High-level Concluding Report

5GRAIL – The first FRMCS demonstrator

The Story, The Outcome, What's Next

Grant agreement No 951725

5GRAIL

5G for future RAILway mobile communication system

Abstract

The purpose of this section is to provide a synthesis of the main contents of the deliverable, giving a brief explanation for each of the main topics included in the document.

This report summarizes the objectives, the context, the key findings of 5GRAIL project, as well as the way forward for the FRMCS 1st Edition implementation – for which 5GRAIL was a very important step. As a reminder, 5GRAIL is an EU funded project in the scope of the European Union's Horizon 2020 research and innovation program, under Grant Agreement No 951725.

One major trigger of this project is the preparation of the successor of the very successful current Railway Standardized radio system GSM-R, a key component of the European Railway Traffic Management System (ERTMS). GSM-R is deployed on more than 130,000 kilometers of track in Europe (with more than 90.000 activated On-Board Cab Radio's), and some 210,000 kilometers worldwide, and completely border-crossing interoperable. GSM-R is 2G based, so it will be obsolete soon. The GSM-R successor is the Future Railway Mobile Communication System (FRMCS), which will be the 5G worldwide standard for railway operational communications, designed by the International Union of Railways (UIC), in close cooperation with the railways stakeholders, considered as an enabler of train digitalization.

5GRAIL, is considered as part of the FRMCS readiness initiatives, aiming at: i) developing prototypes, especially for the On-Board FRMCS called Telecom On-Board Architecture (TOBA box) as well as railway applications prototypes, ii) validating the first set of FRMCS specifications by testing the On-Board equipment and application prototypes, in lab and field environments, based on agreed and relevant use cases and a test plan and iii) providing feedback and lessons-learned to standardization organizations for consideration in updates of the next version of specifications but also prepare future trials. All the above and much more have been achieved thanks to the high professionalism and the good team spirit and collaboration of the 5GRAIL partners, although coming from different environments, telecom equipment providers, railway operators, academic research. For more information about our achievements, please visit: https://uic.org/rail-system/telecoms-signalling/article/frmcs, 5GRAIL - 5G for future RAILway mobile communication system;

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1. THE STRUCTURE OF THE PROJECT

5GRAIL has spanned over a period of 38 months, starting from Q4 2020 and ended in December 2023. It contained 8 Work Packages (WPs), which are detailed in below figure summarizing the structure of the project, as well as the interdependencies between the Work Packages and the leader-partner of each one:

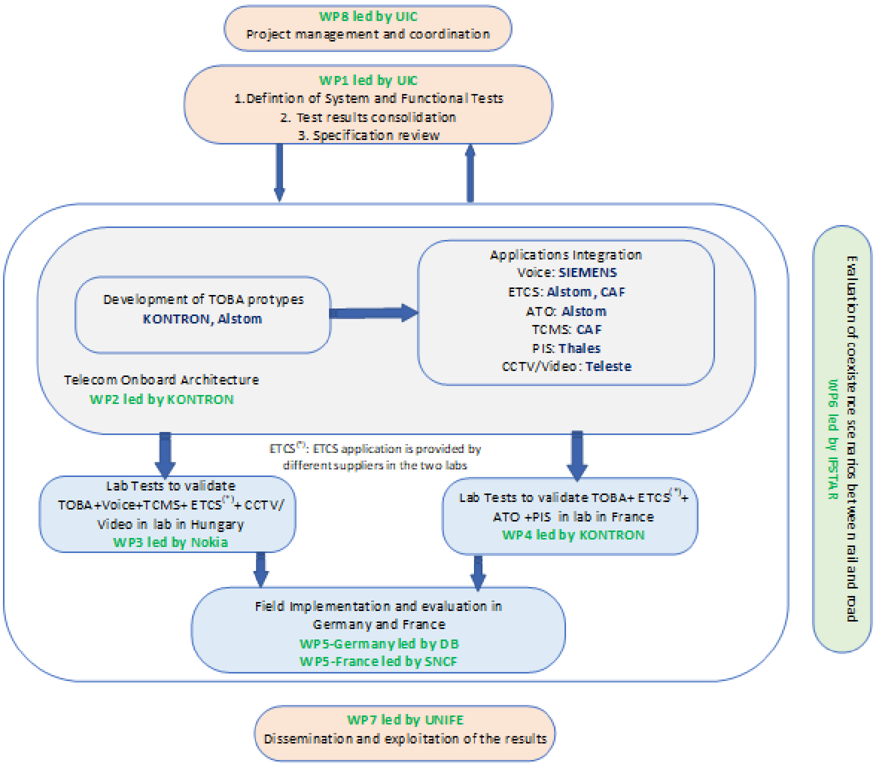


Figure 1: Presentation of 5GRAIL Work Packages and scope

In the scope of the project an innovative work was handled by WP6, to evaluate the potential synergies between rail and road use cases, in the framework of FRMCS.

2. THE CONTEXT

FRMCS is a 3GPP 5G SA, MCX based system and in its first version supporting RMR bands n100 FDD (Frequency-Division Duplexing), Uplink (UL): 874.4-880MHz, Downlink (DL):919.4-925MHz) and n101 TDD (Time-Division Duplexing), 1900-1910 MHz).

The decoupling of strata as presented in the figure below is one key element of the future proofness of the FRMCS architecture:

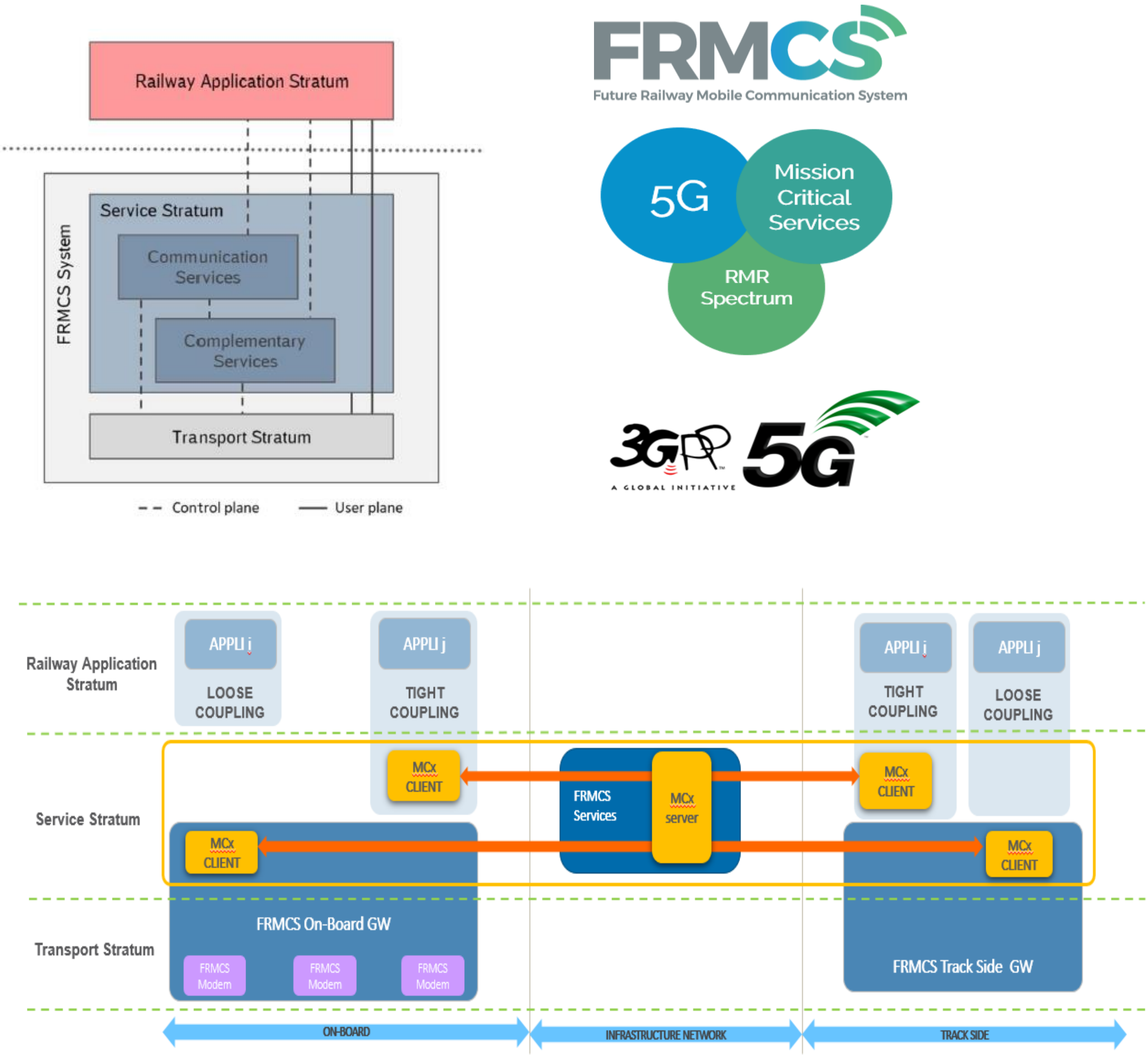
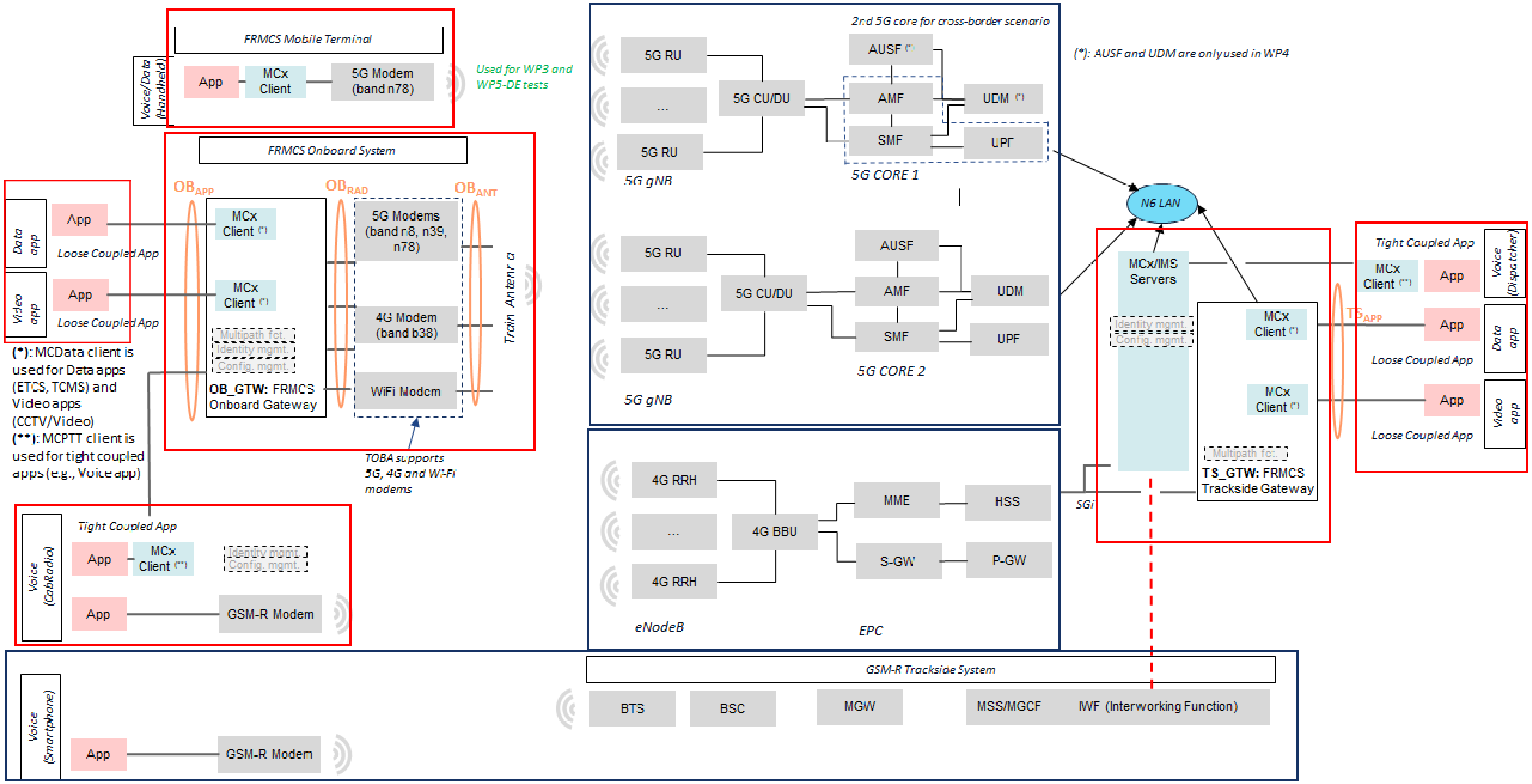


Figure 2: FRMCS is a 5G Stand Alone and Mission Critical (MCX) based system

5GRAIL's main scope was to apply the above principles (see highlighted boxes) in the below end-to-end architecture of the project and validate the compliancy of all prototypes with the FRMCS v1 specifications in this architecture:



5GRail Generic e2e Test Architecture

3. EVALUATION OF COEXISTENCE BETWEEN RAIL AND ROAD

The work undertaken by WP6 led to the implementation of an emulation platform reproducing all the components implemented in the 5GRAIL project architecture, as presented previously excluding the Gateways that were used by the other work packages. This platform, called Emu5GNet (cf. Figure 3), is open source, and is still evolving today. Its aim is to enable rapid prototyping, implementation and evaluation of a large number of scenarios from both the physical infrastructure and network points of view. The main potential applications are as follows:

- Implementation of advanced scenarios in a railway context: Emu5GNet implements an end-to-end 5G architecture, replicating the operation of the 5G architecture developed as part of the 5GRAIL project, and emulates terminal mobility (trains or other) as well as different access technologies (Cellular, WiFi, LPWAN).
- Evaluation of rail communications in a coexistence context: Studying the coexistence of trains and cars was one of the objectives of WP6. As a result, numerous coexistence scenarios have been integrated into the Emu5GNet platform, from the point of view of infrastructure (track parallel to road, level crossing, etc.), applications (automated and connected vehicles) and networks (infrastructure coexistence, shared network). The implementation of a common emergency service has also been proposed to manage critical situations at Level-Crossings. Emu5GNet therefore has great potential for evaluating coexistence scenarios.
- Assessment of the impact of integrating new technologies into railway architecture: Technologies such as Edge Computing and Network Slicing now play an important role in communications networks. As a result, their integration has been implemented in Emu5GNet using Open-Source tools from other European projects and industry. This enables us to consider, for example, a wide range of scenarios for the deployment of rail services, and the adaptation of these services in real time according to network performance and train position. This could therefore offer the possibility of: 1) determining an optimal positioning for a given service according to its needs 2) testing the integration of different types of resource orchestrators 3) designing, from a high-level point of view, an efficient architecture for data and service management. The genericity of Emu5GNet could also enable easy integration of other technologies.

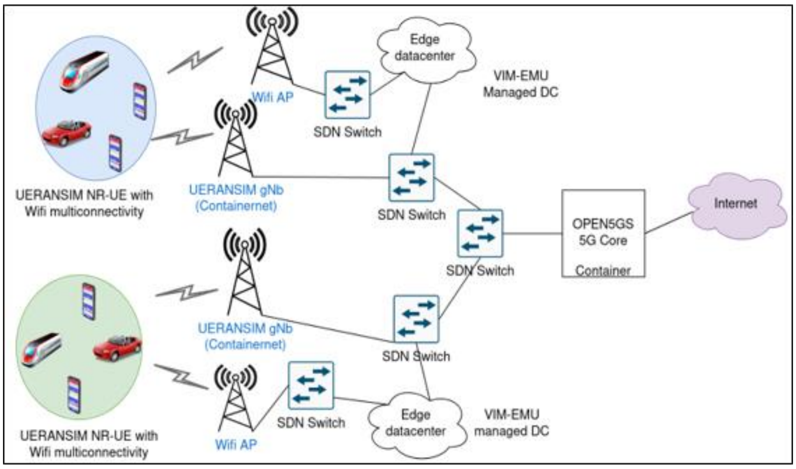


Figure 3: High-level vision of the Emu5GNet platform

4. SUCCESSFUL DESIGN OF TOBA AND APPLICATIONS PROTOTYPES

One key element of this new architecture is the introduction of the On-Board FRMCS equipment in the end-to-end communication chain, providing the decoupling between railway applications and telecommunication network, which allows the transport layer to evolve e.g., to a new radio technology without impacting the application layer. Connections between the on-board and the trackside parts of each application go through the two FRMCS gateways, located on both sides of the 5G infrastructure (mobile and fixed). The usage of standardized interfaces allows any newly created application to be easily inserted in the FRMCS system. This is presented in the following figure were all protypes and their providers are listed:

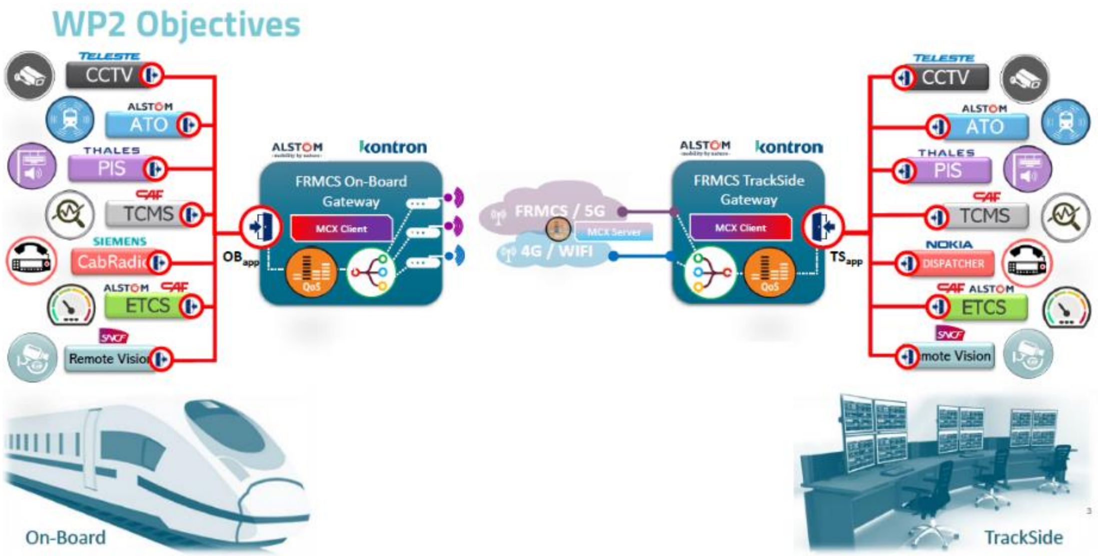


Figure 4: 5GRAIL prototypes in the end-to-end architecture

The integration of the whole FRMCS ecosystem was in the scope of WP2, led by Kontron in France. **Two On-Board gateways were tested in this architecture, provided by Kontron and Alstom**.

The design has successfully applied d the following principles:

- **Decoupling** of Applications and Communication Services/Transport;
- **Bearer Flexibility** (i.e. variety of bearers or Radio Access Technologies simultaneously);
- **Resource Sharing** (e.g. providing transport services for multiple applications of any category using the same FRMCS on-board system considering the individual QoS requirements of the application and possibly priorities among applications).

Moreover, the implementation of FRMCS services is based on one MCX server, located in the infrastructure, and MCX clients, on each side of the FRMCS infrastructure. Railway applications shall use the appropriate client to interconnect both parts of an application, this being one of the key principles of the FRMCS System architecture. There are two integration options for the MCX clients (two variants of coupling mode):

- the MCX client is embedded in the application; defined as **tight coupling mode**.
- or the MCX client is embedded in the gateways, defined as **loose coupling mode**.

The following table summarizes the applications coupling mode:

APPLICATION	TS_{APP} AND OB_{APP} TIGHT COUPLING MODE	TS_{APP} AND OB_{APP} LOOSE COUPLING MODE
Voice, including REC	X	
ETCS		X
ATO		X
TCMS		X
PIS		X
CCTV/Video		X

Table 1: Application coupling mode

5. CRITICAL AND PERFORMANCE RAILWAY APPLICATIONS SUCCESSFULLY TESTED IN LAB AND FIELD

There were two laboratory Work Packages, WP3 and WP4, with complementary interests of testing.

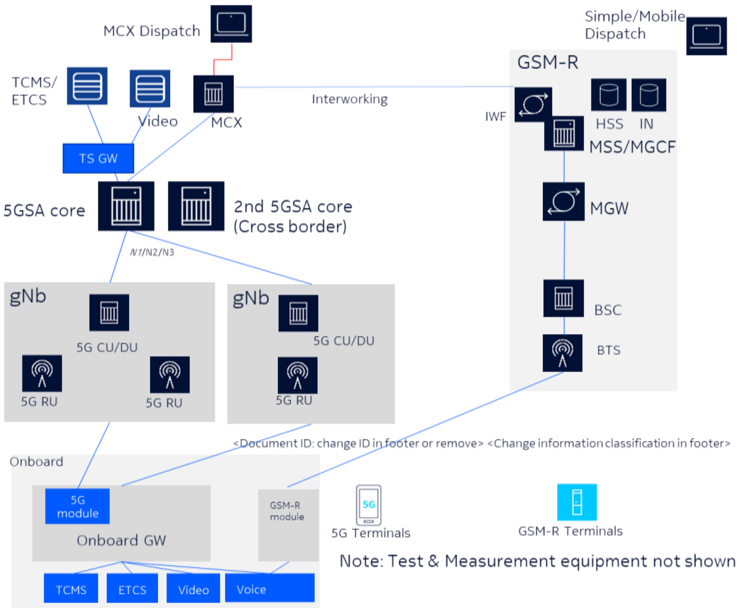
5.1 WP3 lab testing

WP3 has a strong focus on (but is not limited to) the integration of voice applications over FRMCS, being performed in Nokia's lab premises in Budapest, Hungary. Here, the following applications are tested:

- 5G/FRMCS-based MCPTT point-to-point and group voice communication realized by Siemens,
- 5G/FRMCS-based Railway Emergency Call (REC) realized by Siemens,
- European Train Control System (ETCS) realized by CAF,
- Train Control and Monitoring System (TCMS) realized by CAF,
- Non-critical video application and CCTV archive transfer realized by Teleste.

Figure 5: Nokia's premises in Hungary

The WP3 network set-up where the tests have been performed:



With the following lab capabilities:

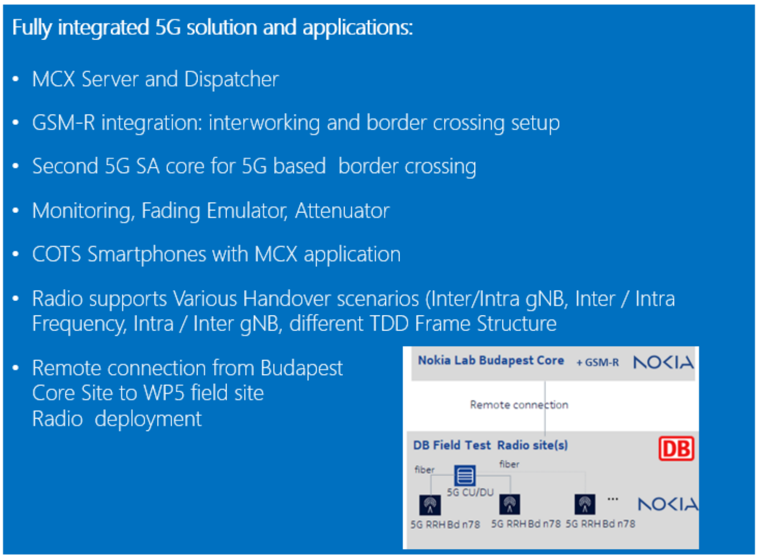


Figure 6: WP3 lab configuration and capabilities

WP3 Performance testing results for handover and MCPTT KPIs:

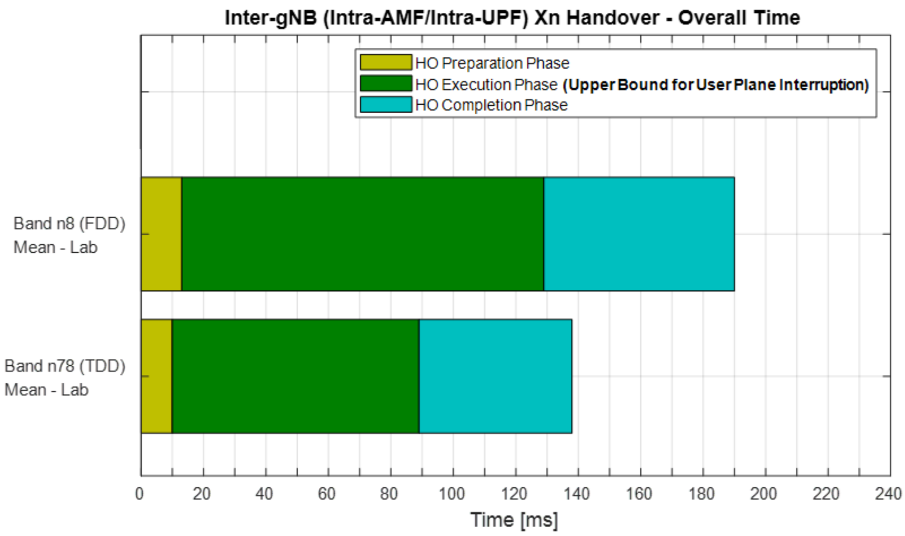


Figure 7: Handover Phase times n78 vs n8

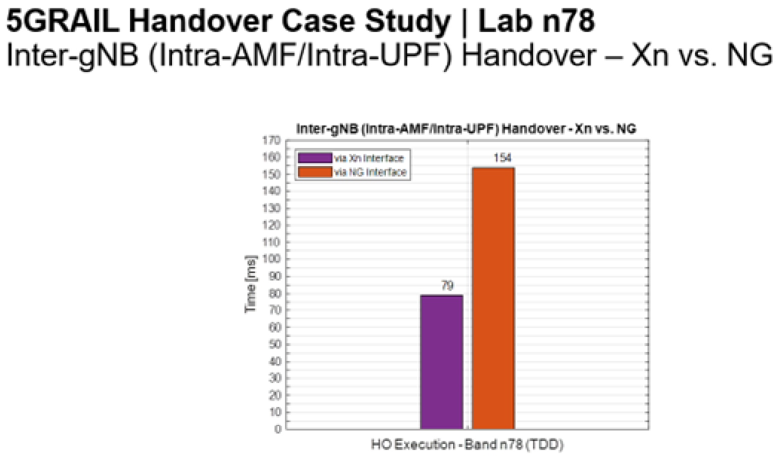


Figure 8: Handover times Xn vs Ng

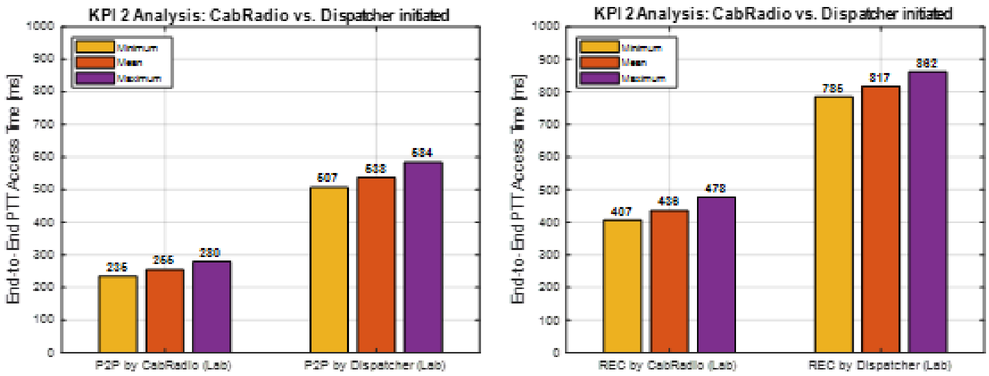


Figure 9: Voice KPI 2 results

WP3 team during testing:

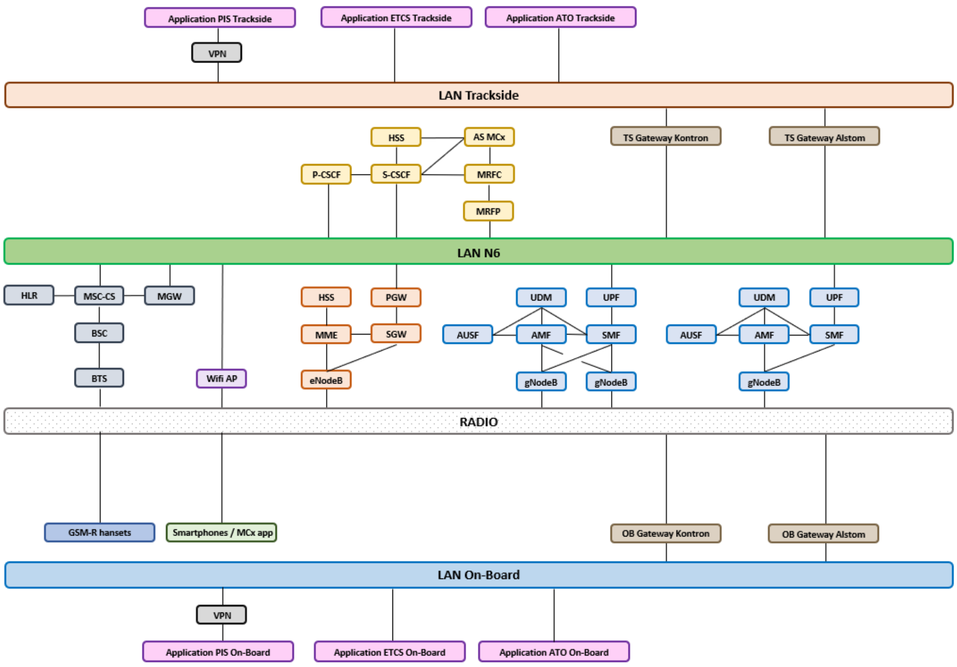
5.2 WP4 lab testing

WP4 concentrates on railway data applications in Kontron's lab in Montigny-le-Bretonneux near Paris, France. Precisely, these data applications are tested:

- European Train Control System (ETCS) provided by Alstom,
- Automatic Train Operation (ATO) provided by Alstom,
- Passenger Information System (PIS) provided by Thales,
- Remote Vision (RV) provided by SNCF and which aims at providing real time video from a camera installed in the front of the train engine – part of the Remote Train operations (RTO).

Figure 10: Kontron's premises in Montigny, near Paris

The WP4 network set-up where the tests have been performed and the applications:



Alstom rack hosting FRMCS applications, installed in WP4 equipment room, used to complete ETCS and ATO OBapp/TSapp integration

Figure 11: WP4 lab configuration and capabilities

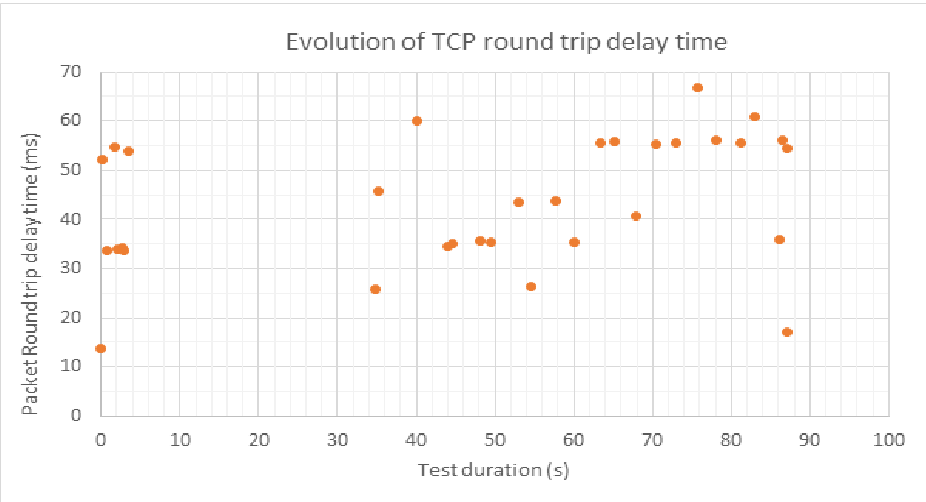
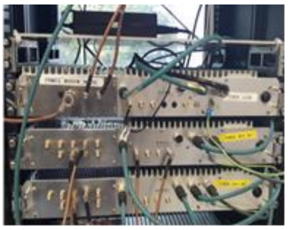


Figure 12: Communication in level 2 between ETCS On-Board application and RBC

WP4 team during testing:



5.3 Field testing in Germany and France

The prototypes developed and lab-tested have been integrated into real railways environment, i.e., rolling stock running on rail tracks with dedicated 5G radio coverage, which allow evaluation of their functionalities and performances. Field tests demonstrate the usability of 5G to answer railway needs using railway applications and application simulators.

The achievements of field testing were:

- Real-world 5G testing of essential functional requirements for the railways;
- Evaluation of End-to-End functionality and connectivity;
- 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 (REC);
- 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 (as MCX Data);
- Emulation of FRMCS bearer flexibility and border-crossing scenarios.

Two field testbeds with complementary scope:

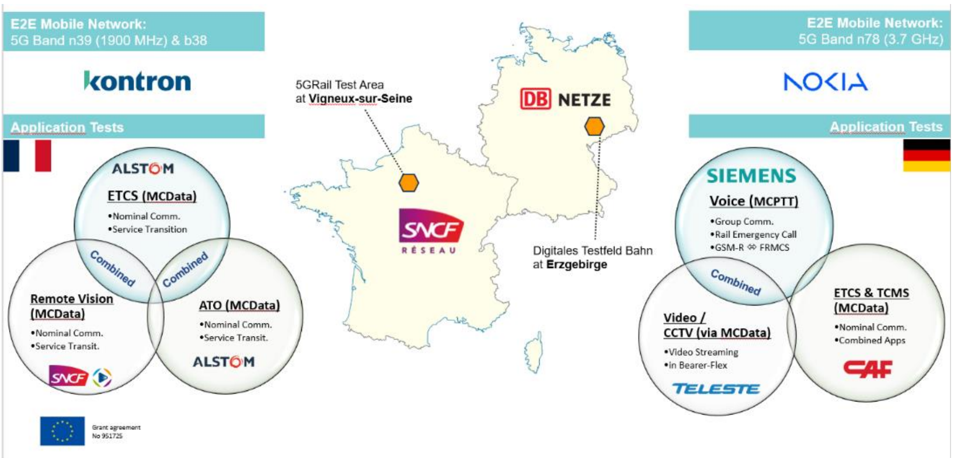


Figure 13: The two field testbeds and their corresponding applications

- **Field tests in Germany**

The German testbed network realization remotely connected to Nokia's lab in Hungary and some performance results with MCPTT and MCData applications:

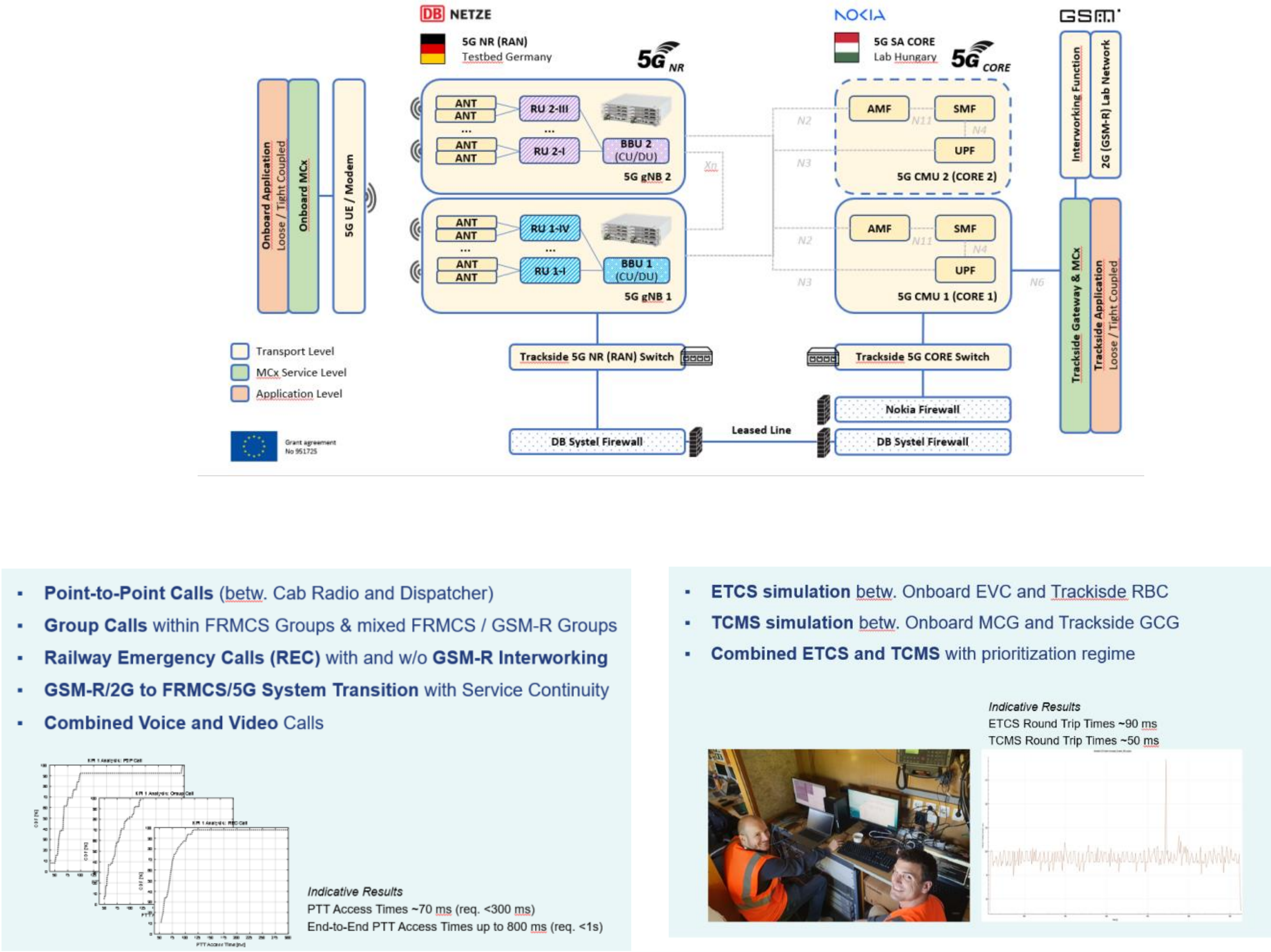


Figure 14: The testbed in Germany and the applications' performance results

WP5-DE team when testing:

- **Field tests in France**

The French testbed network realization remotely connected to Kontron’s lab in Montigny and some performance results with MCData applications:

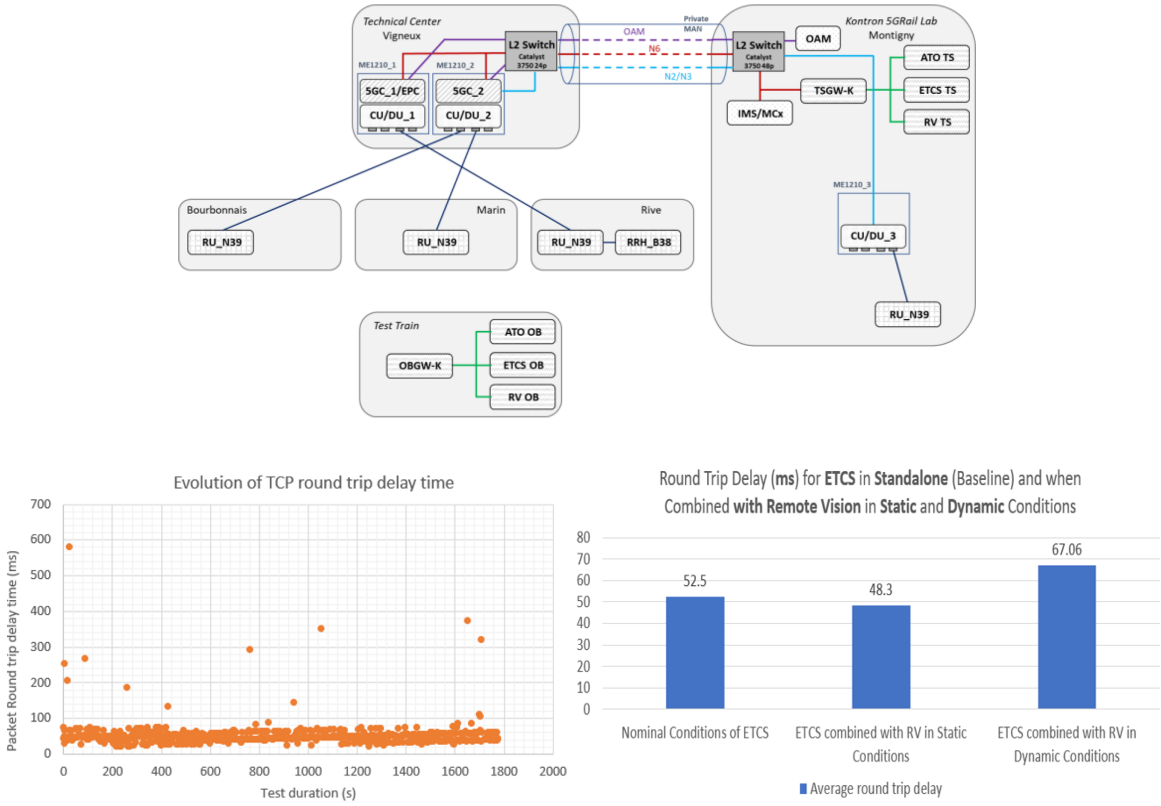


Figure 15: The testbed in France and the applications’ performance results for ETCS only and ETCS combined with Remote Vision in static and dynamic conditions

6. VIDEO APPLICATIONS (CCTV offload with bearer flex and Remote vision)

6.1 CCTV offload from train to trackside

CCTV offload was selected as a demonstrator of Bearer Flexibility feature based on two sub bands on the 5G N78 bands to demonstrate the behavior of relying on a (high performance) second Uplink, as presented in the following testing set-up:

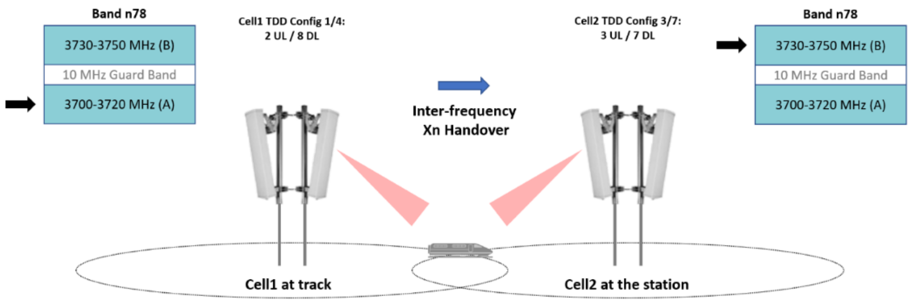


Figure 16: Bearer Flexibility test setup

CCTV offload scenario is in principle uploading data from train to trackside, where uplink data slots are used in the TDD frame structure. In Cell1 the 1 / 4 ratio means that there are 2 uplink and 8 downlink data slots out of 10 time slots, however in Cell2 the 3 / 7 ratio means that there are 3 uplink and 7 downlink data slots for the same. So, in Cell2 there is 1,5x larger bandwidth available (3 data slots instead of 2 data slots in uplink) for data upload.

Therefore, when moving from Cell1 to Cell2, the CCTV offload will utilize a second "access" frequency with higher bandwidth (inter-frequency Xn Handover) to demonstrate a video archive upload from a train reaching the station.

The test case was successfully performed in Nokia's lab in Hungary and field with 3 different resolutions, HD (High Definition)-ready video (1280x720) with avg. bitrate at 2 Mbps, SVGA (Super Video Graphics Array) video (800x600) with avg. bitrate at 1 Mbps and VGA (Video Graphics Array) video (640x480) with avg. bitrate at 700 Kbps.

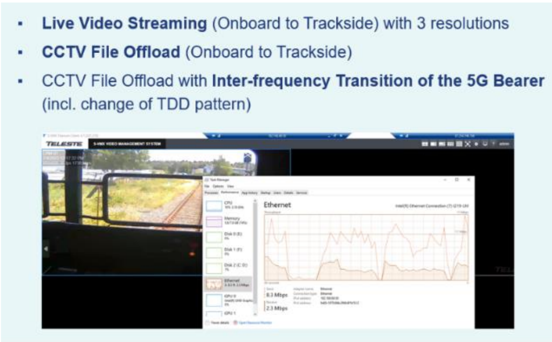


Figure 17: Real-time Video over FRMCS/5G, using MCData

The following figures are presenting the 5G Bearer change with CCTV Offload in field and lab conditions:

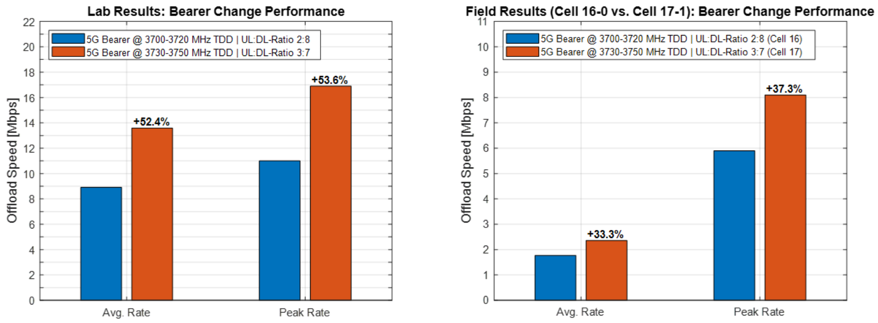


Figure 18: CCTV offload performance in lab and field conditions

6.2 Remote vision

In the 5GRAIL Testbed in France, SNCF has provided and tested the remote vision (RV) application. In this application which is part of the remote control of engines use case, a real-time video is transmitted from the train front to the trackside control center. It is worthy to mention that the remote control of engine is of strategic interest for railways for many operations such as (i) technical centre manoeuvre, (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 behavior, 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 usually set at 1Mbps, which is automatically adjusted to network conditions.

Figure 20: Remote driving simulation through frontal cameras on test train

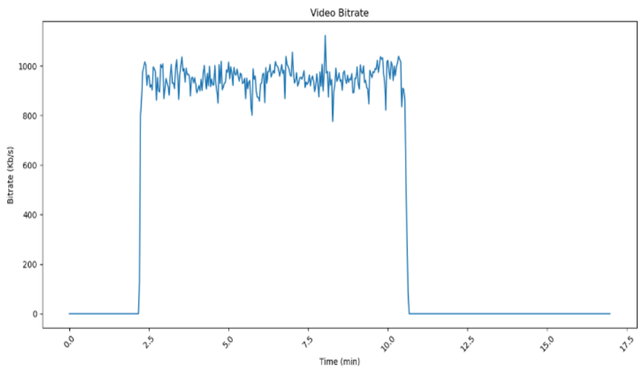


Figure 19: Video bitrate run at 1Mbps for simultaneous operation of remote vision app and simulated ETCS

7. CROSS-BORDER IMPLEMENTATIONS AND TESTING IN LABS AND FIELD

Train crossing the border is an essential requirement for FRMCS and it is a mandatory condition for including FRMCS in the EU legal frame of Technical Specifications for Interoperability. The complexity of this topic mainly comes from the different Strata of the FRMCS architecture involved in the Border Crossing scenarios, as presented in the following figure:

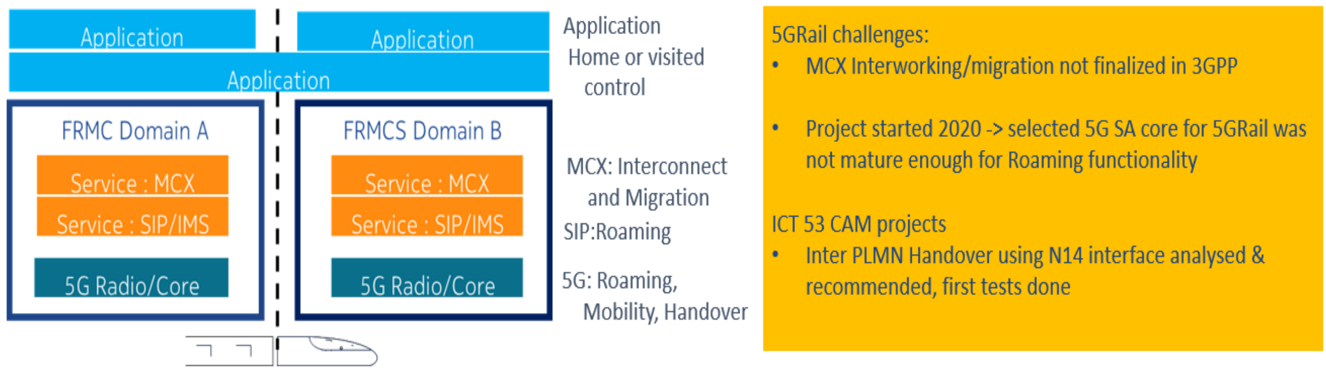


Figure 21: Cross-border principles in FRMCS and 5GRAIL challenges

7.1 5GRAIL Border Crossing in WP3 lab and WP5 testbed in Germany: **One UE solution**

With the below configuration one UE solution has been validated with Voice & Video (replaced by constant data stream using Iperf) applications and two main building blocks:

- Two 5G SA Core network, interworked via N14 interface
- Radio configuration for inter gNB / Ng based handover (via core)

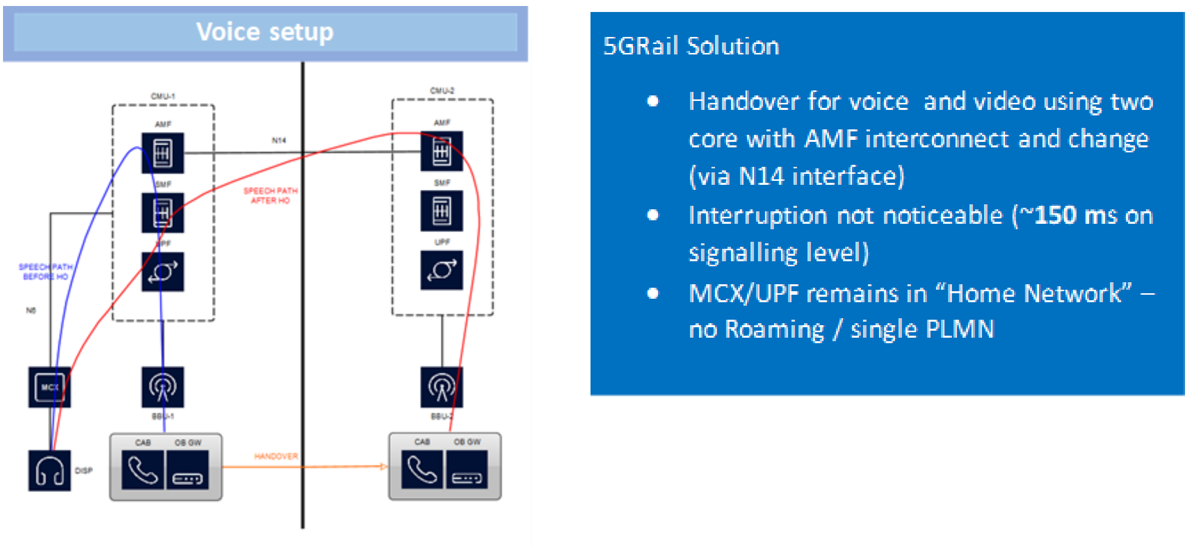


Figure 22: 5GRAIL border crossing with voice & video in WP3 lab

- Network transition FRMCS/GSM-R with IWF (Interworking function) tested in lab and field

This scenario successfully validated in lab and field is very important for migration period:

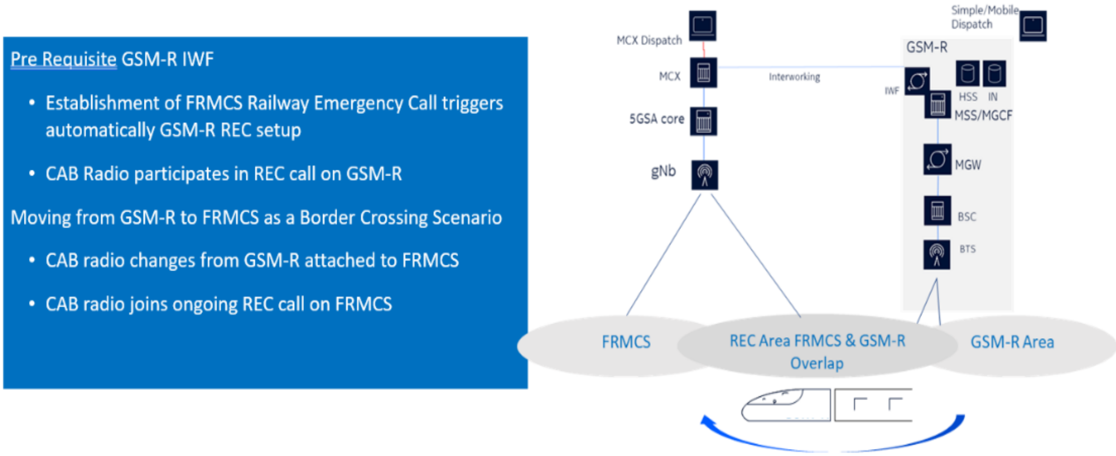


Figure 23: GSM-R to FRMCS network transition with REC voice

7.2 5GRAIL Border Crossing in WP4 lab and WP5 testbed in France: **Two UEs solution**

WP4 lab and WP5 field testbed in France were focused in the 2UEs tested with two different implementations with TOBA-A (TOBA-Alstom) and TOBA-K (TOBA-Kontron):

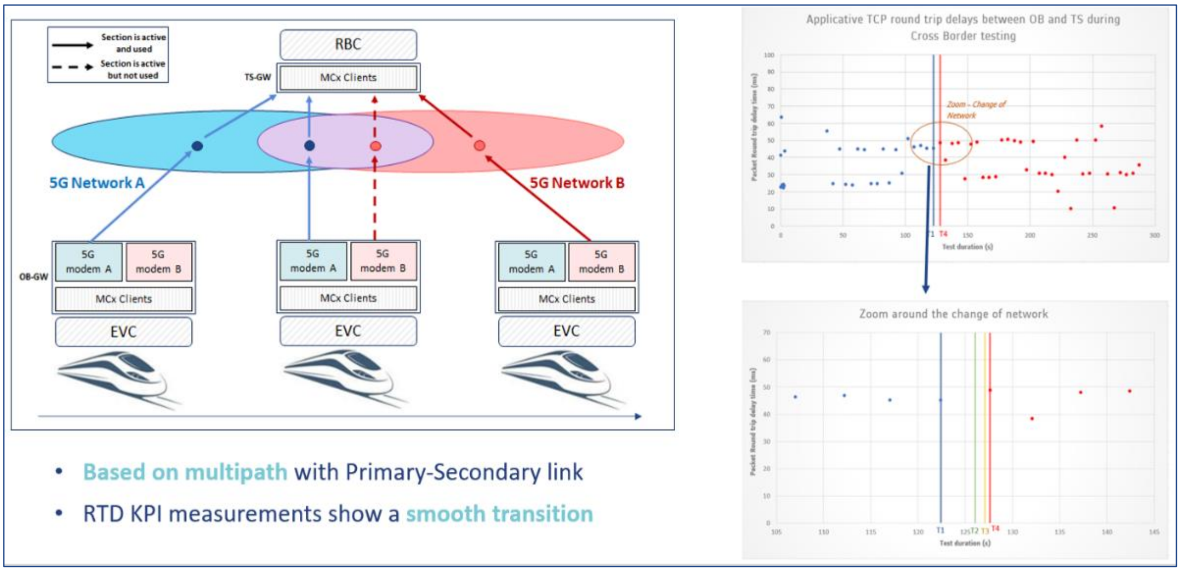


Figure 24: Border crossing in WP4 lab with 2UEs in TOBA-A and ETCS application

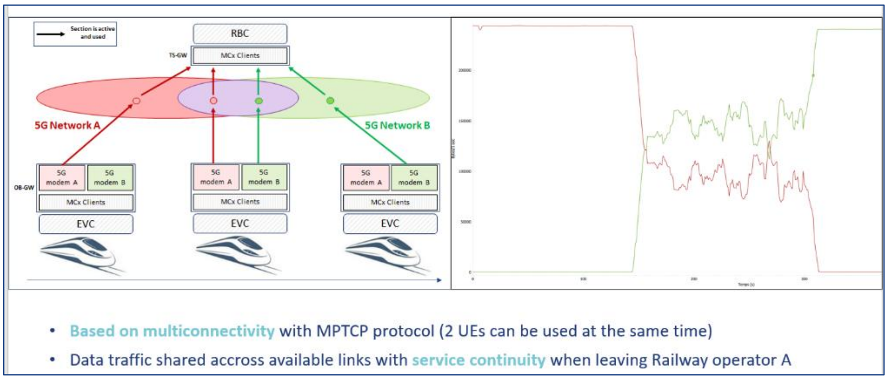


Figure 25: Border crossing in WP4 lab with 2UEs in TOBA-K and ETCS application

7.3 WP6 implements cross-border in the emulation platform Emu5GNet

WP6 reproduced in the Emu5GNet platform cross-border scenario applying the Home Routing Roaming mechanism using 5G Open5GS cores, (cf. Figure 26). As a result, this platform can be used to consider the evaluation of evolutions in railway communication architecture.

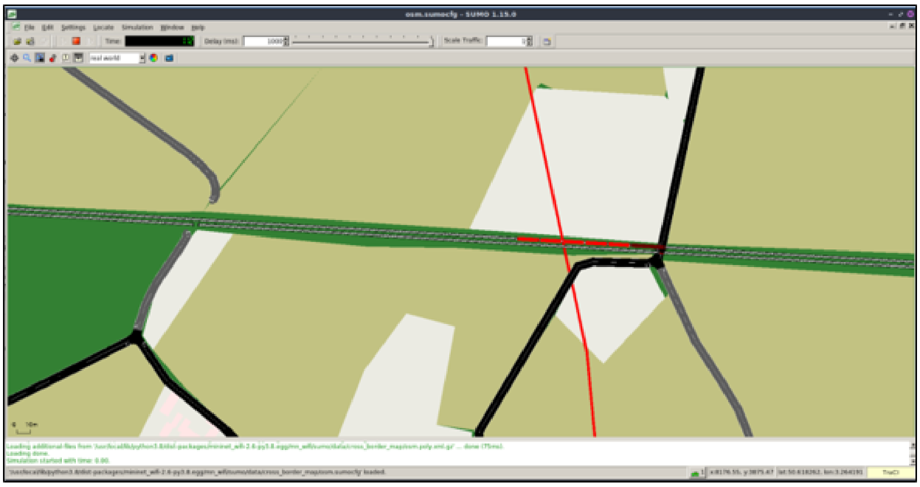


Figure 26: Example of Emu5GNet interface during emulation phase (Cross-Border Scenario)

8. 5GRAIL DEMONSTRATION IN TESTBED IN GERMANY

A successful field demonstration of FRMCS functionalities and test cases took place on the 20th of September 2023 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.

Figure 27: Schedule of the 5GRAIL final demo (Testbed Germany) on 20 Sept. 2023

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

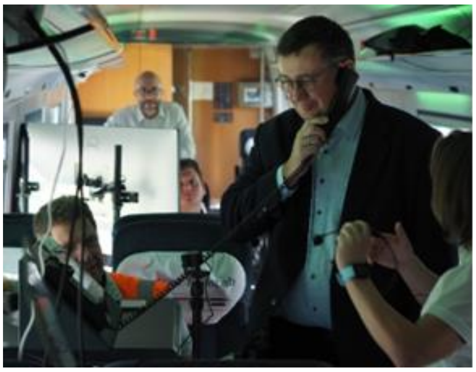


Figure 28: Live demonstration of voice performance

Figure 29: DB's experimental ICE train "advanced TrainLab" in the 5GRAIL Testbed Germany

9. CONCLUSIONS AND NEXT STEPS

9.2 FRMCS Introduction

FRMCS is the GSM-R successor, and being 3GPP 5G (and MCX) based, it will enable railways extended digitalization.

FRMCS system and its V1 specifications have been already introduced in 2023 Control-Command & Signaling Technical Specifications for Interoperability.

5GRAIL has been very useful for this critical FRMCs introduction step.

5GRAIL received innovation recognition from the EC, for the following items:

- FRMCS tailor-made 5G Module (1900 – 1910 MHz TDD)
- 5G FRMCS – GSM-R interworking
- Cyber Security architecture for the MC over 5G ATO application

5GRAIL offered the possibility to have successful field tests in two complementary testbeds in Germany and France in the sense of the test cases chosen to be tested in each testbed. In Germany, the focus was on voice applications (MCPTT) with some data applications (MCData), as well. In France, the focus was on data applications (MCData IP Conn). These two approaches guided two different architecture set-ups adapted to the applications testing scenarios with interesting feedback. The remote connections to labs' infrastructures obliged to think about the suitable capabilities of the leased lines for future field trials but also for evolving modular architectures. Optimization of coverage and interference handling in different 5G NR bands was an important outcome to be further studied.

A non-exhaustive list of 5GRAIL achievements is the following, completely aligned with the objectives of the project:

- **Future proofness:** TOBA designed with decoupling of applications and telecom, as per FRMCS v1 specifications
- **5G NR Spectrum** (with RMR bands: n101 (1900MHz TDD), n100 (900MHz FDD), and n78 (3.7GHz TDD), as an example of PMNO band)
- **MCX features**: validated, with current products and mechanisms
- **QoS**: tested for both MCPTT and MCData, with current available products and mechanisms
- **Combined Applications over same TOBA:** successfully tested (in GSM-R, we use different radios for Voice and ETCS). QoS also tested in scenarios with separated or combined applications of different services.
- **Cybersecurity:** Local binding (OBapp) and e2e TLS (TOBA and ATO application)

- **Cross-border:** Two solutions considered, the 2x5GUEs implementation will be included in FRMCS v2 specifications. Major building blocks of the 1x5GUE solution have been successfully tested in Nokia's lab.
- **Bearer flexibility** tested both as multi-connectivity and multi-access.
- **Support to specifications:** 5GRail have offered valuable input to FRMCS but also 3GPP/ETSI specifications, and will help MORANE 2, the FRMCS European Pilot, planned to start in June 2024.

5GRAIL was a successful first step that asks for completion of future pilot trials where we will deeper study many topics derived from 5GRAIl's outcomes:

- **A more mature cross-border concept** validating the progress of specifications with not only inter-PLMN handover as a transport feature but also migration and interconnection as MCX features, available from Rel.18 and beyond. This will provide valuable feedback for the interoperability testing of the 5GSA architecture.
- **Better knowledge of KPIs** that will allow with stable products to do performance testing and provide evaluation of using 5G and MCX, as main building blocks of the FRMCS system.
- Need for updated **monitoring tools** more adapted to the FRMCS context.
- **Cybersecurity** topics need to be further investigated with different architectures. First trends were provided with the 5GRAIL testing.
- **Innovative authentication, authorization rules** for the FRMCS with efficient storage and update of credentials.
- **Impact of speed in the performance of the end-to-end system** which was not possible in the current field testing.
- Further **interoperability testing with multivendor architectures for On-board and Trackside** but **also for the whole the end-to-end architecture**.

9.3 What’s Next

Currently the FRMCS V2 specifications are being developed under UIC leadership, expected to be finalized in October 2024.

An FRMCS European Trial, called MORANE-2 is being defined, expected to further complete test FRMCS prototypes as GSM-R successor.

The finalization of MORANE-2 will result in the FRMCS V3 specifications, which will define what we call FRMCS 1st Edition, the first FRMCS system that Railways will be able to implement in their first national pilots.

This activity is challenging as timeline and as complexity. Possible some FRMCS components will require additional innovation and test campaigns, this will be treated ‘’au fur et à mesure.’’

Coming back to 5GRAIL, we consider that the project reached and for some items even exceeded that initial scope:

- The first TOBA equipment has been built
- The first Track side gateways have been built
- We had the chance to have access to a first set of FRMCS 1900 MHz compatible chipsets
- We have built MCX compatible applications, for critical and train performance railways applications
- We have succesfully tested these in Lab and Field
- We have tested both two UEs and InterPLMN Handover over N14 interface, at least in Lab conditions.
- We had useful return of experience for many aspects of FRMCS set-up.

We will take the spirit of 5GRAIL and make it grow in the future activities and initiatives for the preparation of a successful FRMCS deployment, in the heart of train digitalization.

10. REFERENCES

[1]: https://5grail.eu/

[2]: https://5grail.eu/wp-content/uploads/2023/12/5GRAIL-Newsletter_WEB_v3.pdf

[3]: D1.2 Test report conclusion from simulated/lab environments

[4]: D1.4 Test report conclusion from real-world environment

[5]: D2.1 TOBA Architecture Report

[6]: D3.3 First Lab Test Report

[7]: D4.3 Second Lab Test Report

[8]: D5.2 Test results on Field Trial for Cross-border Scenario

[9]: D5.3 Conclusion Report on 5G FRMCS Field Trials

[10]: S. Tardif et al: "Experimental Trials for the Future Railway Mobile Communication System in 5GRail Project," 2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring), Florence, Italy, 2023, pp. 1-5, doi: 10.1109/VTC2023 Spring57618.2023.10199568.

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