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Deliverable D5.2

Test Results on Field Trials for Cross-border Scenario

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D5.2 Test Results on Field Trials for Cross-border Scenario

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Executive Summary

The main purpose of this deliverable is to provide the reader with a report on the end-to-end tests defined by 5GRAIL WP1 for field trials and their preparation activities in labs.

The focus is on a description of context and results of the test execution related to activities with relevance for Border-Crossing (BX) scenarios in both Germany and France.

Moreover, this deliverable encompasses some details of the findings obtained during the execution of the BX related test cases elaborated in the test plan (D1.1).

Note that for the field trials, two test sites in Germany (by Deutsche Bahn) and in France (by SNCF) have been equipped with the required infrastructure assets to operate the 5G radio and core networks. The application selection for each test site has been done to allow complementary tests. Also, both test sites have different characteristics in terms of used 5G spectrum and radio access network conditions.

The tests related to BX feature and the corresponding performance results allow the 5GRAIL consortium to feed-back findings into the ongoing FRMCS v1/v2 specification process. This is one of the objectives of 5GRail project. It is important to underline points of concerns and identify enhancements in order to define additional measures that could give further insights at this stage, where many prototypes stand at an early development phase.

Work package 5 has dependence on WP1, WP2, WP3 and WP4 as it brings the developments and outcomes of the input work packages to the field assessment stage. In this respect, the FRMCS experiments of WP5 reflect a selection of test cases that have been previously de-risked and performed under lab conditions in WP3 (Nokia lab Hungary) and WP4 (Kontron lab France), respectively.

The test site and infrastructure preparation activities for the field trials started in Q1 2022 and continued until Q1 2023. They have been strongly aligned with the lab tests in the 5GRAIL project. As the lab testing had been partially impacted by COVID19 restrictions, there have been some delays in the deliveries from lab to field. The main test phase for cross-border scenario tests with active rolling stock took place in Q2 and Q3 2023.

Abbreviations and Acronyms

In this section, we list the different abbreviations that are used in this document.

Abbreviation	Elaborated Form
3GPP	3rd Generation Partnership Project
5G NSA	5G Non-Stand Alone
5G SA	5G Stand-Alone
A.k.a	Also Known As
ARCEP	France's Electronic Communications, Postal and Print media distribution Regulatory Authority
API	Application Programmable Interface
APN	Access Point Name
ATO	Automatic Train Operation
ATP	Automatic Train Protection
Balise	Eurobalise. Recall that a balise is an electronic beacon (transponder) placed between the rails of a railways, part of an automatic train protection (ATP)
BX	Border-Crossing
CCTV	Closed Circuit TeleVision
COTS	Commercial Off The Shelf
CP	Control Plane
CSCF	Call/Session Control Functions
CU	Centralized Unit
DMI	Driver Machine Interface
DN	Domain Name
DSD	Driver Safety Device
DU	Distributed Unit
eMLPP	Enhanced Multi-Level Precedence and Pre-emption service
EPC	Evolved Packet Core
ES3	Engineering Sample 3 (reference to the Thales n39 band chipset)
ETCS	European Train Control System

EU	European Union
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	gNode-B
GNSS	Global Navigation Satellite System
GoA	Grade of Automation
GRE	Generic Routing Encapsulation (RFC8086) -> Tunnel GRE
GTW or GW	Gateway
H2020	Horizon 2020 framework program
HLD	High Level Design
HMI	Human Machine Interface
HR	Home-routed
HSS	Home Subscriber System
IMS	IP Multimedia Subsystem
IP	Internet Protocol
IWF	Inter Working Function
JSON	JavaScript Object Notation
KPI	Key Performance Indicators
KT	Kontron Transportation
LBO	Local Break-out
LLD	Low-Level Design
MAN	Metropolitan Area Network

MCC	Mobile Country Code
MCG	Mobile Communication Gateway
MCX	Mission Critical, with X=PTT (Push-To-Talk for Voice) or X=Data or X=Video
MQTT	Message Queuing Telemetry Transport
MNC	Mobile Network Code
MNO	Mobile Network Operator
MPTCP	Multi-Path Transmission Control Protocol (TCP)
N39	New-Radio TDD band spanning 1880-1920 MHz which encompasses the 10 MHz allocated for the RMR band (1900-1910 MHz)
N3IWF	Non-3GPP Inter Working Function
NR	New Radio
NSA	Non-Stand Alone (5G Core architecture)
NTG	Network Transmission Gateway
NTP	Network Time Protocol
OB	On Board
OB_GTW	On-Board Gateway
OBA	On-Board Application (e.g. ETCS on-board, ATO on-board)
OBU	On-Board Unit
O&M	Operation & Maintenance
OTA	Over The Air
OTT	Over The Top
PCC	Policy and Charging Control
PCRF	Policy and Charging Rules Function
PDB	Packet Delay Budget
PDN	Packet Data Network
PER	Packet Error Rate
PIS	Passenger Information System
PLMN (H-PLMN/V-PLMN)	Public Land Mobile Network Home/Visited PLMN
PoC	Proof-of-Concept

PSS	Process Safety System
QCI	QoS Class Identifier
5QI	5G QoS Identifier
QoS	Quality Of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RBC	Remote Block Centre
REST	REpresentational State Transfer
RF	Radio Frequency
RMR	Railway Mobile Radio
RTP	Real Time Transport Protocol
RTCP	Real-Time Transport Control Protocol
RU	Railway Undertaking
5G SA	5G Stand-Alone
S-CSCF	Servicing-CSCF (Correspondence IMPU - @ IP)
SIP	Session Initiation Protocol
SMF	Session Management Function
SSH	Secure Shell
SRS	System Requirements Specification
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TE	Test Environment
TFT	Traffic Flow Template
TLS	Transport Layer Security
TC	Test case
TCMS	Train Control Management System
TCP	Transmission Control Protocol
TOBA	Telecom On-Board Architecture
TRDP	Train Realtime Data Protocol (see IEC 61375)

TS	Track Side
TS_GTW	TrackSide Gateway
TSE	Track Side Entity (e.g. RBC, KMC, ATO trackside)
TSI	Technical Specification for Interoperability
UE	User Equipment
UIC	Union Internationale des Chemins de fer
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communications (5G)
URS	User Requirements Specification
VM	Virtual Machine
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 on 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 D5.2

This deliverable D5.2 is an output from Task 5.3 (FRMCS cross-border scenario testing). According to the 5GRAIL Grant Agreement, it shall provide a comprehensive description of test execution regarding cross-border scenario testing, a list of performed tests and the results obtained during the execution of the related test plan.

The structure of this document is organized into the following chapters:

- Chapter 2 elaborates the state-of-the-art on border crossing for railways, including viewpoints from industrial and standardization angles.
- Chapter 3 details the lab activities in preparation of the tests by elaborating the context and the approaches for border-crossing (BX) in 5GRail.
- Chapter 4 details the results of the carried test cases that were picked from D1.1 and that were executed in both fields.
- Chapter 5 underlines the final remarks including a retrospective on WP5 BX field experience as well as some perspectives on the way forward to conclude this report.

1.3 Assumptions

The exhaustive list for assumptions identified for both French and German fields are listed in the 5GRAIL deliverable D1.1 “Test-Plan” [2].

2 Border-Crossing (BX) for Railways

Prior delving into the details of the field trials on the BX, we thought it would be interesting to shed some lights on the BX process and share some insights from the related bodies and discuss current progress.

Recall that BX for FRMCS, pertains to the seamless communication and interoperability of railway systems across different countries or regions. When trains cross international borders, they may encounter different communication protocols, signaling systems, and operational procedures. FRMCS aims to establish a unified and standardized communication platform that facilitates the smooth exchange of information between railway networks, even when crossing borders.

Key considerations for BX in the context of FRMCS may include:

- **Interoperability:** Ensuring that the communication systems used by trains are compatible and can seamlessly transition between different networks as they cross borders.
- **Standardized Protocols:** Implementing common communication protocols and standards to enable effective data exchange between different railway systems.
- **Regulatory Alignment:** Ensuring that regulations and standards related to railway communication are harmonized across borders to facilitate cross-border operations.
- **Collaboration:** Promoting collaboration between railway operators, infrastructure managers, and relevant authorities to address challenges related to border crossing and interoperability.

Note that by the time of writing this document, current FRMCS specifications did not elaborate the exact approach to achieve BX.

In this context, in the following sections, we present the different viewpoints on the BX that are deemed interesting for this task. Accordingly, we provide an overview of the BX for railways related works, covering existing knowledge from GSM-R, current 3GPP work in terms of specifications, and current FRMCS specifications for BX, up to date.

2.1 State of the art on BX in GSM-R

The following table reports the outstanding guidelines in the GSM-R that address the BX concept.

Title	Highlights of the Contents
EIRENE Document O-8300	It describes the voice and data services functionality when the onboard Mobile Terminal (MT) crosses the border between two EIRENE networks. Nota: In GSM-R separate Mobile Terminals are used for different applications (e.g., MT of EDOR and MT of Cab Radio). This is the rationale why a two UE based approach could be envisaged for BX for data applications. <u>For ETCS:</u> • ETCS BX is satisfied using an additional MT which is in standby at BX initiation • ETCS balise triggers the network selection procedure for the standby MT

	For Voice: • All ongoing calls are dropped before new ones could be established • The upcoming calls experience a silence period. Therefore, operational aspects shall be adapted to minimize the operational hazard caused by the silent period.
EIRENE Document O-8350	It describes Voice and Data Services Interconnection & Roaming between GSM-R Railway networks
EUG Border crossing guidelines 17E087	It provides an overview of ETCS BX over GSM-R
EUG Border crossing guidelines 17E112	It provides a recommended trackside solution for the engineering of RBC-RBC handover.
ERA GSM-R bearer service requirements SUBSET-093	It provides E2E performance of ETCS, incl. the requirements for network transition. E.g. • Network Registration Delay < 35s (99%) • Connection Establishment Delay < 10s (99%) • E2E Transfer Delay < 0.5s (99%)

2.2 State of the art on BX in 3GPP

The 3GPP specifications [34] provides specifications for two procedures (P1 and P2) depicted in the following figure.

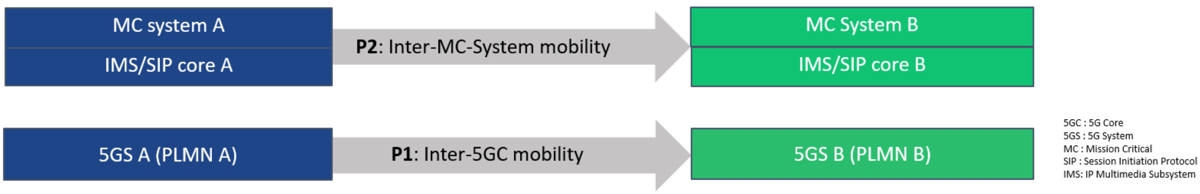

Figure 1 - Two procedures for BX in 3GPP

P1: Two approaches for Inter-5GC mobility

- **Inter-PLMN Handover:** Handing over the ongoing transport session (5G PDU session),
- **Network Reselection:** The UE is forced into idle mode if it is not the case in PLMN A by dropping ongoing transport sessions (E.g. when in "extended idle state"). It then camps on the selected cell within the PLMN B. Registration procedures are then initiated to establish a connection with the PLMN B.

P2: Approach for Inter-MC-System mobility

Note that it is an ongoing work in 3GPP since Rel. 18 [28]. There were no approaches before Rel. 18.

- **MC Migration:** which consists of 1) dropping of the ongoing service session, 2) registering the service user in the MC system B and 3) establishing a new service session to the MC system B.

2.3 State of the art on BX in FRMCS (Items under discussion for the specifications)

By the time of writing this document, the following subjects are currently being addressed in the BX framework within FRMCS:

a) Transition/mobility between two FRMCS Domains[1], e.g., transition period of border crossing
b) Transition/mobility between FRMCS and GSM-R (both directions) in cross-border scenarios
c) Start of Operation in a foreign FRMCS Domain
d) Interconnection, i.e., connectivity between users served by different FRMCS Domains

Items a) and d) are covered in [19], Section 10. Both items are currently under discussion. We will shed some lights on them.

2.3.1 Principles for Inter-FRMCS domain Transitions (two FRMCS domains)

An FRMCS Domain (the realm of an FRMCS Operator) consists of some central and/or regional network infrastructures plus the radio (cell) deployments distributed along the rail lines. The transition between the radio coverages is bound to the cells' deployment along the rail line. The transition happens at a single moment for an onboard modem which is commonly used for multiple applications. However, the transition on upper layer depends on the right moment for handing over a service from the service provider of one side to the service provider of the other side and might be unsynchronized among services due to some functional/operational behaviors.

The following list constitutes the principles for Inter-FRMCS domain Transitions:

- One/multiple active modem(s) on the train are shared among all on-board applications in any of the 2 involved domains and during the period of transition. Accordingly, there is no application-dedicated modem in FRMCS,
- No application can be the trigger or the lead of Inter-FRMCS-Domain transition while all applications' requirements (e.g., w.r.t functional needs or continuity requirements) shall be satisfied during the transition,
- the solution shall not impose any common or interdependent configurations among FRMCS domains which impacts the whole per-IM deployments, e.g., no European-wide identities / IP addresses required,
- At the time of writing this document, a solution using 2 active UEs could be envisaged as a starting point in FRMCS V2 for ETCS trains to prevent being impacted by uncertainties on the performance of the 3GPP solutions, in particular due to open topics on MCX interconnection and migration aspects.

[1] An FRMCS Domain is an administrative domain which comprises all network infrastructure under the control of an FRMCS Operator (e.g., railway infrastructure manager).

The performance of FRMCS solution(s) for BX needs to be approved in future frameworks.

2.3.2 Interconnection (Connectivity betw. users served by different FRMCS Domains)

It involves the establishment of communication links and connectivity between users or systems that are served by different FRMCS domains or network segments.

The main items to be addressed are:

- Reachability of the users of one domain by the users of another domain,
- Share of information, e.g., users' location, group information,
- Establishment of group communications which extend over two FRMCS Domains.

3 5GRAIL Preparations (Lab) for Border-Crossing Scenarios

In this chapter, we elaborate the background and describe the challenges on a BX context. The aim is to shed some lights on the relevance of the BX activities accomplished in the two labs in preparation for the subsequent field activities.

Recall that trains crossing 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. This was already a guiding principle for GSM-R which led to the inclusion of GSM-R in the EU legal frame of Technical Specifications for Interoperability.

Now, when it comes to FRMCS, the different Strata of the FRMCS architecture are impacted and involved in BX scenarios:

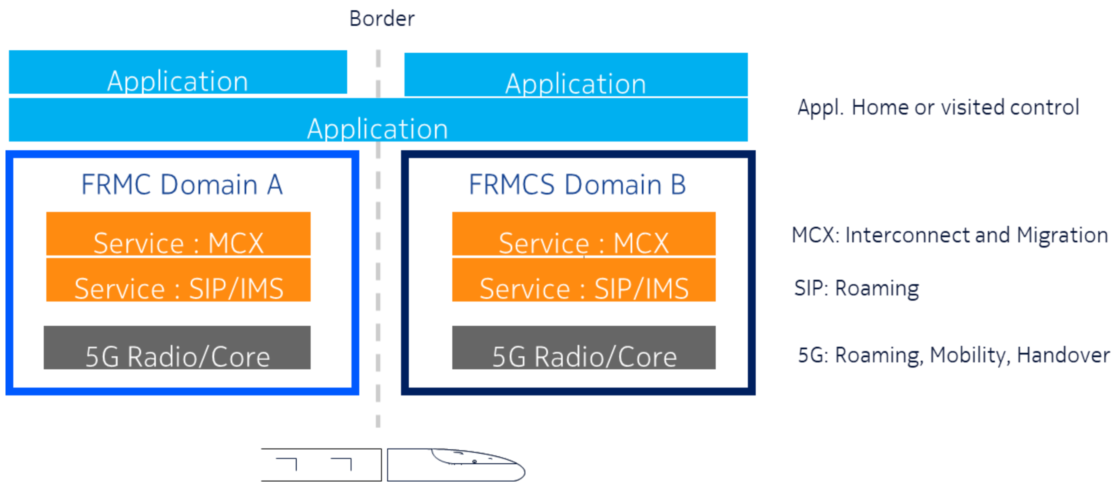

Figure 2 - FRMCS Strata impacted by Border Crossing

The following topics are to be considered:

- On 5G Radio / Core: measures for roaming and cell re-selection or Inter PLMN to be considered
- On Session layer: SIP roaming is the base to allow session handling between different countries, supporting MCX interworking and interconnection

By the time of preparing the field tests for 5GRail, MCX layer interconnection and migration was under further standardization in 3GPP [28], [38] to allow BX.

Recall that Interconnection is about the communication between MC systems whereby MC service users obtaining MC service from one MC system can communicate with MC service users who are obtaining MC service from one or more other MC systems. Interconnections between FRMCS domains is required.

3.1 Envisioned Concepts and Challenges for 5G SA BX Approaches

It should be noted that for concrete test setups in the initial phase of the projects related to Connected and Automated Mobility (CAM), the 5G systems were based on 5G NSA which means it is relying on

LTE core network. In 5G NSA, roaming functionality is available since years and driven by implementation principles of public MNOs. However, the situation is different for 5G SA in general (especially, with the complex 5G SA roaming architectures proposed by 3GPP). This is even more outstanding for private 5G SA networks for the industry / enterprise deployments (such as FRMCS) which have been one of the main drivers for 5G SA development, especially that it had a limited focus on mobility and roaming functionalities, initially.

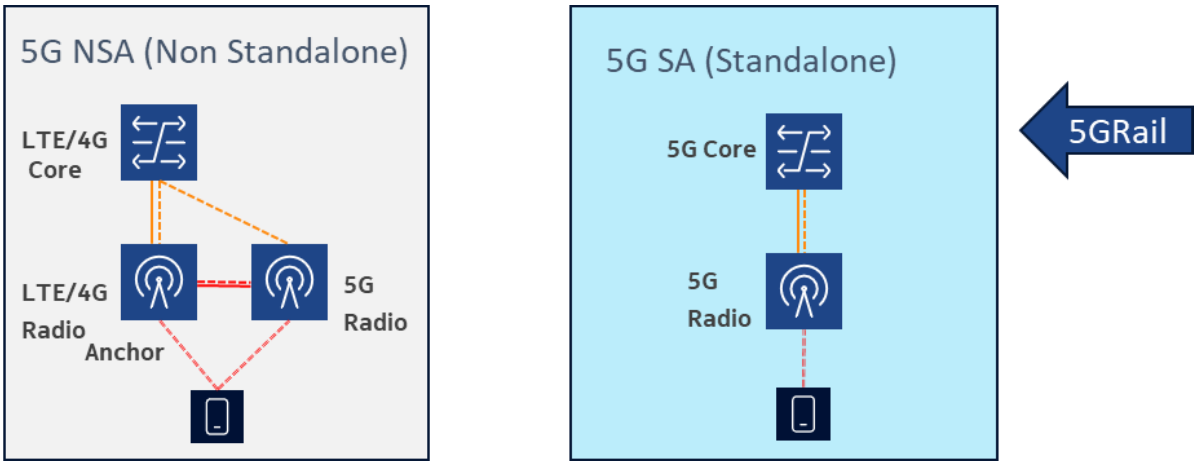

Figure 3 – 5GRAIL implementing a 5G Standalone (5G SA)

When it comes to the 5G NSA/SA evaluations, different steps have so far been analysed and tested in the 5G CAM projects on potential improvements towards seamless service continuity support on 5G level with a focus on automotive requirements for BX between CSP network. For the case of 5G SA scenarios, the differentiation related to **Network Reselection Improvements** is as follows [40]:

Scenario in 5G CAM projects	Description
Scenario 1 / Basic roaming features	UE roaming with new registration (network reselection) It is where the UE being released from a home network when connection is lost (based on thresholds in the controlling RAN), scans for new networks and performs blind attachment attempts (that take some time). This comes before finally registering and authenticating in the visiting network and re-establishing the user plane connection.
Scenario 2 / Intermediate roaming features	UE roaming with AMF relocation (idle mode mobility) It is where idle mode mobility refers to the UE being released from a home network when connection is lost (based on thresholds in the controlling RAN), scans for new admissible networks supported by packet core function ‘equivalent PLMN’ (avoiding blind attempts). This is followed by registering and authenticating in the visiting network and re-establishing the user plane connection via an accelerated process over NG/N14 interface between source and target AMFs (e.g., via N14 the new network can also be aware of the used UPF and UE IP address)

Scenario 3 / Advanced roaming features	<u>UE roaming with Inter-AMF (Inter-PLMN) handover</u> It refers to a seamless Inter-PLMN BX case relying on NG/N14 (and N2) handover commands between source and target networks and advanced exchange of UE information on handover candidates. This allows a huge reduction of the user plane interruption time.

On the second hand, focusing on core network, in terms of **5G SA Roaming Architecture Models** for the transport stratum transition in FRMCS BX, there are two basic ones defined by 3GPP [39]:

- **Home routed (HR):** roamer uses same UPF of home network (H-PLMN)
- **Local break-out (LBO):** roamer uses UPF of visited network (V-PLMN)

An inter-PLMN BX scenario triggers a transition from a Home 5G network (H-PLMN), provided by an Infrastructure Manager (IM)-A to another visited 5G network (V-PLMN) pertaining to another IM-B as depicted in the following figure.

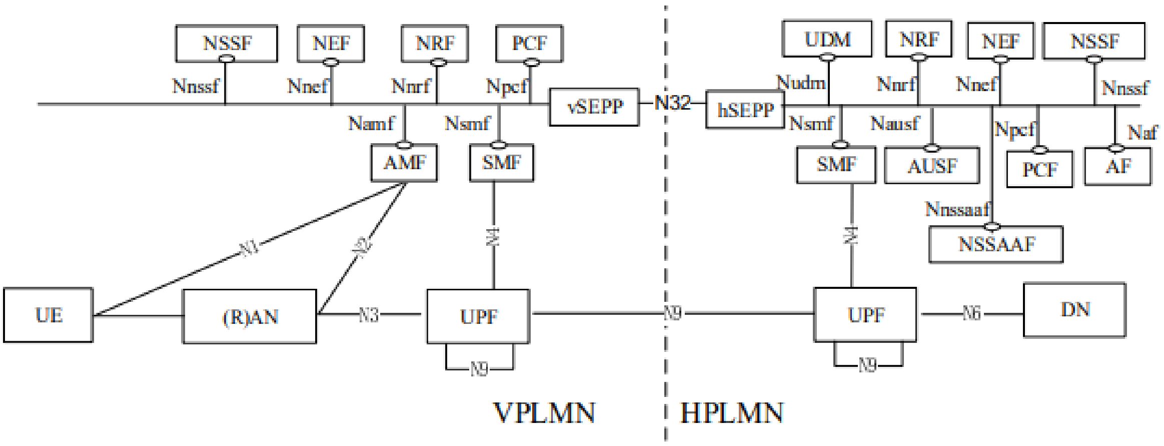

Figure 4 - HPLMN to VPLMN Inter-5GC Architecture [32]

The HR and LBO architecture principles and call flow for Inter-PLMN transition are depicted in the following figure. Note that the service-based HR architecture is more complex compared to LBO, as some home network functions are in charge of selecting home UPF resource for the session, this UPF has to be linked to a V-UPF, as we will discuss in the following section.

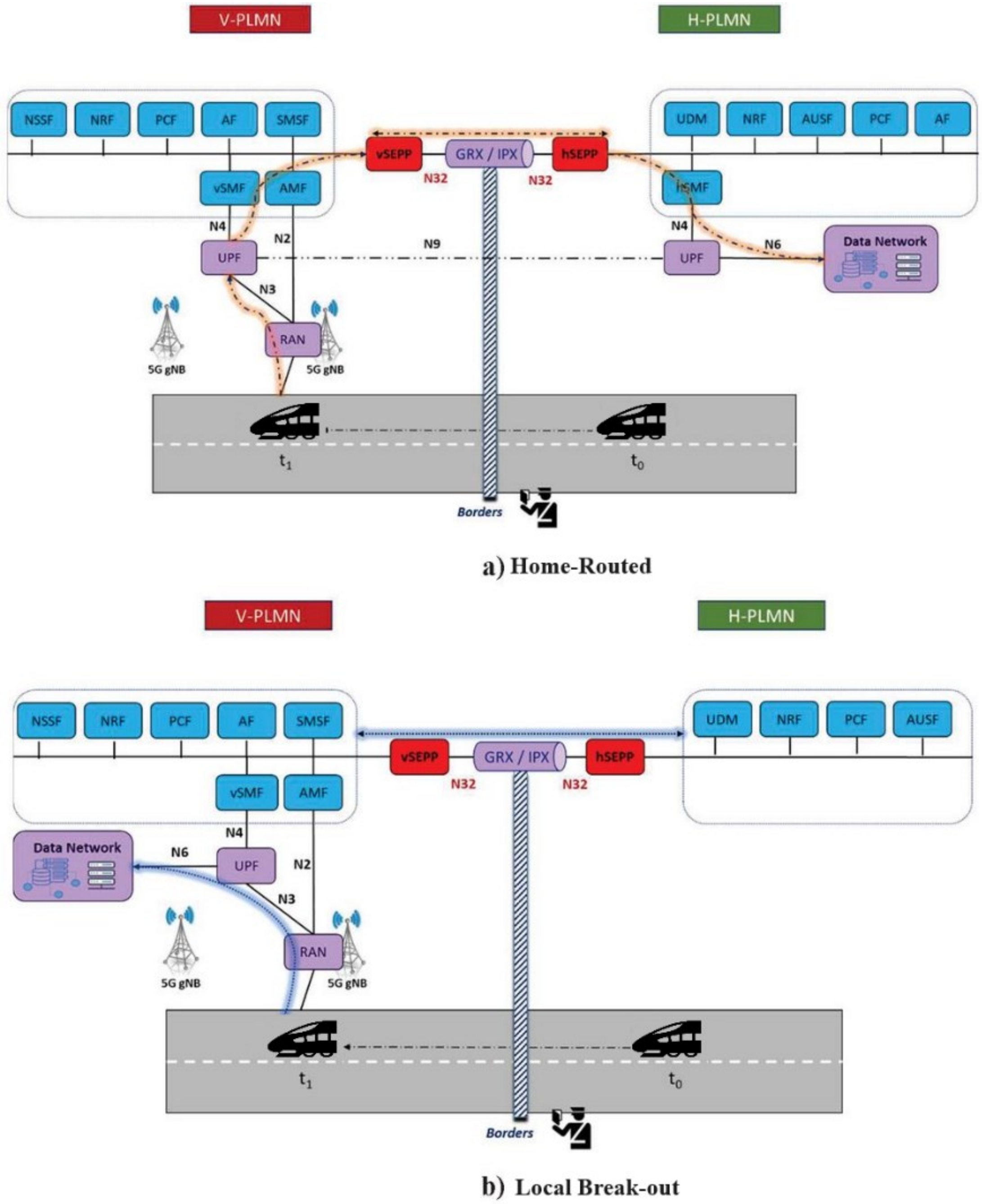

Figure 5 - Inter-PLMN Transition with Home Routed traffic (a) or Local Break-out (b)

3.2 Focus in 5GRAIL

In 5GRAIL, within the elaborated context in previous sections, the focus is geared on the transport stratum only, and not including the service stratum, where IMS/MCX are involved. The latter involves the authentication and authorization followed by the MCX connection establishment. However, even when focused on the transport stratum, several challenges need to be addressed; precisely, regarding the conservation of the IP address used by the UE during BX.

We can distinguish different scenarios:

- A UE does NOT maintain the same IP address after transiting from a HPLMN to a VPLMN: Obviously, this is an over-simplification, and it comes at a cost; as after getting a new IP address, it must re-register on IMS, which impacts the latency.
- A UE maintains the same IP address used in the HPLMN. This is the case where the traffic is "Home-Routed". However, Home routing is challenging due to the increased latency (once again) and the usage of the costly transition links.
- To address the latency challenge, a Local break-out can be used. However, in this case, the train must perform an IMS registration on the visited network to avoid the "anchoring" effect to home network and be able to minimize the latency. Accordingly, the MCX session is broken, and it must be re-established after a new IMS registration. This has an impact on the Obapp interface and will negative affect the service continuity aspects of the upper railway application.

The limits of the maturity of present 3GPP concepts and limits on available infrastructure on Roaming and Handover capabilities in a 5G SA environment, especially for enterprise product lines (and their prototypes), led to the approach to identify and focus on building blocks to derive benefits of the concepts for FRMCS BX. These are mainly:

- the NG handover with 5G SA Inter-AMF support for Inter-PLMN BX
  (FRMCS BX approach with 1 modem), see Section 3.3.1
- the usage of interworking functions for 2G-5G Inter-RAT transition
  (FRMCS BX approach with 2 modems), see Section 3.3.2
- the usage of inter-frequency handover betw. two sub-bands with different TDD configurations
  (FRMCS BX approach with 2 modems), see Section 3.3.3
- the usage of multipath protocols (e.g. MPTCP) for Inter-RAT scenarios
  (FRMCS BX approach with 1 modem), see Section 3.4.1

3.3 BX Scope and Test Implications in Nokia Lab

In this section, we provide three approaches that have been addressed in the Nokia lab in WP3 and (partially) transferred to the field in order to understand BX principles for FRMCS.

3.3.1 Evaluation of Control Plane Procedures in Inter-gNB Inter-AMF Handover via NG Interface – Building Block for 5G SA BX (using 1 modem)

As interworking and cross-border roaming concepts in the MCX service stratum as well as inter-core roaming and handover in 5G SA transport stratum are not fully mature in 3GPP, a full-featured FRMCS cross-border realization is not possible at this point in time.

Instead, it was decided to demonstrate building blocks of 5G SA roaming, in particular ensuring control plane features and procedures, in a set-up with two core networks and radios. The details of the Proof-of-Concept (PoC) trial for such a 5G SA Inter-Core BX scenario are as follows:

- The two-core test system consists of two 5G core instances (two of Nokia's CMUs), each hosting an AMF function on control plane.
- Two PLMNs (home and visited) exist with the following conditions:
  - The "second (visited)" PLMN is only emulated with a focus on AMF, which means other control plane functions in the second 5G core such as the UDM/AUSF of the visited PLMN are not used (as several roaming interfaces are missing),
  - On user plane, the test system and is treated as single PLMN, i.e., the UPF stays with the "first (home)" network and also on MCX layer the user remains in the home network.
- The realization of the control plane procedures for Inter-AMF handover/connectivity via NG interface is tested by the capability of the N14 based interconnection of two AMF in Nokia core;

The described principles of the Inter-gNB inter-AMF NG Handover as a main building block for seamless Inter-PLMN roaming scenario is depicted in the following Figure 6 and Figure 7.

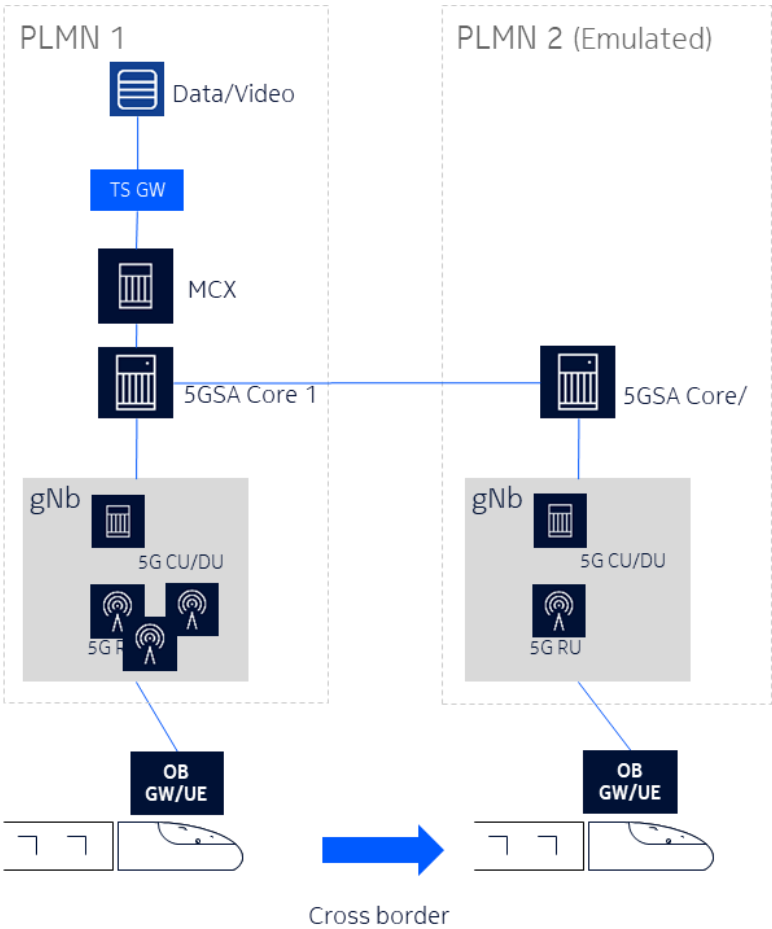

Figure 6 – WP3 Setup for Control Plane Tests in Inter-gNB Inter-AMF Handover via N14 Interface

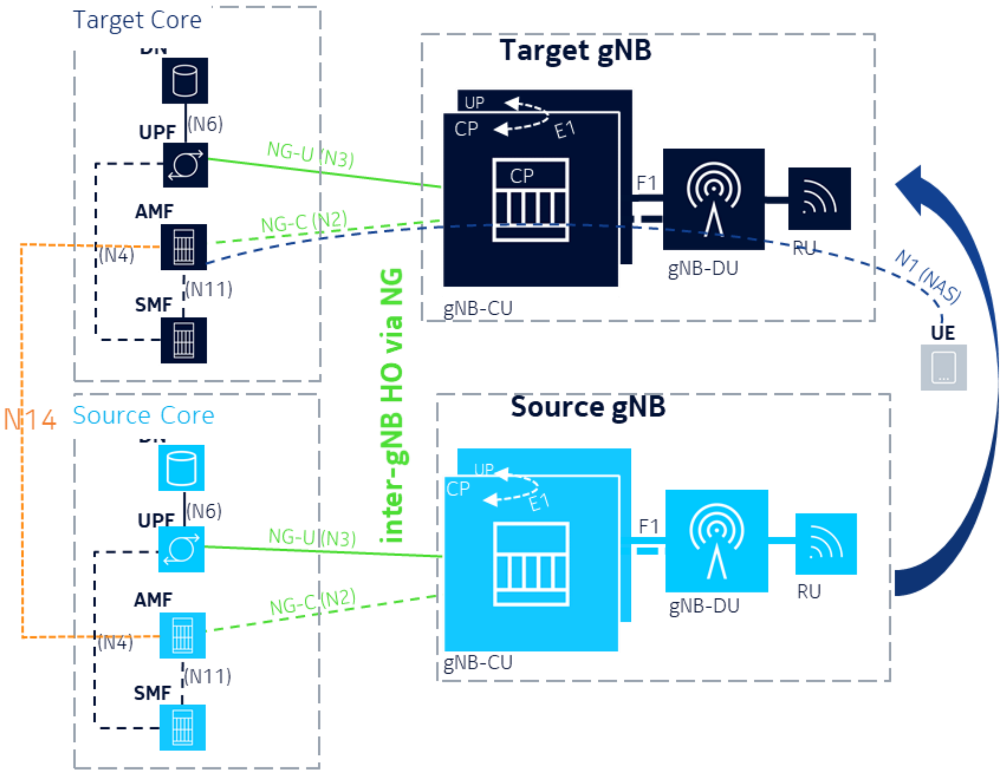

Figure 7 - Overview of Interfaces in NG-based Inter-gNB Inter-AMF Handover

The concrete 5GRAIL configuration for lab (and field) tests is as follows:

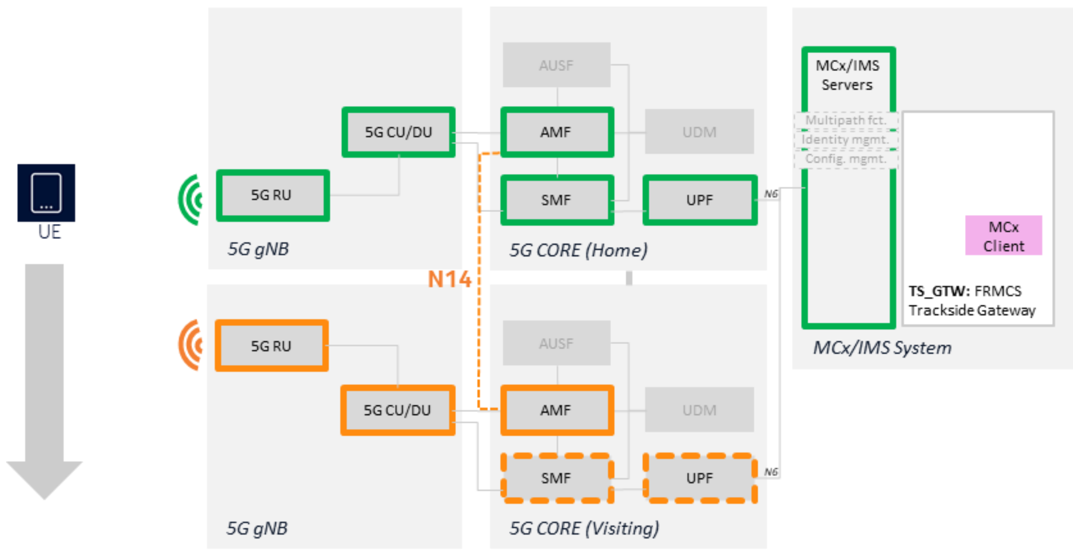

Figure 8 - Involved building blocks during Inter-gNB Inter-AMF Handover via N14 Interface

3.3.2 Evaluation of GSM-R to FRMCS Service Transition using Interworking Functionality – 2G-5G Inter-RAT BX (using 2 modems)

In this scenario, a Railway Emergency Call (REC) involving both of FRMCS and GSM-R, was realized using a GSM-R interworking function (IWF). The following details for the service transition from 2G to 5G in this approach are as follows:

- A terminal on FRMCS coverage establishes a REC call which propagates between FRMCS MCX system and the GSM-R MSC, so that a corresponding connectivity is set-up in GSM-R
- A cab radio on GSM-R side listens to the GSM-R REC
- When the train runs, the cab radio moves from GSM-R coverage to FRMCS. It releases the GSM-R connectivity, connects to 5G, and joins the ongoing FRMCS REC call.

This scenario is relevant when both technologies cover the same area in the network of a railway infrastructure manager. It is also relevant for a BX use case when one country is still running GSM-R, and the neighbour country runs FRMCS, with some overlap areas. This will be the case during the transitory migration period from GSM-R to FRMCS.

3.3.3 Bearer Change with 5G Inter-Frequency Handover between two Sub-Bands with different TDD Configurations (using 1 modem)

In FRMCS cross-border scenarios, a service transition between two networks of infrastructure managers operated on different 5G bearers with different TDD configurations may occur, see Figure 9. For instance, this is the case for 2x 5 MHz sub-bands within the 10 MHz FRMCS bandwidth at RMR band n101 in the future. The 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.

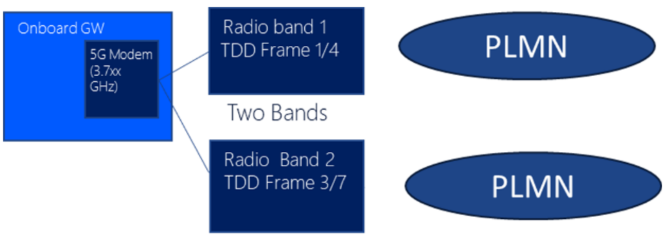

Figure 9 – Different TDD structure for two bands in an inter-PLMN scenario

3.4 BX Scope and Test Implications in Kontron Lab

Before delving into the details of the preparations for the BX in the French lab, let us first examine the context and the related challenges.

First, we note that, by the time of starting the 5GRAIL project and defining the test plans, both Home-Routing and Local Break-Out implementations were not available as native 5G SA features for all 5G equipment manufacturers. One of the reasons is that it is anticipated that MNOs currently opt for the 5G NSA when modernizing their 4G networks. In this perspective, the proposal in the French lab was to implement FRMCS BX based on 4G-5G Inter-RAT with two modems. For this, Multi-Path TCP (MPTCP) approach was envisaged by the Kontron lab.

The emergence of the OB_GTW as key differentiator in FRMCS compared to what was done in the GSM-R era, allows bearer flexibility realization (independence of the traffic from the bearer itself), where MPTCP is one approach.

3.4.1 Usage of MPTCP in Multi-/Inter-RAT BX Scenarios – 4G-5G Inter-RAT BX (using 2 modems)

Note that Multi-Path TCP (MPTCP) is an extension of the traditional Transmission Control Protocol (TCP) that allows a single data stream to be transmitted over multiple network paths simultaneously. The primary goal of MPTCP is to enhance the performance, reliability, and resilience of communication by utilizing multiple paths between two endpoints. In this context, provided that 2 bearers (n39 and b38 that is widely used in LTE) were made available in the French field, 4G-5G transitions are considered.

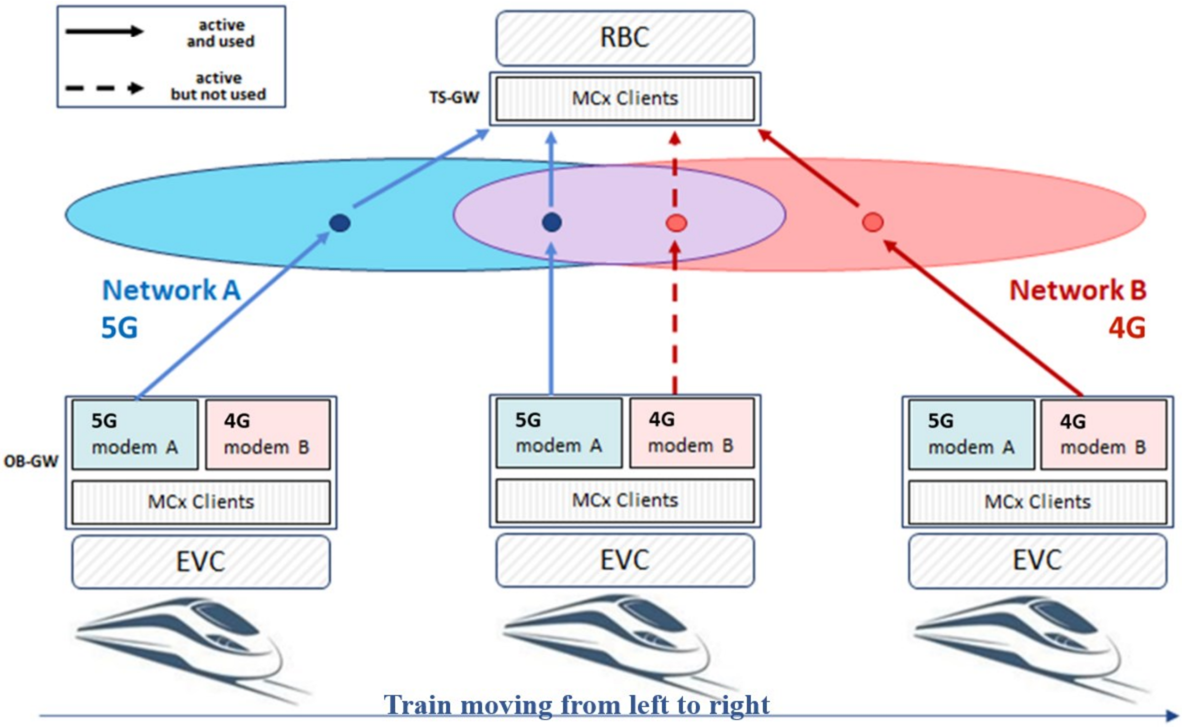

Figure 10 - Multi-Path TCP usage when moving between 5G and 4G networks (ETCS example)

Recall that Traditional TCP operates on a point-to-point basis, establishing a single connection between a sender and a receiver. In contrast, MPTCP enables a connection to be established over multiple paths, such as different network interfaces, subnets, or even different types of networks (e.g., 5G cellular and 4G). This allows for more efficient use of available network resources and improved performance in various scenarios.

Key features of MPTCP include:

- **Seamless Handover**: MPTCP can seamlessly switch between different network paths without interrupting the ongoing data transmission. This is particularly useful in scenarios where a device moves between different networks (e.g., switching from bearer 1 to bearer 2).
- **Increased Throughput**: By distributing the data across multiple paths, MPTCP can aggregate the bandwidth of each path, potentially leading to increased overall throughput.
- **Resilience**: MPTCP improves the resilience of communication by providing redundancy. If one path experiences congestion, packet loss, or failure, the protocol can dynamically shift traffic to alternative paths, reducing the impact on the overall connection.
- **Load Balancing**: MPTCP can balance the load across available paths, ensuring that no single path is overly congested while others remain underutilized.
- **Compatibility**: MPTCP is designed to be backward compatible with existing TCP implementations. If one of the endpoints does not support MPTCP, the communication can still proceed using traditional TCP.

Further details on the lab-validation of MP-TCP in the French lab are available in deliverable D4.3 [11].

4 5GRAIL Activities (Field) with Border-Crossing Relevance

The field activities were accomplished in two complementary testbeds in Germany and France – referred to as German field and French field, respectively. These are described in deliverable D5.1 [12].

5GRAIL cross-border validation involves testing critical railway applications, as well as 3GPP MCX building blocks on top of a 5G SA deployment, which are all in their early stages. The following table reports the summary of the different accomplished test cases which are seen as steps towards FRMCS border-crossing scenarios of the future.

Chapter	Test Case No. (acc. To D1.1)	Description, Relevance for Border-Crossing & Status
4.1	Voice_015 (DE)	Test Case Name: GSM-R to FRMCS system transition with service continuation BX Relevance: Early-stage assessment of network functions, esp. interworking function, which become part of an **Inter-RAT (2G-5G) border-crossing scenario** (for voice) in the future. It is not a full-featured cross-border test. Status: Test performed in lab and field.
4.2	ETCS_WP4-WP5_TC_003 (FR)	Test Case Name: Communication in level 2 between ETCS onboard application and RBC – Test Procedure 3: RBC handover on a different 5G network: Cross-border use case BX Relevance: Early-stage assessment of network functions interworking, which is part of an **Inter-RAT (4G-5G) border-crossing scenario with Inter-PLMN handover**. Dedicated test codes for France MCC-MNC (208-85, 208-90) were configured in this setup. It is not a full-featured cross-border test. Status: Test performed in lab and field.
4.3	Video_TC_004 (DE)	Test Case Name: Cross-border with streaming of video/voice from train to trackside, using inter-gNodeB handover over AMF BX Relevance: Assessment of control plane procedures in **Inter-gNB inter-AMF handover** as relevant part of an **5G SA Inter-Core cross-border scenario**, using NG/N14 interface. Hereby the transition occurs from the source 5G Core (AMF1) to the target 5G Core (AMF2). Notably, throughout this operation, session management remains within the source 5G Core (SMF1 and UPF1), see details in Section 3.3.1. Only one IP address is used, as if it was one PLMN, although there are two 5G cores implemented. PLMN2 was emulated, means it is treated as the same network. It is not a full-featured cross-border test, but an important subfunction of an envisaged Inter-PLMN 5G Handover scenario.

		Status: Test performed in lab, but not performed in field (due to lack of stable specifications and readiness of field-equipment at the time of planning of the field test cases).
4.4	CCTV_TC_002 (DE)	Test Case Name: CCTV offload from train to trackside with bearer-flex BX Relevance: Analysis of 5G Inter-Frequency mechanisms in the **transition between two 5G TDD bearers**. Changing TDD patterns/configurations is a possible scenario for border crossing railway operations. It is not a full-featured cross-border test. Status: Test performed in lab and field.

4.1 Test case No. Voice_015 (2G-5G Inter-RAT): GSM-R to FRMCS system transition with service continuation

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-5G transition scenario was demonstrated based on a voice (MCPTT) application, for which Siemens provided the onboard part (cab radio with tight coupled MCX client) and Nokia the trackside part (dispatcher and MCX server). 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.

In 5GRAIL deliverable D1.1, moving from GSM-R to FRMCS is described as a proof-of-concept test case using a combined field-lab setup. It is performed for an on-going Railway Emergency Call (REC), initiated by the train driver (cab radio) in the field. Please refer to Section 7.6.6 in D1.1 [1] for details of the test plan including the description of the initial state/configuration.

4.1.1 Purpose

This test case focuses on the evaluation of the service continuity for the voice application Railway Emergency Call (REC) when moving a user from GSM-R (2G) to FRMCS (5G) in a REC call area with GSM-R and FRMCS overlap. To realize the test, a GSM-R interworking function (IWF)[2] is required.

[2] The standardization of the interworking function in ETSI is still ongoing, thus the realized implementation is realized as pre-standard functionality.

4.1.2 Test Architecture

The architecture of the test case is presented below. The used end-to-end building blocks for the initial REC call are marked in green, the building blocks for the transition scenario (Cab Radio in the Lab joining the ongoing REC call on FRMCS) are marked in red.

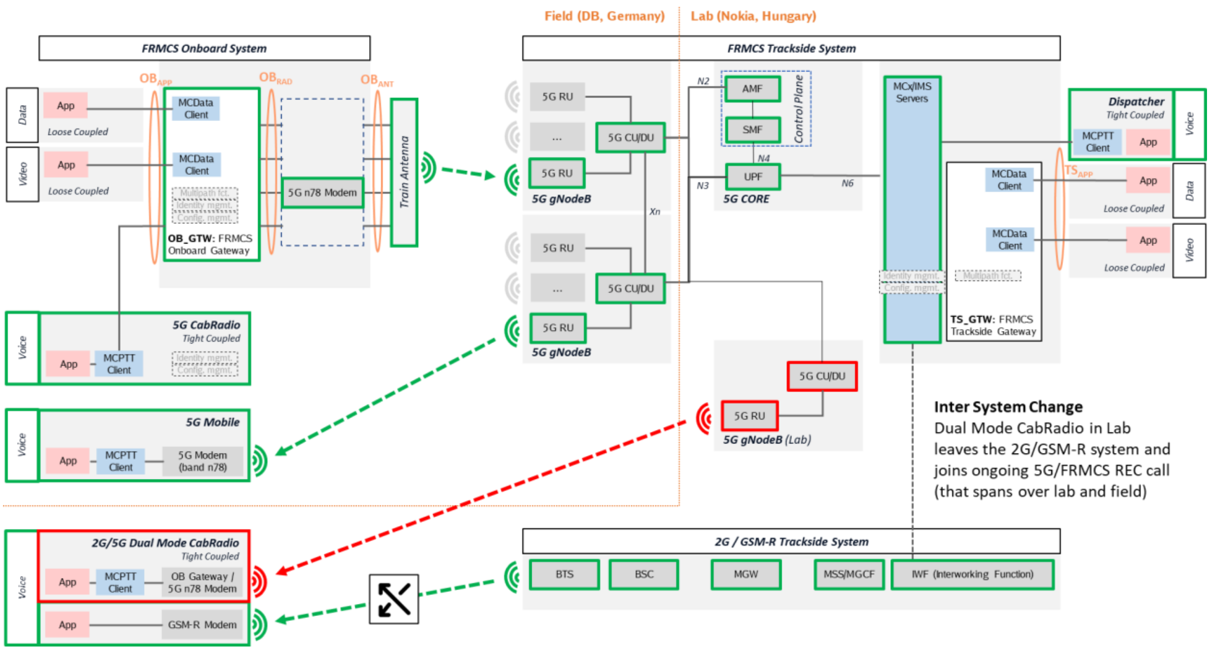

Figure 11 - Architecture for the GSM-R (2G) to FRMCS (5G) system transition test with service continuation, being performed in a combined field-lab setup.

4.1.3 Test Procedure

The test case is using the following procedure:

- Establishment of FRMCS REC call (initiated by Cab Radio A in the Field) triggers automatically GSM-R REC setup, using an GSM-R interworking function (IWF)
- Several participants are included in the REC call area which covers an FRMCS and GSM-R overlapping zone[3], Cab Radio B in the Lab participates in REC call on GSM-R
- By manual switching Cab Radio B in the Lab changes from GSM-R attached to FRMCS
- Cab Radio B in the Lab joins ongoing REC call on FRMCS[4]

[3] In the test case a virtual REC call area has been set up which spans over field and lab.

[4] The realization uses the pre-configuration / pre-affiliation of the MCPTT group call on the FRMCS side to allow the Cab-Radio B to do standard Late Join functionality.

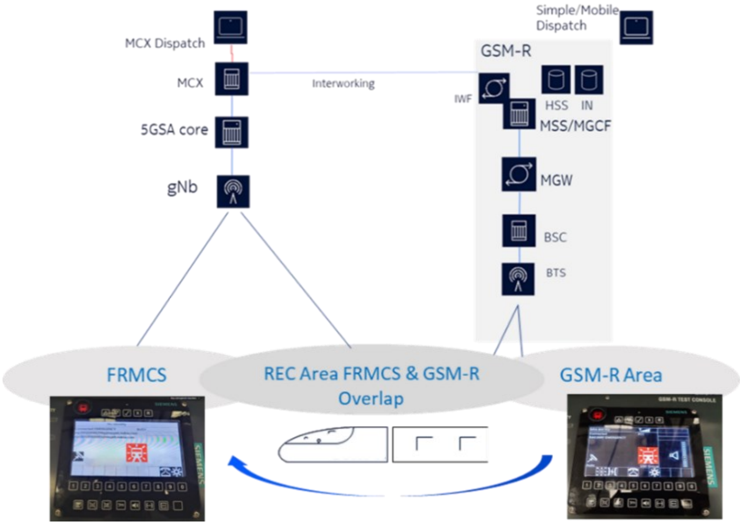

Figure 12 - Principle of a REC call transition from GSM-R (2G) to FRMCS (5G)

The test case is described step by step in more details in the table below:

Step	Action	Expected result(s)
1	FRMCS User A (Cab Radio in the Field) initiates a Railway Emergency Call	• Audible indication for call proceeding is given. • Visual indication for call proceeding is displayed. • The FRMCS system automatically routes the Railway Emergency Call to the Users in the targeted area including the GSM-R User B (Cab Radio in the Lab) and the Controller responsible for the train movement area. • Audible indication for Railway Emergency Call is given via the loudspeaker of the Cab Radio B • Visual indication for Railway Emergency Call is displayed on the GDCP of the Cab Radio B
2	GSM-R User B (Cab Radio in the Lab) and the Controller (Dispatcher in the Lab) responsible for the train movement area automatically accept the call	• The Railway Emergency Call is established with a setup time specified as IMMEDIATE. • Visual indication for call established is displayed on the FRMCS device and the GDCP of the Cab Radio B • Visual indication to use Push to Talk is displayed on the FRMCS device
3	FRMCS User A (Cab Radio in the Field) presses PTT button	• The FRMCS device is activated, and communication is possible. • The voice quality is clear and loud
4	FRMCS User A (Cab Radio in the Field) releases the PTT button	• Visual indication to use Push to Talk is displayed on the FRMCS device
5	GSM-R User B (Cab Radio in the Lab) picks up the Cab Radio B handset and presses PTT button	• The Cab Radio B loudspeaker sets to reduced volume. • The Cab Radio B handset is activated, and communication is possible. • The voice quality is clear and loud

6	GSM-R User B (Cab Radio in the Lab) releases the PTT button	• Visual indication to use Push to Talk is displayed on the GDCP of the Cab Radio B
7	GSM-R system becomes unavailable	• Audible indication is given via the loudspeaker of the Cab Radio B • Visual indication is displayed on the GDCP of the Cab Radio B
8	GSM-R User B (Cab Radio in the Lab) presses the network switch button on the GDCP of the Cab Radio B	• Cab Radio B switches from the GSM-R system to the FSMCS system
9	GSM-R User B (Cab Radio in the Lab) registers to the FRMCS system	• Registration request is sent to the FRMCS system. • Registration progress is displayed on the GDCP of the Cab Radio B
10	FRMCS system accepts the registration request	• Registration status is displayed on the GDCP of the Cab Radio B (e.g., train running number appears on the display) • Audible indication is given via the loudspeaker. • The FRMCS system automatically routes the ongoing Railway Emergency voice communication to the GSM-R User B • Audible indication for Railway Emergency Call is given via the loudspeaker of the Cab Radio B • Visual indication for Railway Emergency Call is displayed on the GDCP of the Cab Radio B
11	The GSM-R User B (Cab Radio in the Lab) receives and automatically joins the Railway Emergency Call as FRMCS User B now	• Incoming audio is connected to the loudspeaker of the Cab Radio B • Visual indication is displayed on the Controller's terminal.
12	FRMCS User A (Cab Radio in the Field) presses PTT button	• The FRMCS device is activated, and communication is possible. • The voice quality is clear and loud
13	FRMCS User A (Cab Radio in the Field) releases the PTT button	• Visual indication to use Push to Talk is displayed on the FRMCS device
14	FRMCS User B (Cab Radio in the Lab) picks up the Cab Radio B handset and presses PTT button	• The Cab Radio B loudspeaker sets to reduced volume. • The Cab Radio B handset is activated, and communication is possible. • The voice quality is clear and loud
15	FRMCS User B (Cab Radio in the Lab) releases the PTT button	• Visual indication to use Push to Talk is displayed on the GDCP of the Cab Radio B

16	FRMCS User A (Cab Radio in the Field) terminates the Railway Emergency Call	• The FRMCS system terminates the Railway Emergency Call. • Visual indication is displayed on the FRMCS device, the GDCP of the Cab Radio B and the Controller's terminal. • Idle screen is displayed on all devices

4.1.4 Specifics of the Test implementation and Execution

The test was demonstrated with a manual switch of the network for Cab Radio B in the Lab (to showcase that the current GSM-R (2G) network becomes unavailable, and an available FRMCS (5G) REC call can be joined). In the future, this feature will become an automatic function.

4.1.5 Results and Observations

The test was successfully performed, both with REC as a single application and in a combined scenario with REC and video calls.

It was working in stationary mode and under driving conditions, i.e., with intra- and inter-gNB handover situations in the 5G network.

An open topic remains the voice codec optimization. It was observed that the FRMCS (5G) user is unable to hear the voice of the GSM-R (2G) user unless all codecs except G711 are disabled on the FRMCS device. Once these adjustments were made, the voice was transmitted without any interruptions. This has been identified as a known issue lacking specifications, which will be addressed in future specification releases.

4.2 Test case No. ETCS_WP4-WP5_TC_003 (4G-5G Inter-RAT): Transition Scenario for Critical Data Application Simulator

This scenario focuses on the testing and evaluation of the loose-coupled critical data application involving the main FRMCS functionalities. Precisely, testing the communication in level 2 between ETCS onboard application and RBC while having a transition. These will be realized using 5G NR, 5G stand-alone core, 4G radio, 4G core (EPC) and the MCX service and application server.

The data application is provided by ALSTOM for the onboard and trackside. Tests are being performed in the French lab and field.

For the sake of completeness and to keep this report, as a stand-alone document, the test procedure is summarized below. However, the details of the test plan including the description of the initial state/configuration is described in Deliverable D1.1 [2] – Section 8.2.2.3.5.

4.2.1 Purpose

The purpose of this test is to demonstrate that a data application is not impacted when simulating a transition from PLMN-A to a PLMN-B as it is the case when crossing the border.

The aim is to test a loose-couple data application using the OBapp interface (ETCS simulator) and its transitions scenarios on different PLMN (different 5G network). This is the anticipated scenario when crossing a border.

It was initially envisioned having this test case involving two 5G networks as depicted in the following architecture. This 5G architecture features two gNodeB and two 5G Core networks. One RU and the RRH will be connected to one gNodeB and one 5G Core network. The two other RU will be connected to the second gNodeB and the second 5G Core network.

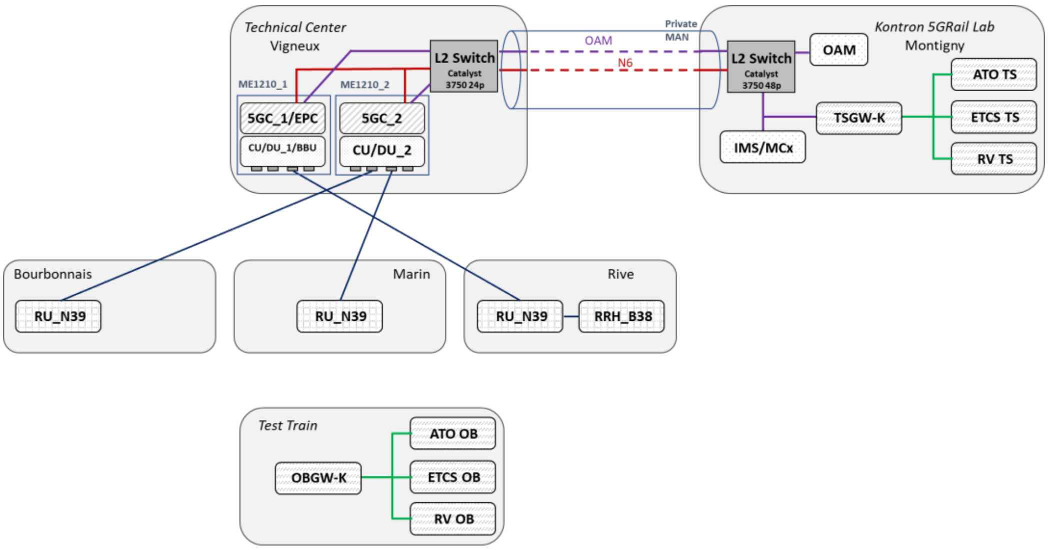

Figure 13 - Configuration "B" with two cores envisioned for BX Tests [12]

However, there was a physical limiting factor on the OB_GTW TOBA-K as two 5G modems could not be integrated inside it. Throughout the design, it was concluded that it is not possible for it to integrate two 5G modems as they are i) too big to fit within the chassis and ii) they would dissipate extensive heat during operation. Consequently, this test case was adapted to make use of a single 5G modem and a 4G built-in one, which is natively integrated. Accordingly, this test was adapted to a transition between a 5GC and a 4G one (EPC).

4.2.2 Test Architecture

This test is realized using 5G RAN, 5G-SA core, 4G RAN, and EPC, and FRMCS/MCX application client/server, as well as the IMS (SIP-Core). In this perspective, the RAN and core were configured to use the MCC-MNC 208-85, 208-90, respectively, as these are the allocated ones for test networks by the ARCEP.

The data application is provided by Alstom for the onboard and Trackside. The infrastructure is provided by Kontron, and it will be pre-tested in the lab of WP4 in France.

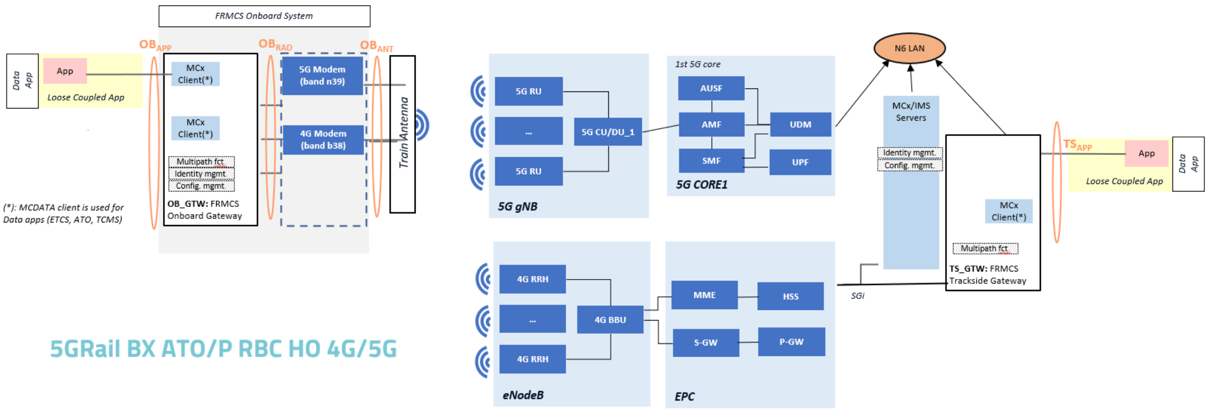

Figure 14 - Architecture for ATO/ATP BX transition from 5G to 4G test in France

4.2.3 Test procedure

This is the Test procedure no. 3: RBC Handover on a different NETWORK: BX-like use case.

As a prerequisite, this test will be performed in WP4 lab with TOBA-K with 1x5G UE in n39 and 1x4G UE in b38 band. Both gateways cross-border implementation is making use of *multi-connectivity feature*, employing 2UEs.

The BX-like test case, when performed with TOBA-K and 1x5G UE in n39, is implemented as a *Radio degraded* kind of test.

The overall performances in lab in case of TOBA-K in n39 are of particular interest due to the repetition of this test case in field conditions.

Step	Action	Expected result(s)
1	Establishment of a new session for communication with RBC1 (session start message)	• The FRMCS GTW is correctly answering OK with the session ID1 and RBC1 @IP. • Check that the FRMCS GTW is sending "working" notification before the timeout (12sec).
2	Check that the user plane communication is established	• Data transfer using the RBC1 IP
3	Establishment of a new session for communication with RBC2 (session start message), based on a balise simulation request to the On-Board application. RBC2 is on a different network	• The FRMCS GTW is correctly answering OK with the session ID2 and RBC2 @IP • Check that the FRMCS GTW is sending "working" notification before the timeout (12sec)
4	Check that the user plane communication is established	• Data transfer using the RBC2 @IP

5	Terminate the user plane communication with the RBC1, on balise request for close connection to the On-Board application	• No error returned
6	Terminate the session1. The train becomes out of coverage from network, where RBC1 belongs	• The content of the session status "deleted" message (session ID1) is correct
7	Check that the user plane communication is still established with the RBC2	• Data transfer using the RBC2 IP • The communication is not impacted by the network handover
8	Terminate the user plane communication with the RBC2	• No error returned
9	Terminate the session2	• The content of the session status "deleted" message (session ID2) is correct
10	Check that the FRMCS GTW is responding to the connection status request	• Connection status is OK

4.2.4 Specifics of the Test implementation and Execution

The test execution is conducted according to the following steps:

CASE A: When circulation is from Juvisy to Vigneux (Site 3 → Site 1)

- Telecom operator is asked to switch-off 5G at Rives
- TOBA is under 4G coverage at Rives (PLMN A)
- Attachment on 4G, Registration, Start of ETCS traffic toward RBC 1
- 2nd modem attaches to Marin 5G (PLMN B) whenever it can. Traffic should also start on that bearer.
- This is a trigger to ask Alstom people to start talking with RBC 2
- Multi-connectivity 4G+5G should happen then (ETCS on both bearers)
- Traffic exchange should resume on 5G only as 4G coverage will be lost around Marin: cross-border is achieved.

CASE B: When circulation is from Vigneux to Juvisy (Site 1 → Site 3)

- Telecom operator is asked to switch-off 5G at Rives Site
- TOBA is under 5G coverage at Marin (PLMN B)
- Attachment on 5G, Registration, Start of ETCS traffic toward RBC 1 (It is anticipated that this will be difficult to achieve as time is limited, but it was tried anyway)

- 2nd modem attaches to Rives 4G (PLMN A) whenever it can. Traffic should start on that bearer
- Ask Application provider (Alstom Team) to trigger exchange with RBC 2: multi-connectivity 4G+5G should happen then (ETCS on both bearers)
- Traffic should resume through 4G only as 5G coverage will be lost when arriving at Juvisy: cross-border is achieved

4.2.5 Results and Observations

This procedure was tested in Lab with some issues reported in Deliverable D4.3 [11]. Nevertheless, it was also tested in field for additional observations. Below are the outcomes.

Comments from Infrastructure Provider (Kontron) on First Attempt (31/08/2023):

Static area in Juvisy:

- Successful connection of 4G and 5G modems.
- Test of multi-connectivity done: session opening and data transfer with the two RBCs.

Circulation from Juvisy to Vigneux:

- Deactivation of 5G network (BBU1, PLMN A) at the starting point, connection established, and data transfer to the 4G network with RBC 1.
- At Marin site, connection to 5G network impossible (BBU2, PLMN B).
- End of the run without connection to 5G network.

Circulation from Vigneux to Juvisy:

- No coverage at the starting point.
- At Marin site, connection to 5G network impossible (PLMN B, BBU2) but connection to 4G (BBU1, PLMN A) done.
- End of the run with successful connection to 5G but problem of ETCS connection following the 4G loss of coverage before starting the logs.

Identified issue: The 5G network at Rives site should be cut-off before TOBA power on.

Comments from the Application Provider (ALSTOM) on First Attempt (31/08/2023):

Baselining: Static test on Juvisy (site 3): Handover of RBC is performed to be sure the multi-connectivity is working. The connection on 2 RBCs is working, and ETCS data is successfully exchanged.

Run1: Case A – (4G → 5G) (circulation is from Juvisy to Vigneux):

Steps of test execution	Result
(1) MTY operator is asked to switch off 5G at Rives	Done, 5G PLMNA and BBU1 are stopped
(2) TOBA is under 4G coverage at Rives (PLMN A)	OK

(3) Attachment on 4G, Registration, Start of ETCS traffic toward RBC 1	Attachment is OK, connection to RBC1 is OK and ETCS data exchanged with RBC1
(4) 2nd modem attaches to Marin 5G (PLMN B) whenever it can. Traffic should also start on that bearer.	No 5G coverage when the train was around Marin site. Loss of the 4G signal. → Step not passed

Run2: Case B – (5G → 4G) (circulation is from Vigneux to Juvisy):

Steps of test execution	Result
(1) MTY operator is asked to switch off 4G at Marin.	Not done as there was no coverage at the starting point.
(2) TOBA is under 5G coverage at Marin (PLMN B)	The modem is on the 5G network but not detected by the TOBA. → Step not passed
(3) Attachment on 5G, Registration, Start of ETCS traffic toward RBC 1 (will be difficult to achieve as time is very short, but it could be tried)	→ Step not passed
(4) 2nd modem attaches to Rives 4G (PLMN A) whenever it can. Traffic should also start on that bearer	Attachment to 4G is OK, then 5G attachment is OK. Start of the ETCS equipment but no time to be connected to the RBC before the loss of signal. → Step not passed

Comments from the Infrastructure Provider (Kontron) on Second Attempt (01/09/2023):

Static area in Juvisy:

- 5G at Marin site cut off.
- Connection to the 4G, start of ETCS application but no data transfer.

First circulation from Juvisy to Vigneux:

- Start of the run under 4G coverage but no data transfer
- Restart of ETCS and TOBA but still no data transfer until the end of the run.

Static area in Vigneux:

- Root cause of the problem in data transfer identified: TOBA configuration to be changed.

Circulation from Vigneux to Juvisy:

- Cut-off of 4G of Marin site
- 5G modem connection to 5G at Marin site
- Start of ETCS application and 4G Marin on service.
- When the train arrived under 4G and 5G coverage area, no connection to 4G of Marin site for subsequent ETCS session establishment before loss of 5G coverage. So it was impossible to perform the test.

Static area in Juvisy:

- Cut-off of 5G of Marin site
- Connection to the 4G, start of ETCS application and data transfer

Second circulation from Juvisy to Vigneux:

- Start of the run under 4G coverage with ETCS data traffic.
- 5G power on
- When the train arrived in 4G and 5G coverage area, no connection to 5G of Marin site
- Restart of ETCS and TOBA to connect to 5G of Marin
- The train was out of 4G and 5G coverage area before resuming data transfer.

Comments from the Application Provider (ALSTOM) on Second Attempt (01/09/2023):

Run1: Case A – (4G → 5G) (circulation is from Juvisy to Vigneux):

Steps of test execution	Result
(1) MTY operator is asked to switch off 5G at Rives	Done, 5G PLMN A and BBU1 are stopped
(2) TOBA is under 4G coverage at Rives (PLMN A)	OK
(3) Attachment on 4G, Registration, Start of ETCS traffic toward RBC 1	No data transfer → Step not passed Trackside devices are not reachable. Need to change the VM MPTCP and change the TS_{APP} GTW configuration.

Run2: Case B – (5G → 4G) (circulation is from Vigneux to Juvisy):

Steps of test execution	Result
(1) MTY operator is asked to switch off 4G at Marin	Done, 4G PLMN B and BBU2 are stopped. No coverage at the starting point.
(2) TOBA is under 5G coverage at Marin (PLMN B)	Connection to 5G is OK
(3) Attachment on 5G, Registration, Start of ETCS traffic toward RBC 1 (this will be difficult to achieve as time is limited, but it could be tried)	Attachment is OK, connection to RBC1 is OK and ETCS data is exchanged with RBC1
(4) 2nd modem attaches to Rives 4G (PLMN A) whenever it can. Traffic should also start on that bearer	No 4G attachment when the train was around Rives site. Loss of the 5G signal. → Step not passed

As a bottom line, 5GRAIL was ahead of the implementation roadmap of 5G SA features in the products used for field in this test. However, when in field, due the additional complications and constraints (limited time during the run when under coverage, potential need of restart of the prototype, manual steps within the procedure), the outcome of this test case is not conclusive. For additional details, we refer the readers to deliverable D4.3 [11].

4.3 Test Case No. Video_TC_004 (5G Inter-Core): Cross-border with streaming of video/voice from train to trackside, using inter-gNodeB handover over AMF

One aspect of 5G cross-border communication is the UE roaming with inter-AMF (inter-PLMN) handover using NG/N14 interface. This is an Inter-Core Transition scenario as described in Section 3.3.1. There has been one test case with continuous traffic (video/voice streaming) defined to evaluate the performance.

The details of the test plan including the description of the initial state/configuration is described in Deliverable D1.1 [2] – Section 9.4.3.

4.3.1 Purpose

The purpose of this test is to demonstrate that the performance of Video application is not impacted in border-crossing conditions. The border-crossing scenario was set to assess the inter-gNodeB inter-AMF handover behavior, using NG/N14 interface. Hereby, the transition occurs from the source 5G Core (AMF1) to the target 5G Core (AMF2). Notably, throughout this operation, session management remains within the source 5G Core (SMF1 and UPF1). Only one IP address is used, as if it was one PLMN, although there are two 5G cores implemented. PLMN2 was emulated, means it is treated as the same network. No full-featured cross-border test but important subfunction of an envisaged Inter-PLMN 5G Handover scenario.

4.3.2 Specifics of the Test implementation and Execution

An Iperf data flow serves as emulation of constant video bitrate for test with continuous data call. Also, a point-to-point voice call is considered for test with continuous voice call.

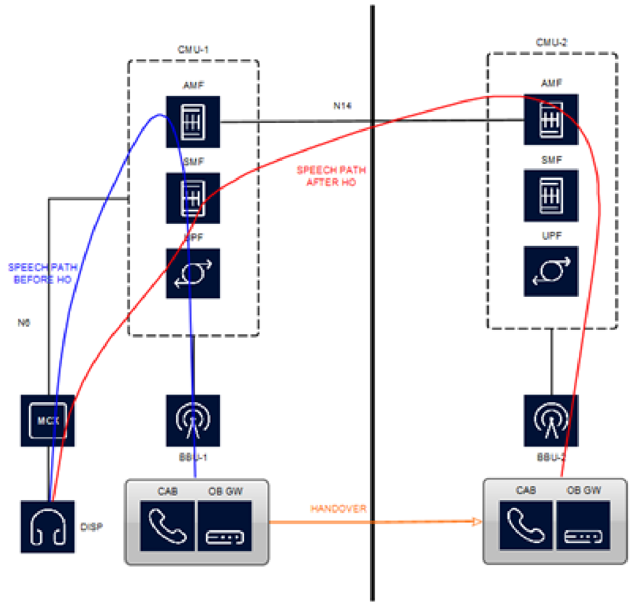

Figure 15 – Call flow for testing NG interface in Inter-gNB Inter-AMF HO during voice call

4.3.3 Test Limitations (in Field)

It was not possible to conduct the test in the field due to limitations with NG handovers with the given field equipment. 5GRAIL was ahead of the implementation roadmap of 5G SA features in the products used for field commissioning. The test was performed in the Nokia lab in Budapest/Hungary with prototypical implementations, though. Please refer to deliverable D3.3 [8] for further details.

4.3.4 Results and Observations (in Lab)

The test in lab was successfully performed, showing that for both the emulated video and real voice service/application no interruption is noticeable. Cab radio towards train controller (dispatcher) speech path was continuous during handover, short crackling was hearable without any loss. For handover procedure times on control plane / signalling level, please refer to [8].

4.4 Test case No. CCTV_TC_002 (5G Inter-Frequency): CCTV offload from train to trackside with bearer-flex

The test case, being performed with a continuous CCTV (video) traffic offload scenario, is described in details in D1.1 [2] – Section 9.5.2.

4.4.1 Purpose

Border crossing relevance

The relation to FRMCS BX has been described in Section 3.3.3 of this document. The test case shall demonstrate the feasibility of a 5G Inter-frequency transition with TDD frame structure change by having one UE that conducts a 5G bearer change within two 5G sub-bands, as possible in future railway operational BX scenarios. The case is exemplified using the n78 spectrum in the 5GRAIL Testbed Germany. As test application in the setup a CCTV (video archive) offload has been selected, that is in principle uploading data from train to trackside, where uplink data slots are used in different TDD frame structures in the two 5G bearers. In radio cell 17 (located in the station Scheibenberg Bf.), there is 1.5x larger uplink bandwidth available than in radio cell 16 (located along the track before the station).

Data offload relevance

The drive test can also be seen as a PoC scenario for increasing the uplink bandwidth / performance when reaching a train station for offloading data recorded during a drive.

In a CCTV offload system, FRMCS provides means for transferring recorded video surveillance data between a mobile communication unit in the train and ground communication units located on stations and alongside the predetermined route of the train. The mobile communication unit in the train forwards the recorded video surveillance data from the onboard video recorder to ground communication unit. The ground communication unit then forwards the recorded video surveillance data to Trackside VMS. Whenever the train approaches the stations and/or stops or arrives at the depot, FRMCS facilitates the communication between the mobile and ground communication unit with the frequency available at stations and depots. In addition, FRMCS may facilitate the communication between the mobile and ground communication unit outside of the depots or stops as well using other links / sub-bands with the frequency available along track. With this use case the bearer flexibility is demonstrated as multi access use case using two sub bands for track and station coverage.

4.4.2 Test Architecture

The principle architecture of the test case is depicted below.

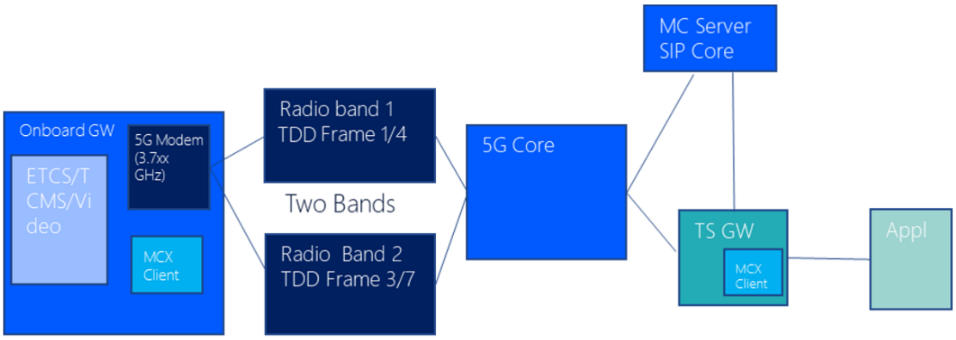

Figure 16 – Architecture for test case CCTV_TC_002

The test case can be considered as a 5G inter-frequency inter-gNB handover scenario with different TDD settings. It has been implemented with one core (i.e., intra-AMF) as the focus was on testing the principle functionality. In a real FRMCX BX scenario, a two core setup (i.e., inter-AMF) would exist.

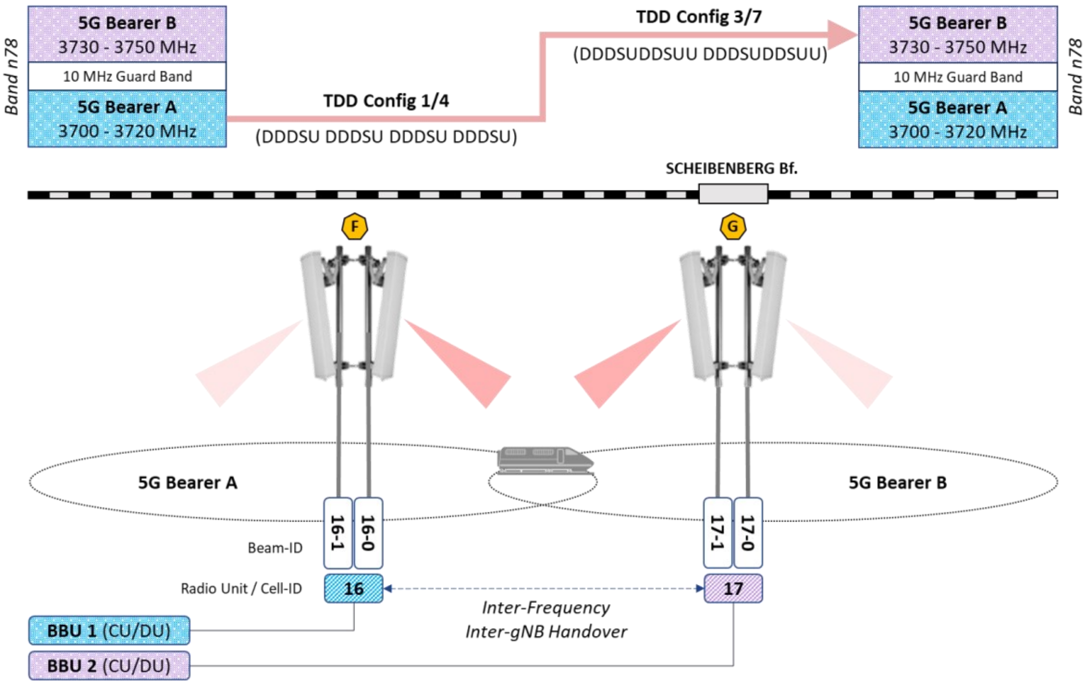

Figure 17 – TDD change via inter-frequency inter-gNB (intra-AMF) handover in test case CCTV_TC_002

In Figure 17, cell ID 16 represents coverage of 5G Bearer A at track, and cell ID 17 represents coverage of 5G Bearer B at the train station. Conditions for both 5G bearers have been as follows:

- **5G Bearer A:**
  - 20 MHz system bandwidth at n78 sub-band 3700-3720 MHz
  - TDD configuration 1/4 (DDDSU DDDSU DDDSU DDDSU)
- **5G Bearer B:**
  - 20 MHz system bandwidth at n78 sub-band 3730-3750 MHz
  - TDD configuration 3/7 (DDDSUDDSUU DDDSUDDSUU)

The TDD frame structure is just a single configurable parameter in the Nokia gNB.

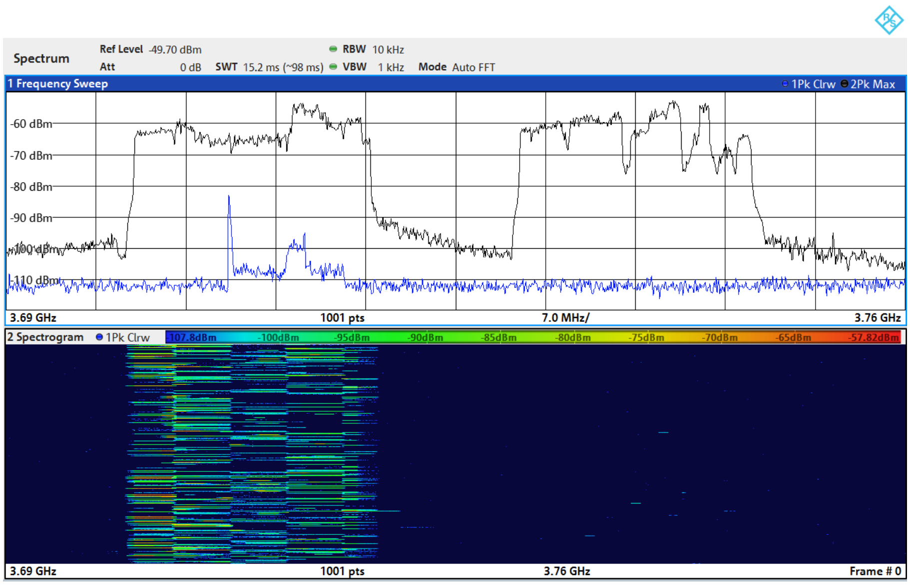

Figure 18 - Spectrogram visible in sub-band of 5G n78 bearer A (3700-3720 MHz) in radio cell 16

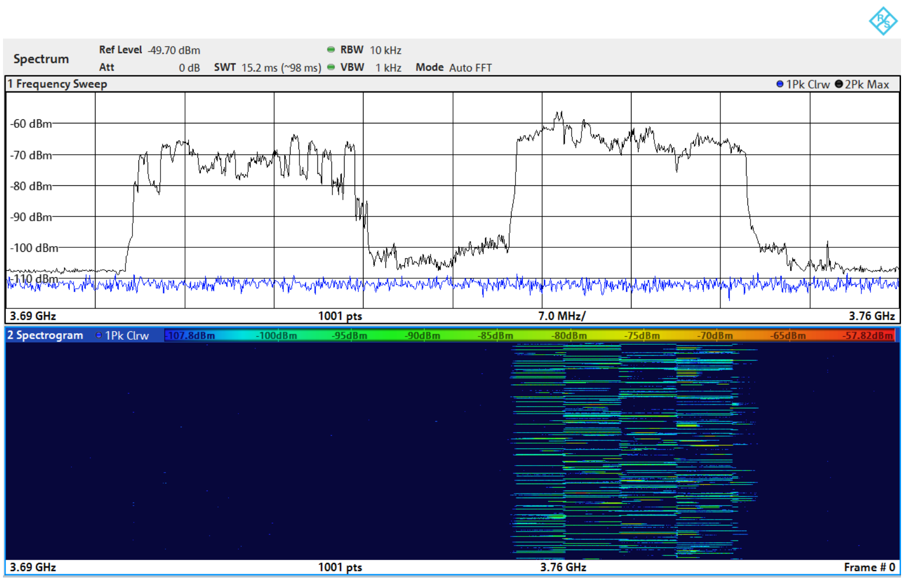

Figure 19 - Spectrogram visible in sub-band of 5G n78 bearer B (3730-3750 MHz) in radio cell 17

4.4.3 Specifics of the Test Implementation and Execution

The test was executed in drive test mode. The onboard CCTV system was set to perform CCTV video offload to the Trackside VMS server, with no limitation on the sending data rate allowing full possible offload speed in uplink direction.

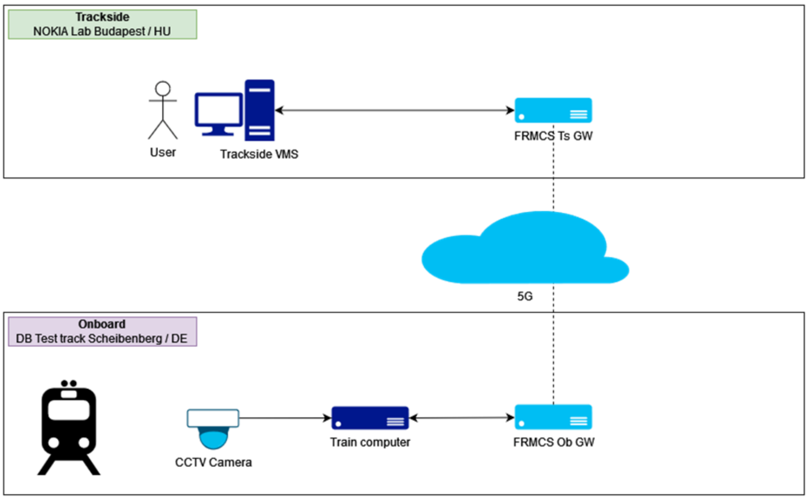

Figure 20 - CCTV offload – Abstract Test Architecture

The offload stream was not entirely constant during the full drive tests which covered more cells along the 10 km test track, see Section 3.1.4 in 5GRAIL report D5.1 [12]. Some breaks in the transmission have occurred due to impacts of the leased line in the end-to-end network between the field site (5G RAN) in Germany and the lab site (5G CORE) in Hungary, see Section 3.1.3 in 5GRAIL report D5.2 [12]. However, in the moment of changing between radio cell 16 with 5G Bearer A and radio cell 17 with 5G Bearer B, there has been an (almost) continuous data uplink steam observed, giving feasible performance results. For the analysis of the 5G inter-frequency transition scenario, the average offload speed rates, and peak offload speed rates in both considered cells of the handover were noted.

4.4.4 Results and Observations

The test was successfully performed.

The general behaviour of the CCTV archive offload application is described in 5GRAIL deliverable D5.1 [12]. The change of the bearers based on 5G Inter-frequency Inter-gNB handover mechanisms worked well in repeated drive tests with 40-50 km/h train speed. In the following, the measured performance of the bearer transition field test case in terms of offload speed (uplink rates) is described.

First, we depict the achieved increase upon TDD configuration change during 5G bearer change. Note that, according to the used uplink bandwidths, the expected increase is 1.5x when going from TDD config ‘1/4’ (radio cell 16) to TDD config ‘3/7’ (radio cell 17). In the field with certain conditions on the propagation environment and, hence, the radio channels, approx. 33% gain has been observed in the average uplink rates.

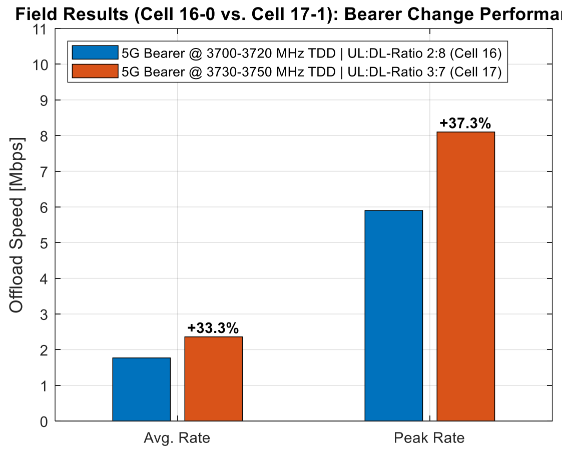

Figure 21 – Uplink gains through TDD Change during 5G Bearer Transition in Field Trials

Second, for comparison, we provide the achieved increase under lab conditions (with more ideal conditions), measured at Nokia's 5GRAIL premises in Hungary. Here, the observed gain was indeed about 52% for the average uplink rates. This outcome corresponds to the expected theoretical value.

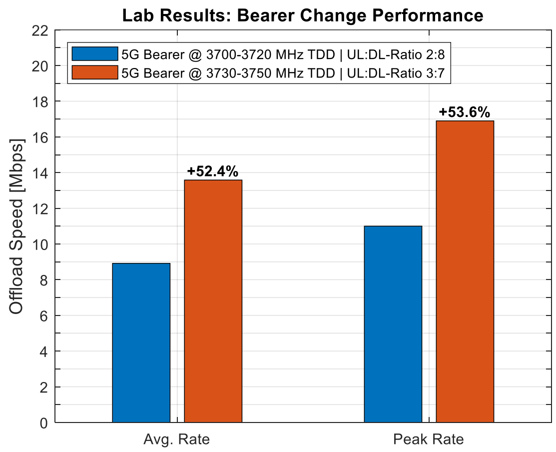

Figure 22 – Uplink gains through TDD Change during 5G Bearer Transition in Lab Trials (for comparison)

Since the final FRMCS system at TDD band n101 will use bandwidths of 5 or 10 MHz within 1900-1910 MHz, the observed average and peak rate results are only indicative. What is relevant for the presented results of the 5G inter-frequency scenario is the achieved service continuity and relative performance increase when realizing a transition between two 5G bearers with potentially different TDD configurations.

5 Closing Remarks

In this deliverable, we have provided a description of test preparation and execution results related to Border Crossing testing in both German and French fields. Moreover, we elaborated a list of tests performed and the outcomes obtained during the execution of the selected test cases from the 5GRAIL test plan D1.1 [2].

5.1 Future Perspectives on the Way Forward (UIC Perspective)

From UIC standpoint, it is anticipated that the FRMCS would outperform the GSM-R, which is a fully interoperable border-crossing system, successfully deployed in more than 130’000 Km in Europe and in around 210’000 Km worldwide. In this context, it is a technical and legal obligation to have a system with solid border crossing approach. Accordingly, all UIC’s specifications Working Groups (WGs) are working towards this direction.

In what follows, we recap on current cross-border implementation in FRMCS, which summarizes the main constraints. Recall that BX has some implications on the three strata during the BX procedures: i) transport, ii) service, and iii) applications.

Focusing on the transport part, the relevant features (e.g. Home Routing or Local break-out) were not well advanced at the beginning of 5GRAIL project, three years ago (back to 2021), especially for 5G SA architecture. This is due to the very limited deployment of 5G SA by Public MNOs which, to a certain extent, is still applicable in our days (end of 2023). Among the features, to ensure transport mobility, local break-out 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.

On the second hand, referring to the service layer, MCX Migration and Interconnection features are still on-going in 3GPP specifications, and they are anticipated at releases R18 or even R19. Moreover, the triggering procedure for border-crossing (which will not be initiated by the application), is still under discussion by the FRMS WGs. Finally, it is worth mentioning, that the UE(s) will be shared by multiple applications with potentially different functional and conceptual requirements (e.g. Railway Undertaking (RU) applications depending on their home FRMCS domain).

For all the above-mentioned reasons, at FRMCS V2 for ETCS and ATO applications which need service continuity, the 2UE(s) approach tested in 5GRAIL, but with one MCX server (due to labs set-up limitations), shall be included in FRMCS V2. We argue that for voice application, short interruption can be tolerated. Accordingly, one UE solution might be suitable.

In all cases, we will keep assessing the one UE approach, especially that a good progress has been performed with WP3 lab when testing inter gNode-B handover over AMF, over N14 interface. The first results have demonstrated that we are on the right path since interruption of ~150ms was observed.

Our efforts are focused to have the features and prototypes available, when lab tests for MORANE2 will start, so that we could test some more ambitious cross-border scenarios.

5.2 Retrospective on BX Test Experience and Conclusion

From railway infrastructure manager (IM) perspective, it is interesting that we have managed to test different preparations for FRMCS BX even though the specifications for it are not yet finalized. E.g., 5G SA Inter-PLMN handover was not available when starting the lab tests which have been a prerequisite for the field trials in 5GRAIL.

In the 5GRAIL project, field test campaigns on FRMCS Border Crossing activities (WP5 Task 5.3) have been performed, during several weeks of drive tests both in France (sub-urban track) and Germany (rural track). For this, a timely and well-planned preparation of onboard and trackside infrastructures was necessary. In particular, the test track owners DB and SNCF together with the providers of telco and application equipment managed to:

- secure the test licences for the considered frequency bands in consultation with the national spectrum regulation authorities, e.g., 5G band n78 (3.7 GHz) in Germany and 5G band n39 (1.9 GHz) as well as another 4G band b38 (2.6 GHz) in France;
- book the drive test slots and test trains well in advance, while being prepared and flexible for adaptation of test plans;
- plan the equipment integration and optimization of rolling stock, e.g., power supply, rack modules, antenna and cabling, additional filtering accessories, switches and IT concepts, options to remotely access the train, if needed;
- plan the transfer and commissioning of onboard FRMCS TOBA modules and application equipment from 5GRAIL labs to the test trains;
- perform and verify radio planning to select appropriate radio sites along the test track for the radio equipment installations (under certain deployment constraints of the test tracks);
- prepare the basic infrastructure assets in the field, e.g., antenna masts, central server rooms, power supply, fiber-optical installations for front- and backhaul;
- plan and realize a firewall concept to allow remote connection and management of trackside equipment under given security policies and give access to the field networks to partners;
- organize the transfer and commissioning of trackside FRMCS 5G stand-alone network equipment in the testbeds in the field, in particular for 5G RAN (gNB) and 5G Core equipment;
- plan and realize leased lines to connect on-site 5G RAN with remote 5G Core as well as trackside MCX and application servers (in case of Testbed Germany) or to connect the overall on-site 5G network remotely with trackside MCX and application servers (in case of Testbed France) through a dedicated link.

Numerous achievements were accomplished in preparation of rail operational FRMCS BX scenarios. Here, the 5GRAIL project was following the needs of future railway operations with 5G-based FRMCS. We can enumerate them as follows:

- Integration of 5G Standalone (SA) (5G NR, virtualized 5G core) networks in Germany and France, for the first-time including usage of 1.9 GHz 5G spectrum; it is anticipated that the MNOs would opt for 5G Non-Standalone (NSA) for their initial deployments,
- Integration of the (mission-critical) service Stratum (SIP Core/IMS and MCX),

- Realization of the first FRMCS field networks over complete end-to-end chain, i.e., including Onboard Gateway, 5G SA infrastructure and trackside gateway,
  - for MCPTT-implemented voice scenarios (OBapp compliant in tight-coupling mode): we progressed to test **2G (GSM-R) to 5G (FRMCS) inter-RAT transition via interworking function while keeping continuous service** in a railway emergency call (which is amongst the most difficult railway applications and, hence, of high importance for European railways) : this test was successful in lab and field
  - for MCData-implemented data scenarios with ETCS and ATO simulators (OBapp compliant in loose-coupling mode): we progressed to test **4G-5G inter-RAT with service continuity based on a two modems / UE approach**: this test was successful in lab
  - for an example of MCData-implemented CCTV video service (OBapp compliant in loose-coupling mode): we progressed to test **5G Inter-Frequency bearer transition with change of TDD configurations**, using one UE, as may occur in RMR TDD band n101 in the future train rides between countries: this test was successful in lab and field
  - for further tests performed on control plane procedures in a **NG/N14 interface based Inter-AMF Inter-PLMN handover** which is one building block for future FRMCS BX with one UE: this test was successful in lab.

Due the constraints and complications when in field (limited time during the train runs, instability of the prototype potentially requiring restarts, limited coverage in the 5G/FRMCS bands, limited number of runs), some of the results were not conclusive. Nevertheless, they serve as lessons-learned and a way forward for the future, which is ultimately, one the foreseen objectives of the 5GRAIL project.

In close collaboration with WP1, WP2, WP3 and WP4, it was possible to de-risk the planned field test cases as much as possible, despite some delays in the transfer and commissioning of test equipment.

The field trials on border-crossing fulfilled the target to proof technical feasibility and end-to-end functionality of the 5GRAIL prototypes for 5G-based FRMCS.

The performed tests and observations with pre-standard implementations help to improve the upcoming FRMCS specifications and can deliver guidelines for enhanced evaluation and validation in future field experiments of FRMCS. The field trials do not serve as a reference for final operations or to derive final principles for border crossing. For this, further developments, and tests on FRMCS equipment, both on 5G, MCX and application side, are needed.

6 REFERENCES

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[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)
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[14]	FRMCS Principle Architecture	UIC MG-7904 (v0.3.0)
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[17]	FRMCS User Requirements Specification	UIC FU-7100 (v5.0.0)
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