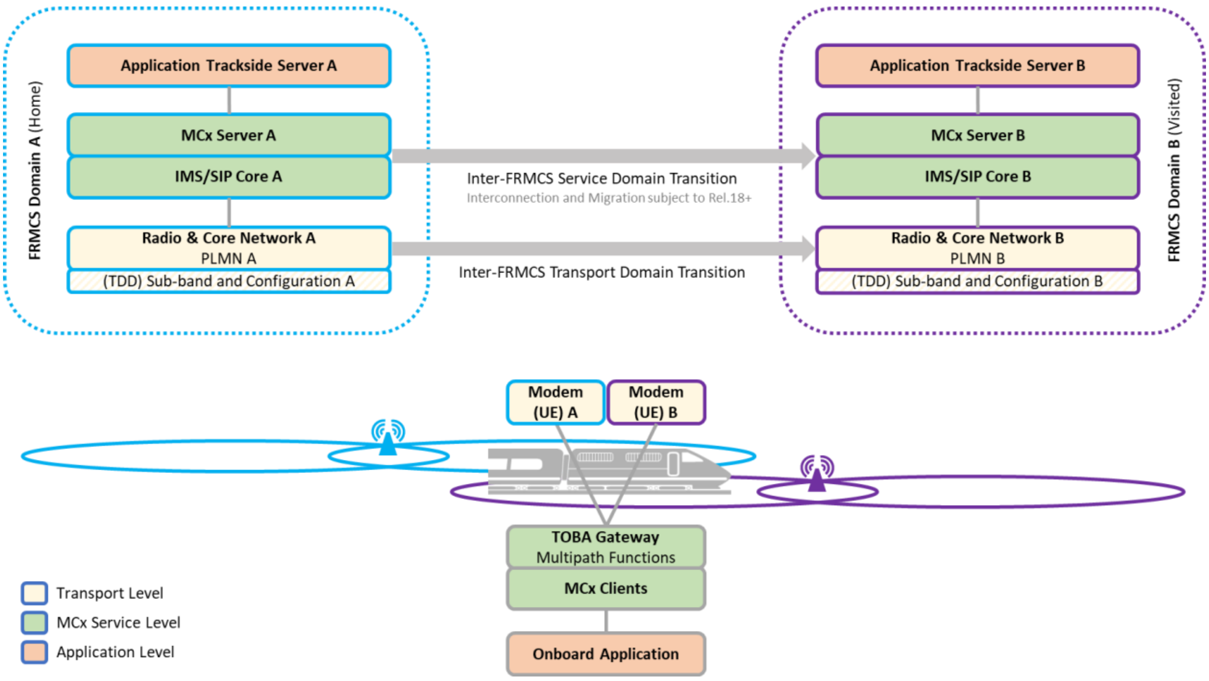

Figure 13: Schematic FRMCS Border-Crossing framework with 2 modems

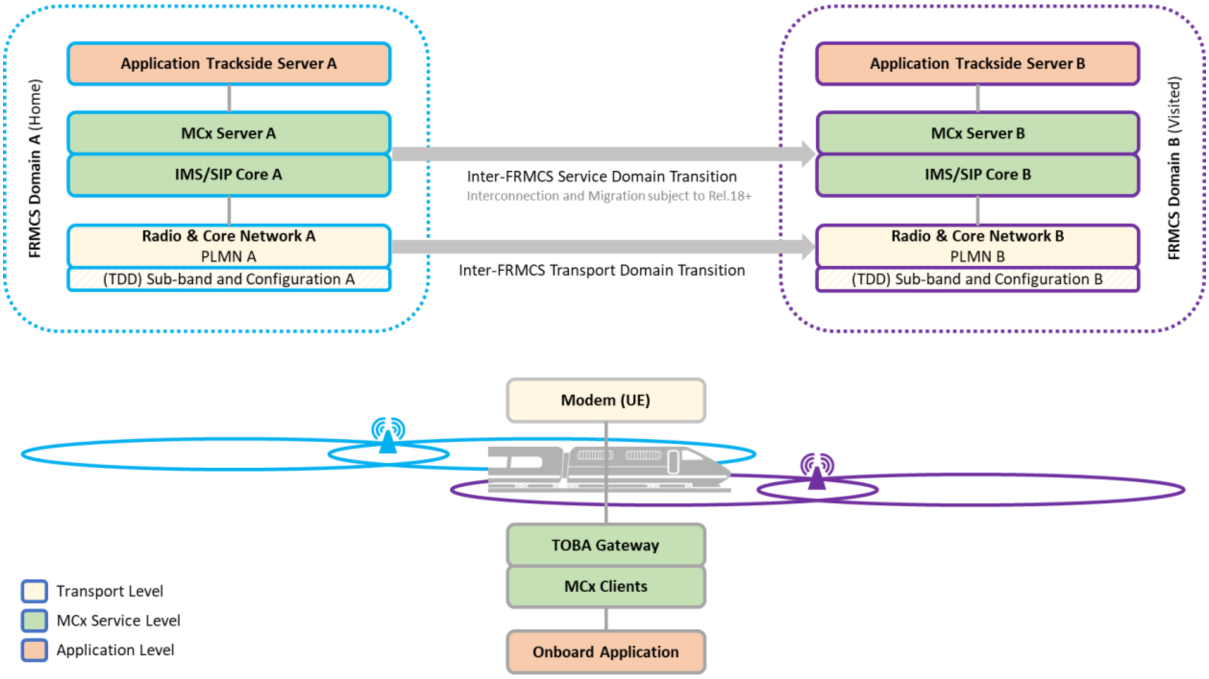

Figure 14: Schematic FRMCS Border-Crossing framework with 1 modem

In FRMCS cross-border scenarios, a service transition between two transport networks operated by the infrastructure managers on different 5G bearers with different TDD configurations may occur. This may be the case for 2x 5 MHz sub-bands within the 10 MHz FRMCS bandwidth at RMR band n101 in the future. The 5G UE for FRMCS BX must be capable to handle such a **5G inter-frequency scenario with TDD change** as there may be no default (but flexible) TDD frame structure across European railway networks. Different TDD frame structures may assign different capacity for downlink versus uplink.

In general, the relevant 3GPP features (e.g. Home Routing or Local break-out) were not sufficiently advanced at the beginning of 5GRAIL project, especially for 5G SA architecture. Among the features, to ensure transport mobility, local break-out (using visited-network controlled user plane function) seems the outstanding one for latency reasons. However, it implies retrieving a new IP address and a new registration at the foreign IMS system and consequently the MCX session is broken. This has an impact on critical railway applications such as ETCS and ATO that require stringent Service Continuity. For these applications, a two modem (UE) approach shall be included in FRMCS v2. For voice applications, short interruption can be tolerated and, accordingly, a one modem (UE) solution might be suitable.

The limits of the maturity of present 3GPP concepts and of available infrastructure on roaming and handover capabilities in a 5G SA environment led to the approach to identify the building blocks that derive benefits for the concepts for FRMCS BX. In this respect, a focus was given to building blocks for inter-FRMCS transport domain transition. In all performed 5GRAIL field tests (as well as pre-tests in the 5GRAIL labs), only one MCX and application server was used.

The following building blocks have been analysed together with specific applications in 5GRAIL:

3.1.1 5G SA Inter-gNB Inter-AMF handover via NG/N14 for 5G SA Inter-PLMN border-crossing (element for FRMCS BX approach with 1 modem)

Tests with a focus on control plane procedures have been performed by example of MCPTT voice and MCData applications emulating constant video bitrate. They have been successful in lab (WP3), showing NG/N14 handover interruption times of 154 ms [8], while field tests (WP5) were impacted by equipment-readiness issues. Please refer to 5GRAIL deliverable D5.2 [13], Section 4.3, for more details.

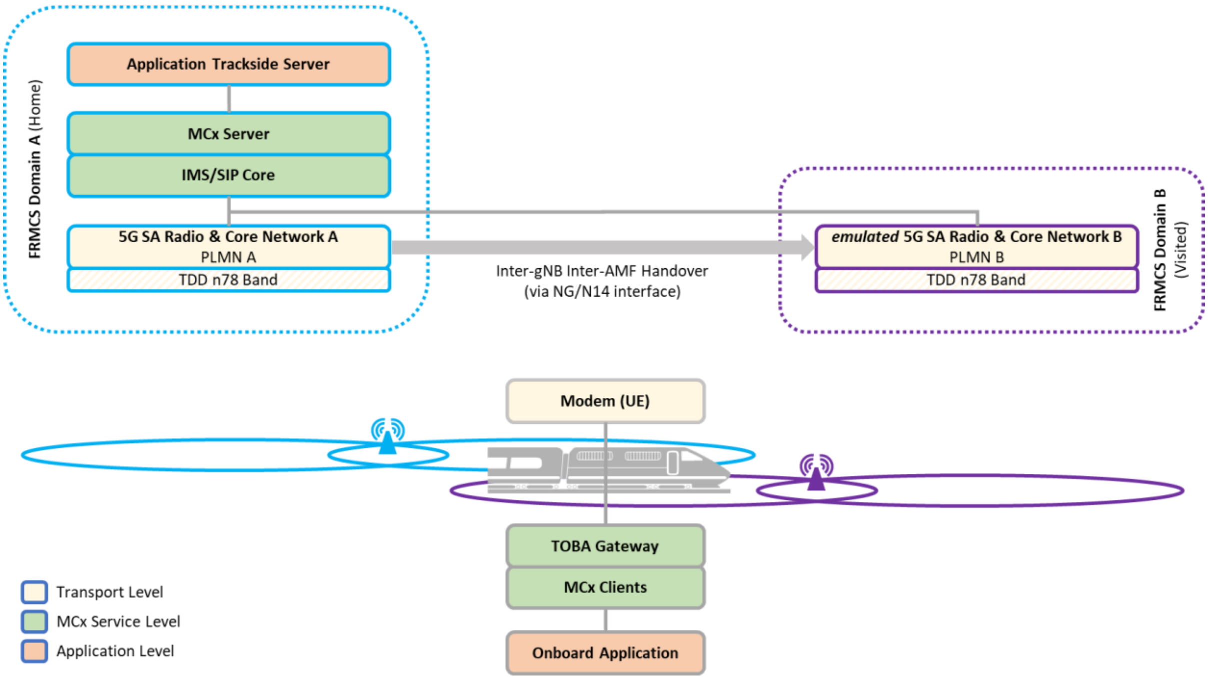

Figure 15: Test architecture to verify the NG/N14 handover with 5G SA Inter-AMF support for Inter-PLMN BX with one modem (Testbed Germany)

3.1.2 5G Inter-frequency handover between two sub-bands with different TDD configurations (element for FRMCS BX approach with 1 modem)

Tests have been successfully performed by example of MCData-implemented CCTV video uplink service. In the considered setup, uplink data slots are used in different TDD frame structures in the two 5G bearers, which are seen during a transition between two radio cells. On radio cell 17 (TDD configuration 'DDDSUDDSUU'), there is 1.5x larger uplink bandwidth available than in radio cell 16 (TDD configuration 'DDDSU'). Please refer to 5GRAIL deliverable D5.2 [13], Section 4.4, for more details.

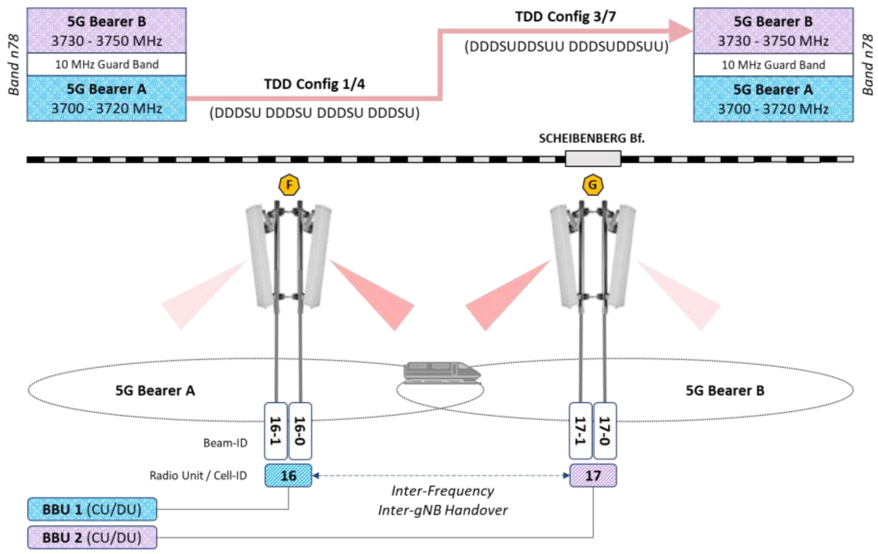

Figure 16: TDD change via inter-frequency inter-gNB handover between two 5G bearers (Testbed Germany)

3.1.3 Usage of multipath protocol (MPTCP) for an 4G/5G Inter-RAT scenario with Inter-PLMN handover (element for FRMCS BX approach with 2 modems)

Tests with an assessment of network functions interworking via multipath schemes have been performed for the MCData scenarios with ETCS and ATO application simulators. Dedicated mobile network test codes (MCC-MNC 208-85 and 208-90) were configured in the 5GRAIL Testbed France for this setup, where an Inter-RAT transition from FRMCS domain A with a 5G SA network to FRMCS domain B with a 4G network occurred. Refer to 5GRAIL deliverable D5.2 [13] Section 4.2 for details.

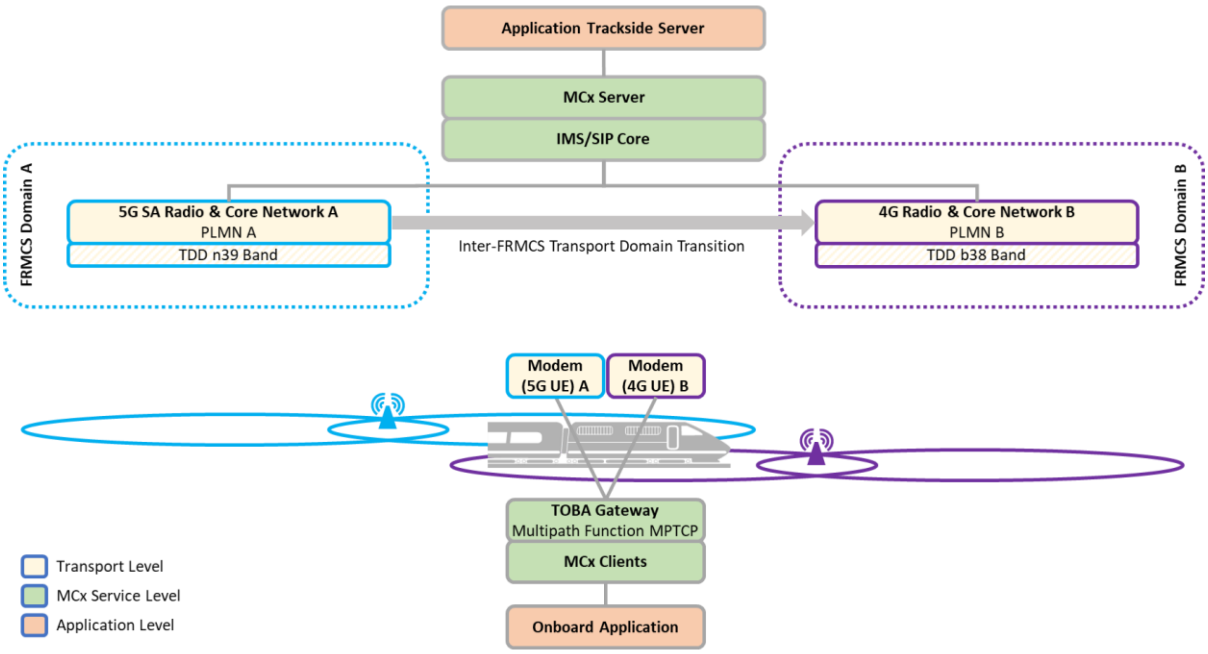

Figure 17: Test architecture to verify Inter-PLMN BX with two modems, using multipath MPTCP functions (Testbed France)

3.2 Transition between FRMCS and GSM-R

Switching between 2G and 5G railway networks is relevant both (i) as a border-crossing scenario and (ii) as a functionality for GSM-R – FRMCS interworking during the migration phase where both technologies will be supported at the same time in a railway communication network of an infrastructure manager. In both scenarios network switching is needed when the current network becomes unavailable.

In 5GRAIL the 2G (GSM-R) to 5G (FRMCS) transition scenario was successfully demonstrated based on a voice (MCPTT) application. In particular, service continuity for Railway Emergency Call (REC) when moving a user from 2G to 5G in a REC call area with GSM-R and FRMCS overlap was studied. The focus was given to the implementation and evaluation of an interworking function (IWF) that connects the 2G network with the 5G network via a single trackside MCX system. In a real cross-border railway case, each country would host different MCX servers. However, the testing in 5GRAIL can be seen as a first step to the evolution of main mobile network and MCX functionalities needed to allow a system transition of a user.

Further details can be found in 5GRAIL deliverable D5.2 [13], Section 4.1.

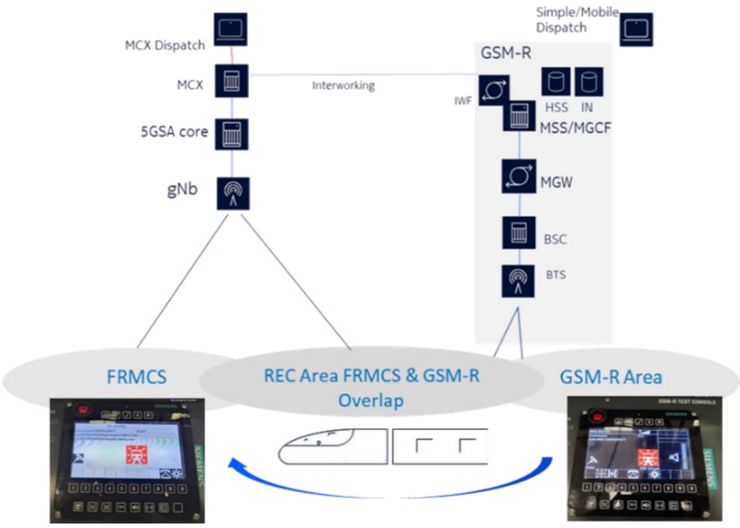

Figure 18 - Principle of a REC call transition from GSM-R (2G) to FRMCS (5G)

4 Report about the 5GRAIL Final Demo

A special project achievement was the successful field demonstration of FRMCS functionalities and test cases on the 20th of September 2023. The field demo took place on-board of DB's lab ICE "advanced TrainLab" during a two hours train run in the 5GRAIL Testbed Germany, departing and arriving at the station *Annaberg unterer Bf*. with FRMCS live demonstrations (in stationary and driving conditions) between *Scheibenberg Bf.* and *Markersbach Bf.* The demo run was joined by project partners and project reviewers from the European Commission funding program Horizon 2020. The following parties attended the 5GRAIL final demo: UIC, DB, SNCF, SBB, Kontron, Nokia, Siemens, Teleste, CAF, UNIFE and 3 project reviewers.

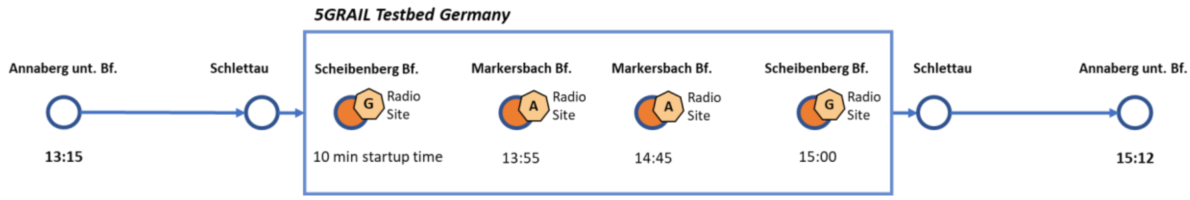

Figure 19: Schedule of the 5GRAIL final demo (Testbed Germany) on 20 Sept. 2023

Figure 20: 5GRAIL project team at the final demonstration event in Annaberg-Buchholz, Germany

The 5GRAIL final demo was one of the project's key moments for showcasing several achievements for railway operational functions and performance over 5G SA based FRMCS networks such as:

- Voice/MCPTT 5G Point-to-Point Calls
- Voice/MCPTT 5G Point-to-Point Calls incl. 5G Inter-frequency handover between two n78 bearers on sub-bands with different TDD frame structure
- Voice/MCPTT 5G Group Calls
- Voice/MCPTT 5G Group Calls with 2G (GSM-R) Interworking
- Voice/MCPTT 5G REC Calls *(with simulated GPS coordinates for group ID definition)*
- Voice/MCPTT 5G REC Calls with 2G (GSM-R) Interworking

- Moving from 2G (GSM-R) to 5G (FRMCS) while on on-going REC Call
- Live Video Uplink/MCDATA
- Simultaneous Voice/MCPTT & Live Video Uplink/MCDATA over the same TOBA FRMCS gateway to demonstrate high traffic capability

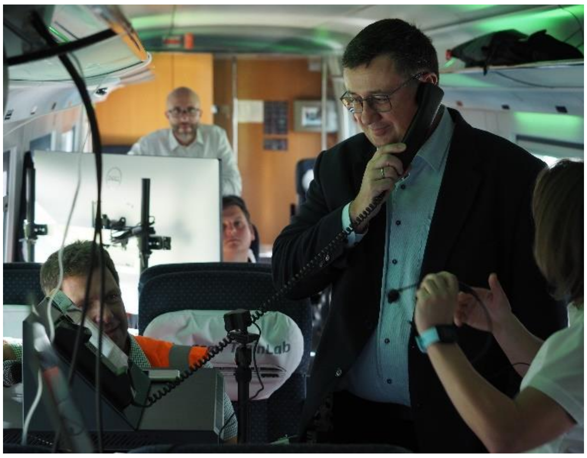

Figure 21: Live demonstration of voice performance at 5GRAIL final demo[1]

Figure 22: DB's experimental ICE train "advanced TrainLab" in the 5GRAIL Testbed Germany

[1] The photo shows Dr. Kristian Weiland, CTO of DB Netz AG, performing a voice call with 5GRAIL cab radio equipment. Mr. Weiland has agreed that this photo can be used in the context of 5GRAIL publications.

5 Considerations for future 5G/FRMCS Experimentation and Test Deployments

The Future Railway Mobile Communication System (FRMCS) is a cornerstone in the digitalization of train operation. It is an enabler for future digital rail applications to achieve optimized and streamlined processes in an aim to increase sustainability of this rail industry.

It is certain that the accomplished field experimentation and test deployments help gain a comprehensive technology understanding of FRMCS principles and 5G including its key features, capabilities, and architecture options as well as the concept of the MCX layer.

Interestingly, the split among the two fields (in France and Germany) achieved complementarity for a wider scope of test findings as it comes to infrastructure planning. Although deriving from a holistic generic architecture, the implemented network architectures in the French and German fields were defined based on specific use, considering factors such as latency, throughput, and communication reliability.

Provided that the core networks in the French field were deported from the lab to the SNCF field, this has allowed to test the concept of multi-access edge computing (MEC) deployment. Conversely, in DB field, 5G Core network as well as the MCX/IMS layers were remotely interconnected through a remote long-haul link. This complementarity help plan for a flexible and scalable architecture that accommodates future growth and evolving requirements.

Moreover, using different spectrum allocation assists on the radio planning by understanding the spectrum bands available for the FRMCS to choose the appropriate frequency band for a deployment. This includes anticipating live network challenges including interference when it comes to deployment in an urban/sub-urban environment. Certainly, there is a need to comply with local and international regulations to the deployment by obtaining necessary permits and approvals for spectrum usage and infrastructure installation as it is the case for the experimental test licenses for n39 and b38 spectra that were allocated by the regulatory authority (ARCEP) in France and the n78 in Germany (BNetzA).

Furthermore, defining and prioritizing Quality of Service (QoS) requirements based on heterogeneous applications and service's needs is an interesting consideration. Findings on QoS optimization are elaborated and made available in the deliverable on functional and performance testing D5.1 [12].

5GRAIL is a successful first step towards FRMCS. Nevertheless, the journey to the FRMCS era is still in its early stages. As future work, **some topics are identified to be addressed in future upcoming projects**:

- One aspect to be addressed in future projects is the **cross-layer evaluation of inter-correlated transport, service and application KPIs**. That was not fully addressed in 5GRAIL as it was not envisaged with the project scope according to the roadmap of the developed products.
- One item is the **validation of FRMCS using high speed tests (incl. 300 km/h)**. Recall that the scope of 5GRAIL, considered only moderate speed up to 50-80 Km/h in fields. Interestingly, up to 175 km/h were emulated in labs but not realized in field. Further evaluating the performance on high-speed lines would be necessary.

- Another topic is the **optimization of TDD deployments at 1900 MHz RMR using n101 band (1900-1910 MHz), including assessment of coverage.** Indeed, the tests in France using 5G band n39 which encompasses the n101 as sub-band are considered as a first step in this direction. This is specifically interesting when recalling that n101 is close to other FDD bands, particularly, n1 UL (1920-1980 MHz) and n3 DL (1805-1880 MHz) that are used by the MNOs in both of France and Germany as well as many other European countries.
- Also, as a future work, **multi-strata cross-border tests** would be needed covering all the different FRMCS layers including the transport network and the MCX service ones. This implies future testing with two MCX and application servers. Indeed, this is a very important step for interoperability and standards compliance. Recall that 5GRAIL was kicked-off in advance of the specifications and its objective was to feed the specs in its first version (v1) with lessons-learned. In this context, different inter-RAT scenarios were considered in the labs and fields (2G/5G, 5G/5G, 5G/4G) to test compatibility with existing technologies and systems.
- **Security and Privacy** is also an interesting topic that should be further addressed for FRMCS. It is necessary to understand how to prioritize security measures to protect the FRMCS from cyber threats and targeted attacks. Some of this was investigated in 5GRail when validating robust authentication and encryption mechanisms as part of the integrated OB_{APP}/TS_{APP} interfaces in 5GRAIL. This concept comes along to privacy concerns due to the vast amount of data generated and transported by the 5G/FRMCS network.
- Finally for a maintained competitiveness, advanced **multi-vendor configuration tests** for interoperability of 5G RAN, 5G Core and the Service Stratum should be envisaged for upcoming projects.

As a bottom line, 5GRAIL can be seen as a success-story for the steps towards the modernization of the telecom networks for railways. Additional steps should be undertaken in order to keep the momentum towards this journey to the FRMCS.

6 REFERENCES

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[2]	Test Plan	5GRAIL D1.1 (v4.0)
[3]	Test report conclusion from simulated/lab environments	5GRAIL D1.2 (v2.0)
[4]	TOBA Architecture report	5GRAIL D2.1
[5]	TOBA Integration report	5GRAIL D2.2
[6]	First Lab Integration and Architecture Description	5GRAIL D3.1 (v1.0)
[7]	First Lab Test Setup Report	5GRAIL D3.2 (v3.0)
[8]	First Lab Test Report	5GRAIL D3.3 (v2.0)
[9]	Second Lab Integration and Architecture Report	5GRAIL D4.1 (v3.0)
[10]	Second Lab Test Setup Report	5GRAIL D4.2 (v3.0)
[11]	Second Lab Test Report	5GRAIL D4.3 (v2.0)
[12]	Test Results on Field Trials on FRMCS Functions and Performance	5GRAIL D5.1 (v1.0)
[13]	Test Results on Field Trials for Cross-border Scenario	5GRAIL D5.2 (v1.0)
[14]	FRMCS Use Cases	UIC MG-7900 (v2.0.0)
[15]	FRMCS Principle Architecture	UIC MG-7904 (v0.3.0)
[16]	FRMCS Telecom On-board System – Functional Requirements Specification (TOBA FRS)	UIC TOBA-7510 (v1.0.0)
[17]	FRMCS On-Board System Requirements Specification (TOBA SRS)	UIC TOBA-7530
[18]	FRMCS User Requirements Specification	UIC FU-7100 (v5.0.0)
[19]	FRMCS Functional Requirements Specification (FRS)	UIC FU-7120 (v1.0.0)
[20]	FRMCS System Requirements Specification (SRS)	UIC FW-AT-7800 (v1.0.0)
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[22]	FRMCS Form Fit Functional Interface Specification (FFFIS)	UIC FFFIS-7950 (v1.0.0)

[23]	ERTMS/ETCS GSM-R Bearer Service Requirements	UNISIG Subset 093 (v4.0.0)
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[25]	GSM-R EIRENE System Requirements Specification (SRS)	v16.1.0
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[28]	Service requirements for the 5G system, Stage 1 (Release 17)	3GPP TS 22.261 (v17.9.0)
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[30]	Mission Critical Data services, Stage 1 (Release 17)	3GPP TS 22.282 (v17.0.0)
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[32]	Study on Future Railway Mobile Communication System, Stage 1 (Release 16 & Release 17)	3GPP TR 22.889 (v17.4.0) 3GPP TR 22.889 (v16.6.0)
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Grant agreement
No 951725