Deliverable D5.1

Test Results on Field Trials on FRMCS Functions and Performance

Grant agreement No 951725

5GRAIL

5G for future RAILway mobile communication system

D5.1 Test Results on Field Trials on FRMCS Functions and Performance

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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 WP5 field trials. The focus is on functional and performance tests of voice (incl. point-to-point calls, group calls, railway emergency calls) and data applications (incl. ETCS, TCMS, ATO, live video) over a field-deployed FRMCS test network based on 5G stand-alone technologies. For the field trials, two test sites in Germany (by Deutsche Bahn) and in France (by SNCF RESEAU) 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 selected mission-critical applications for field evaluation are of utmost importance for future railway operations, with the objective of achieving a first insight in related 5G-based FRMCS end-to-end communication performance in realistic environments when using on-board and trackside gateway prototypes that have been developed in 5GRAIL. The feature tests and the performance results allow the 5GRAIL consortium to feed back findings into the ongoing FRMCS v1/v2 specification process. This is important in order to underline points of concerns and trigger enhancements, and to define additional measurements that could give further insights at this stage of the mock up where many prototypes stand at an early development phase.

Work package 5 has dependencies to WP1, WP2, WP3 and WP4 as it brings the developments and outcomes of the prior 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 derisked 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 functional and performance tests with active rolling stock took place in Q2 and Q3 2023. Extensive times have been spent in Q4 2023 to analyze and evaluate the recorded field data. The results and achievements of WP5 have been possible due to a strong and very good cooperation among the project partners.

Abbreviations and Acronyms

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

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

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

QoS	Quality Of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RBC	Radio Block Centre
RDS	Remote Driving System
REC	Railway Emergency Call
REST	REpresentational State Transfer
RF	Radio Frequency
RSRP	Reference Signal Received Power
RTCP	Real-Time Transport Control Protocol
RTD	Round Trip Delay
RTP	Real Time Transport Protocol
RTT	Round Trip Time
RU	Radio Unit
RV	Remote Vision
SA	Standalone
SCS	Subcarrier Spacing
S-CSCF	Servicing-CSCF (Correspondence IMPU - @ IP)
SIP	Session Initiation Protocol
SINR	Signal to Interference and Noise Ratio
SMF	Session Management Function
SSH	Secure Shell
SRS	System Requirements Specification
TC	Test case
TCMS	Train Control Management System
TCN	Train Communication Network
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TE	Test Environment

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

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1 INTRODUCTION

1.1 Background of WP5

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

The prototypes developed and tested in the laboratories as part of work being executed in WP2, WP3 and WP4 are integrated into real railway 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 D5.1

This deliverable D5.1 is an output from Tasks 5.1 (test site and field trial preparations) and 5.2 (FRMCS functional and performance testing). According to the 5GRAIL Grant Agreement, it shall provide a comprehensive description of test execution, an exhaustive list of tests performed and the results obtained during the execution of test plan.

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

Chapter 2 gives a brief description about the two 5GRAIL test sites in Germany (operated by Deutsche Bahn) and in France (operated by SCNF) as well as an overview of the applications selected for each test site.

Chapter 3 and 4 provide detailed information about the realized trackside and onboard infrastructure for the 5G based FRMCS network which has been deployed in Germany and France, respectively. It also provides a characterization of the deployment of the 5G based FRMCS mobile test networks, using selected key performance indicators (KPIs).

Chapter 5 presents the generic 5GRAIL end-to-end test architecture which is used to derive the different test cases.

Chapter 6 to 8 provide detailed test results of the functional application tests performed in the 5GRAIL testbed Germany, with information on voice tests in Chapter 6, on ETCS and TCMS data tests in Chapter 7 and video streaming and CCTV offload tests in Chapter 8.

Chapter 9 to 11 provide detailed test results of the functional application tests performed in the 5GRAIL testbed France, with information on ETCS tests in Chapter 9, on ATO tests in Chapter 10 and remote vision tests in Chapter 11.

Chapter 12 concludes the report with a summary of the findings of the test results on field trials on FRMCS functions and performance.

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 Overview of Field Test Sites

WP5 tests take place in two locations, in Germany and France, with complementary test scope.

The 5GRAIL Testbed Germany, operated by Deutsche Bahn, is an experimental test track in a rural environment located in the Ore Mountains (Erzgebirge) in the east part of Germany. In this test track Nokia is the network provider for a 5G stand-alone field trial network operating at 3.7 GHz (TDD band n78) which is a frequency band allocated for private industrial networks in Germany. 5G band n78 was selected in Germany for the purpose of FRMCS testing due to the availability of 5G equipment with appropriate pre-commercial functional scope and due to an accelerated application process for the test spectrum. Application partners in the Testbed Germany are Siemens (voice communication tests), CAF (automatic train protection / ETCS data communication tests and TCMS data communication tests) and Teleste (video streaming and CCTV offload tests), see Figure 1 below. Further details of the test track are provided in Chapter 3.

The 5GRAIL Testbed France, operated by SNCF, is a portion of a commercial line in sub-urban environments in France located at Vigneux-sur-Seine in the south-east of Paris. In this test track, Kontron Transportation is the network provider for a 5G stand-alone field trial network operating at 1.9 GHz (TDD Band n39). Application partners in the Testbed France are Alstom (ETCS data communication tests and ATO data communication tests) and SNCF in collaboration with Railenium/Ektacom (remote vision data communication tests with train front camera real-time video), see Figure 1 below. Further details of the test track are provided in Chapter 4.

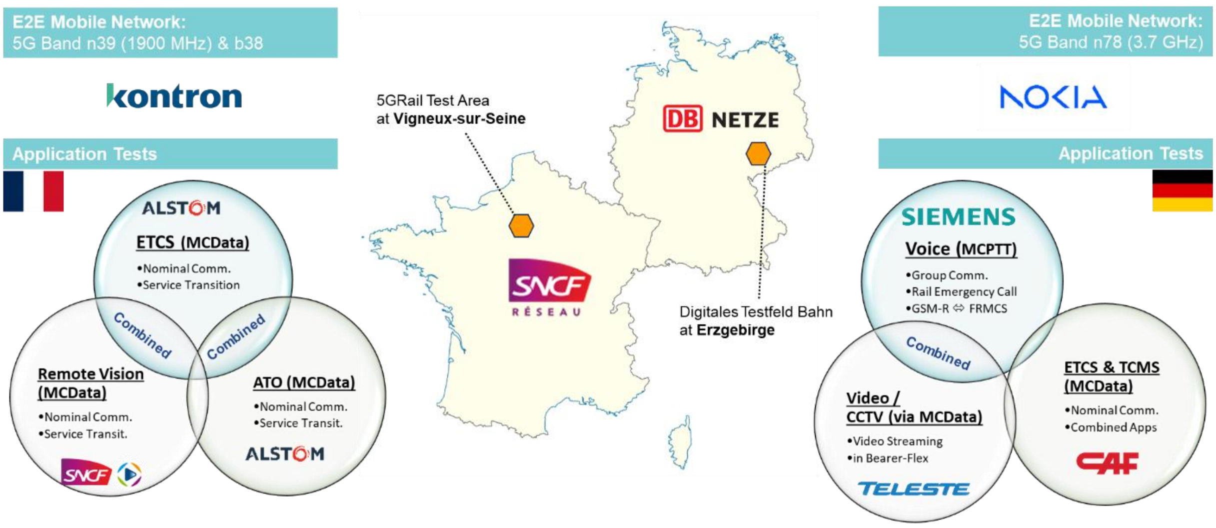


Figure 1: Location and scope of 5GRAIL Testbed in France and Germany

3 FRMCS/5G Network – Testbed Germany

3.1 Trackside Realization

3.1.1 Testbed & Infrastructure Overview

DB Netz, the infrastructure manager of Deutsche Bahn, is operating a test track in the Erzgebirge region which is known as *Digitales Testfeld Bahn* (located between the towns of Schwarzenberg and Annenberg-Buchholz). The line is characterized by a rural and moderately hilly environment with some track segments going through forestal areas. The line used is dedicated for experimental trials with a speed limitation of 50-80 km/h. There is no regular operational train traffic on the line. A 10 km long stretch of the track – covering the stations Markersbach Bf., Scheibenberg Bf. and Schlettau Bf. – is equipped with basic infrastructure needed for network operation, e.g., radio sites with antenna masts of 10 m height and with cabinets to host remote radio units (RUs), fiber-optical connections between the sites and a central lab room (Scheibenberg Bf.) to host 5G CU/DU. In the 5GRAIL project, 7 out of 8 radio locations are used.

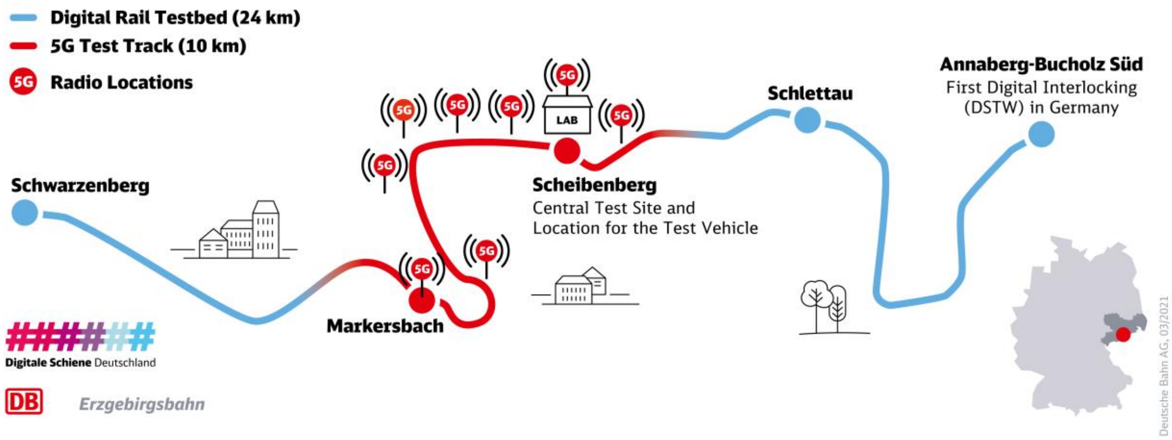


Figure 2: Overview of the 5GRAIL Testbed Germany, operated by Deutsche Bahn as Digitales Testfeld Bahn

Figure 3: Impressions of the 5GRAIL Testbed Germany

Spectrum conditions: 5G RAN is deployed as a test network at TDD band n78 for which the regulation authority BNetzA (Bundesnetzagentur) has granted Industrial Private Network Spectrum test licenses at 3700-3750 MHz with the target to be able to use two different 20 MHz chunks within the band.

3.1.2 High Level Architecture Design

On transport level the network in 5G standalone mode (5G SA) consists of a 5G RAN field part (in Germany) and a remote 5G CORE lab part (at Nokia premises in Hungary). The high level design for the transport stratum, including 3GPP compliant interfaces, is given in Figure 4.

The 5G RAN realization is using 2 gNBs, where gNB1 uses one BBU (CU/DU) being connected to 4 RUs and gNB2 uses one BBU (CU/DU) being connected to 3 RUs. The gNBs are from Nokia's AirScale ASIK/ABIL family and the RUs from Nokia's AZQU product line. For more details refer to [6] and [8]. Each RU is connected to two antennas, forming one cell per RU and two sector beams (one per antenna). In total, the 5G field RAN spreads over 7 radio cells and 14 beam sectors in the 5GRAIL Testbed Germany.

The 5G CORE realization, called Nokia Compact Mobility Unit (CMU), provides the UPF and control plane functions AMF, SMF (as well as AUSF, UDM). As the PCF is not implemented, static PCC configuration rules are supported.

5G RAN and remote 5G CORE are connected via a leased line which is described in Section 3.1.3.

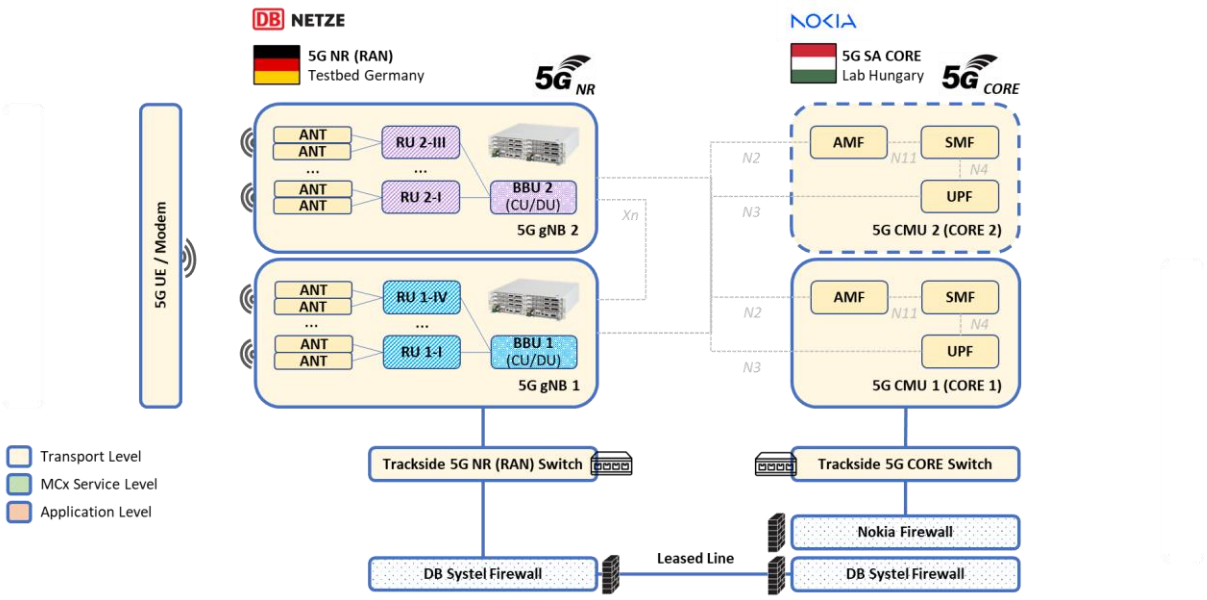


Figure 4: 5G SA network realization in the Testbed Germany with onsite 5G Radio and remote 5G Core

In addition to transport stratum equipment, the MCX and application stratum elements are depicted in Figure 5 for on-board (field) and trackside (lab) parts. TOBA GW and Trackside GW functions are fully described in 5GRAIL deliverable D2.1 [4].

A GSM-R (2G) network, being operated in Nokia's lab in Hungary, is connected to the 5G-based FRMCS network via an interworking function. Further details can be found in deliverable D3.1 [6].

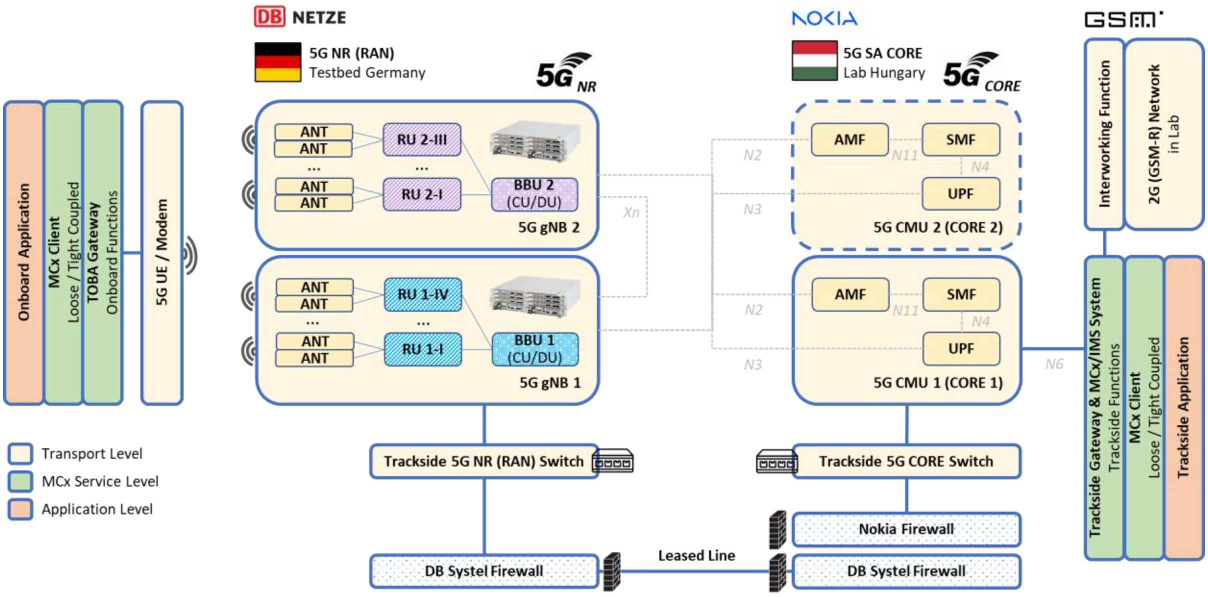


Figure 5: End-to-end network realization in the Testbed Germany

3.1.3 Leased Line for Remote 5G Core Connection

The 5G RAN, located in the Testbed Germany, was connected to the 5G CORE, located in Nokia's lab premises in Budapest/Hungary, bridging a distance of approx. 570 km over-the-air. The remote connection was realized via a leased line with two different last mile providers at each side of the connection in Germany and Hungary, respectively. The leased line has been ordered with 20 Mbps bandwidth which was considered sufficient for the planned tests (where the bottleneck was seen with the uplink video streaming application in the order of Mbps). Transmission characteristics have been tested over several minutes in Q4 2022 and, again, prior to the active field test period in Q2 2023 with rather stable results. The round trip time of the leased line was identified as 19 ms (or 9.5 ms one-way latency), see Figure 6. This time needs to be considered in the end-to-end user plane and application latencies of the FRMCS tests.

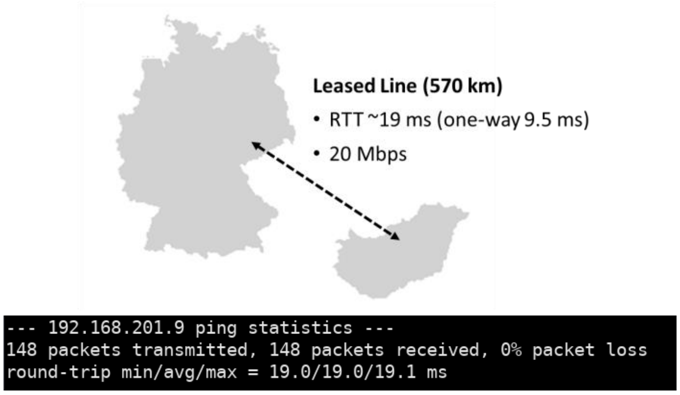


Figure 6: Leased line impact in the Testbed Germany.

In the execution of the FRMCS functional tests in WP5, the leased line was working well for voice and (small) data applications while there have been QoS issues on the video transmission with data rates higher than 1.5 Mbps, for which continuous streaming became problematic. In fact, for this or higher rates of the video application, frequent transmission interruptions occurred. In discussions with the leased line providers, the issue could be identified as one end of the line has been configured as “unmanaged leased line” with too few performance guarantees and priorities which led to buffering effects in the internet nodes between Germany and Hungary (despite the availability of 20 Mbps bandwidth). For future trials, the remote line realization is still recommendable, however with managed leased line contracts and stricter end-to-end guarantees.

3.1.4 5G RAN and Handover Situations

The figure below shows the 7 radio sites (A) to (G) which have been equipped with 5G RUs and antennas in 5GRAIL. It also shows the central server room at site (G) in which the 5G CU/DU equipment is hosted. RUs and CU/DUs are connected via fronthaul fiber lines which have been installed in cable ducts along the track.

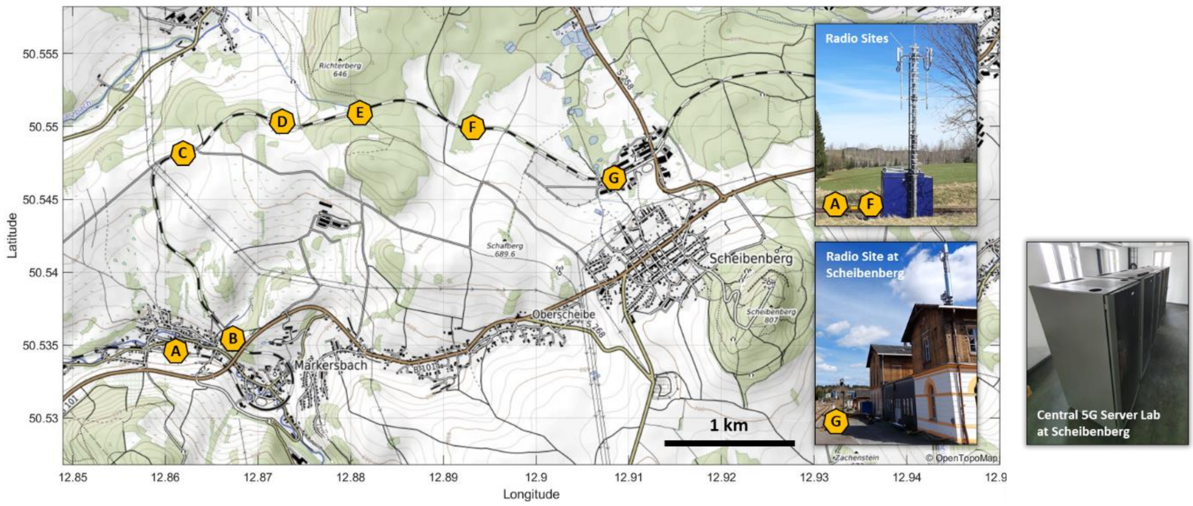


Figure 7: Layout of the 5G radio access network in the Testbed Germany

Figure 8: 2x 5G CU/DU in Testbed Germany

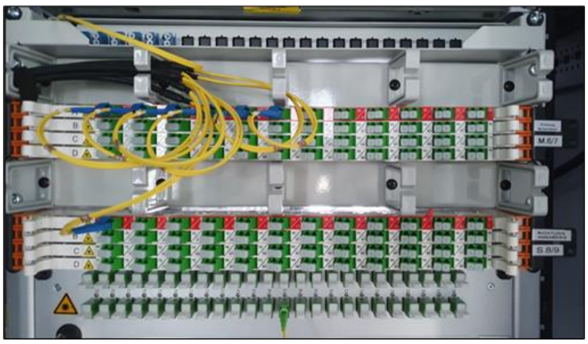


Figure 9: Fiber patches to connect CU/DUs with RUs

The association of the 5G CU/DUs (equivalent to BBUs in the realized network) to cell IDs and beam sector IDs is provided in Figure 10 for the two gNBs. Different 5G network function-based handover situations have been observed during the field trials in the network, which are:

- **Beam-switching:** By definition, this is not considered as handover. It is very fast as less signalling involved.
- **Intra-gNB (intra-AMF) handover:** The serving and target gNBs are the same and the handover procedure occurs in the frequency level or in the beam level of the cells connected to the gNB.
- **Inter-gNB (intra-AMF) handover:** The serving and target gNBs share the same AMF and UPF. The handover procedure could occur on gNB level if interface Xn exists. The control messages could be also exchanged via NG (N2) interface.

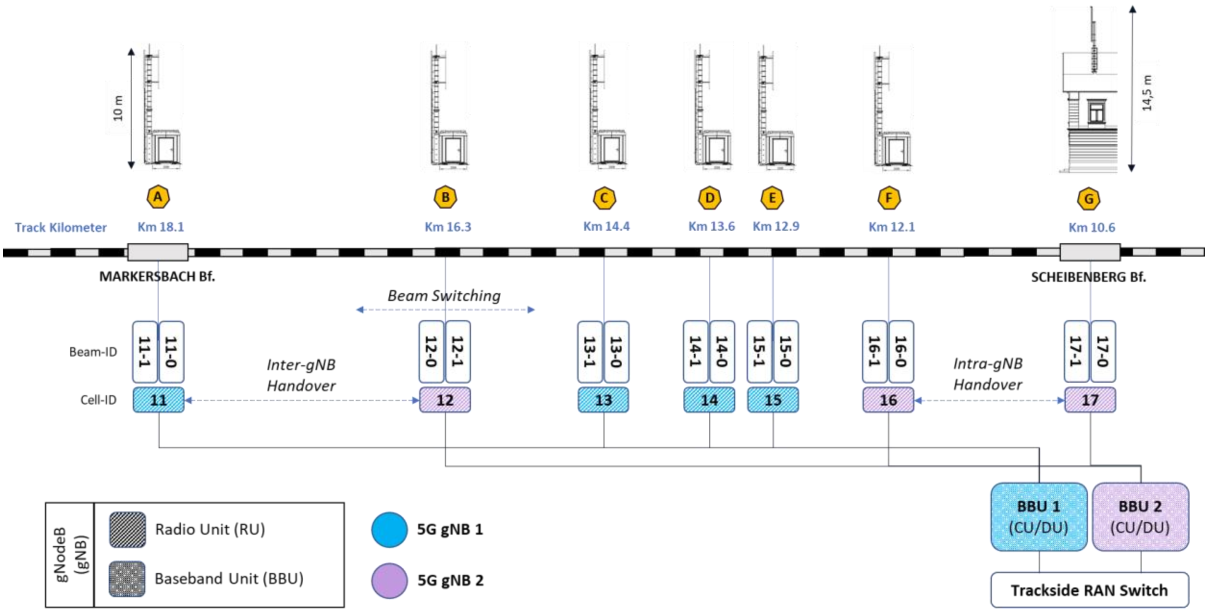


Figure 10: Handover characteristics of the 5G radio access network RAN in the Testbed Germany

Different to the 5GRAIL lab tests, in the field trials at Testbed Germany only Xn handovers have been realized which is supposed to be the fastest method to realize Inter-gNB (intra-AMF) handovers [37]. Realizing NG-based handovers was not possible due to versioning constraints of the field equipment which has been chosen at early stages of the 5GRAIL project. In consequence, functions for the cross-border scenarios that relate to UE roaming with AMF relocation over NG (N14/N2), i.e., Inter-gNB (inter-AMF) handover, have been tested in lab conditions only, see also deliverable D5.2.

- **Inter-gNB (inter-AMF) handover:** Since the AMF and UPF are not the same for serving and target gNBs, the handover procedure is handled in NG (N14/N2) level between two AMFs.

Figure 11 below gives an overview of 5G network function-based handovers.

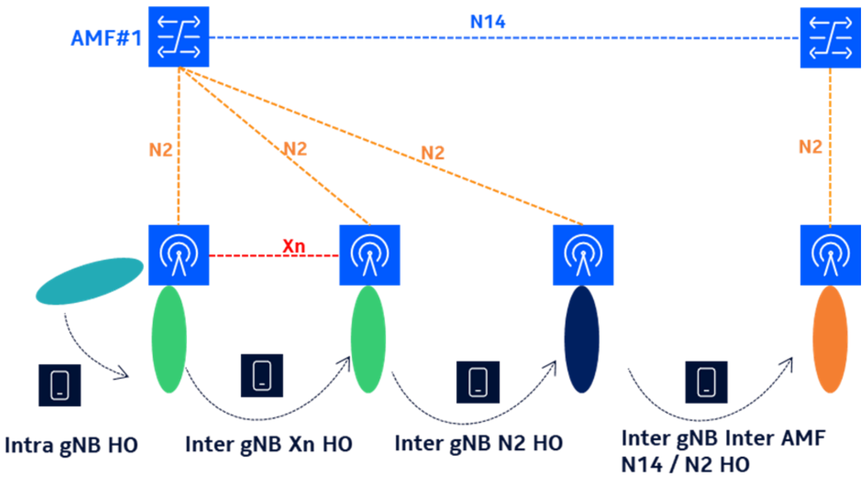


Figure 11: General overview of 5G handover situations, using one or two AMFs [8]

3.2 On-board Realization

3.2.1 Test Vehicles / Rolling Stock

The field trials took place during 6 test weeks in 2023: CW19,21,25,27,34,36. In addition, a final demo drive was organized in CW38. Pre-tests with a test van on roads following the train tracks took place in CW12. For the field trials different test vehicles were used:

- DB Netz connectivity measurement car (yellow) with diff. locomotives – CW19, CW21, CW25
- Digitale Schiene Deutschland testbed train BR708 – CW27
- Digitale Schiene Deutschland testbed train BR707 – CW34
- Deusche Bahn's experimental ICE "advanced TrainLab" (BR605) – CW36, CW38
- Digitale Schiene Deutschland testbed van – CW12 of 2023 (pre-tests)

Figure 12: Overview of the different test vehicles used in the 5GRAIL Testbed Germany

The mounted antennas on each test vehicle were from the same supplier and the same model number, see Section below. Also, the installed cables between cabin and antennas on rooftop have been of same type and comparable length (6 m to 9 m) to realize similar test conditions, especially in terms of cable attenuation and antenna losses, on all rolling stock.

3.2.2 Telecom On-board Design and Equipment

The following figures provide an overview of the on-board network, comprised of the FRMCS on-board gateway (TOBA-K Box), see details in [4] and [5] and an on-board switch (Juniper EX4200-24T) with multiple ports to connect to the voice (CabRadio), data (ETCS/TCMS) and video applications.

The cables to connect the TOBA-K box with the rooftop antennas have been Huber+Suhner SPUMA_400-FR-01 models for all test vehicles. From different rooftop antenna models, the two Huber+Suhner models no. 1399.99.0152 (with GPS) and no. 1399.17.0221 (w/o GPS) have been chosen, which have same technical performance at the considered frequency of 3.7 GHz and only differ in the availability of integrated GPS/localization.

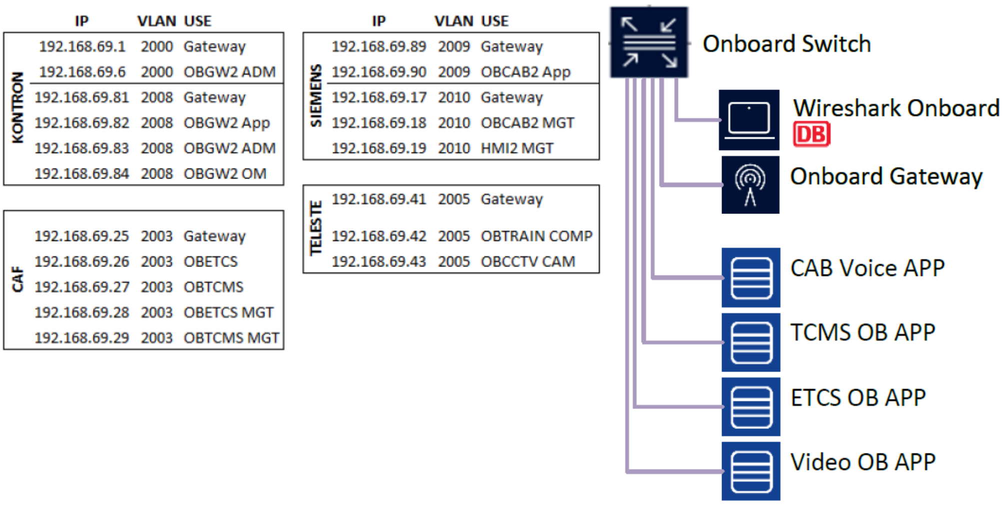


Figure 13: High-level on-board network design and IP plan (Testbed Germany)

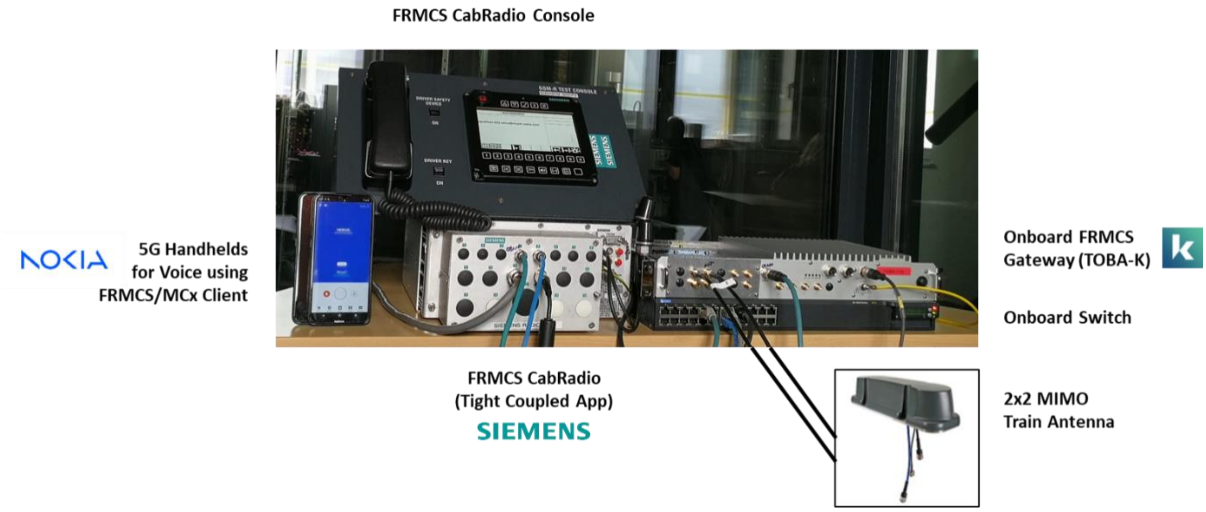


Figure 14: Example of the on-board equipment setup used for voice tests (Testbed Germany)

The on-board equipment has been mounted in a portable 19 inch rack of 6 height units, see Figure 12. Thus, it was easily possible to change the equipment between test trains.

It was possible to realize remote access from Kontron France to the FRMCS gateway (TOBA-K box) in the testbed in Germany via public mobile onboard connectivity for remote configuration and administration.

3.3 Mobile Network Characteristics (Band n78)

The following table reports the configuration of the 5G test network for FRMCS end-to-end field tests in Germany.

Band	n78
Bandwidth	5G bearer A: 20 MHz (3700-3720 MHz) – for tests of Task 5.2 5G bearer B: 20 MHz (3730-3750 MHz) – for additional tests in Task 5.3
Subcarrer Spacing	30 kHz
TDD Configuration (UL/DL)	5G bearer A: '1/4' DDDSU 5G bearer B: '3/7' DDDSUDDSUU *see explanation in Appendix 14.1*
MIMO Configuration	4T2R Network with • 4x2 MIMO in DL, max. 256 QAM • 1x2 SIMO (2Rx Diversity) in UL, max. 64 QAM
Spatial Multiplexing	Open Loop
PUCCH Format	Long (Format 3)
Trackside Antenna	TDQ-33818DER-60v01 (17.5 dBi gain)
EIRP Antenna Sites	64,0 – 64,5 dBm
Onboard Antenna	H+S 1399.17.0221 and H+S 1399.99.0152 (2 ports)
UE Tx Power	23 dBm

3.3.1 Air Interface KPIs (5G Control Plane Measurements)

In the following, we provide scanner measurement results of KPIs from the air interface of the 5G radio system. Two control plane values have been analysed which are:

- RSRP (Reference signal received power)
- SINR (Signal to interference and noise ratio)

Note that the measured metrics on TDD band n78 (3.7 GHz) are less relevant for final FRMCS deployments which will run on RMR TDD band n101 (1.9 GHz.). Nevertheless, some analysis is provided to understand the characteristics of the implemented radio access network in 5GRAIL Testbed Germany and to give an indication for application behaviour based on the 5G coverage.

Figure 15 shows an example of a drive test along the railway track between site (A) in *Markersbach Bf.* and site (G) in *Scheibenberg Bf.* It can be seen that some areas with low coverage existed, i.e., in the order of -110 dBm or below, which were often related to (intra- or inter-gNB) handover zones.

In few of the conducted application performance trials, connection losses occurred in low coverage areas. Mostly, the 5G n78 modem of the TOBA gateway was able to automatically re-connect to the cell in these moments. Sometimes, however, the UE experienced detachment and re-attachment procedure was needed.

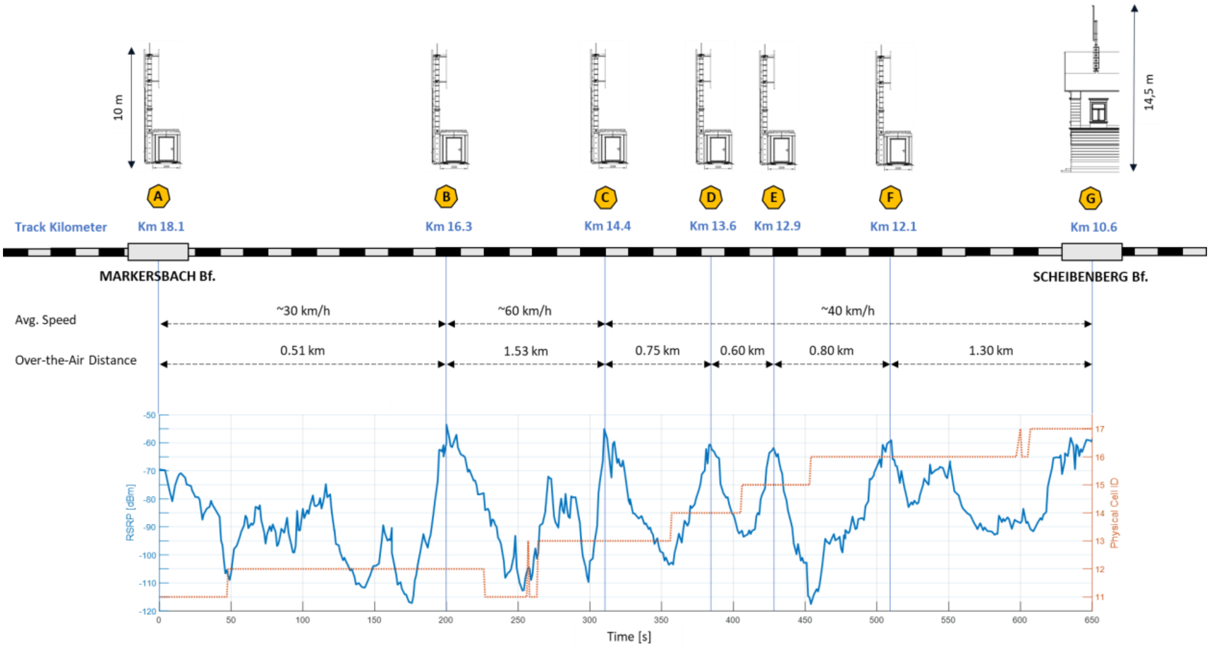


Figure 15: Observed RSRP and Cell IDs during a drive test (Testbed Germany)

Figure 16 and Figure 17 below depict the RSPR and Cell and Beam ID information over the geo-coordinates, respectively.

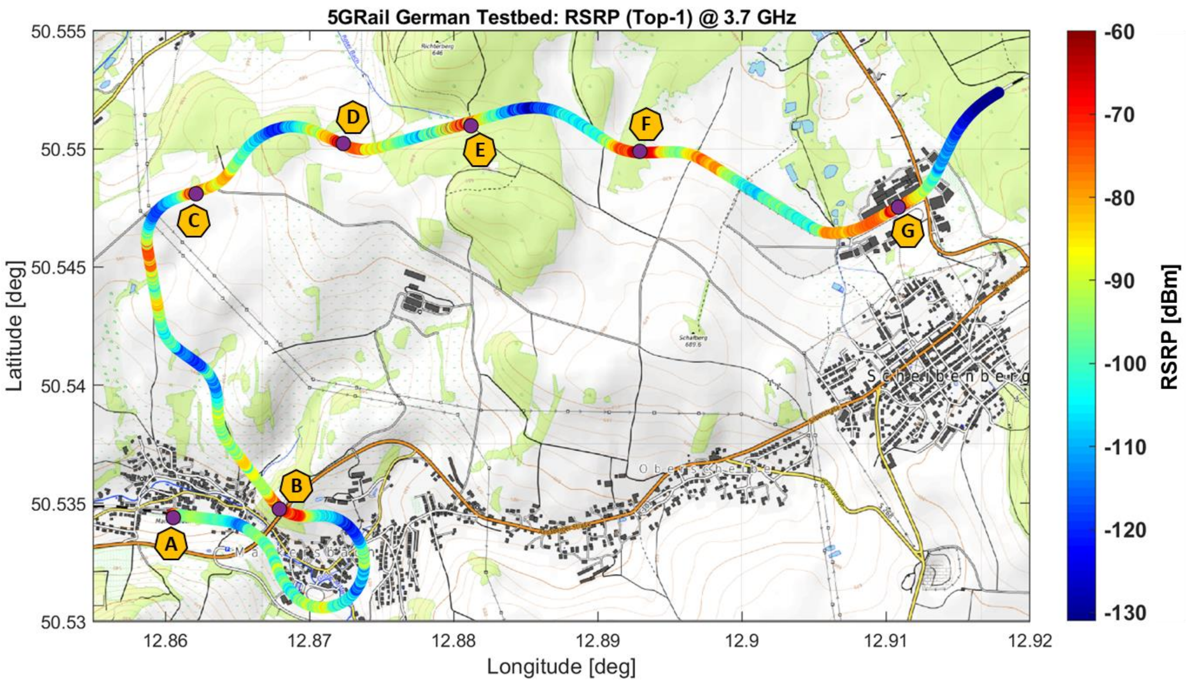


Figure 16: RSRP along the test track (Testbed Germany)

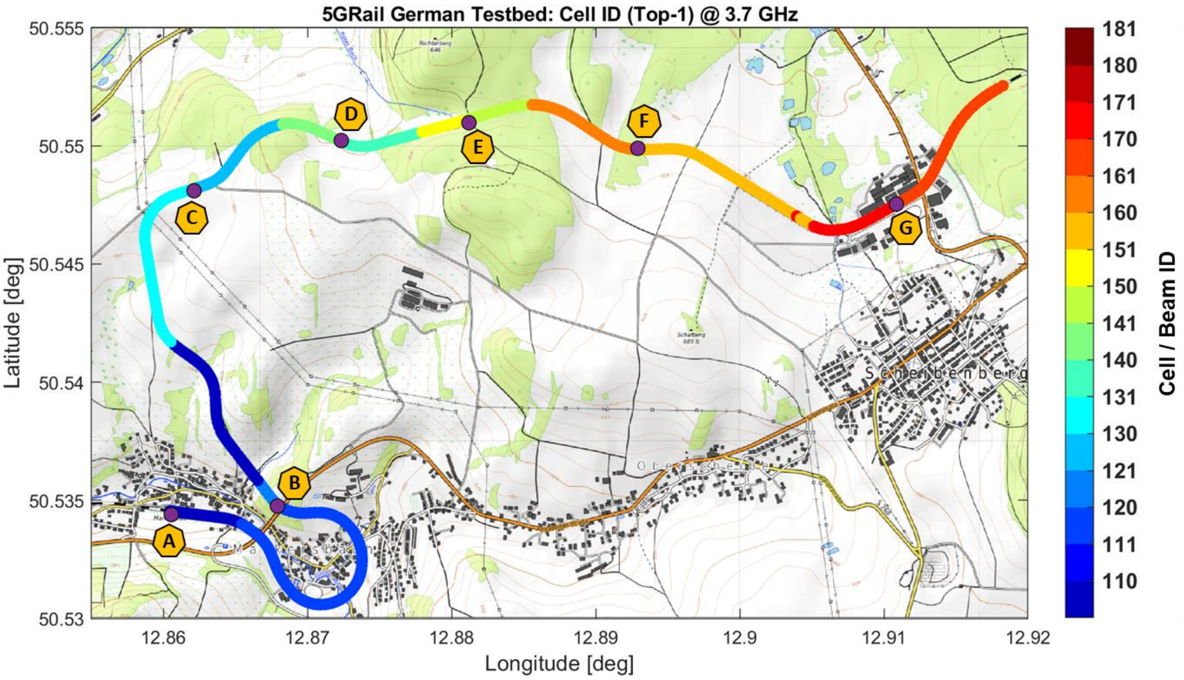


Figure 17: Cell IDs ('XX') and Beam IDs ('Y') in format 'XXY' along the test track (Testbed Germany)

To complete the characterization of the radio access performance we also provide the cumulative distribution function (CDF) of RSRP and SINR, evaluated for all recorded samples over all 7 radio cells (or 14 beam sectors) along the test track, in Figure 18. Average RSRP and SINR over distance is provided in Figure 19, where the binning of recorded values has been applied for 20 m segments.

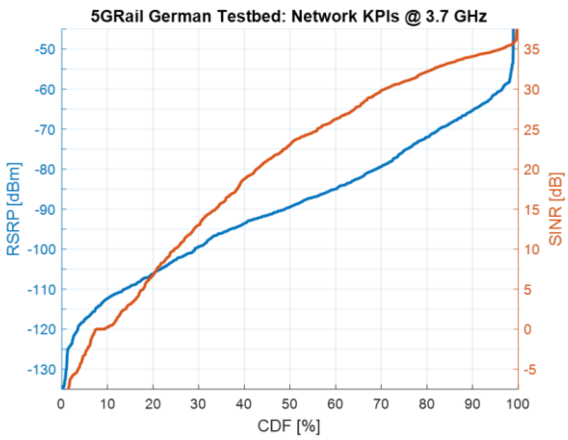


Figure 18: CDFs of RSRP and SINR (Testbed Germany)

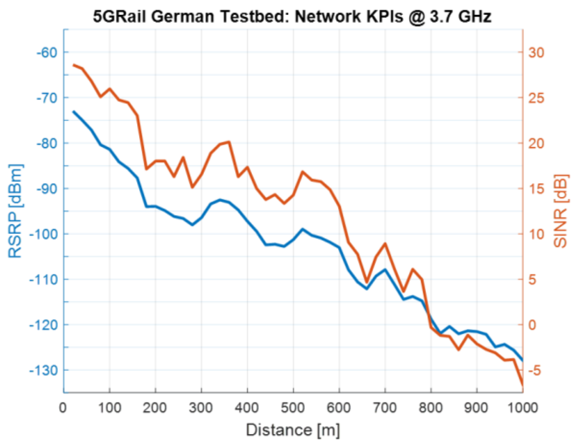


Figure 19: RSRP and SINR over Distance (Testbed Germany)

3.3.2 Handover KPIs (5G Control Plane Measurements)

In the following, we provide control plane measurement results for Xn-interface based handover (HO) situations in the 5G TDD test network, performed with Wireshark tool. It must be mentioned that the Xn handover procedure is complex to measure precisely as it needs both signalling information from gNB(s) messages and UE messages which implies time-synchronized on-board and trackside measurements.

The Xn handover involves a signalling time over three phases: HO preparation, HO execution and HO completion. Only a part of the Xn handover time (within the HO execution phase) is the real interruption time for the User Plane data – in general between UE message *RRCReconfiguration* and *RRCReconfigurationComplete*, see Figure 20. For the 5GRAIL analysis, we assume that the HO execution phase, defined between gNB message *HandoverRequestAcknowledge (XnAP)* and AMF message *PathSwitchRequest (NGAP),* serves as an upper bound for the user plane data interruption. Measurements of trackside signalling of time points in all handover phases in shown in Figure 21.

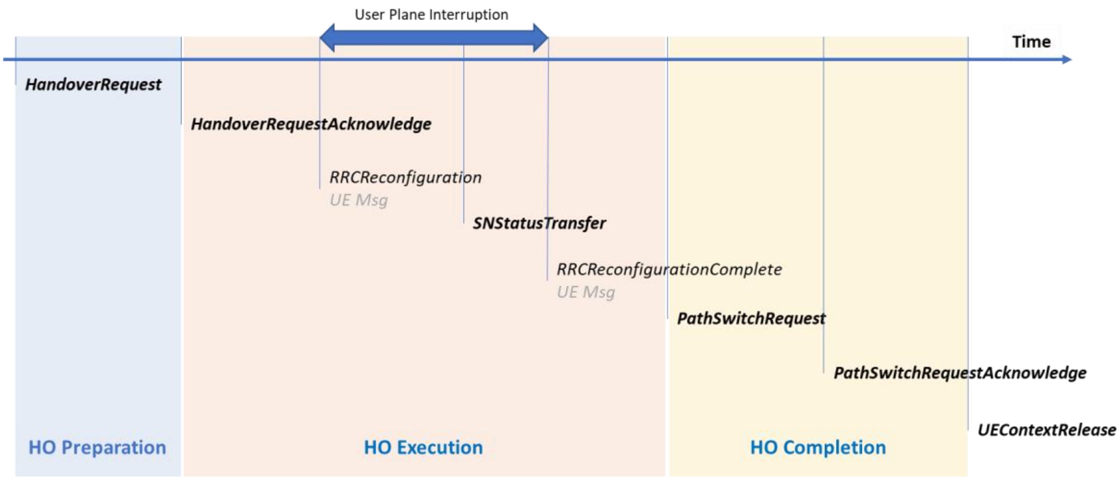


Figure 20: Phases and signalling information of Xn-based HO in 5G acc. to Appendix 14.1

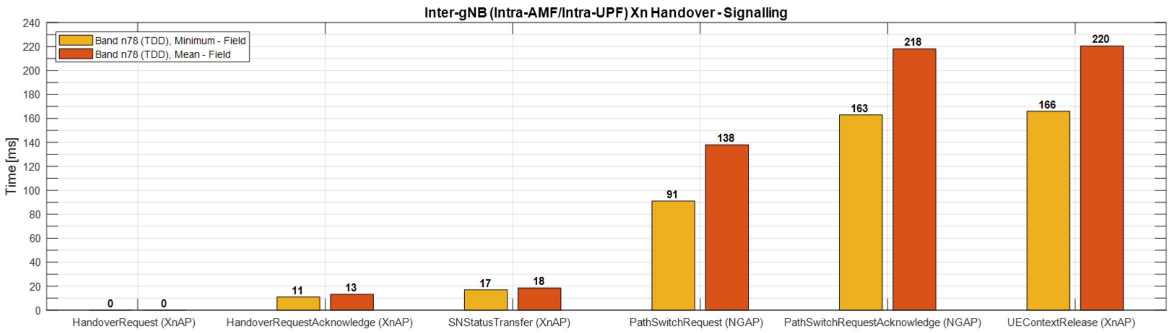
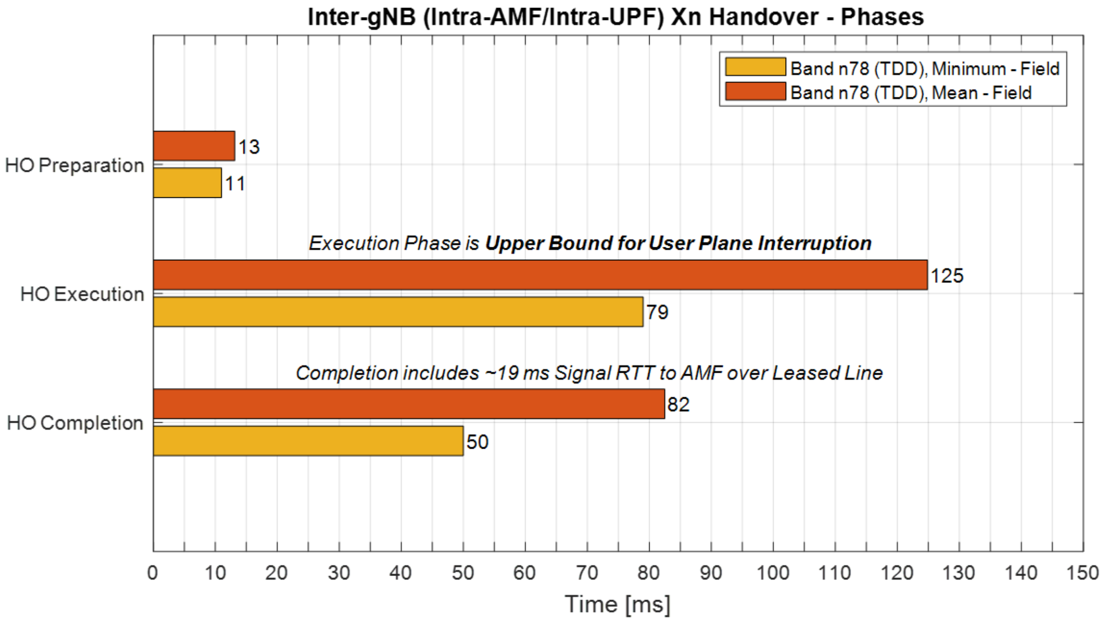


Figure 21: Measured times of the signalling information in different handover phases during Xn-based HO (analysis based on 120 handover records)

Note that, in the network realization of the 5GRAIL Testbed Germany, the control plane latencies in HO execution phase and HO completion phase are subject to impacts from additional leased line delays since message exchange occurs between gNB(s) of the 5G RAN in the German field (messages with label XnAP) and the AMF function of the 5G Core in Nokia's lab in Hungary (messages with label NGAP).

Moreover, the real User Plane data interruption has dependencies on coverage and deployment optimization in a network. E.g., a mobile user needs to establish a connection from source gNB to target gNB based on RRC reconfigurations and RACH procedures within the HO Execution phase and these depend also on signal quality in the cell overlap zone (and size of the overlap zone).

In Figure 22, we provide a detailed assessment of control plane latencies in Xn based inter-gNB HO on TDD band n78 for all handover phases. Shown are minimum and mean values. Note again, that the HO execution phase serves as an upper bound for the user plane interruption, while the real interruption time on user plane is expected to be some tens of milliseconds lower.



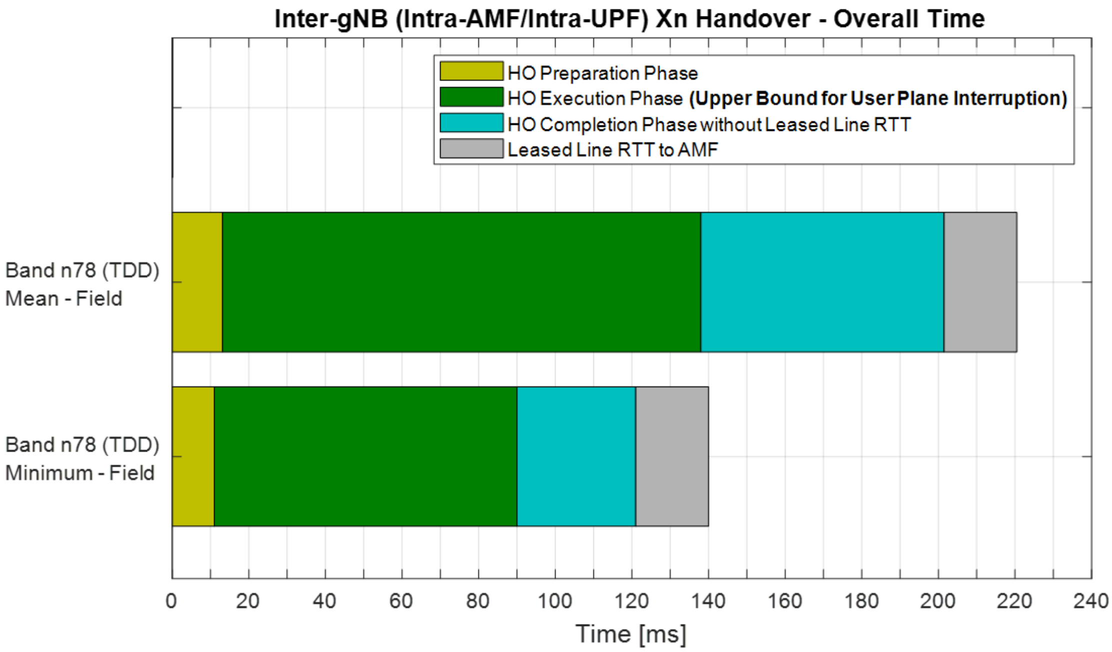
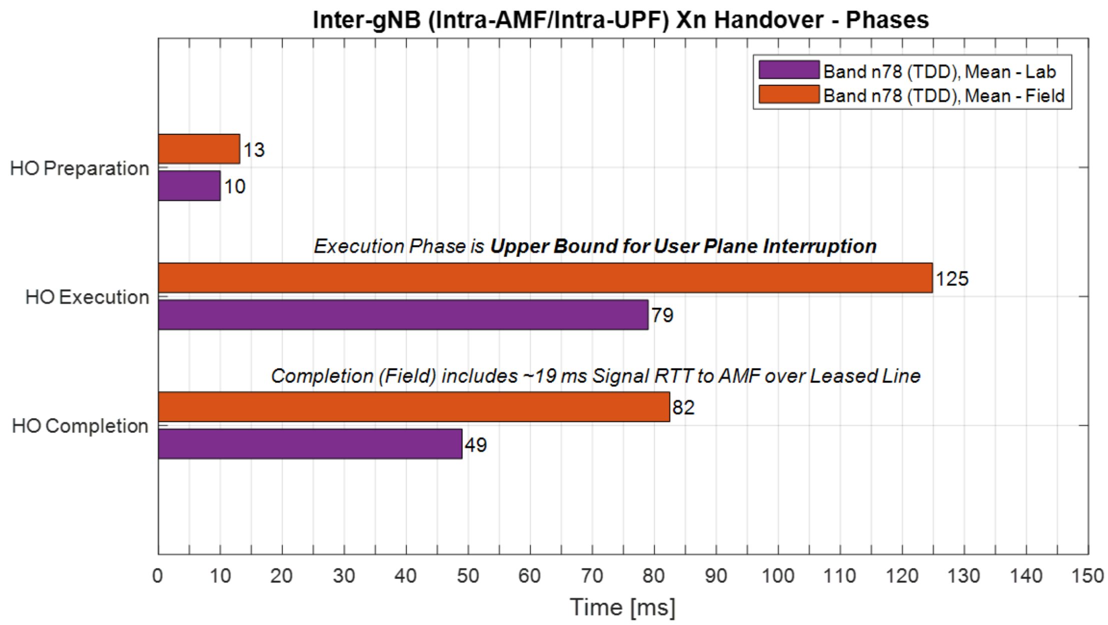


Figure 22: Control plane latencies in Xn-based Inter-gNB Intra-AMF HO (Testbed Germany)

Figure 23 provides a comparison of measured control plane latencies in Xn based inter-gNB HO on TDD band n78 between field (WP5) and lab (WP3). Shown are mean values. It can be observed that, with more ideal conditions in a lab environment, the handover latency is actually lower than in a real field deployment.



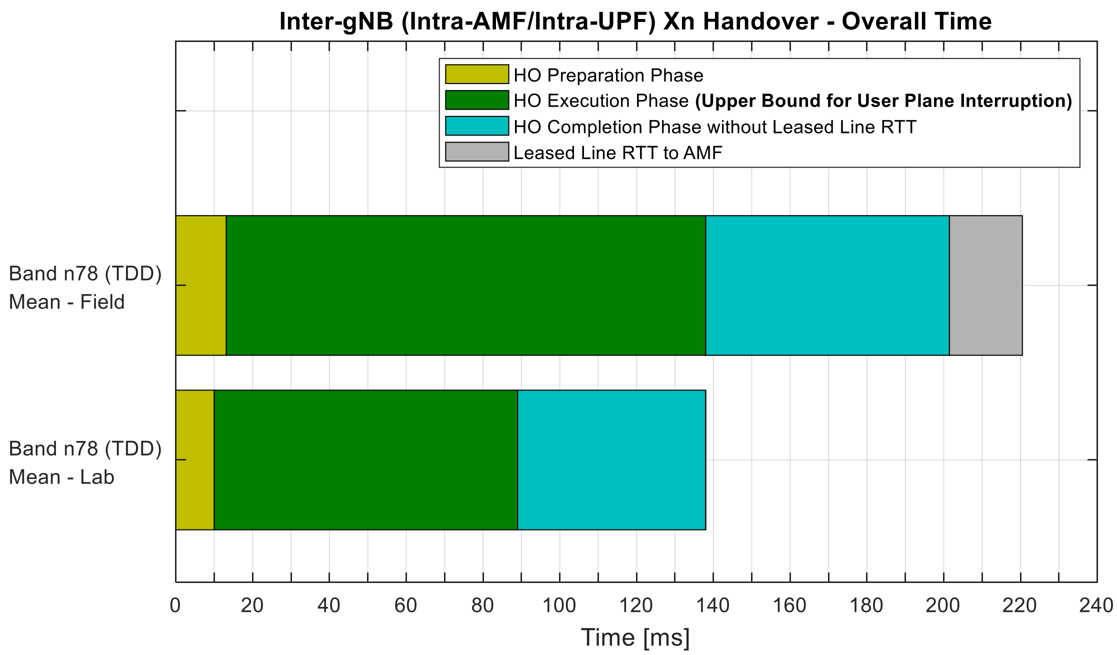
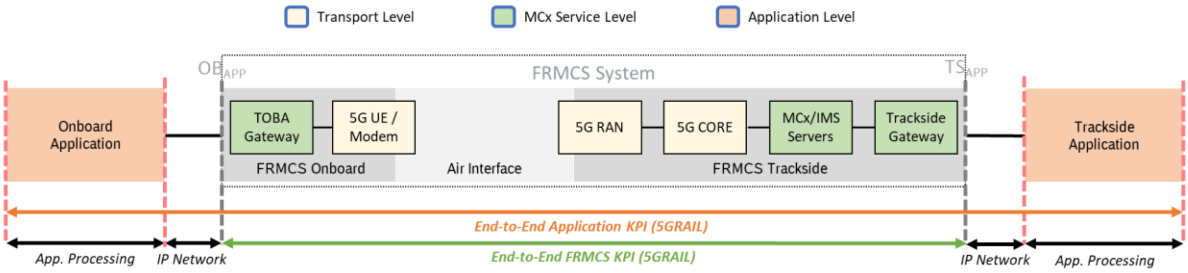


Figure 23: Comparison of control plane latencies in Xn-based Inter-gNB Intra-AMF HO for field conditions (Testbed Germany) vs. lab conditions (Lab Hungary)

3.3.3 End-to-End Transmission KPIs (5G User Plane Measurements)

Besides 5G control plane measurements, an evaluation of the 5G user plane evaluation has been performed. In particular, two end-to-end measurements are of interest: (i) the evaluation of end-to-end transmission KPIs of the FRMCS network, measured at the onboard and trackside interfaces between application and MCX service stratum, and (ii) the evaluation of end-to-end application KPIs which include application processing times and procedures, measured at onboard and trackside application equipment.



<u>FRMCS End-to-End Transmission KPIs</u>

For this type of measurement, the following data has been analysed for both uplink and downlink:

- Packet Losses
- Packet Transmission Latencies
- Jitter

First, results in 5G TDD band n78 are shown for a drive test along the railway track between site (A) in *Markersbach Bf.* and site (G) in *Scheibenberg Bf.* The transmission KPI analysis has been performed for packets transmitted in a voice call. Note that the (one-way) transmission latency includes the impact of the leased line between 5G RAN and 5G CORE with a delay of approx. 9.5 ms.

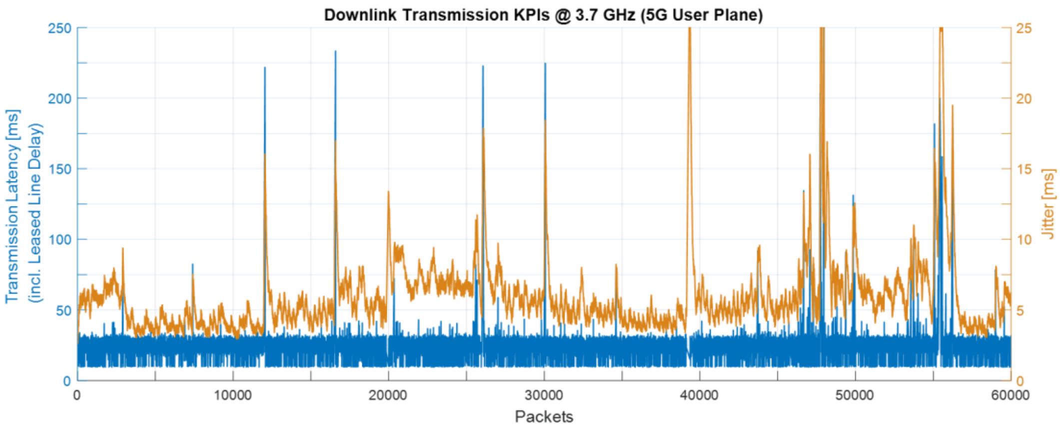


Figure 24: 5G user plane latencies and jitter in Downlink measured betw. trackside gateway and on-board switch during a drive test (excl. application processing delays)

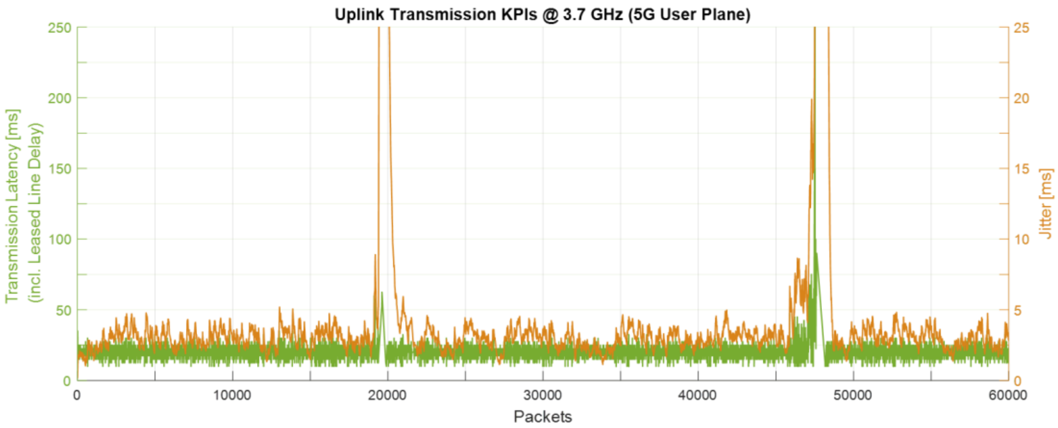
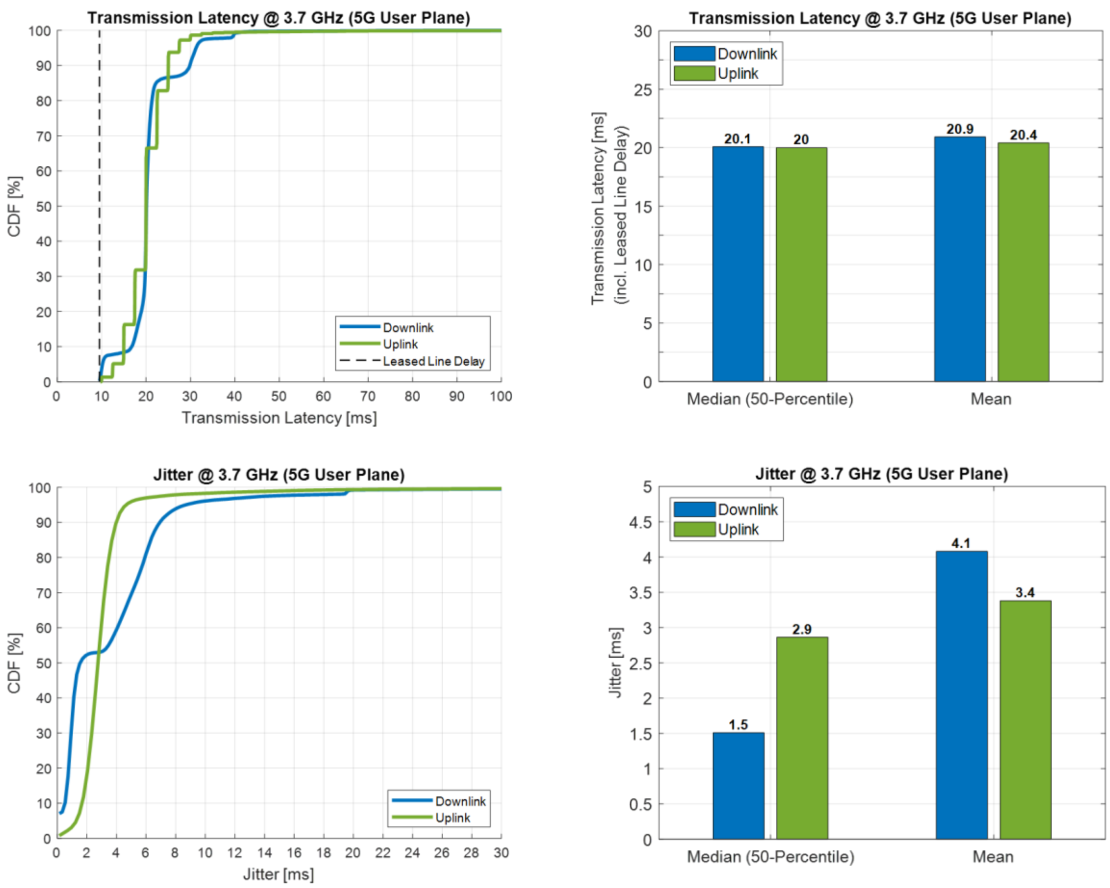


Figure 25: 5G user plane latencies and jitter in Uplink measured betw. on-board switch and trackside gateway during a drive test (excl. application processing delays)

Second, statistical performance results for latency and jitter from the field trials in 5G TDD band n78 are shown for packets transmitted in a voice call. Performance has been evaluated for all recorded samples over all 7 radio cells (or 14 beam sectors) along the test track, in Figure 18. Hence, the outliers with larger latency in the CDFs are likely due to intra- and inter-gNB handover situations.



Application End-to-End Transmission KPIs (incl. Application Processing)

For this type of measurement, the following data has been analysed:

- Application Delays
- Round Trip Times
- Jitter

The results will be discussed in the subsequent chapters of this document for the different mission-critical voice, data and video applications that have been tested in 5GRAIL WP5 field trials.

4 FRMCS/5G Network – Testbed France

4.1 Trackside Realization

4.1.1 Testbed & Infrastructure Overview

France (SNCF Test Site) is a portion of commercial line in the suburb of Paris southeast. 5G RAN is deployed in 3 sites with reuse of existing GSM-R/GPRS mast infrastructures of 20 m height and cabinets to host remote radio heads. The traffic from these three sites, called *Bourbonnais*, *Marin* and *Rive* is concentrated in the "Command Centre" non-radio site. The train speed is up to 70 km/h. The RU and CU/DU equipment of 5G RAN, the 4G BBU and RRHs as well as the 5GC and 4G EPC core networks, all supplied by Kontron, are located in SNCF's sites. The central site ("Command Centre"), is connected to WP4 lab at Kontron premises in Montigny, located in the western part of Île-de-France.

Spectrum conditions: SNCF Réseau applied and was granted temporary test licenses from the regulation authority ARCEP for both of the 1900 MHz RMR 5G-based tests on band n39 (using 10 MHz bandwidth) as well as band b38 (2600 MHz) for testing a second network that was 4G-based.

Figure 26: Test site in France in the scope of WP5

Figure 27: Impressions of the 5GRAIL Testbed France with antenna masts of 20m height

4.1.2 High Level Architecture Design

This section describes the High-Level and Low-Level Designs (HLD/LLD) for the infrastructure that was used for the functional application and performance tests described in this report and was further set up to prepare for the border-crossing scenarios discussed in deliverable D5.2.

The WP5 5G architecture is an evolution of the French lab where two sets of equipment are moved either to the SNCF's technical center in Vigneux-sur-Seine central site or to the on-board the test train. The diagram in Figure 28 gives an overview of the WP5 France global architecture.

For radio access network, three RU n39 are deployed on three sites along the track to provide the 5G radio coverage in 1900 MHz. Also, one RRH b38 is installed, collocated with one RU n39, to provide a 4G radio coverage at 2.6 GHz. These RU and RRH will be connected to two CU/DU housed in two ME1210 servers in Vigneux, forming two gNB units.

The two ME1210 servers are also used to house two 5G Core networks and, for one of them, one EPC, i.e., a 4G Core network. The use of one or two 5G Core networks will depend on the test case scenario.

A dedicated leased line (with point-to-point layer 2 VPN) is used to connect the 5GCs and EPC to Kontron's 5G lab in Montigny. Several interfaces will use this leased line, in particular:

- OAM for the supervision of the gNodeB and 5GC installed in Vigneux,
- N2/N3 to connect the gNodeB located in Kontron's lab in Montigny to the 5G Core networks installed in Vigneux,
- N6 to connect the 5G Core Networks in Vigneux to the IMS/MCX and the track side gateway.

There are two WP5 configurations foreseen in Testbed France for different test scenarios.

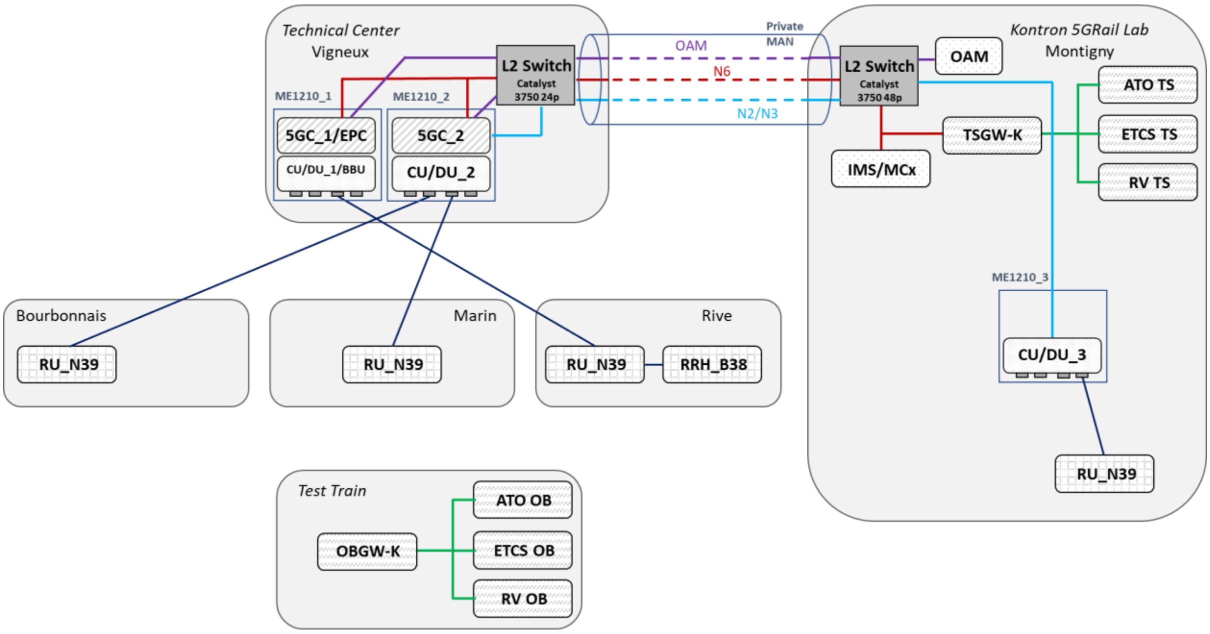


Figure 28: 5G (and 4G) network realization and interconnection of sites in the 5GRAIL Testbed France

<u>Configuration A</u>

This is a configuration where only one 5G Core is used, as the architecture in the figure below shows. Configuration A is used for the tests *without* cross-border relevance.

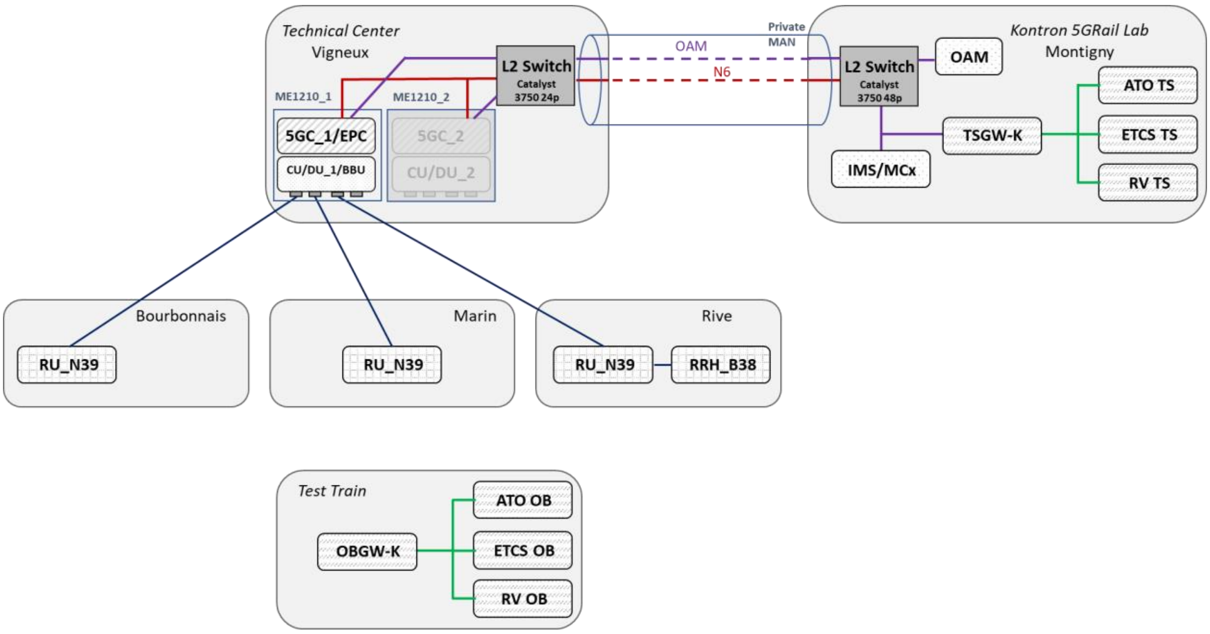


Figure 29: 5G architecture configuration A (Testbed France)

This 5G architecture features one gNodeB and one 5G Core network. The three RU and the RRH will be connected to this single gNodeB.

Configuration B

This is a Configuration where two 5G Core are used for cross border test cases, as the architecture in the figure below is showing. Configuration B is used for the tests *with* cross-border relevance as described in deliverable D5.2.

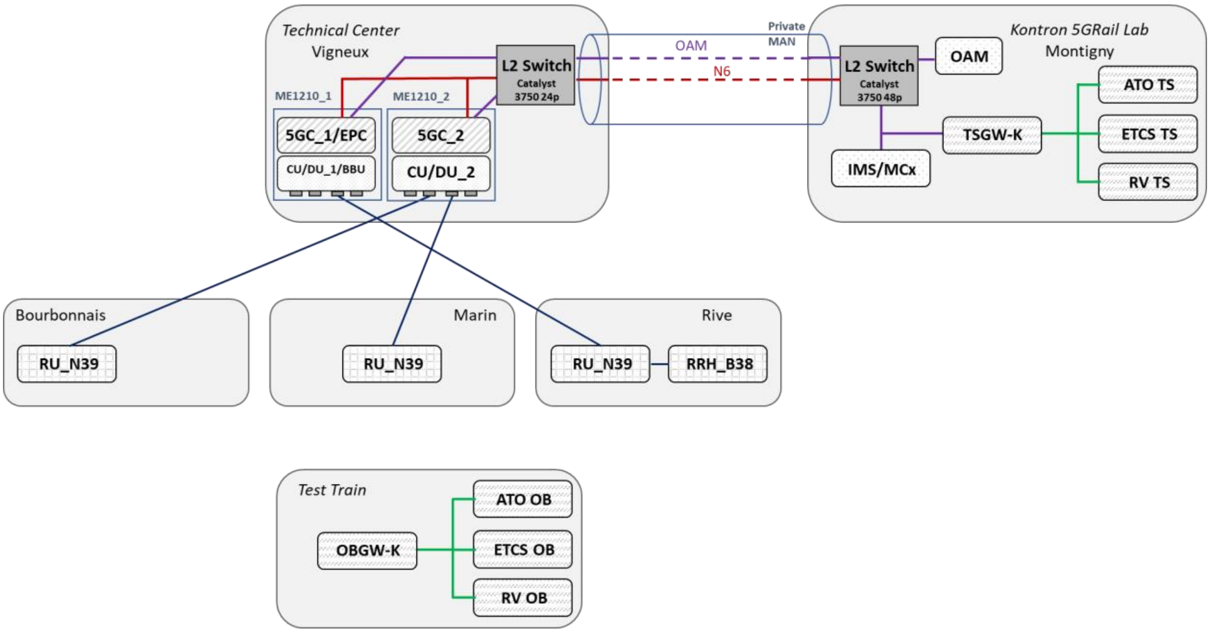


Figure 30: 5G architecture configuration B (Testbed France)

This 5G architecture features two gNodeB and two 5G Core network. 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.

Inter-sites MAN connection

The SNCF's Technical Center in Vigneux and the Kontron's 5Grail laboratory in Montigny are interconnected by a private MAN made available by SNCF.

This private MAN provides a level 2 link to carry the VLANs OAM, N6 and, if needed, N2. The private MAN extends the IP addressing used in the 5GRail laboratory in Montigny. The 5GRail laboratory in Montigny is protected by a Firewall.

4.2 On-board Realization

4.2.1 Test Vehicles / Rolling Stock

SNCF has made available a dedicated test train, named “Martine” consisting of a BB60137 locomotive and a VENG 234 Corail car.

Figure 31: Test train “Martine”

4.2.2 Telecom On-board Design and Equipment

Kontron’s FRMCS gateway (TOBA-K box) on-board equipment is based on a Kontron’s TRACe PC box. The on-board equipment is 1.5U height and can be installed in a 19 inch rack. The on-board equipment is fed in -24V DC.

Figure 32: Front view of the on-board equipment *TOBA-K*

The TOBA-K box is equipped with the modems 1x 5G Thales ES3 (band n39), 1x 4G Quectel EP06-E and 1x Wifi WPEQ261. These modems are connected to the on-board antennas. The on-board TOBA equipment is also equipped with a GNSS module.

The application providers equipment (from Alstom and SNCF) will be connected to the FRMCS gateway as shown below:

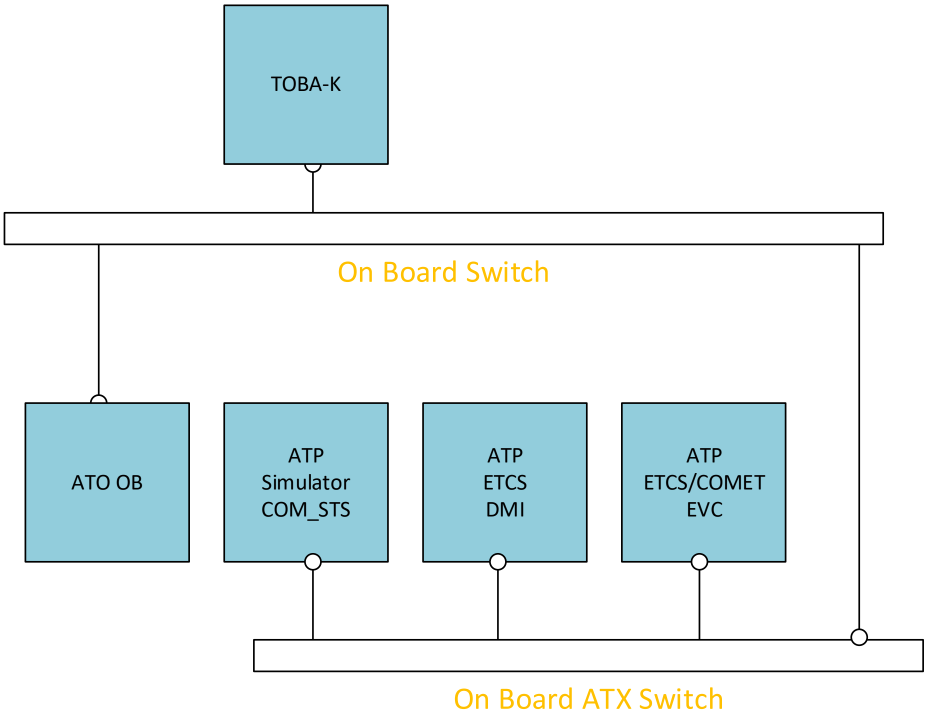


Figure 33: On-board equipment connections used in Testbed France

4.2.3 Application On-board Design and Equipment (ETCS/ATO Data App)

Below, an overview of the proposed application architecture is provided, including the sub-assemblies that will be used to pass data between ATO-OB and ATO-TS under the FRMCS protocol.

- **On-board equipment**
  - SS130 adaptor – the communication between ETCS-OB and ATO-OB shall be realized as specified in Subset 130. IP addresses of both communication partners shall be static for lab purposes. The lower levels of communication are given in Subset-130-APP. For the test bench activities, the communication will be based on payload data only without any security layers.
  - SS126 adaptor – the SS126 Adaptor allows the communication between the ATO-OB and the ATO-TS of mission data in the format SS126 format (Mission Profile, Journey Profile, Segment Profile).
  - It also manages the communication with the OBApp. This module is directly connected to the FRMCS Gateway through an ethernet connection.
  - SS139 Adaptor – the SS139 Adaptor will allow the ATO to communicate with the TCMS to control the train system in traction/braking.
  - The remaining applications manage the autonomous driving functions

- **Trackside equipment**
  - ATO-TS server – the server on which the different trains will connect to retrieve their routes, route updates, and feedback of their positions on the track

- **Test platform**
    - ATO replay – sends a set of pre-defined ATO frames to reproduce a real-life scenario
    - SS130 adaptor – simulate the presence of the EVC
    - SS139 adaptor – simulate the presence of the TCMS

This test environment is installed in a test bench on board the train. The purpose of this installation is to be able to test the communication between the ATO-OB and the ATO-TS on site 5G network.

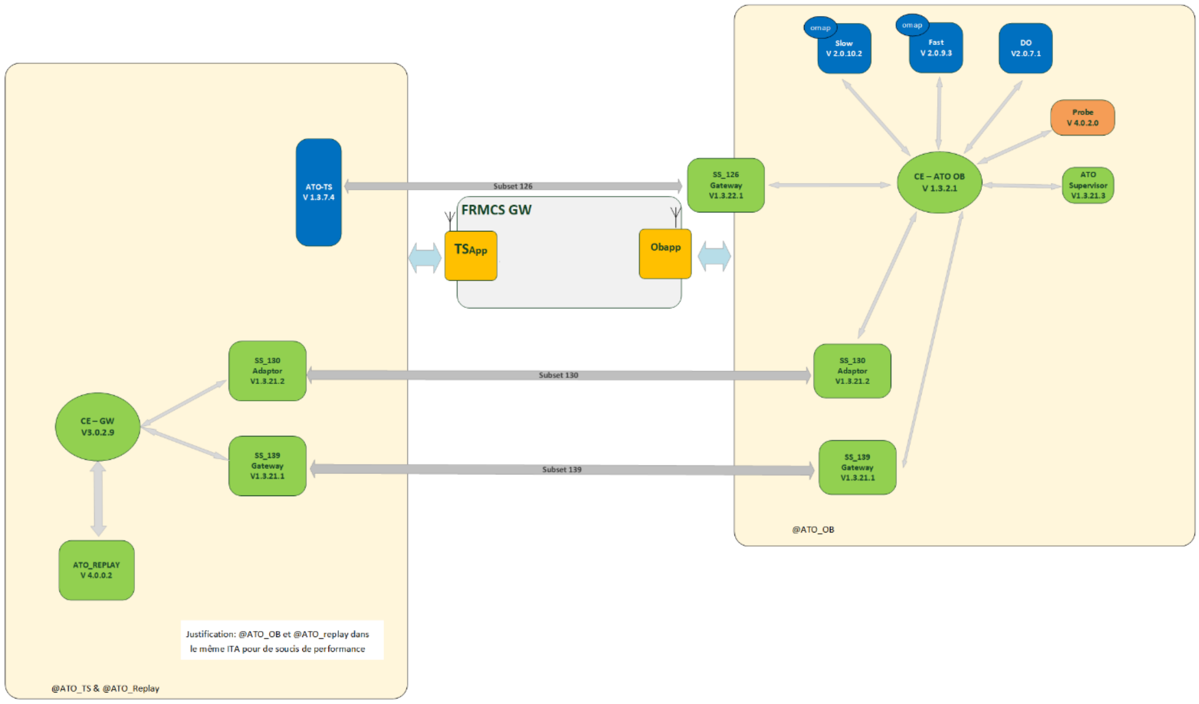


Figure 34: Architecture for ATO over FRMCS tests (Testbed France)

The Alstom ETCS application is embedded in a simulator. This simulator is directly connected to the FRMCS Gateway through an ethernet connection. The complete on-board simulation system also includes:

- a DMI: it is necessary to make communication requests to the track side equipment
- a train and beacons (a.k.a. “balises”) simulator: to be able to do handover scenario

This test environment is installed in a test bench on board the train. The purpose of this installation is to be able to check communication level 2 between ETCS on board applications and RBC on site 5G network.

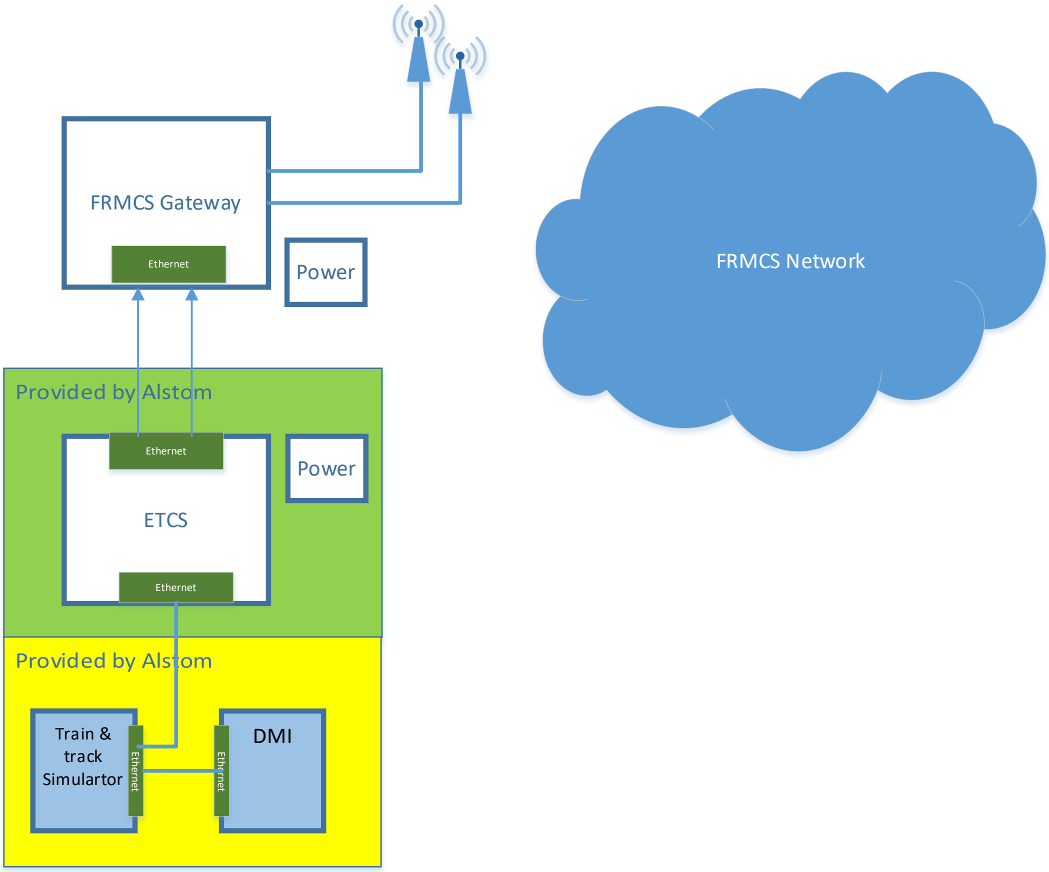


Figure 35: On-board design for ETCS/ATP over FRMCS tests (Testbed France)

Alstom's on-board equipment consist of ATP DMI, ATP Comet/EVC, ATO OB and ATP COM STS. This equipment is installed in a rack as shown below:

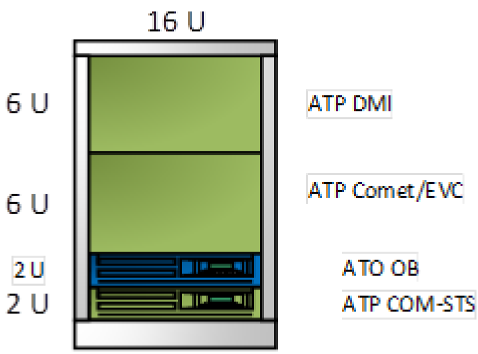


Figure 36: Rack implementation for ETCS/ATP over FRMCS tests (Testbed France)

4.3 Mobile Network Characteristics (Band n39)

The following table reports the configuration of the 5G test network for FRMCS end-to-end field tests in France. It also served as hypotheses for the simulation prior to equipment commissioning.

Band	n39
Bandwidth	10 MHz (1900-1910 MHz)
Sub-carrier Spacing	30 kHz
TDD Configuration (UL/DL)	DDDDDDDSUU (6:4:4) *see explanation in Appendix 14.1* DL-UL-Periodicity: 5 ms DL_slots: 7, DL_symbols: 6, UL_slots: 2, UL_symbols: 4
MIMO Configuration	2T2R Network allowing 2x2 MIMO (max. 256 QAM in DL)
Emitter	AW2S RRH Power 20W/43 dBm (10 W per direction)
Trackside Antenna	HPBW: 65° Antenna gain: 15 dB
Modem Category	DL UE Category 16 UL UE Category 20
Onboard Antenna Gain	6.5 dB
Modem TX power	31 dBm (5GRAIL tailor-made module)

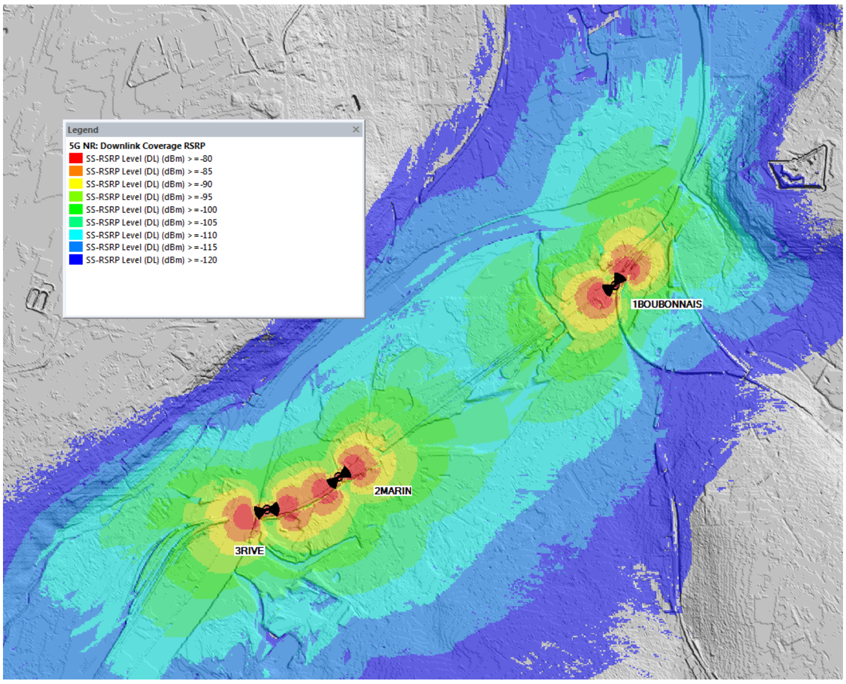


Figure 37 – RSRP Downlink Coverage Simulation using N39 band

5 Common Test Architecture for End-to-End Field Evaluation

The generic end-to-end network architecture of the FRMCS trials in the two fields is depicted in Figure 38. It includes both onboard and trackside building blocks of the 5G transport stratum (5G modem, 5G gNB and 5G CORE) as well as the respective interfaces as defined by 3GPP. It was planned in the project scope, to have a focus on Voice in Germany, while in France, the emphasis would be on data.

The 5G radio access network in the Testbed France operates at TDD band n39 (1.9 GHz) and in the Testbed Germany at TDD band n78 (3.7 GHz). In the French testbed, an additional 4G system (using 4G modem, 4G eNB and EPC) is implemented at band b38 (2.6 GHz), see Figure 39. The German testbed provides remote connection to an additional 2G transport (900 MHz) in Nokia's lab premises in Hungary. Here, 5G and 2G systems are linked via an interworking function, see Figure 40**Fehler! Verweisquelle konnte nicht gefunden werden.**. The 2G transport network is used for voice tests. To allow both single- and multi-user voice tests, multiple onboard devices (cab radios and additional handhelds) exist in the Testbed Germany.

The mission-critical service and application strata are shown with blue and red colors, respectively. The applications use the on-board application (OBapp) and trackside application (TSapp) interfaces [19],[20]. In case of voice applications, the mission-critical application (MCx) client is the MCPTT service client realized in the cab radio device and, hence, tight coupled. For data/video applications the MCx client is the MCData service client being implemented in the TOBA GW following the loose-coupling principle. With 5GRAIL's TOBA GW prototype, a parallel operation of mission-critical application with a unified FRMCS onboard system is possible.

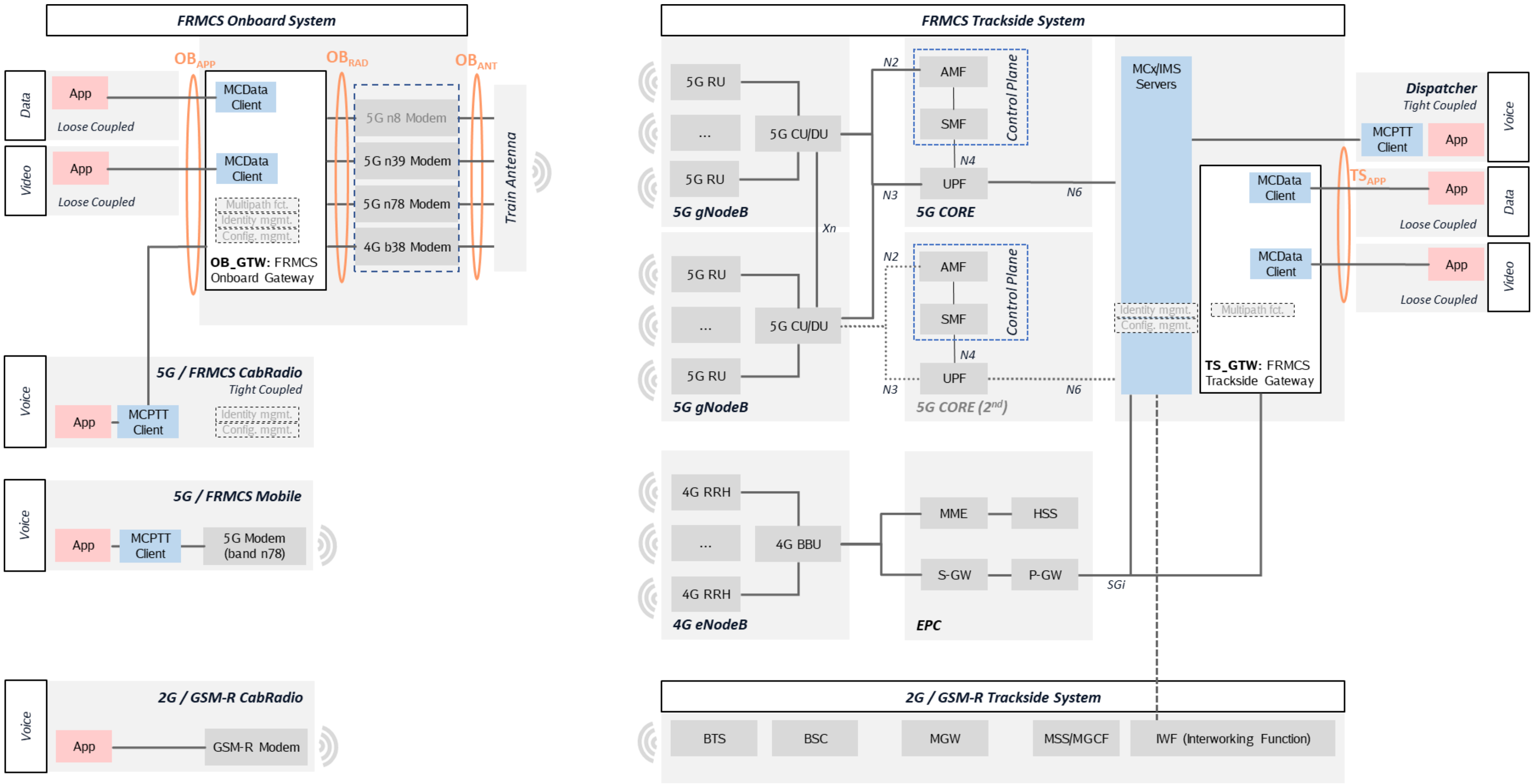


Figure 38: Common end-to-end test architecture of WP5 to perform the functional and performance tests of the FRMCS system.

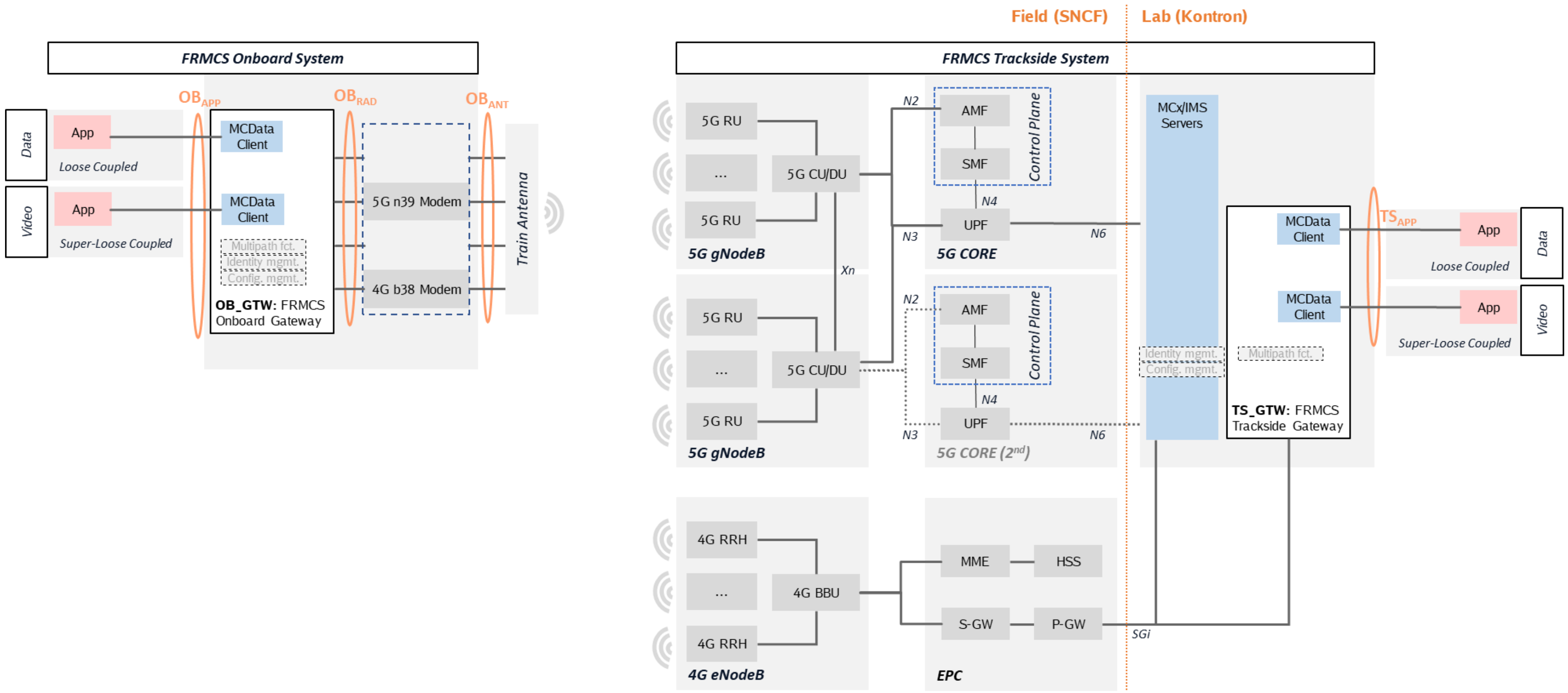


Figure 39: End-to-end test architecture of WP5 used for the field campaigns in the 5GRAIL Testbed France

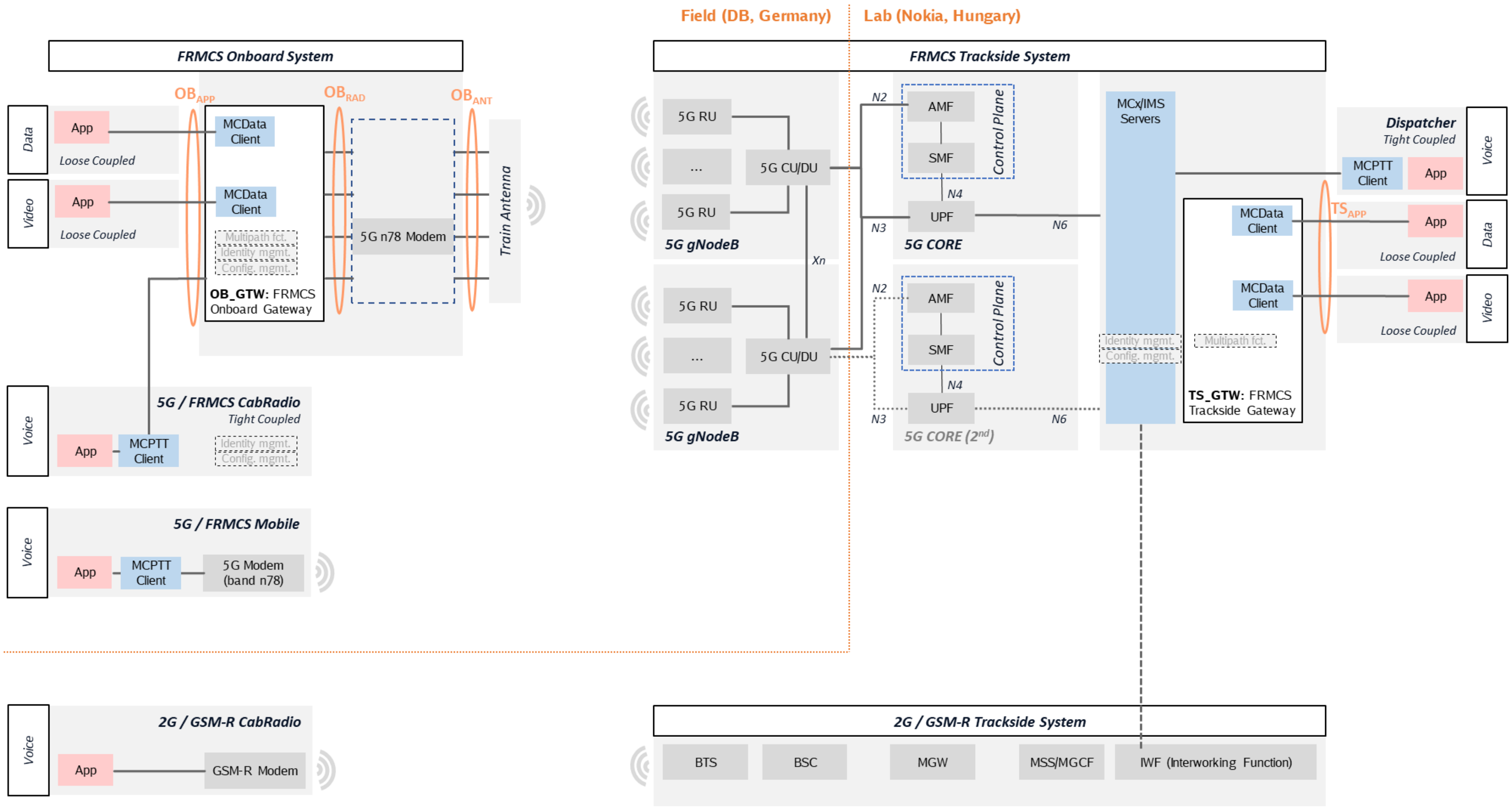


Figure 40: End-to-end test architecture of WP5 used for the field campaigns in the 5GRAIL Testbed Germany

6 Voice / REC Tests (using MCPTT) – Testbed Germany

The following chapter gives a report about Voice and REC call tests that have been performed with the application provider SIEMENS in the 5GRAIL Testbed Germany, operated at 5G band n78. Tests have been performed in several weeks, incl. Calendar Week 19, 25, 34 and 36 of 2023.

For all voice tests the QoS parameter 5QI was configured as 5QI=2, using guaranteed bitrate (GBR) class. As agreed in WP1 the filtering for the different QoS classes is done by the DSCP marking received from the application settings. As the used cab radios do not support DSCP marking, the voice QoS was set with a workaround using IP filtering rules instead of DSCP filtering. [7]

The tests have been supported by DB Netz AG (providing the track and rolling stock infrastructure), by Kontron (providing the onboard connectivity using FRMCS TOBA-K gateway and 5G modem plus FRMCS trackside gateway) and by Nokia (providing the 5G SA trackside network, the MCX trackside server and voice dispatcher). MCX clients came from Siemens on their cab radios and from Nokia on additional handhelds used in some tests.

The pictures below show some impressions of the tests:

6.1 List of Functional Test Cases

In total, five groups of application tests as specified in [2] have been successfully conducted. These are:

- **General functionalities**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
6.3	Voice_006	Arbitration

- **Point-to-Point voice calls**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
6.4	Voice_008	Initiation of a voice communication from a train driver (CabRadio) towards a train controller (Dispatcher) responsible for the train movement area
6.4	Voice_009	Initiation of a voice communication from a train controller (Dispatcher) towards a train driver (CabRadio)
6.4	Voice_019	MCPTT private point-to-point voice call (driver to controller) with HO (inter or intra) gNodeB

- **Group voice calls**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
6.5	Voice_005	Multi-user talker control
6.5	Voice_010	Initiation of a multi-train voice communication from a train driver (CabRadio) towards train drivers and ground users (FRMCS only)
6.5	Voice_021	Initiation of a multi-train voice communication from a train driver (CabRadio) towards train drivers and ground users (FRMCS and GSM-R)

- **REC – Railway emergency calls**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
6.6	Voice_011	Railway Emergency Call initiated by a train controller (Dispatcher) without interworking (FRMCS only)
6.6	Voice_022	Railway Emergency Call initiated by a train driver (CabRadio) without interworking (FRMCS only)
6.6	Voice_012	Railway Emergency Call initiated by a train driver (CabRadio) including interworking (FRMCS and GSM-R)

- **Combined Voice Calls (using MCPTT) and Video Uplink (using MCDATA)**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
6.7	Voice_017	Combined MCPTT private point-to-point voice call in parallel with MCData application

6.2 Test Requirements and Measurement Principles

3GPP defines several key performance metrics that shall be used to assess mission-critical push-to-talk (MCPTT) services, see [25]. These metrics, also being described in 5GRAIL deliverable D1.3, will be used for the evaluation of voice tests herein after.

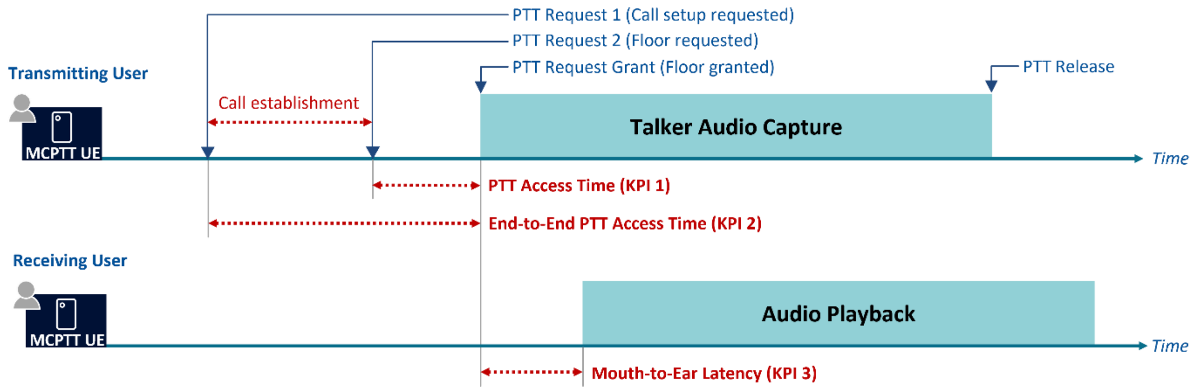


Figure 41: KPIs for MCPTT measurements in voice applications acc. to 3GPP TS 22.179

Of particular interest is the MCPTT Access Time (KPI 1) which is defined as the time between when an MCPTT User request to speak (normally by pressing the MCPTT control on the MCPTT UE) and when this user gets a signal to start speaking. This time does not include confirmations from receiving users. The test requirements for this KPI are as follows:

- For **MCPTT point-to-point calls** and **group calls** where the call is already established, the MCPTT Service shall provide an MCPTT Access time (KPI 1) less than 300 ms for 95% of all MCPTT PTT Requests.
- For **MCPTT Emergency Group Calls** the MCPTT Service shall provide an MCPTT Access time (KPI 1) less than 300 ms for 99% of all MCPTT Requests.

Another assessment criterion is the End-to-End MCPTT Access Time (KPI 2) which is defined as the time between when an MCPTT User requests to speak and when this user gets a signal to start speaking, including MCPTT call establishment (if applicable) and acknowledgement (if used) from first receiving user before voice can be transmitted. A typical case for the End-to-end MCPTT Access time including acknowledgement is an MCPTT Private Call (with Floor control) request where the receiving user's client accepts the call automatically. The test requirement for this KPI is as follows:

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

6.3 Arbitration (Voice_006)

The purpose of this test was to demonstrate that the FRMCS system terminates a lower-priority call when a higher-priority call is received.

6.3.1 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 7.2.6.

6.3.2 Specifics of the Test Implementation and Execution

The FRMCS arbitration currently relies on the GRM-R arbitration tables, as no specific FRMCS standards for arbitration have been established yet.

Additionally, there is no specification defining how the functional identities of all other participants in a group call, such as the REC call, should be displayed on each participant's terminal.

Lastly, clarification is required regarding whether, after the release of a high-priority call, in this case, the REC call, the original point-to-point communication between users A and B should be re-established.

6.3.3 Results and Observations

The test was performed successfully, with the following observations and findings:

- Communication between users A and B was established within the setup time, with clear and loud voice quality. User C successfully initiated the Railway Emergency Call (REC). Subsequently, the communication between users A and B was terminated to connect the REC call. Communication among users A, B, and C was then established within the setup time, maintaining clear and loud voice quality. Finally, the REC call was successfully terminated.

6.4 Point-to-point voice calls (Voice_008, Voice_009, Voice_019)

The purpose of the following tests was to demonstrate that point-to-point communication between a train driver and a train controller, responsible for the train movement area, can be established in either direction and will be maintained without drops and with good quality, even in mobility conditions, i.e., with inter- and intra-gNodeB handover situations.

List of considered test cases:

- Initiation of a voice communication from a train driver (CabRadio) towards a train controller (Dispatcher) responsible for the train movement area *(Voice_008)*
- Initiation of a voice communication from a train controller (Dispatcher) towards a train driver (CabRadio) *(Voice_009)*
- MCPTT private point-to-point voice call (driver to controller) with HO (inter or intra) gNodeB *(Voice_019)*

6.4.1 Detailed Test Architecture

The architectures of the test cases are presented below. The voice application is implemented in the FRMCS network as a tightly coupled application using an MCPTT client embedded in the voice application. The utilized end-to-end building blocks are marked in green.

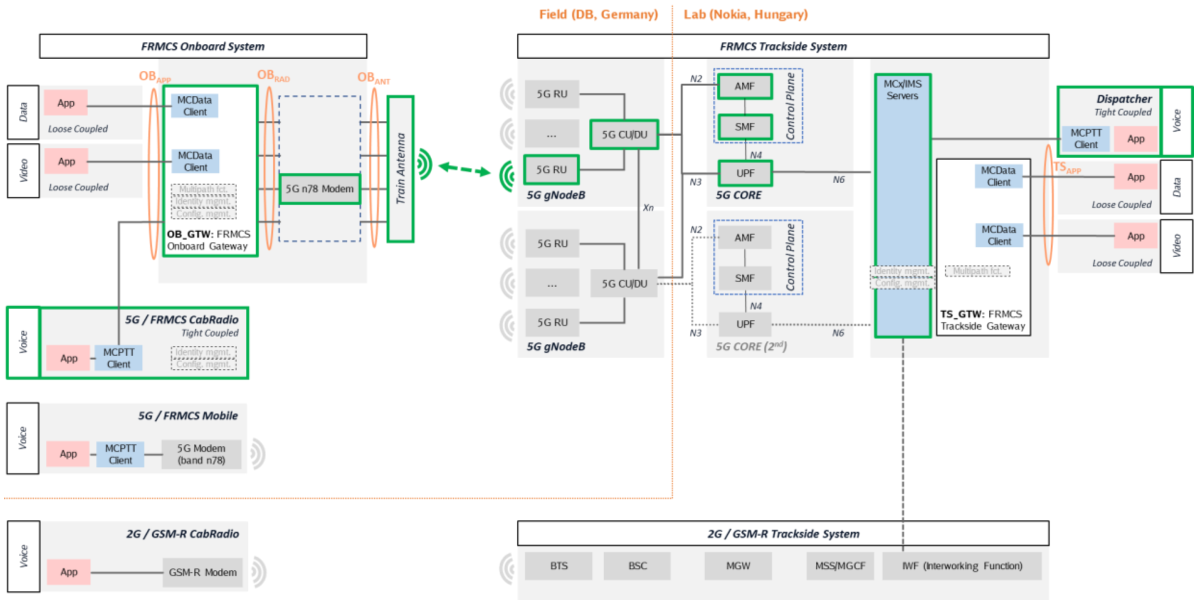


Figure 42: Architecture for test cases Voice_008 and Voice_009 (Testbed Germany)

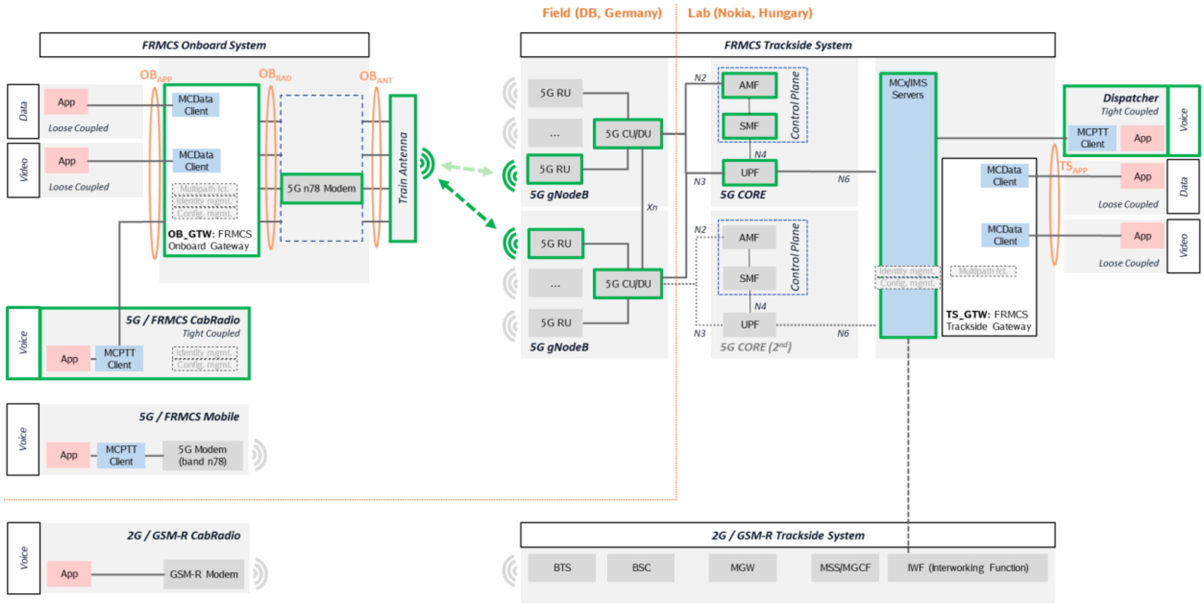


Figure 43: Architecture for test case Voice_019,
with intra- and inter-gNodeB handover (Testbed Germany)

6.4.2 Detailed Test Plan

The test plan for Test Case No. *Voice_008* is described in Deliverable D1.1v4 – Section 7.3.1.
The test plan for Test Case No. *Voice_009* is described in Deliverable D1.1v4 – Section 7.4.1.
The test plan for Test Case No. *Voice_019* is described in Deliverable D1.1v4 – Section 7.10.

6.4.3 Specifics of the Test Implementation and Execution

The test cases outline the requirement that the functional alias of the controller should be visible on the graphical display of the cab radio throughout the voice communication. However, as the controller terminal is not signed on to the functional alias, the MCID of the controller is displayed instead of the functional alias.

The test cases specify that the functional alias of the cab radio should be displayed on the controller's terminal during the entire voice communication process. Unfortunately, this expectation cannot be met due to limitations on the controller terminal, resulting in the functional alias of the cab radio not being displayed, and the MCID of the cab radio is shown instead.

Additionally, the controller's terminal lacks the capability to initiate a call with a manual answer option; therefore, the call was automatically accepted by the cab radio.

6.4.4 Results and Observations

The tests were performed successfully, with the following observations and findings:

- Communication between the users was established within the setup time, with clear and loud voice quality in either direction. The communication was maintained without drops and with good quality, even in mobility conditions.

Below, an analysis of recorded KPIs is provided. All recorded data has been taken from drive tests, i.e., with potential intra- and inter-gNB handover situations, which gives realistic conditions for future operations.

MCPTT Access Time (KPI1) Analysis

The evaluation of the MCPTT Access Time has been done jointly for Test Cases No. *Voice_008* and *Voice_019* (CabRadio initiated calls). The recorded KPI1 values of all captured PTT requests have been below the 300 ms limit as defined in Section 6.2 (which requires 95% of all requests below the limit). The mean value of KPI1 is 86 ms, while few records have shown higher access times.

Higher access times occur likely due to an inter-gNB handover situation or a short coverage gap which leads to increased re-transmission attempts. Note that the 5G radio deployment along the utilized test track was well planned for the purpose of prototype testing but not optimized for official acceptance tests as on real operational lines.

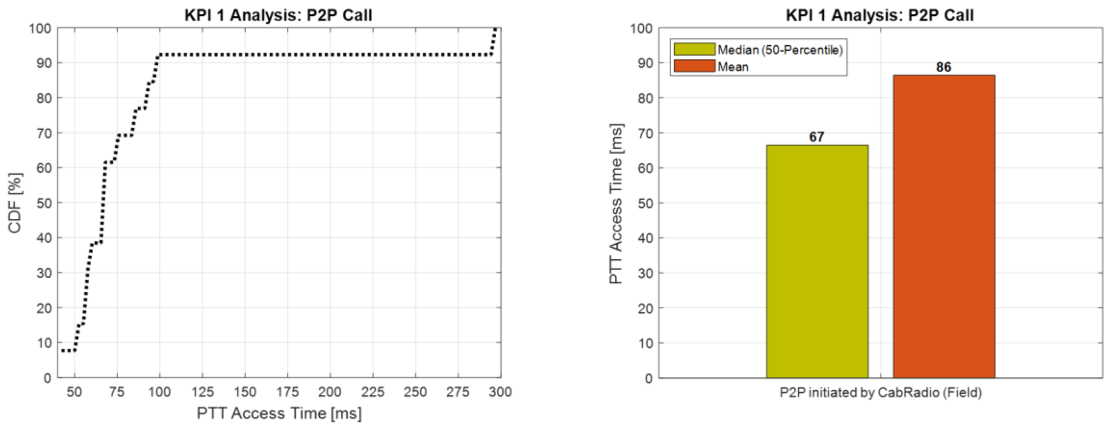


Figure 44: Statistical analysis of PTT Access Times for MCPTT point-to-point voice calls (Testbed Germany)

Voice Packet Loss Analysis

The evaluation of packet loss rates from the voice application on user plane has been done for both uplink and downlink directions. It shows almost no packet drops during voice communication in downlink and few packet drops in uplink. Note that the 5G radio deployment along the utilized test track was well planned for the purpose of prototype testing but not optimized for official acceptance tests as on real operational lines. It is expected that uplink packet loss rates improve in case of enhanced uplink-oriented deployment optimization.

Packet losses in train-to-ground communications have been assessed from packets of the transmitted uplink streams in Test Cases No. *Voice_008*, *Voice_009* and *Voice_019*, giving 1.11% loss rate for the considered point-to-point calls.

Voice Packet Losses (User Plane) in Uplink – Onboard to Trackside			
	Transmitted Packets	Lost Packets	Packet Loss Rate
Point-to-Point Call	65862	731	1.110%
Group Call	4187	41	0.979%
REC Call	1633	0	0.000%
Total	71682	772	1.077%

Packet losses in ground-to-train communications have been assessed from packets of the received downlink streams in Test Cases No. *Voice_008*, *Voice_009* and *Voice_019*, giving 0.02% loss rate for the considered point-to-point calls.

Voice Packet Losses (User Plane) in Downlink – Trackside to Onboard			
	Transmitted Packets	Lost Packets	Packet Loss Rate
Point-to-Point Call	63164	12	0.019%
Group Call	2514	0	0.000%
REC Call	6278	3	0.048%
Total	71956	15	0.021%

6.5 Group voice calls (Voice_005, Voice_010, Voice_021)

The purpose of the following tests was to demonstrate that multi-user voice communication between train drivers and a train controller, responsible for the train movement area, can be established and will be maintained without drops and with good quality, even in mobility conditions, i.e., with inter- and intra-gNodeB handover situations.

List of considered test cases:

- Multi-user talker control *(Voice_005)*
- Initiation of a multi-train voice communication from a train driver (CabRadio) towards train drivers and ground users (FRMCS only) *(Voice_010)*
- Initiation of a multi-train voice communication from a train driver (CabRadio) towards train drivers and ground users (FRMCS and GSM-R) *(Voice_021)*

The test case *Voice_005* demonstrated that multiple FRMCS Users can speak simultaneously in a multi-user voice conversation if the number of users granted the right to talk does not exceed the maximum number set in the FRMCS system.

On the other hand, the test case *Voice_010* demonstrated that a train driver can initiate a multi-user voice communication towards other train drivers registered to the FRMCS System, and *Voice_021* demonstrated that a train driver registered to the FRMCS system can initiate a multi-user voice communication towards other train drivers registered to the FRMCS and GSM-R Systems, as well as a train controller subscribed to the same valid MCPTT Group ID.

6.5.1 Detailed Test Architecture

The architectures of the test cases are presented below. The voice application is implemented in the FRMCS network as a tightly coupled application using an MCPTT client embedded in the voice application. The utilized end-to-end building blocks are marked in green.

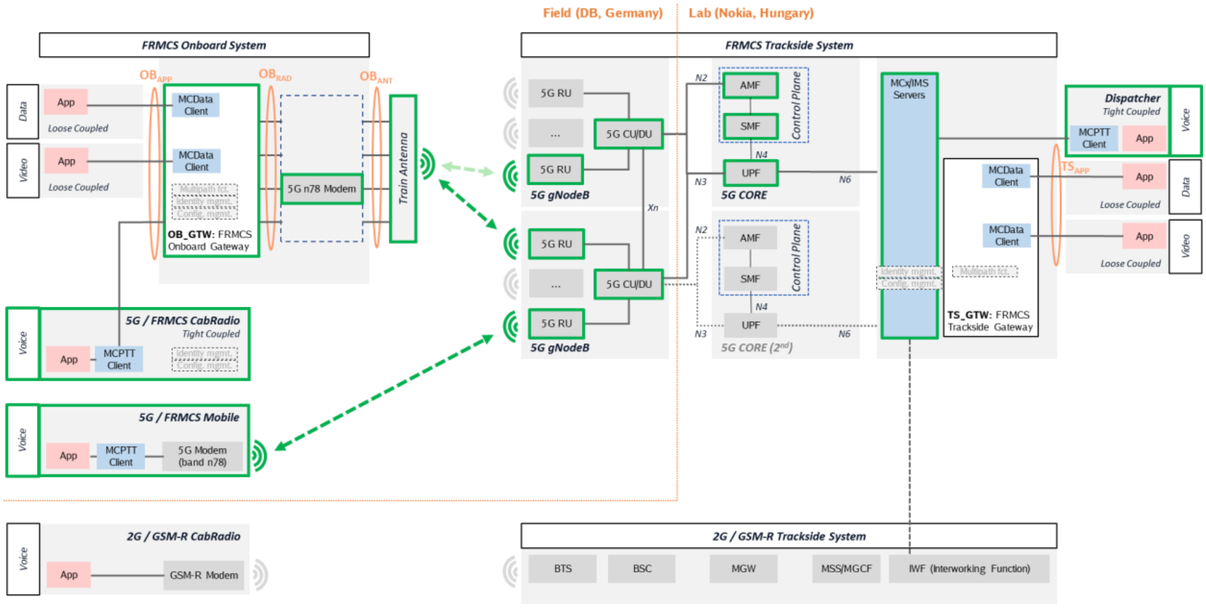


Figure 45: Architecture for test cases Voice_005 and Voice_010 (Testbed Germany)

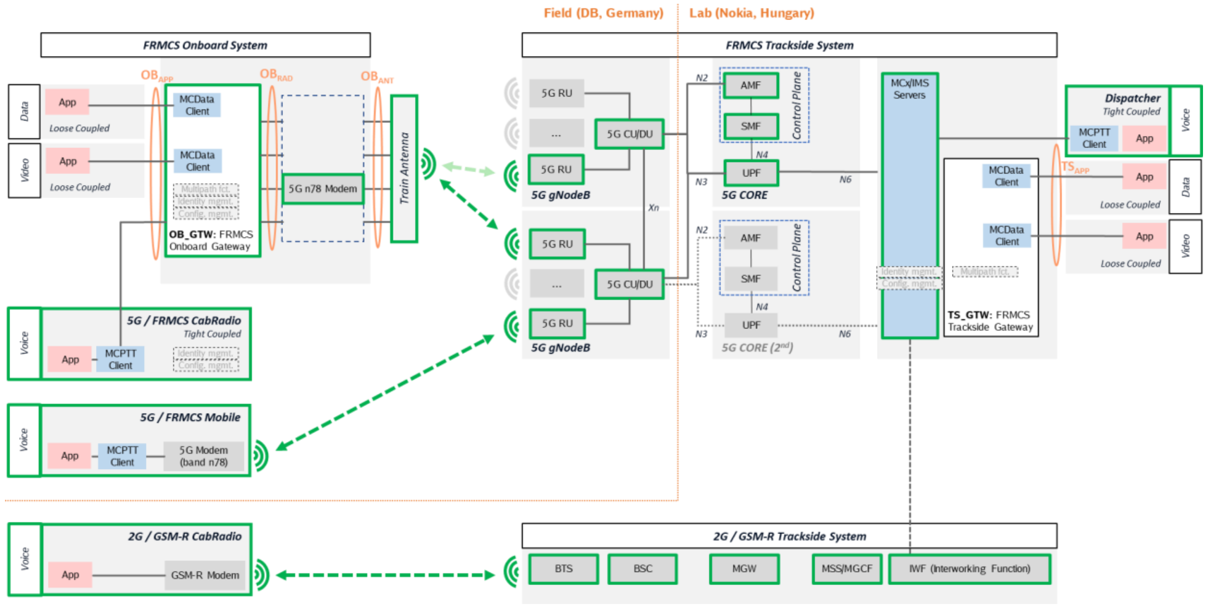


Figure 46: Architecture for test case Voice_021 (Testbed Germany)

6.5.2 Detailed Test Plan

The test plan for Test Case No. *Voice_005* is described in Deliverable D1.1v4 – Section 7.2.5.
The test plan for Test Case No. *Voice_010* is described in Deliverable D1.1v4 – Section 7.5.1.
The test plan for Test Case No. *Voice_021* is described in Deliverable D1.1v4 – Section 7.5.2.

6.5.3 Specifics of the Test Implementation and Execution

For group communication to be established, all users must subscribe to the same MCPTT Group ID before the communication is initiated. Looking ahead, there is a need to explore how subscriptions to groups will be handled, as the current method involves subscribing to a list of preconfigured groups stored on the cab radio.

In the current system, the initiation of a multi-user call is done through the phonebook since the insertion of the group ID for the FRMCS system has not been implemented yet. To establish dynamic group calls in the future, it is necessary to refer to the relevant standards and determine the procedures for affiliation and utilization of location information.

Additionally, there is no specification defining how the functional identities of all other participants in a group call should be displayed on each participant's terminal.

6.5.4 Results and Observations

The tests were performed successfully, with the following observations and findings:

- The test case results specify that there should be a clear indication on the remaining devices when a user leaves the call. Unfortunately, during the test, there was no indication on either the cab radio or the controller terminal when FRMCS User B left the call. This lack of indication highlights a potential issue that needs to be addressed to ensure proper communication feedback in such scenarios.
- During the *Voice_021* test cases, it was observed that the FRMCS user is unable to hear the voice of the GSM-R 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.

Below, an analysis of recorded KPIs is provided. All recorded data has been taken from drive tests, i.e., with potential intra- and inter-gNB handover situations, which gives realistic conditions for future operations.

<u>MCPTT Access Time (KPI1) Analysis</u>

The evaluation of the MCPTT Access Time has been done jointly for Test Cases No. *Voice_010* and *Voice_021* (CabRadio initiated calls). The recorded KPI1 values of all captured PTT requests have been below the 300 ms limit as defined in Section 6.2 (which requires 95% of all requests below the limit). The mean value of KPI1 is 75 ms.

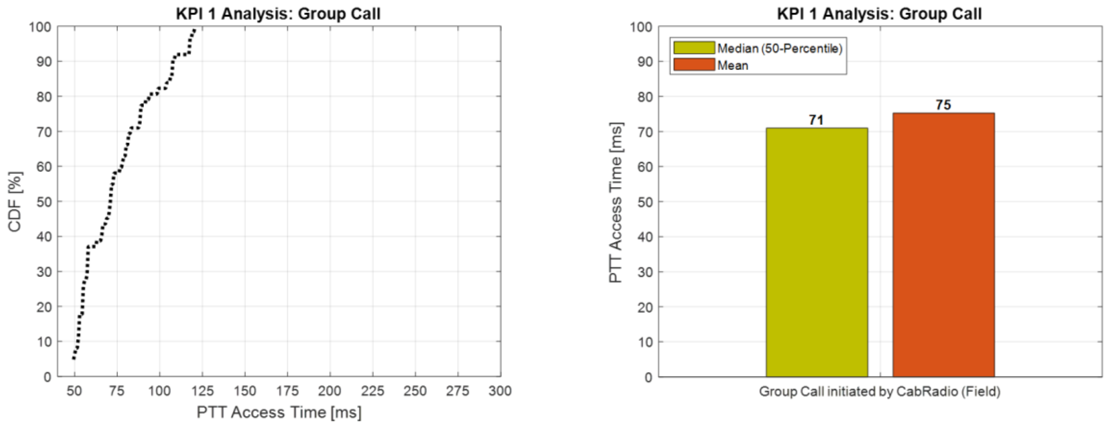


Figure 47: Statistical analysis of PTT Access Times for MCPTT group voice calls (Testbed Germany)

End-to-End MCPTT Access Time (KPI2) Analysis

The evaluation of the End-to-End MCPTT Access Time (which includes call establishment phase) has been done jointly for Test Cases No. *Voice_010* and *Voice_021* (CabRadio initiated calls). The recorded KPI2 values of all captured PTT requests have been below the 1000 ms limit as defined in Section 6.2. The mean value of KPI2 is 678 ms, the maximum value was seen at 814 ms.

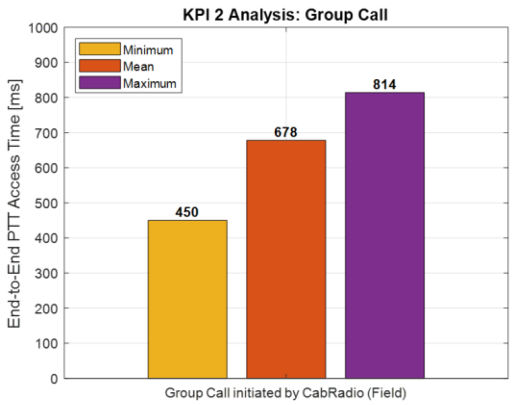


Figure 48: Statistical analysis of End-to-End PTT Access Times for MCPTT group voice calls (Testbed Germany)

Voice Packet Loss Analysis

The evaluation of packet loss rates from the voice application on user plane has been done for both uplink and downlink directions. It shows almost no packet drops during voice communication in downlink and few packet drops in uplink. Note that the 5G radio deployment along the utilized test track was well planned for the purpose of prototype testing but not optimized for official acceptance tests as on real operational lines. It is expected that uplink packet loss rates improve in case of enhanced uplink-oriented deployment optimization.

Packet losses in train-to-ground communications have been assessed from packets of the transmitted uplink streams in Test Cases No. *Voice_010* and *Voice_021*, giving 0.98% loss rate for the considered group calls.

Voice Packet Losses (User Plane) in Uplink – Onboard to Trackside			
	Transmitted Packets	Lost Packets	Packet Loss Rate
Point-to-Point Call	65862	731	1.110%
Group Call	4187	41	0.979%
REC Call	1633	0	0.000%
Total	71682	772	1.077%

Packet losses in ground-to-train communications have been assessed from packets of the received downlink streams in Test Cases No. *Voice_010* and *Voice_021*, giving zero losses for the considered group calls.

Voice Packet Losses (User Plane) in Downlink – Trackside to Onboard			
	Transmitted Packets	Lost Packets	Packet Loss Rate
Point-to-Point Call	63164	12	0.019%
Group Call	2514	0	0.000%
REC Call	6278	3	0.048%
Total	71956	15	0.021%

6.6 REC- Railway emergency calls (Voice_011, Voice_012, Voice_022)

The purpose of the following tests was to demonstrate that a Railway Emergency Call between train drivers and a train controller, responsible for the train movement area, can be established in either direction.

List of considered test cases:

- Railway Emergency Call initiated by a train controller (Dispatcher) without interworking (FRMCS only) *(Voice_011)*
- Railway Emergency Call initiated by a train driver (CabRadio) without interworking (FRMCS only) *(Voice_022)*
- Railway Emergency Call initiated by a train driver (CabRadio) including interworking (FRMCS and GSM-R) *(Voice_012)*

In *Voice_011* and *Voice_022*, the FRMCS system automatically routed the Railway Emergency voice communication to all FRMCS users in the targeted area. Meanwhile, in *Voice_012*, the FRMCS system automatically routed the Railway Emergency voice communication to all users in the targeted area, including GSM-R users.

6.6.1 Detailed Test Architecture

The architectures of the test cases are presented below. The voice application is implemented in the FRMCS network as a tightly coupled application using an MCPTT client embedded in the voice application. The utilized end-to-end building blocks are marked in green.

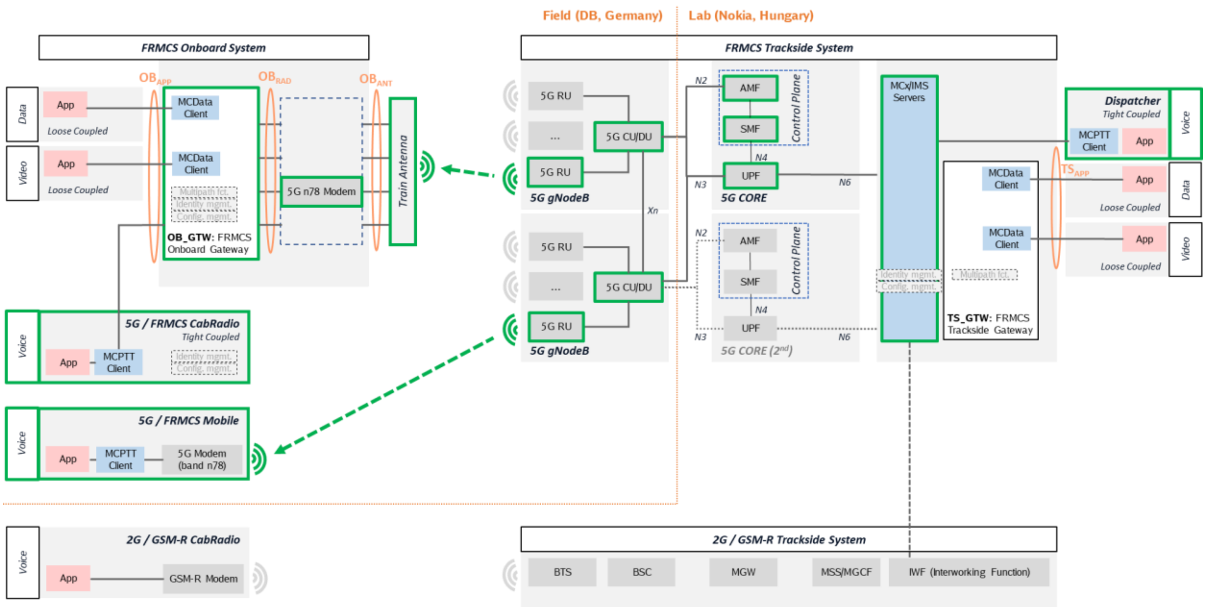


Figure 49: Architecture for test cases Voice_011, Dispatcher initiated (Testbed Germany)

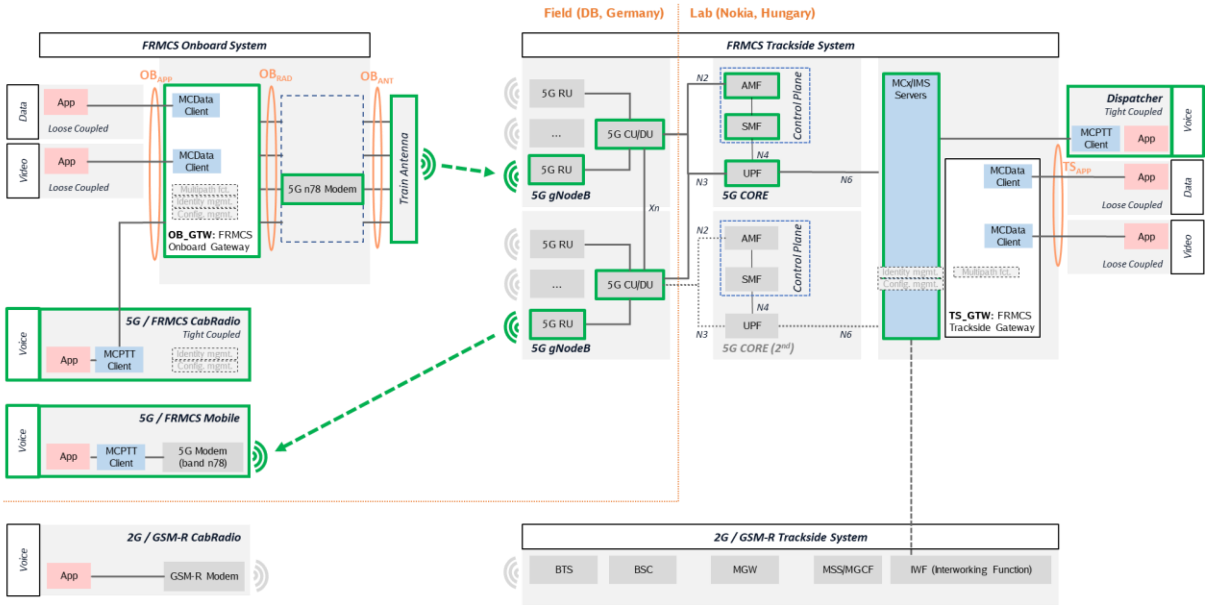


Figure 50: Architecture for test cases Voice_022, CabRadio initiated (Testbed Germany)

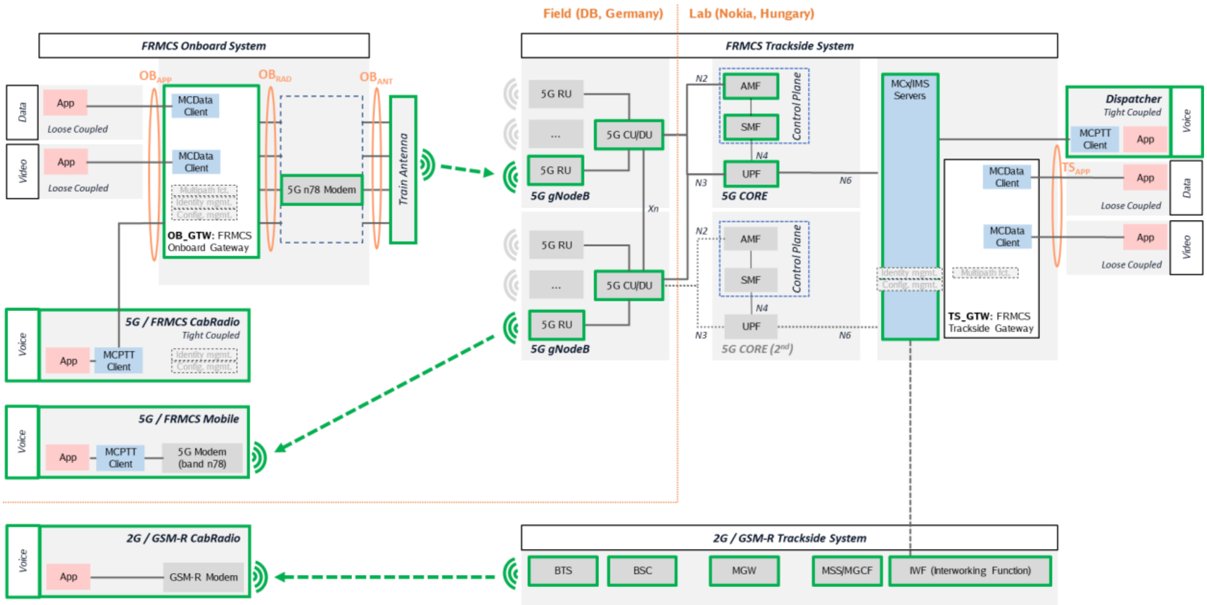


Figure 51: Architecture for test cases Voice_012, CabRadio initiated (Testbed Germany)

6.6.2 Detailed Test Plan

The test plan for Test Case No. *Voice_011* is described in Deliverable D1.1v4 – Section 7.6.1.
The test plan for Test Case No. *Voice_022* is described in Deliverable D1.1v4 – Section 7.6.2.
The test plan for Test Case No. *Voice_012* is described in Deliverable D1.1v4 – Section 7.6.3.

6.6.3 Specifics of the Test Implementation and Execution

For the Railway Emergency Call to be established, all users must subscribe to the same MCPTT Group ID before the communication is initiated. Looking ahead, there is a need to explore how subscriptions to groups will be handled, as the current method involves subscribing to a list of preconfigured groups stored on the cab radio.

The Railway Emergency Call's targeted area is currently simulated on the cab radio by running an MOC journey that simulates a train movement along a track. In the future, the cab radio will send real GPS coordinates to the MCX Server, allowing the server to determine if the cab radio is within the targeted area.

Additionally, there is no specification defining how the functional identities of all other participants in a group call, such as the REC call, should be displayed on each participant's terminal.

6.6.4 Results and Observations

The tests were performed successfully, with the following observations and findings:

- The test cases results specify that there should be a clear indication on the remaining devices when a user leaves the call. Unfortunately, during the test, there was no indication on either the cab radio or the controller terminal when FRMCS User B left the call. This lack of indication highlights a potential issue that needs to be addressed to ensure proper communication feedback in such scenarios.
- During the Voice_012 test cases, it was observed that the FRMCS user is unable to hear the voice of the GSM-R 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.

Below, an analysis of recorded KPIs is provided. All recorded data has been taken from drive tests, i.e., with potential intra- and inter-gNB handover situations, which gives realistic conditions for future operations.

<u>MCPTT Access Time (KPI1) Analysis</u>

The evaluation of the MCPTT Access Time has been done jointly for Test Cases No. *Voice_012* and *Voice_022* (CabRadio initiated calls). The recorded KPI1 values of all but one captured PTT requests have been below the 300 ms limit as defined in Section 6.2 (which requires 99% of all requests below the limit for REC calls). Due to one outlier beyond 300 ms and the small size of the sample set, we fulfilled the KPI1 criterion only with 98%. The mean value of KPI1 is 81 ms.

Higher access times occur likely due to an inter-gNB handover situation or a short coverage gap which leads to increased re-transmission attempts. Note that the 5G radio deployment along the utilized test track was well planned for the purpose of prototype testing but not optimized for official acceptance tests as on real operational lines.

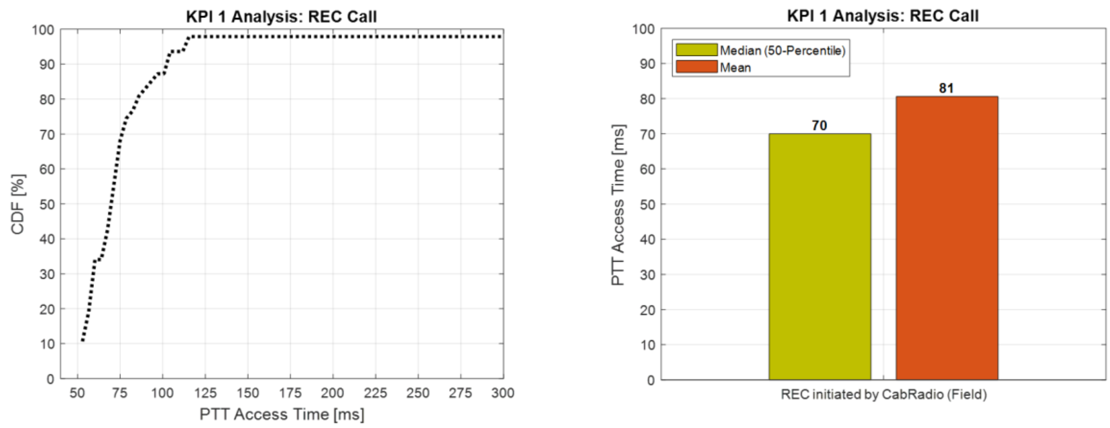


Figure 52: Statistical analysis of PTT Access Times for MCPTT railway emergency calls (Testbed Germany)

<u>End-to-End MCPTT Access Time (KPI2) Analysis</u>

The evaluation of the End-to-End MCPTT Access Time (which includes call establishment phase) has been done jointly for Test Cases No. *Voice_012* and *Voice_022* (CabRadio initiated calls). The recorded KPI2 values of all captured PTT requests have been below the 1000 ms limit as defined in Section 6.2. The mean value of KPI2 is 586 ms in the field trials (as compared to 436 ms in the lab trial conditions of WP3), the maximum value in the field trials was seen at 828 ms.

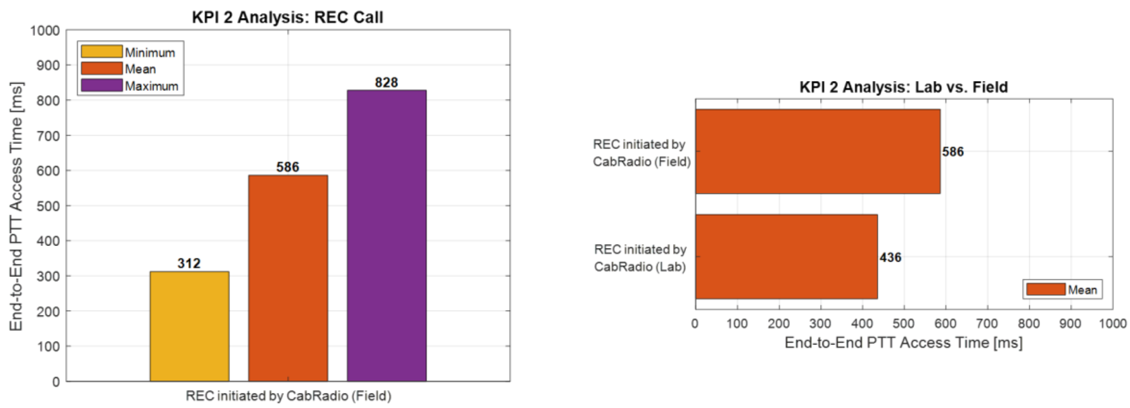


Figure 53: Statistical analysis of End-to-End PTT Access Times for MCPTT railway emergency calls and comparison of field vs. lab performance results (Testbed Germany)

<u>Voice Packet Loss Analysis</u>

The evaluation of packet loss rates from the voice application on user plane has been done for both uplink and downlink directions. It shows almost no packet drops during voice communication in downlink and few packet drops in uplink. Note that the 5G radio deployment along the utilized test track was well planned for the purpose of prototype testing but not optimized for official acceptance tests as on real operational lines. It is expected that uplink packet loss rates improve in case of enhanced uplink-oriented deployment optimization.

Packet losses in train-to-ground communications have been assessed from packets of the transmitted uplink streams in Test Cases No. *Voice_011*, *Voice_012* and *Voice_022*, giving zero losses for the considered REC calls.

Voice Packet Losses (User Plane) in Uplink – Onboard to Trackside			
	Transmitted Packets	Lost Packets	Packet Loss Rate
Point-to-Point Call	65862	731	1.110%
Group Call	4187	41	0.979%
REC Call	1633	0	0.000%
Total	71682	772	1.077%

Packet losses in ground-to-train communications have been assessed from packets of the received downlink streams in Test Cases No. *Voice_011*, *Voice_012* and *Voice_022*, giving 0.05% loss rate for the considered REC calls.

Voice Packet Losses (User Plane) in Downlink – Trackside to Onboard			
	Transmitted Packets	Lost Packets	Packet Loss Rate
Point-to-Point Call	63164	12	0.019%
Group Call	2514	0	0.000%
REC Call	6278	3	0.048%
Total	71956	15	0.021%

6.7 Combined Voice Calls (using MCPTT) and Video Uplink (using MCDATA) (Voice_017)

The purpose of this test was to demonstrate the FRMCS system behaviour while simultaneously using two applications, each requesting different MCX services – specifically, the MCPTT service for the voice application and the MCData service for the data application. The expected outcome of this test case was that each application maintains the standalone performance.

The combined scenario encompasses a MCPTT point-to-point call from driver (CabRadio) to controller (Dispatcher) and an onboard to trackside MCData communication, using MCData IPCon. The latter one has been chosen to be a live video streaming application from Teleste that uses uplink resources of the 5G TDD band n78, see also Chapter 8.

The associated test case is:

- Combined MCPTT private point-to-point voice call in parallel with MCData application (*Voice_017*)

6.7.1 Detailed Test Architecture

The architecture of the test case is presented below. The live video service is implemented in the FRMCS network as a loose coupled application using an MCData client, which is realized in the FRMCS Onboard Gateway (TOBA box) and FRMCS Trackside Gateway. The voice application is implemented in the FRMCS network as a tightly coupled application using an MCPTT client embedded in the voice application. The utilized end-to-end building blocks are marked in green.

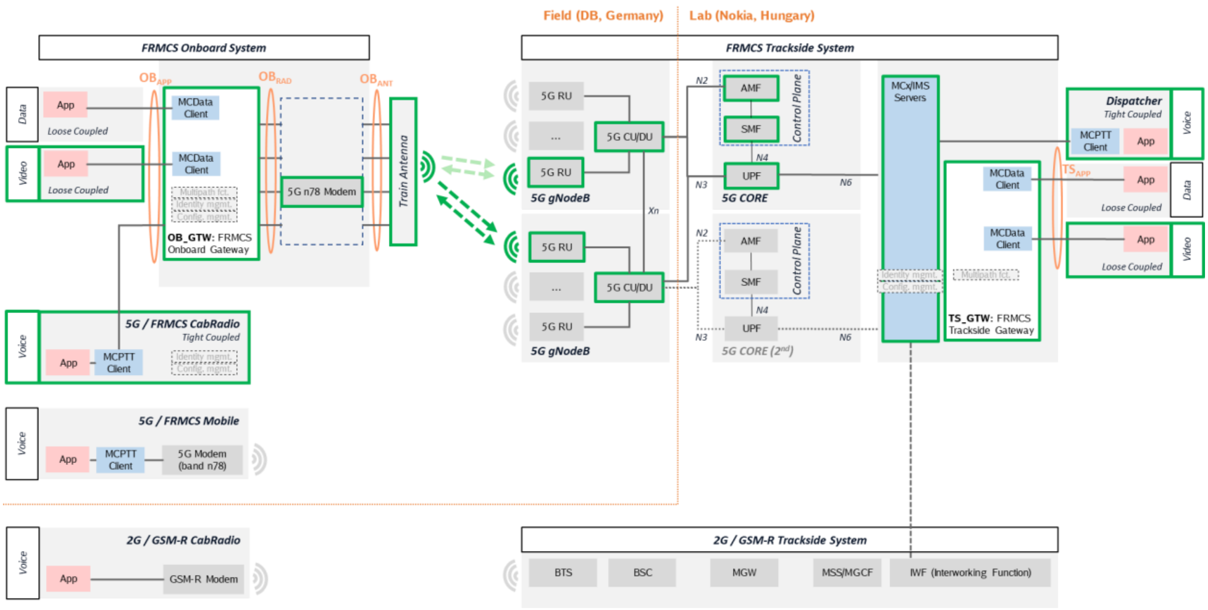


Figure 54: Architecture for test cases Voice_017 (Testbed Germany)

6.7.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 7.8.

6.7.3 Specifics of the Test Implementation and Execution

See Section 6.4 for the implementation specifics of the point-to-point voice service.

The MCPTT-based voice application was configured as GBR service with 5QI=2 while the MCData-based video application was configured as non-GBR service with 5QI=7. [7] In such conditions the QoS, prioritization and radio resource management schemes will prioritize the voice application, as the most critical one, over the video application if needed.

6.7.4 Results and Observations

The test was performed successfully, with the following observations and findings:

- Both applications maintained a good performance.
- Voice communication between the users was established within the setup time, with clear and loud voice quality in either direction. The communication was maintained without drops and with good quality, even in mobility conditions.
- In stationary tests, the video view and object move within the view was smooth, no major jerks or picture blinking, the trackside video management system indicated around 20-25 fps on the display overlay. This means the quality of the video was very good, see Chapter 8. In driving conditions, due to changing coverage conditions, the video frame rate was lower giving degraded but still acceptable video quality.

7 ETCS and TCMS Tests (using MCDATA) – Testbed Germany

The following chapter gives a report about ETCS & TCMS tests that have been performed with the application provider CAF in the 5GRAIL Testbed Germany, operated at 5G band n78. All tests have been performed in Calendar Week 21 of 2023.

For the tests the QoS parameter 5QI was configured as 5QI=5 (ETCS) and 5QI=9 (TCMS), both using non-guaranteed bitrate (non-GBR) class. As agreed in WP1 the filtering for the different QoS classes is done by the DSCP marking received from the application settings. [7]

The tests have been supported by DB Netz AG (providing the track and rolling stock infrastructure), by Kontron (providing the onboard connectivity using FRMCS TOBA-K gateway and 5G modem plus FRMCS trackside gateway) and by Nokia (providing the 5G SA trackside network and MCX trackside server). MCX clients were provided by Kontron for MCData in onboard and trackside gateways.

The pictures below show some impressions of the tests:

7.1 List of Functional Test Cases

In total, three groups of application tests as specified in [2] have been successfully conducted. These are:

- **ETCS simulation between onboard EVC and trackside RBC**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
7.4	ETCS_WP3-WP5_TC_001	Nominal communication between ETCS on board application and RBC [static]
7.4	ETCS_WP3-WP5_TC_005	Nominal communication between ETCS on board application and RBC, including BTS handover (same 5G network) [dynamic]
7.4	ETCS_WP3-WP5_TC_003	Increased data transferred in the ETCS communication [static & dynamic]

- **Combined ETCS and TCMS simulations with prioritization regime**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
7.5	ETCS_WP3-WP5_TC_004	ETCS onboard combined with other data application [static & dynamic]

- **TCMS simulation between onboard MCG and trackside GCG**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
7.6	TCMS_TC_001 (TC_001a)	Nominal communication between MCG on board application and GCG [static]
7.6	TCMS_TC_001 (TC_001b)	Nominal communication between MCG on board application and GCG, including BTS handover (same 5G network) [dynamic]

All tests have been performed both in static conditions, i.e., at a fixed location in the tracks of a railway station, and in dynamic conditions, i.e., during train runs in the 5GRAIL Testbed Germany between the stations of *Scheibenberg Bf.* and *Markersbach Bf.* During the dynamic tests, the application continuity within intra- and inter-gNB handover situations has been tested.

7.2 ETCS Prototypes Architecture

Both ETCS and TCMS applications have been provided and implemented as simulations using an onboard and trackside simulator.

The architecture that was designed for the ETCS simulator in the 5GRAIL project was composed by EVC and RBC simulators. The simulators include the full protocol stack defined in the Subset 037 standard [22] and were adapted to support the Obapp interface. Each application (EVC and RBC) is able to generate packets based on patterns that can be configured before executing the test case. The configuration is composed by the duration (in time) of the simulation, the size of the packets and the packets to be sent per second. The ability to configure any pattern helps to "simulate" future increase of data in the ETCS applications, as well as to better probe the quality of the network. A constant bitrate was configured to identify possible coverage lack within the track.

The diagram in Figure 56 represents the protocol stack of the ETCS application. The rectangles in orange are the blocks that are shared between all technologies (GSM-R, GPRS, FRMCS). The blocks in grey are the ones only aplicable for the circuit-switched technology GSM-R. The blocks in blue represent the protocols that are shared between the packet-switched technologies GPRS and FRMCS. Blocks in green represent the protocols for FRMCS only. As the diagram shows, the main changes comes from the control plane between the application and the FRMCS Gateway (Obapp/websocket) and from the implementation and integration of the Ethernet protocol.

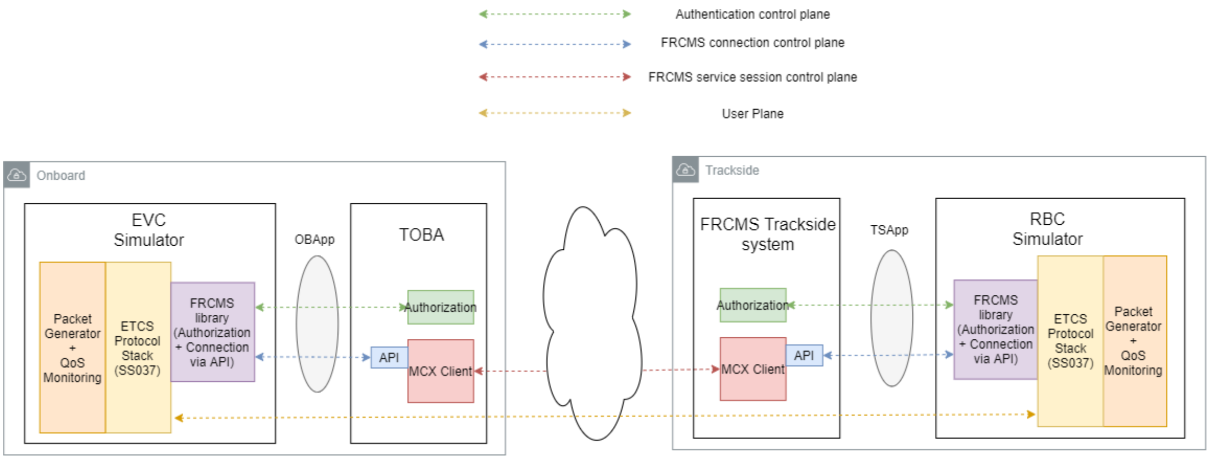


Figure 55: ETCS prototype architecture (provided by CAF)

Figure 56: Evolution of the ETCS protocol stack for FRMCS.

7.3 TCMS Prototypes Architecture

TCMS follows a similar approach as the one presented for ETCS: Simulating traffic information from the train to the ground, following current standards and data protocols such as train communication network (TCN) data following IEC 61375 [33].

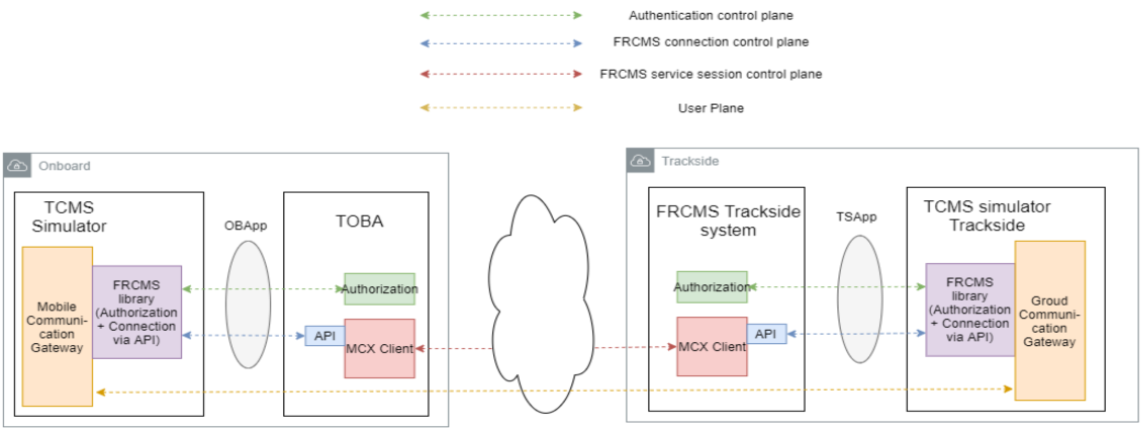


Figure 57: TCMS prototype architecture (provided by CAF)

7.4 ETCS simulation between onboard EVC and trackside RBC (ETCS_WP3-WP5_TC_001, ETCS_WP3-WP5_TC_003, ETCS_WP3-WP5_TC_005)

The following section provides results from stationary and dynamic (drive) tests with an ETCS application that was implemented using an onboard and trackside simulator. The purpose was to demonstrate that the data communication will be maintained without drops and with good quality, even in mobility conditions. The usual nominal data transfer rate for ETCS simulations was set to 2.7 kbit/s. Another test case with increased data transfer for ETCS simulations has been performed with a data rate of 5 kbit/s.

List of considered test cases:

- Nominal communication between ETCS on board application and RBC [static] *(ETCS_WP3-WP5_TC_001)*
- Nominal communication between ETCS on board application and RBC, including BTS handover (same 5G network) [dynamic] *(ETCS_WP3-WP5_TC_005)*
- Increased data transferred in the ETCS communication [static & dynamic] *(ETCS_WP3-WP5_TC_003)*

7.4.1 Detailed Test Architecture

The architectures of the test cases are presented below. The ETCS application is implemented in the FRCMS network as a loose coupled application using a MCData client embedded in the FRMCS Onboard Gateway (TOBA box) and FRMCS Trackside Gateway. Static (stationary) mode involves only one cell of the 5G radio access network in the German field while dynamic (drive) test mode involves intra- and inter-gNB handover situations over multiple cells. The utilized end-to-end building blocks are marked in green.

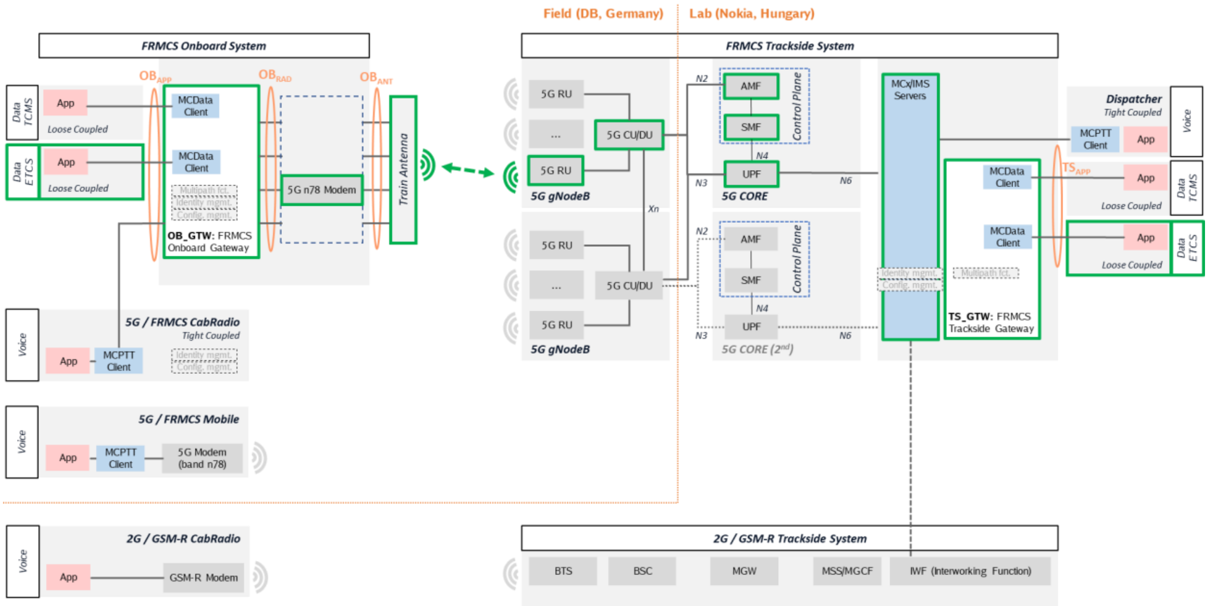


Figure 58: Architecture for test case ETCS_WP3-WP5_TC_001 (Testbed Germany)

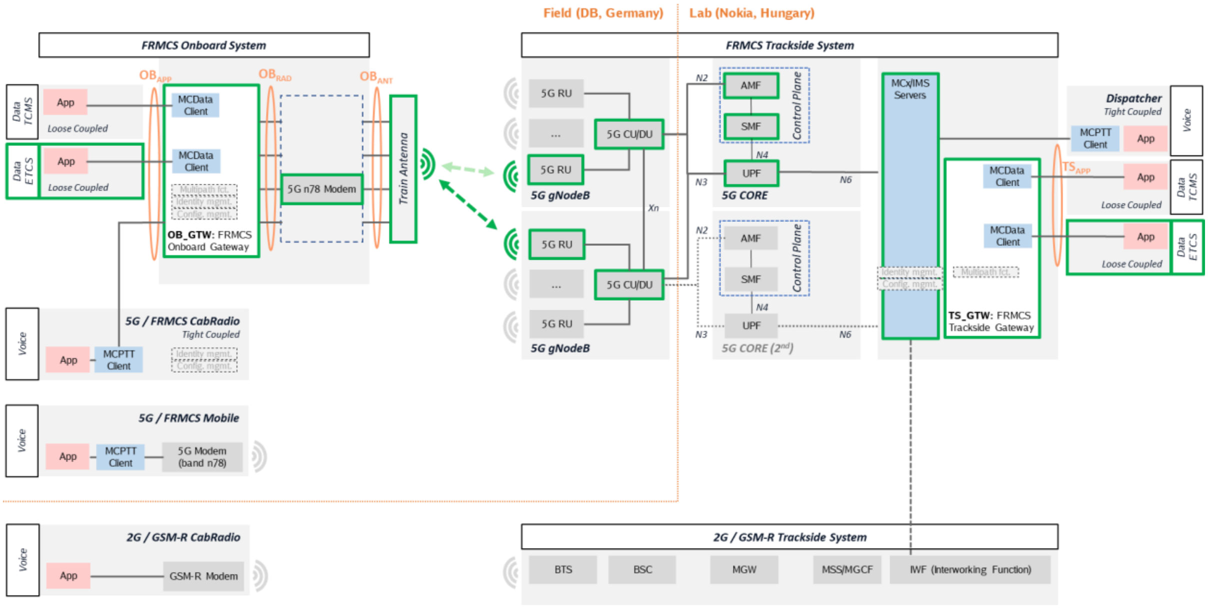


Figure 59: Architecture for test case ETCS_WP3-WP5_TC_005, with intra- and inter-gNodeB handover (Testbed Germany)

7.4.2 Detailed Test Plan

The test plan for Test Case No. *ETCS_WP3-WP5_TC_001* is described in Deliverable D1.1v4 – Section 8.1.1.3.
The test plan for Test Case No. *ETCS_WP3-WP5_TC_005* is described in Deliverable D1.1v4 – Section 8.1.1.4.
The test plan for Test Case No. *ETCS_WP3-WP5_TC_003* is described in Deliverable D1.1v4 – Section 8.1.3.

7.4.3 Specifics of the Test Implementation and Execution

From integration perspective, a delay between the OBapp registration response and the session start command have been implemented in the application side to avoid the FRMCS GW to get stuck in trying state (see deliverable D2.4 for more detailed description about the specification issue).

Wireshark traces have been obtained on the OBU as well as the RBC. The KPIs have been derived analyzing the TCP performance on wireshark.

Note: The round trip average time value have been derived from the TCP acknowledgements, to minimize the processing times of the applications (on-board and trackside). However, there is still a processing delay from the applications inherent in this value. Therefore, it can be assumed that the real RTT is lower than the value monitored in the application side. The processing time is normally between 40 to 55 ms on the application side.

7.4.4 Results and Observations (usual data transfer rate of 2.7 kbit/s)

The tests were performed successfully, with the following observations and findings:

Static test results: From performance perspective, it can be observed that the communication is very stable. The round-trip-time stays always below 120 ms. Compared to the lab test, a slight increase of about 10 ms in the RTT can be observed on the onboard side. This delay might come from the leased line link between the field test location in Germany and the trackside application location in Hungary.

Dynamic test results: From performance perspective, an increment of about 20 ms can be observed in the RTT compared to static or lab values. The figures show that there was an specific frame of time during the test where the radio conditions were degraded (low coverage or interferences), but still the application was able to handle it.

<u>Analysis of Onboard Traces (Static Tests)</u>

Nominal_Static_EVC.pcapng: Traces captured in the On-Board application

- Number Packets sent: 591
- Number Packets received: 591
- Number of retransmitted packets: 0
- Average sent data rate: 2677 bits/s
- Average received data rate: 2677 bits/s
- Average round trip time: 91,5 ms

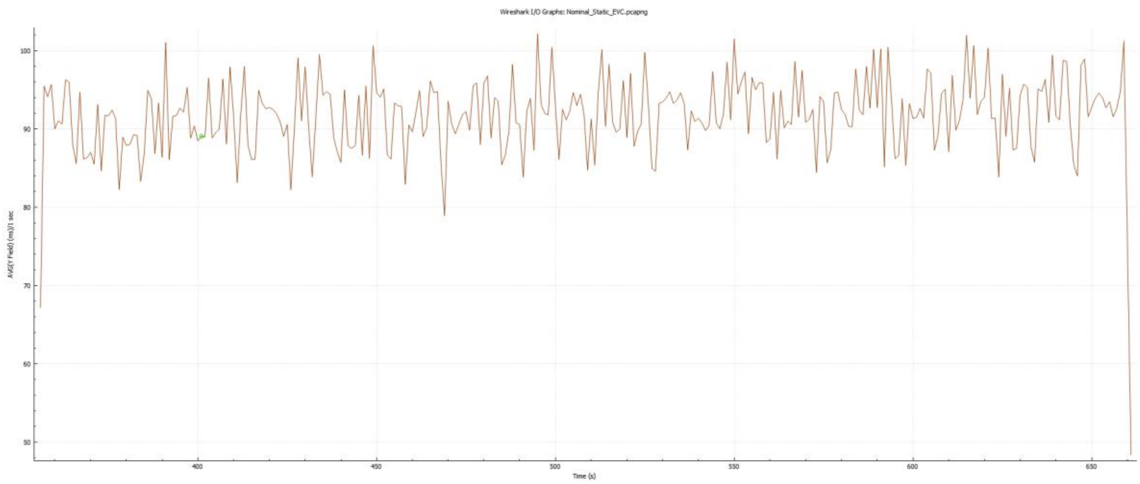


Figure 60: RTT for ETCS Static Tests, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_001 (Testbed Germany)

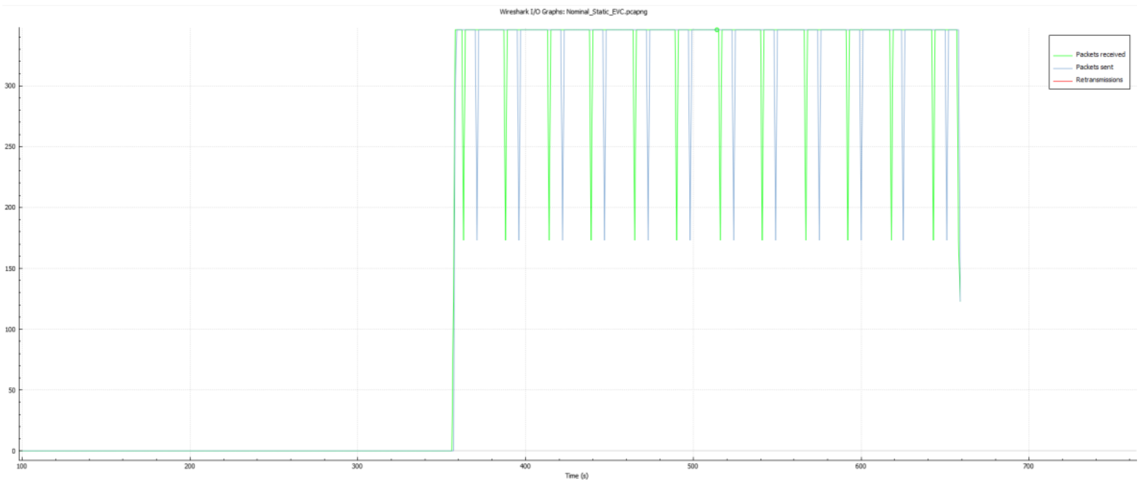


Figure 61: Packet Information (Sent/Received/Retransmissions) for ETCS Static Tests, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_001 (Testbed Germany)

<u>Analysis of Trackside Traces (Static Tests)</u>

Nominal_Static_RBC.pcapng: Traces captured in the Trackside application

- Number Packets sent: 591
- Number Packets received: 591
- Number of retransmitted packets: 0
- Average sent data rate: 2677 bits/s
- Average received data rate: 2677 bits/s
- Average round trip time: 89,1 ms

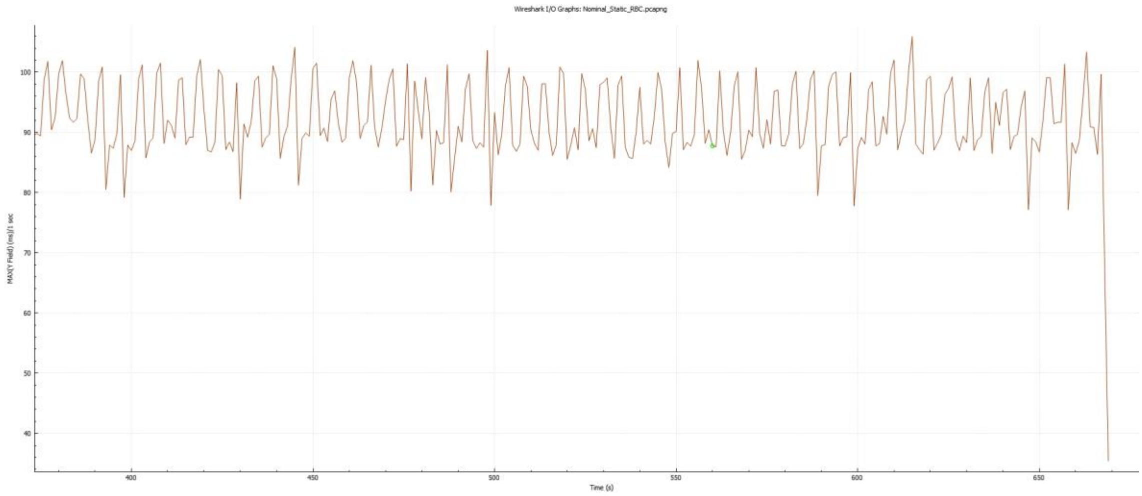


Figure 62: RTT for ETCS Static Tests, captured in trackside traces (RBC),
Test Case No. ETCS_WP3-WP5_TC_001 (Testbed Germany)

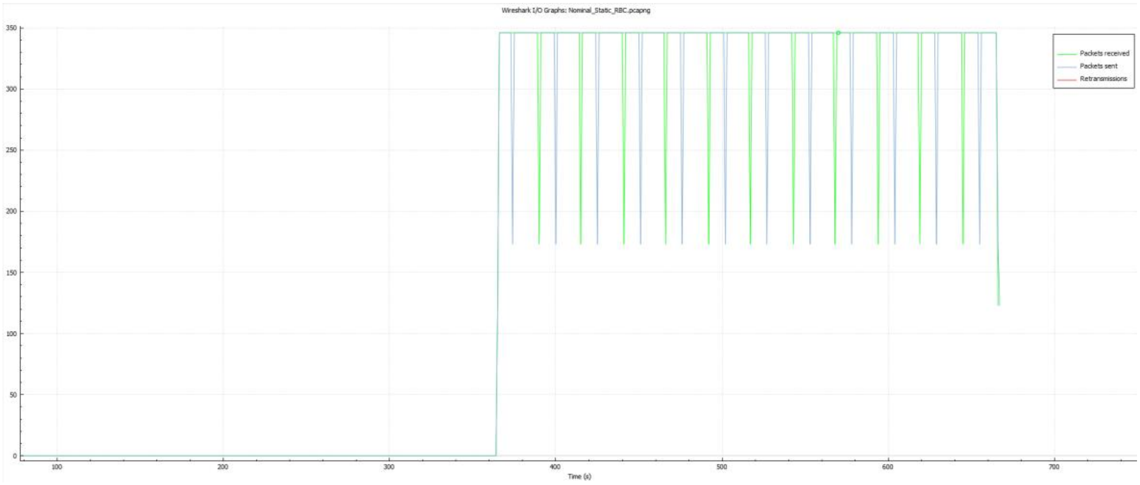


Figure 63: Packet Information (Sent/Received/Retransmissions) for ETCS Static Tests, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_001 (Testbed Germany)

<u>Analysis of Onboard Traces (Dynamic Tests)</u>

Nominal_Dynamic_EVC.pcapng: Traces captured in the On-Board application

- Number Packets sent: 591
- Number Packets received: 593
- Number of retransmitted packets: 0
- Average sent data rate: 2693 bits/s
- Average received data rate: 2692 bits/s
- Average round trip time: 111,2 ms

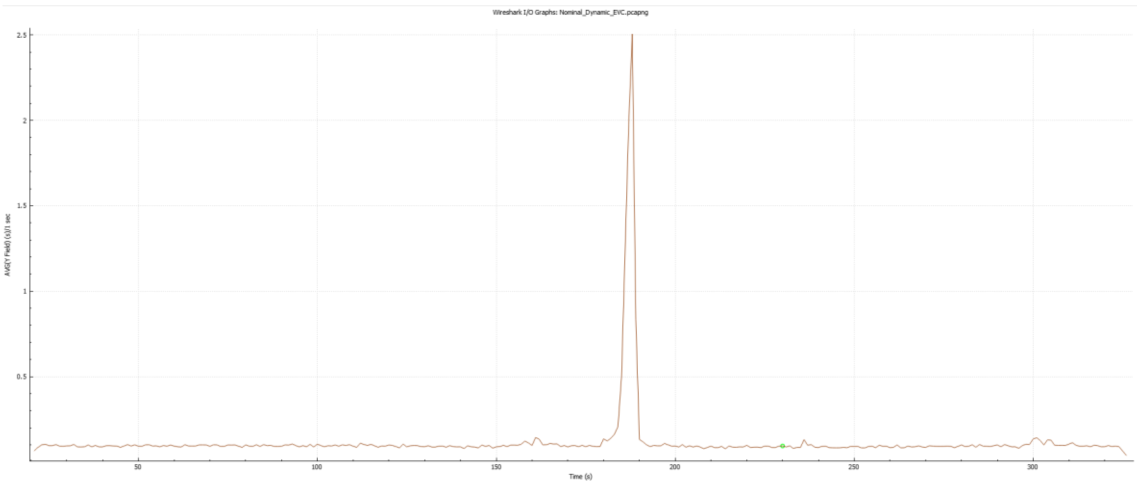


Figure 64: RTT for ETCS Dynamic Tests, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_005 (Testbed Germany)

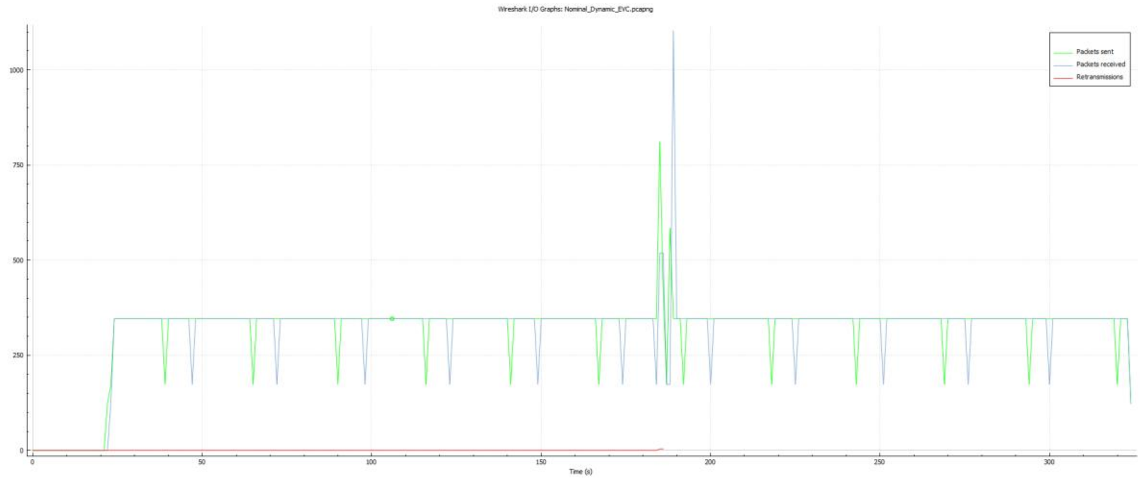


Figure 65: Packet Information (Sent/Received/Retransmissions) for ETCS Dynamic Tests, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_005 (Testbed Germany)

<u>Analysis of Trackside Traces (Dynamic Tests)</u>

TC05_RBC.pcapng: Traces captured in the Trackside application

- Number Packets sent: 591
- Number Packets received: 591
- Number of retransmitted packets: 2
- Average sent data rate: 2692 bits/s
- Average received data rate: 2693 bits/s
- Average round trip time: 98,7 ms

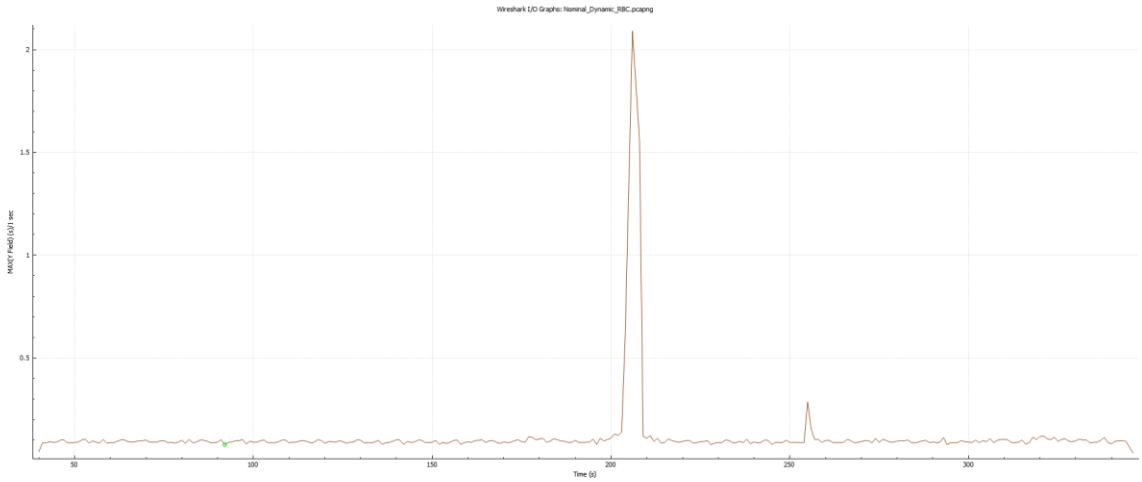


Figure 66: RTT for ETCS Dynamic Tests, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_005 (Testbed Germany)

Figure 67: Packet Information (Sent/Received/Retransmissions) for ETCS Dynamic Tests, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_005 (Testbed Germany)

7.4.5 Results and Observations (increased data transfer rate of 5 kbit/s)

The tests were performed successfully, with the following observations and findings:

Static test results: From performance perspective, it can be observed that the communication is as stable as the performance observed in the lab tests. The RTT is always below 110 ms and the data rate is constant.

Dynamic test results: From performance perspective, it can be observed that there is an increase of delay in a concrete point of the track, but no retransmission was required from application, so the performance of the overall test was as expected.

Analysis of Onboard Traces (Static Tests)

Increased_Static_EVC.pcapng: Traces captured in the On-Board application

- Number Packets sent: 591
- Number Packets received: 591
- Number of retransmitted packets: 0
- Average sent data rate: 4991 bits/s
- Average received data rate: 4991 bits/s
- Average round trip time: 86,7 ms

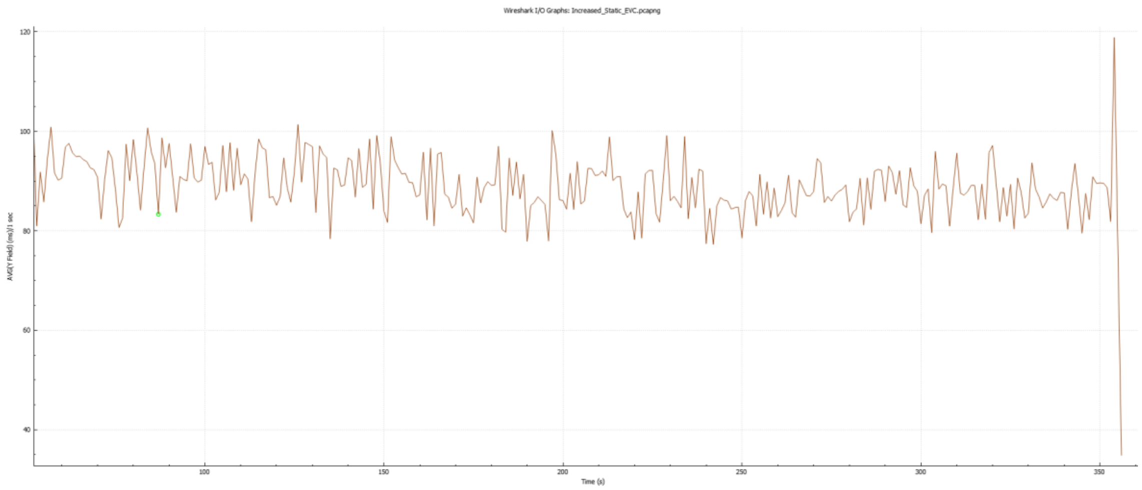


Figure 68: RTT for ETCS Static Tests with increased traffic, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_003 (Testbed Germany)

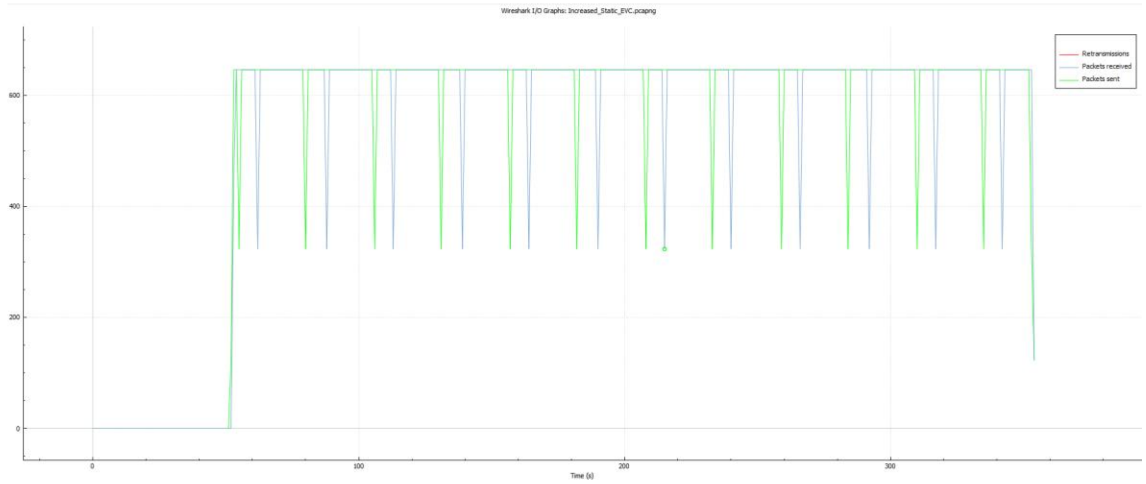


Figure 69: Packet Information (Sent/Received/Retransmissions) for ETCS Static Tests with increased traffic, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_003 (Testbed Germany)

<ins>Analysis of Trackside Traces (Static Tests)</ins>

Increased_Static_RBC.pcapng: Traces captured in the Trackside application

- Number Packets sent: 591
- Number Packets received: 591
- Number of retransmitted packets: 0
- Average sent data rate: 4992 bits/s
- Average received data rate: 4992 bits/s
- Average round trip time: 89,1 ms

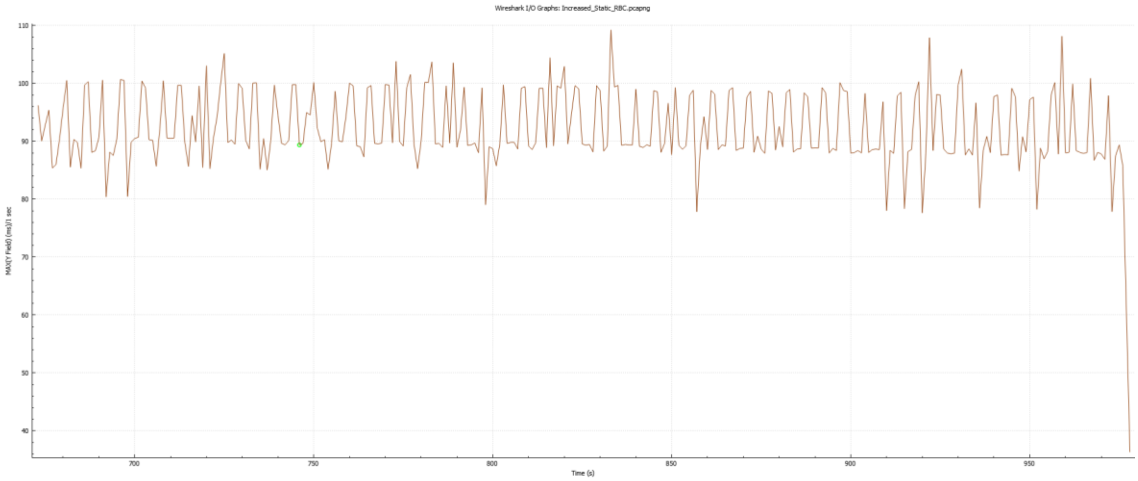


Figure 70: RTT for ETCS Static Tests with increased traffic, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_003 (Testbed Germany)

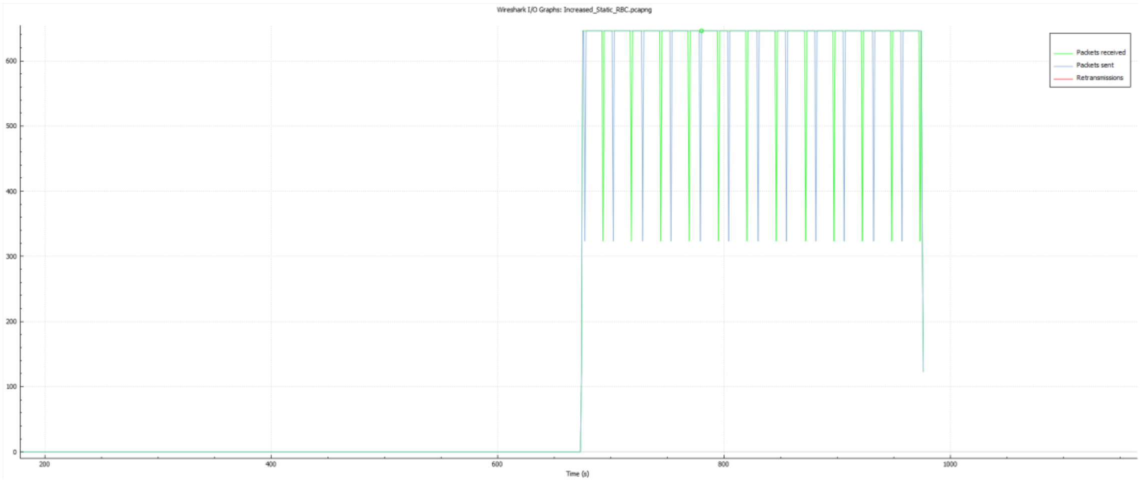


Figure 71: Packet Information (Sent/Received/Retransmissions) for ETCS Static Tests with increased traffic, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_003 (Testbed Germany)

<u>Analysis of Onboard Traces (Dynamic Tests)</u>

Increased_Dynamic_EVC.pcapng: Traces captured in the On-Board application

- Number Packets sent: 591
- Number Packets received: 591
- Number of retransmitted packets: 0
- Average sent data rate: 4993 bits/s
- Average received data rate: 4993 bits/s
- Average round trip time: 92,4 ms

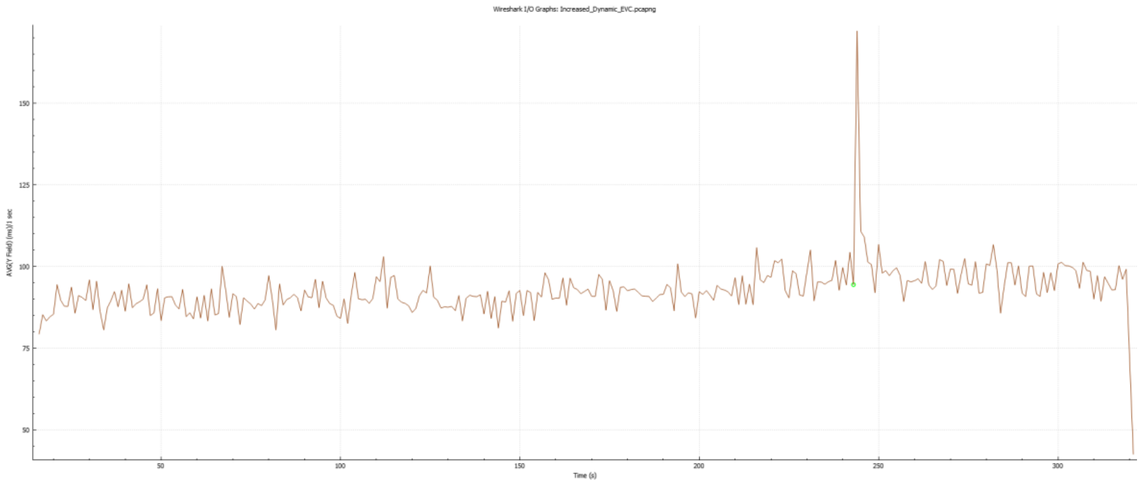


Figure 72: RTT for ETCS Dynamic Tests with increased traffic, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_003 (Testbed Germany)

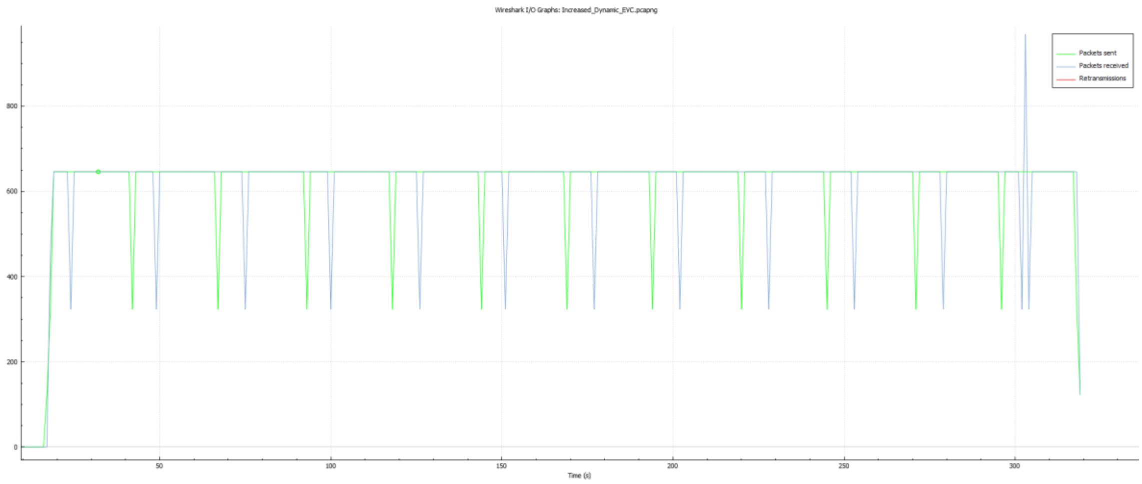


Figure 73: Packet Information (Sent/Received/Retransmissions) for ETCS Dynamic Tests with increased traffic, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_003 (Testbed Germany)

<u>Analysis of Trackside Traces (Dynamic Tests)</u>

Increased_Dynamic_RBC.pcapng: Traces captured in the Trackside application

- Number Packets sent: 591
- Number Packets received: 591
- Number of retransmitted packets: 0
- Average sent data rate: 4994 bits/s
- Average received data rate: 4994 bits/s
- Average round trip time: 89,6 ms

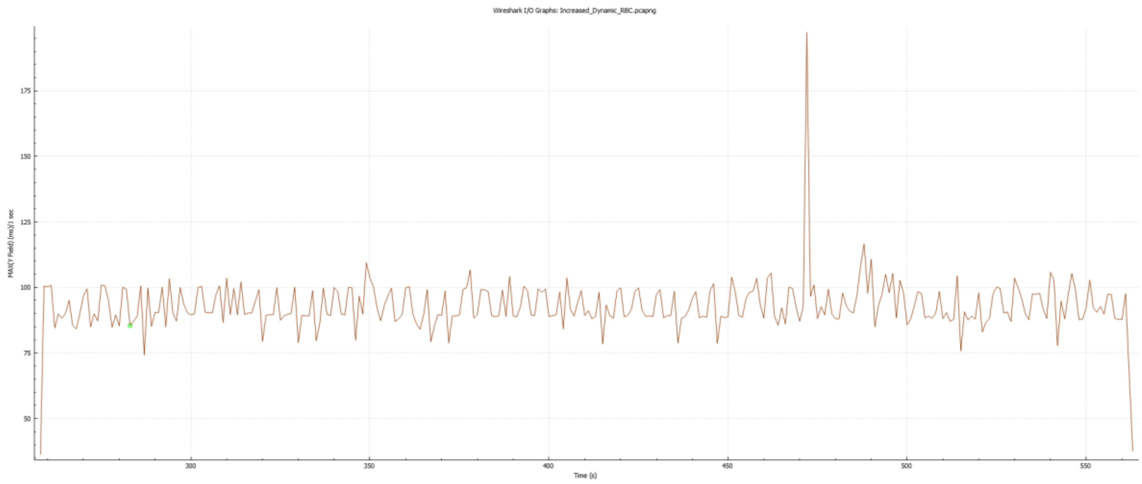


Figure 74: RTT for ETCS Dynamic Tests with increased traffic, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_003 (Testbed Germany)

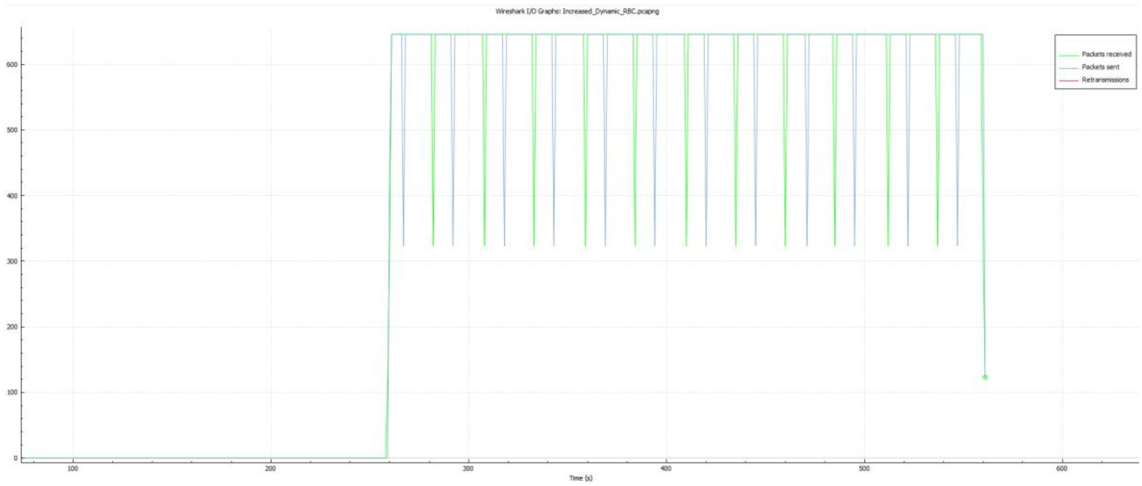


Figure 75: Packet Information (Sent/Received/Retransmissions) for ETCS Dynamic Tests with increased traffic, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_003 (Testbed Germany)

7.5 Combined ETCS and TCMS simulations (ETCS_WP3-WP5_TC_004)

The combined test case has been performed with data transfers of an ETCS simulation and of a TCMS simulation running in parallel. Due to the criticality of the ETCS application, it has to be transmitted with higher priority than the TCMS application in order not to be affected by parallel data streams. The purpose of the test case was to maintain the ETCS (and TCMS) data communication without drops and with good quality, even in mobility conditions.

The associated test case is:

- ETCS onboard combined with other data application [static & dynamic] *(ETCS_WP3-WP5_TC_004)*

7.5.1 Detailed Test Architecture

The architecture of the test case is presented below. Both ETCS and TCMS applications are implemented as loose coupled applications using a MCData client embedded in the FRMCS Onboard Gateway (TOBA box) and FRMCS Trackside Gateway. Static (stationary) mode involves only one cell of the 5G radio access network in the German field while dynamic (drive) test mode involves intra- and inter-gNB handover situations over multiple cells. The utilized end-to-end building blocks are marked in green.

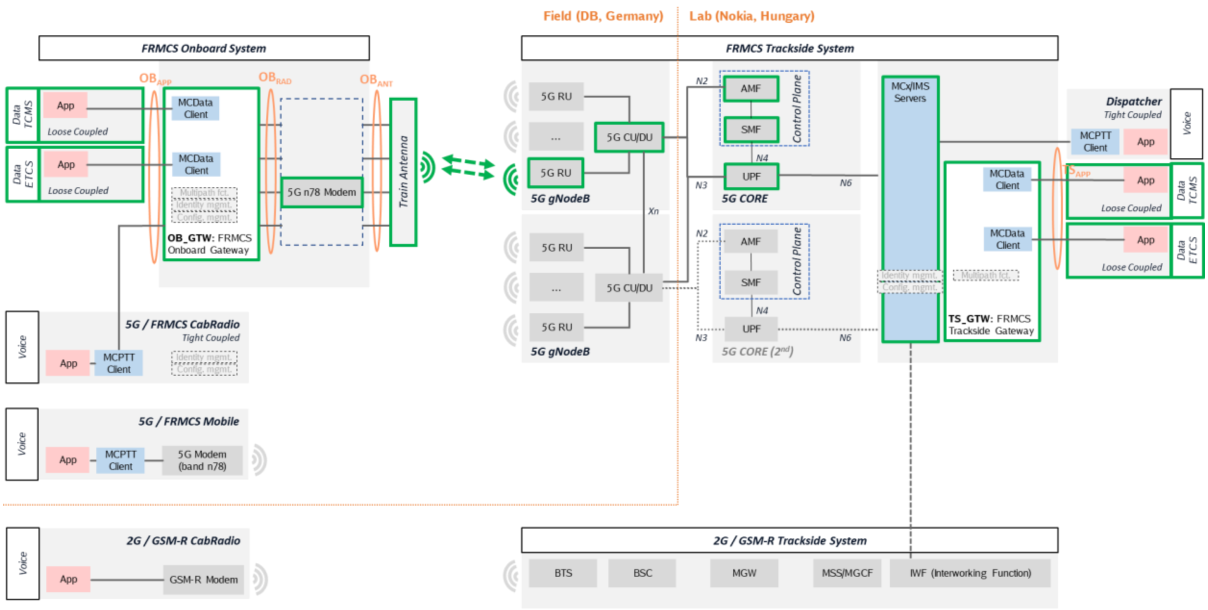


Figure 76: Architecture for test case ETCS_WP3-WP5_TC_004 (Testbed Germany)

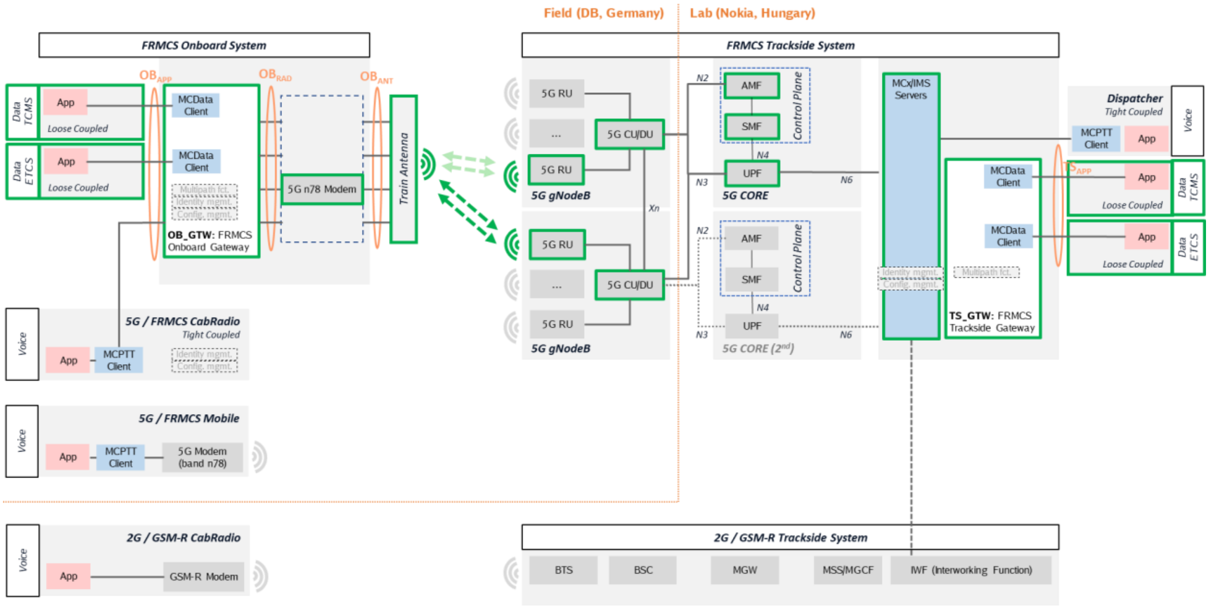


Figure 77: Architecture for test case ETCS_WP3-WP5_TC_004, with intra- and inter-gNodeB handover (Testbed Germany)

7.5.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.1.4.

7.5.3 Specifics of the Test Implementation and Execution

From integration perspective, a delay between the OBapp registration response and the session start command have been implemented in the aplication side to avoid the FRMCS GW to get stuck in trying state (see deliverable D2.4 for more detailed description about the specification issue).

Wireshark traces have been obtained on the OBU as well as the RBC. The KPIs have been derived analyzing the TCP performance on wireshark.

Note: The round trip average time value have been derived from the TCP acknowledgements, to minimize the processing times of the applications (on-board and trackside). However, there is still a processing delay from the applications inherent in this value. Therefore, it can be assumed that the real RTT is lower than the value monitored in the application side. The processing time is normally between 40 to 55 ms on the application side.

7.5.4 Results and Observations

The test was performed successfully, with the following observations and findings:

Static test results: From performance perspective, it can be observed that the communication is as stable as the nominal test case in the lab, very low RTT and constant data rate.

Dynamic test results: From performance perspective, the RTT and data rate values were good until the coverage was lost and the modem lost registration. At this point, the test was ended with about 5 minutes of execution. The coverage loss was due to some coverage outage areas within the track.

<u>Analysis of Onboard Traces (Static Tests)</u>

Combined_Static_EVC.pcapng: Traces captured in the On-Board application

- Number Packets sent: 1179
- Number Packets received: 1179
- Number of retransmitted packets: 0
- Average sent data rate: 2694 bits/s
- Average received data rate: 2694 bits/s
- Average round trip time: 89,7 ms

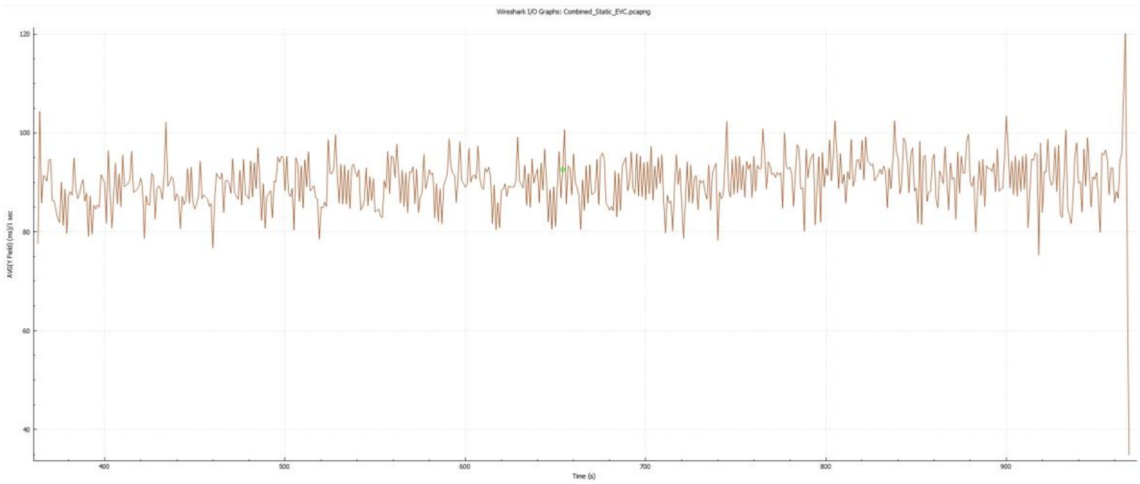


Figure 78: RTT for ETCS in Combined Application Static Tests, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_004 (Testbed Germany)

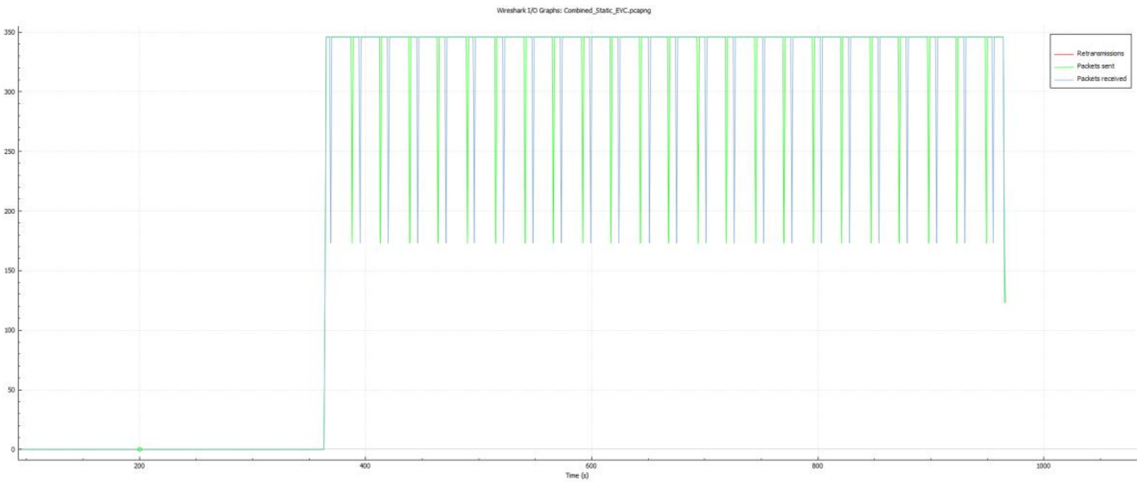


Figure 79: Packet Information (Sent/Received/Retransmissions) for ETCS in Combined Application Static Tests, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_004 (Testbed Germany)

<u>Analysis of Trackside Traces (Static Tests)</u>

Combined_Static_RBC.pcapng: Traces captured in the Trackside application

- Number Packets sent: 1179
- Number Packets received: 1179
- Number of retransmitted packets: 0
- Average sent data rate: 2694 bits/s
- Average received data rate: 2694 bits/s
- Average round trip time: 87,9 ms

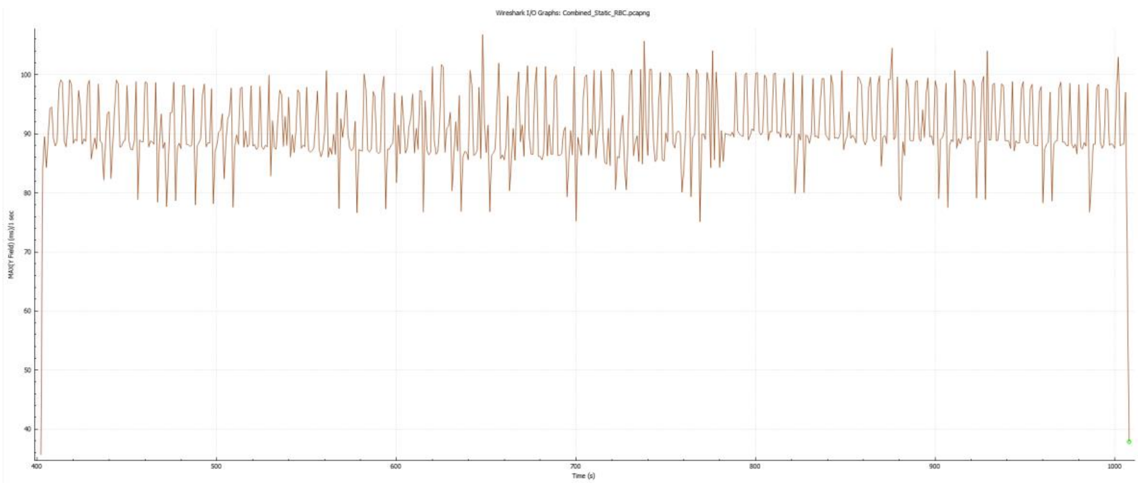


Figure 80: RTT for ETCS in Combined Application Static Tests, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_004 (Testbed Germany)

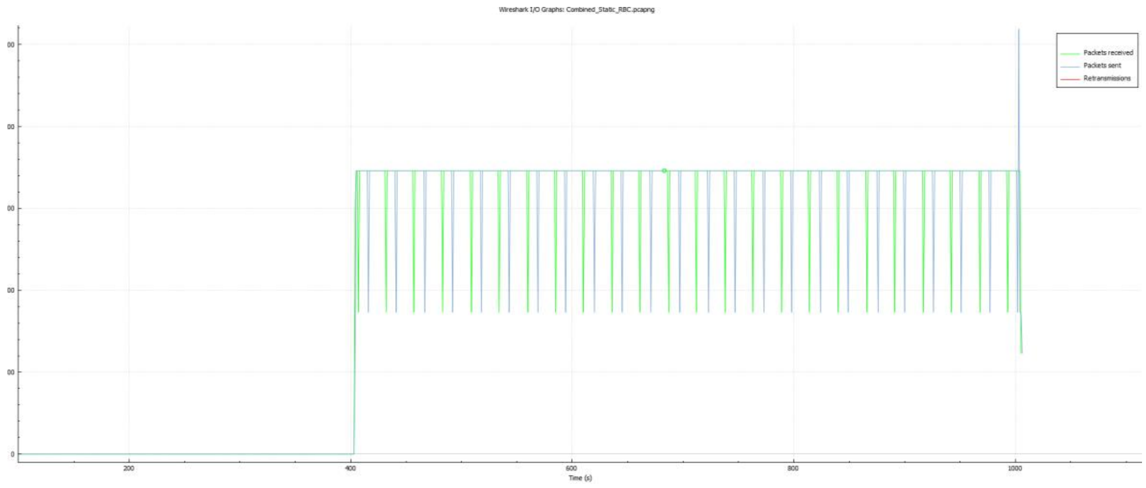


Figure 81: Packet Information (Sent/Received/Retransmissions) for ETCS in Combined Application Static Tests, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_004 (Testbed Germany)

<u>Analysis of Onboard Traces (Dynamic Tests)</u>

Combined_Dynamic_EVC.pcapng: Traces captured in the On-Board application

- Number Packets sent: 579
- Number Packets received: 560
- Number of retransmitted packets: 14
- Average sent data rate: 1816 bits/s
- Average received data rate: 1628 bits/s
- Average round trip time: 103,0 ms

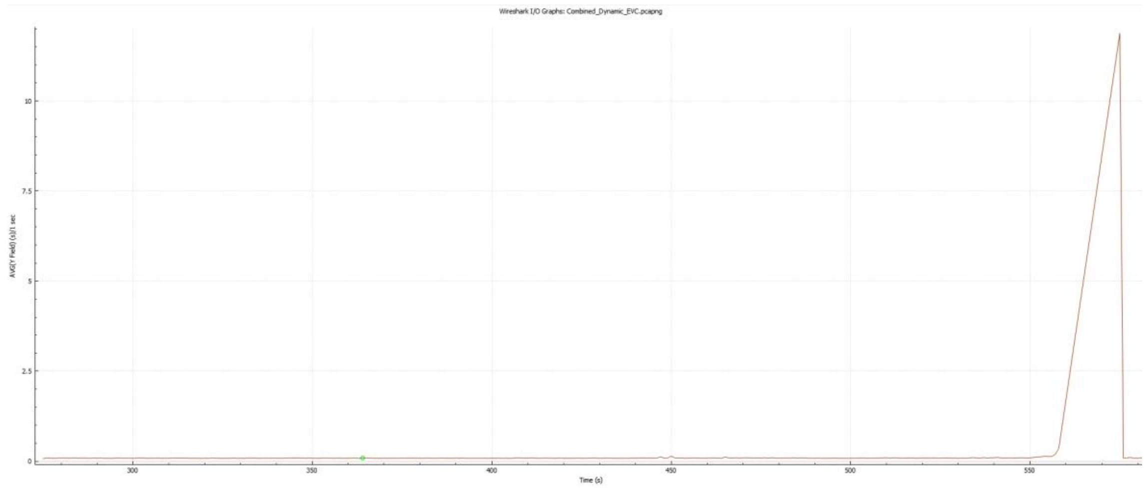


Figure 82: RTT for ETCS in Combined Application Dynamic Tests, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_004 (Testbed Germany)

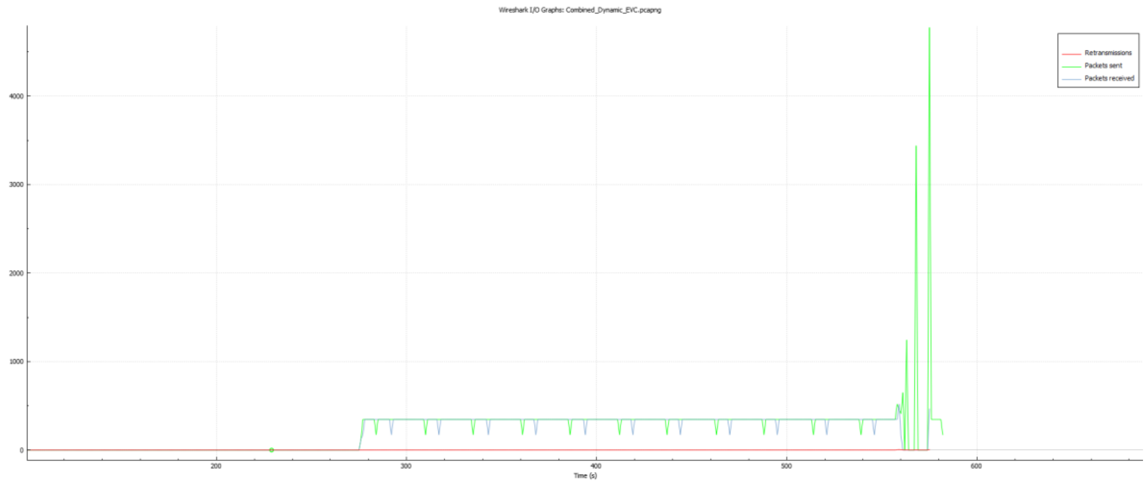


Figure 83: Packet Information (Sent/Received/Retransmissions) for ETCS in Combined Application Dynamic Tests, captured in onboard traces (EVC), Test Case No. ETCS_WP3-WP5_TC_004 (Testbed Germany)

<u>Analysis of Trackside Traces (Dynamic Tests)</u>

Combined_Static_RBC.pcapng: Traces captured in the Trackside application

- Number Packets sent: 562
- Number Packets received: 574
- Number of retransmitted packets: 10
- Average sent data rate: 2701 bits/s
- Average received data rate: 2535 bits/s
- Average round trip time: 93,9 ms

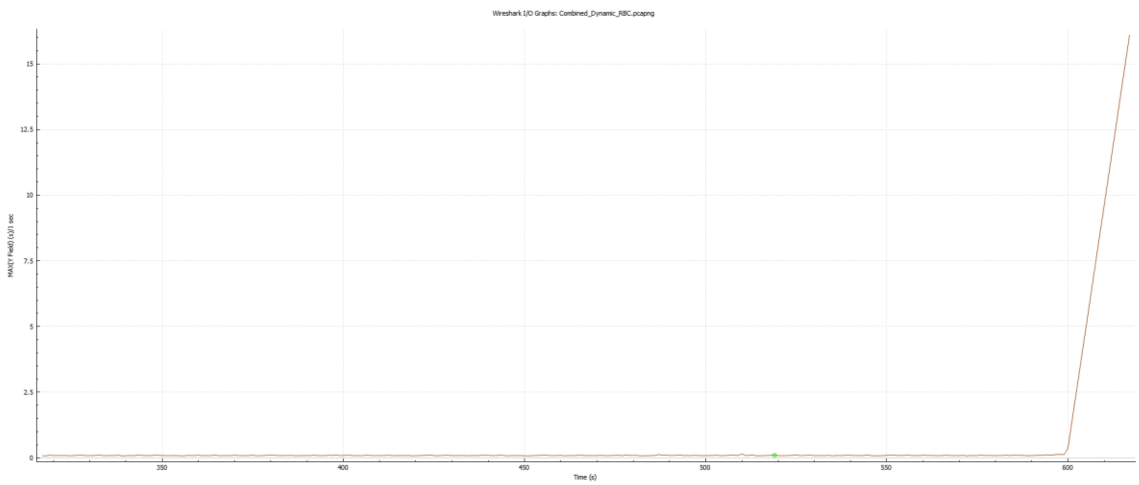


Figure 84: RTT for ETCS in Combined Application Dynamic Tests, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_004 (Testbed Germany)

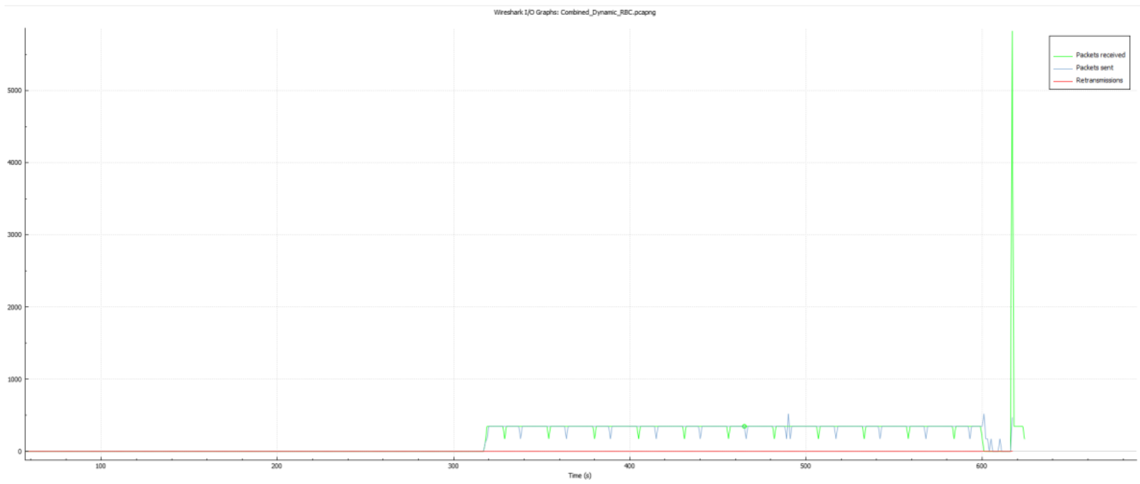


Figure 85: Packet Information (Sent/Received/Retransmissions) for ETCS in Combined Application Dynamic Tests, captured in trackside traces (RBC), Test Case No. ETCS_WP3-WP5_TC_004 (Testbed Germany)

7.6 TCMS simulation between onboard MCG and trackside GCG (TCMS_TC_001)

The nominal data transfer test case for TCMS simulations is not a standard test and data rates vary based on the vehicle subsystem information that shall be send from/to the train. In the following case passenger count services have been selected with only small and not fixed data rates being transmitted.

List of considered test cases:

- Nominal communication between MCG on board application and GCG [static] *(TCMS_TC_001 (TC_001a))*
- Nominal communication between MCG on board application and GCG, including BTS handover (same 5G network) [dynamic] *(TCMS_TC_001 (TC_001b))*

7.6.1 Detailed Test Architecture

The architectures of the test cases are presented below. The TCMS application is implemented in the FRCMS network as a loose coupled application using a MCData client embedded in the FRMCS Onboard Gateway (TOBA box) and FRMCS Trackside Gateway. Static (stationary) mode involves only one cell of the 5G radio access network in the German field while dynamic (drive) test mode involves intra- and inter-gNB handover situations over multiple cells. The utilized end-to-end building blocks are marked in green.

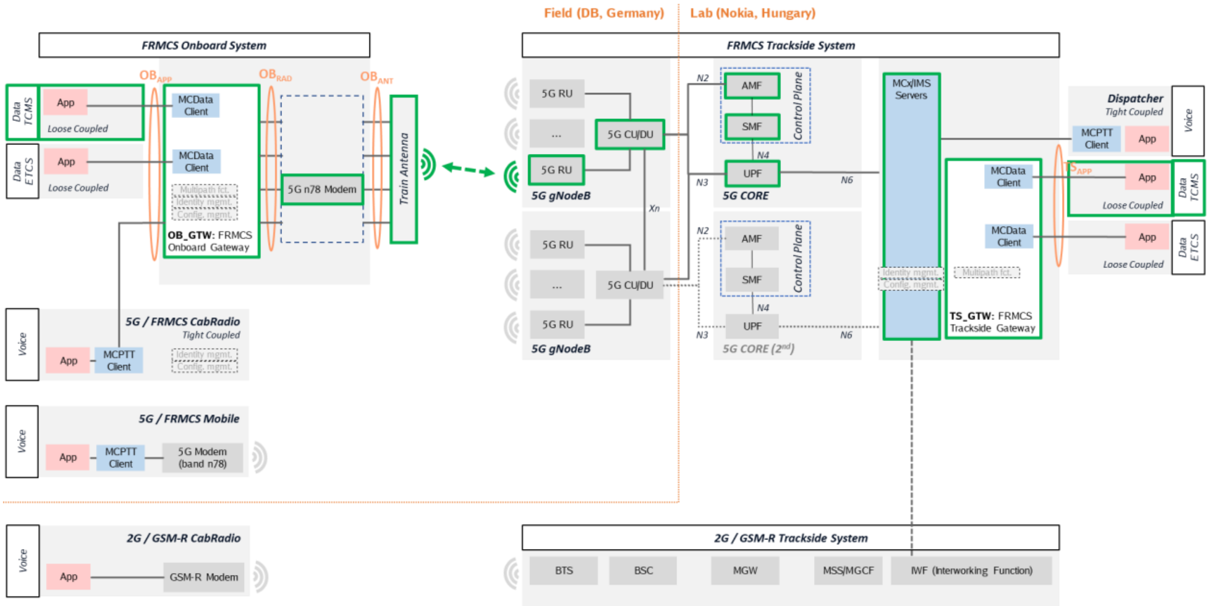


Figure 86: Architecture for test case TCMS_TC_001 (TC_001a) (Testbed Germany)

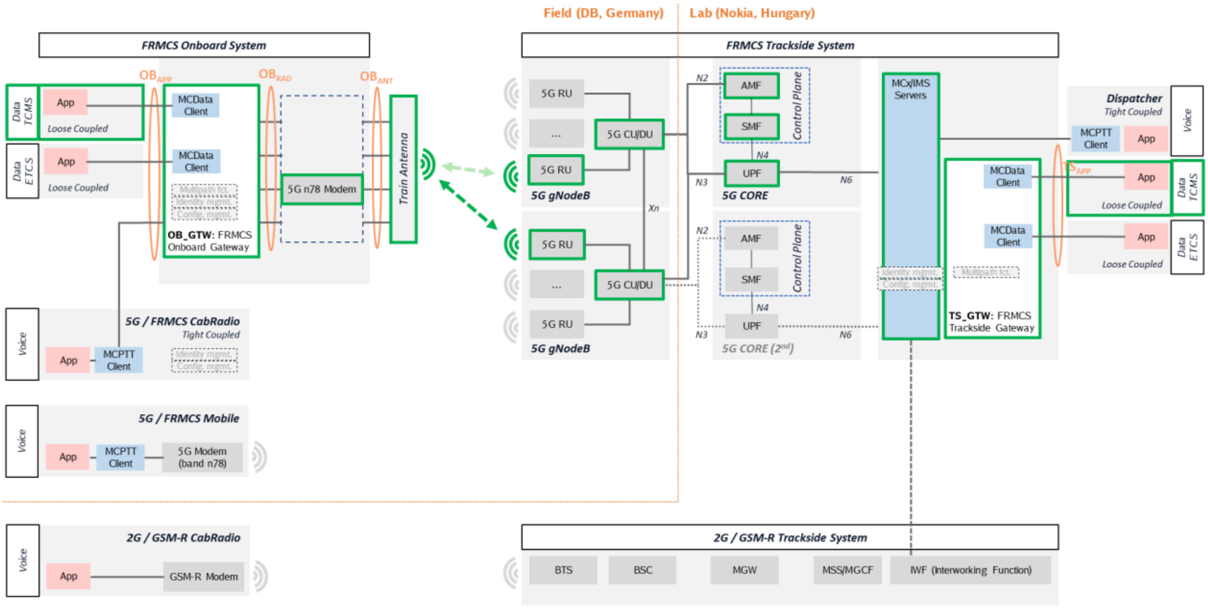


Figure 87: Architecture for test case TCMS_TC_001 (TC_001b), with intra- and inter-gNodeB handover (Testbed Germany)

7.6.2 Detailed Test Plan

The test plan for Test Case No. *TCMS_TC_001 (TC_001a)* is described in Deliverable D1.1v4 – Section 9.2.1.3.
The test plan for Test Case No. *TCMS_TC_001 (TC_001b)* is described in Deliverable D1.1v4 – Section 9.2.1.4.

7.6.3 Specifics of the Test Implementation and Execution

From the integration perspective, the equipment used during the field test were not the same used in the labs, due to the need to the need to do parallel test to keep on going with the project. That incur in the need to up-to-date the systems on-board (dependencies and application). However, the latest version was not used and one of the issues faced was the need of the FRCMS GW to receive the exchanged JSON information to be sent in a specific format to avoid parsing issues.

Wireshark traces have been obtained on the TCMS on-board as well as the trackside. The KPIs have been derived analysing the TCP performance on Wireshark. Once the communication is established, it is sufficient to analyse the on-board application KPIs in order to determine the behaviour of the channel.

7.6.4 Results and Observations

The tests were performed successfully, with the following observations and findings:

Static test results: Two static tests have been performed. Below, results are shown for the combined test case where TCMS and ETCS simulations run in parallel. As TCMS is not impacted by the combination of it with ETCS application, it serves also as a reference for the nominal test case. The achieved average RTT is 43 ms.

Dynamic test results: Two dynamic tests have been performed. One for the nominal case and another for the combined static test. In both cases, the RTT is in the range of 50 ms. Few times there are RTT peaks of some hundreds of milliseconds which are due to connection loss (e.g. handover situations with too low coverage for longer period of time or outage areas). In all these situations, the onboard modules have been capable to recover the connection as the figures show continued streaming after these RTT peaks.

<u>Analysis of Onboard Traces (Static Tests)</u>

static_tcms_02_ob.pcap: Traces captured in the On-Board application

- Average received data rate (TCMS packets): 8 bits/s (1 Byte/s)
- Average round trip time: 43,26 ms

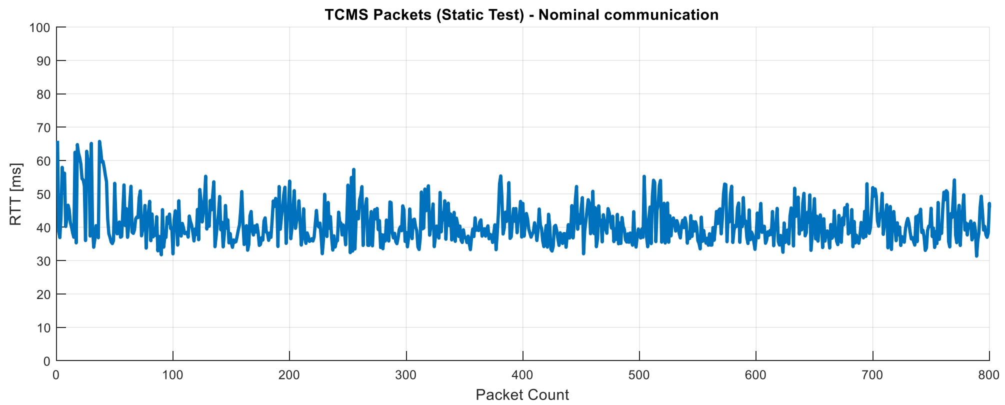


Figure 88: RTT for TCMS Static Tests, Test Case No. TCMS_TC_001 (TC_001a) (Testbed Germany)

<u>Analysis of Onboard Traces (Dynamic Tests)</u>

dynamic_tcms_01_ob.pcap: Traces captured in the On-Board application

- Average received data rate (TCMS packets): 32 bits/s (4 Byte/s)
- Average round trip time: 53,46 ms

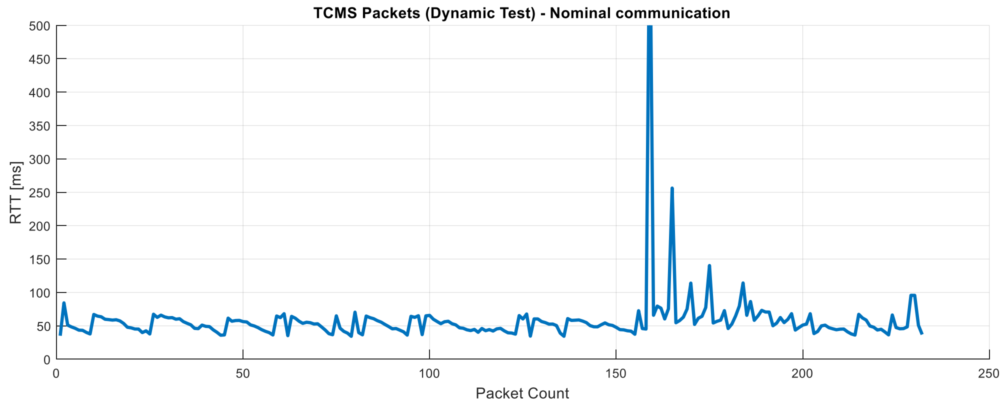


Figure 89: RTT for TCMS Dynamic Test 1/2, Test Case No. TCMS_TC_001 (TC_001b) (Testbed Germany)

<u>Analysis of Onboard Traces (Dynamic Tests) – Combined communication, with ETCS</u>

dynamic_tcms_02_ob.pcap: Traces captured in the On-Board application

- Average received data rate (TCMS packets): 8 bits/s (1 Byte/s)
- Average round trip time: 47,81 ms

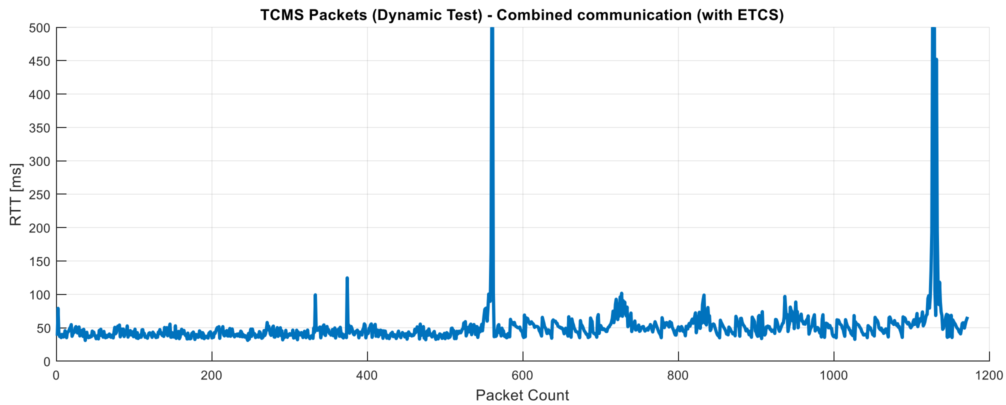


Figure 90: RTT for TCMS Dynamic Test 2/2, Test Case No. TCMS_TC_001 (TC_001b) (Testbed Germany)

8 Video Streaming / CCTV Offload Tests (using MCDATA) – Testbed Germany

The following chapter gives a report about Live View and CCTV File Offload tests that have been performed with the application provider TELESTE in the 5GRAIL Testbed Germany, operated at 5G band n78. Tests have been performed in several weeks, incl. Calendar Week 27, 34 and 36 of 2023.

The test setup is presented below. The Teleste S-VMX software is deployed on both onboard and trackside systems. The server on trackside continuously keeps active connection with the train. This solution offers on-demand, real-time video streaming from any onboard camera. The onboard video recorder facilitates the transmission of video from onboard cameras to the wayside server. In the Teleste solution, the video data is transmitted as TCP stream to minimize the loss of video frames and ensure the best possible user experience.

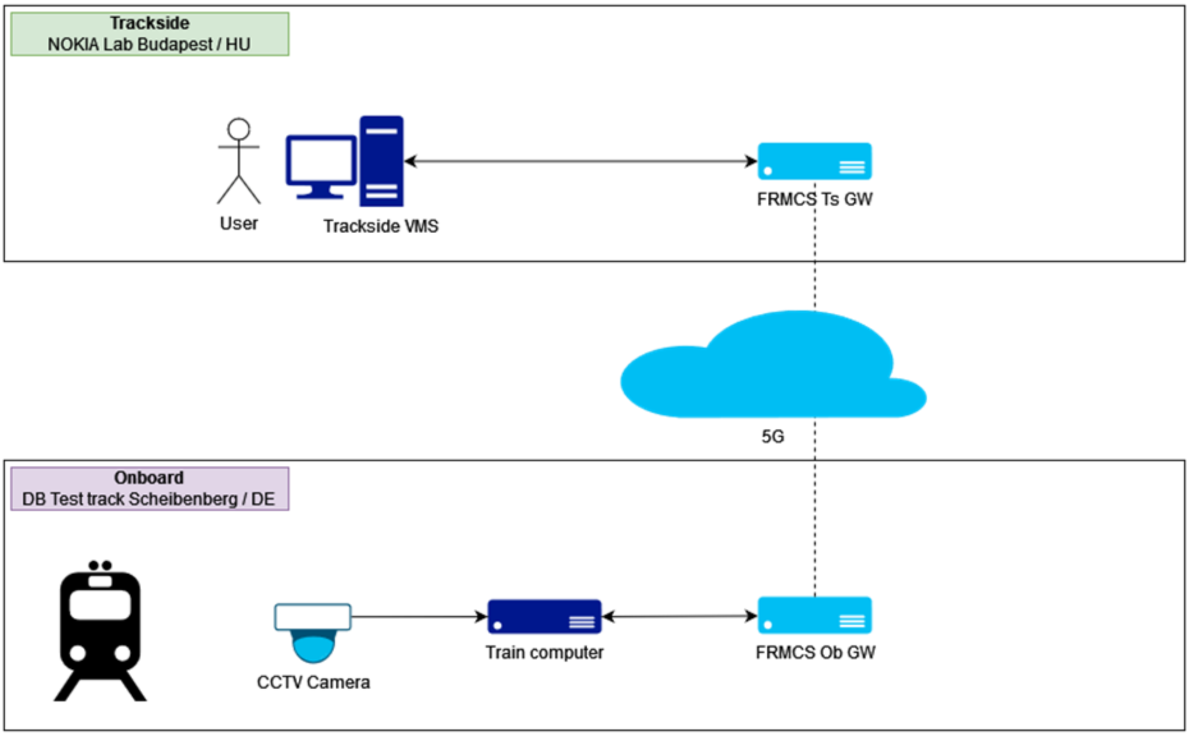


Figure 91: Test setup for the CCTV video field trials (Testbed Germany)

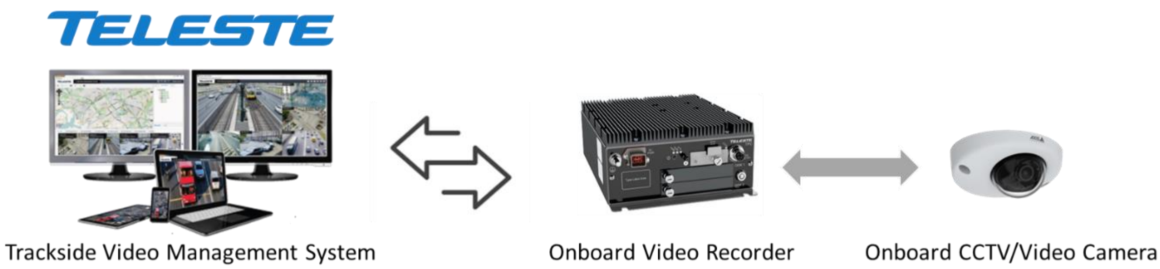
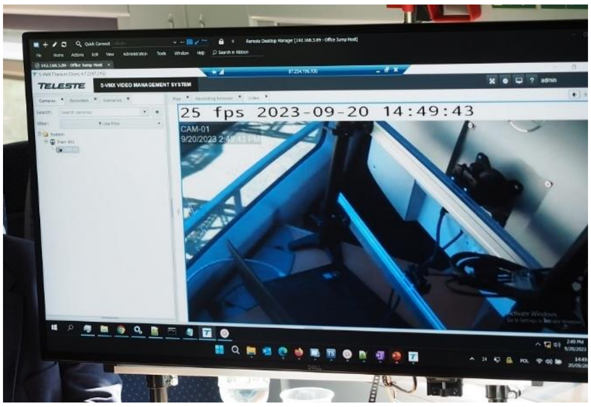


Figure 92: Trackside and onboard equipment of the CCTV video system

For the video tests the QoS parameter 5QI was configured as 5QI=7, using non-guaranteed bitrate (non-GBR) class. As agreed in WP1 the filtering for the different QoS classes is done by the DSCP marking received from the application settings. [7]

The tests have been supported by DB Netz AG (providing the track and rolling stock infrastructure), by Kontron (providing the onboard connectivity using FRMCS TOBA-K gateway and 5G modem plus FRMCS trackside gateway) and by Nokia (providing the 5G SA trackside network and MCX trackside server). MCX clients were provided by Kontron for MCData in onboard and trackside gateways.

The pictures below show some impressions of the tests:



8.1 List of Functional Test Cases

The following table shows the functional test cases performed in the field in accordance with Deliverable D1.1 [2].

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
8.2	Video_TC_001	Streaming of video from train to trackside [static]
8.3	Video_TC_003	Streaming of video from train to trackside including BTS handover (same 5G network) [dynamic]
8.4	CCTV_TC_001	CCTV offload from train to trackside [static & dynamic]

All tests have been performed both in static (stationary) conditions, i.e., at a fixed location in the tracks, and in dynamic (driving) conditions, i.e., during train runs in the 5GRAIL Testbed Germany between the stations of *Scheibenberg Bf.* and *Markersbach Bf.* During the dynamic tests, the application continuity within intra- and inter-gNB handover situations has been tested.

8.2 Streaming of video from train to trackside (Video_TC_001)

The purpose of this test case is to test live streaming of CCTV video from the onboard video management system (Train computer) into the trackside video management system in nominal communication and stationary mode.

8.2.1 Detailed Test Architecture

The architecture of the test case is presented below. The live view service is implemented in the FRCMS network as a loose coupled application using a MCData client which is realized in the FRMCS Onboard Gateway (TOBA box) and FRMCS Trackside Gateway. The uplink transmission test in stationary mode involves only one cell of the 5G radio access network, i.e., the transmission is routed over one 5G radio unit (RU) and one 5G CU/DU in the German field to the 5G CORE at Nokia premises in Hungary. The used end-to-end building blocks are marked in green.

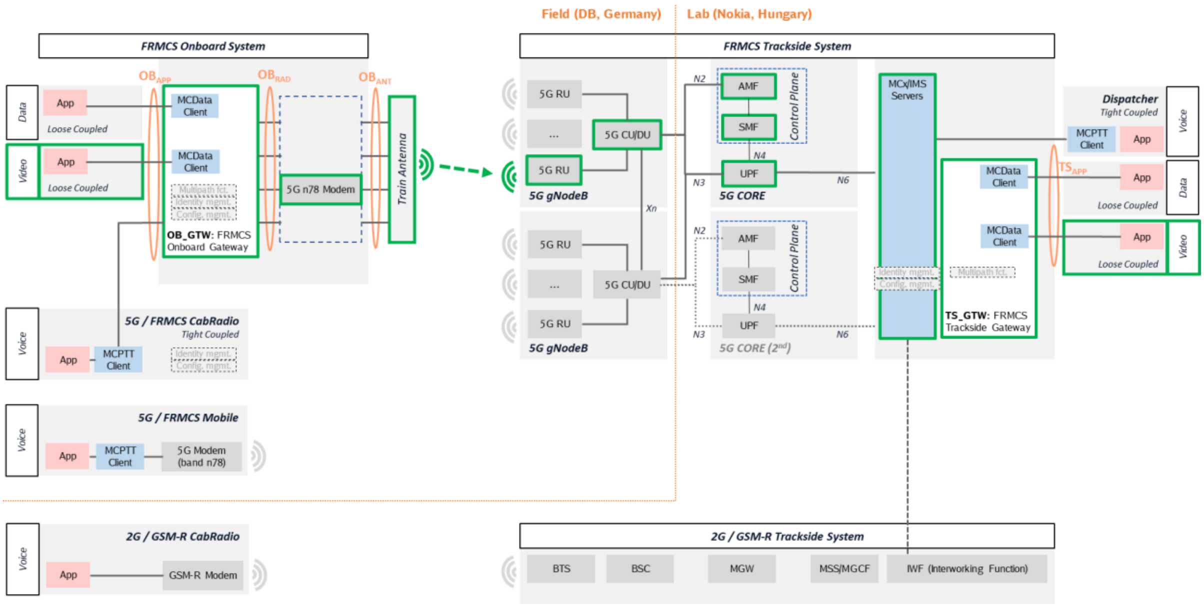


Figure 93: Architecture for test case Video_TC_001 (Testbed Germany)

8.2.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 9.4.1.3.

8.2.3 Specifics of the Test Implementation and Execution

The test was executed with different video resolutions and bitrates used to validate the environment and its capabilities for further tests that were executed with the train on the move.

Video resolutions and bitrate tested:

- HD video (1280x720) with average bitrate at 2 Mbps
- SVGA video (800x600) with average bitrate at 1 Mbps
- VGA video (640x480) with average bitrate at 700 Kbps

Note that the camera can send higher or lower bitrate then set depending on the scene conditions. The application decoder on the trackside presents fps (frames per second) and bitrate values on the video overlay.

The live video from onboard side was connected to the Trackside VMS client decoder available on the Trackside VMS server. During the test the network data dump was performed and the screen of the Trackside VMS client decoder was recorded.

The onboard application sends video data to the trackside application over TCP. The video over TCP is considered a better choice than over UDP for unstable network conditions where network degradations may occur.

In the video over TCP, the onboard application can buffer some data for a short time when network degradations occur before the data are dropped (depends on the data rate and brake time) and send it immediately when network communication is back.

The experience and visual effects of the video over TCP is such scenarios is much better (especially for identification) then video over UDP. The video over TCP when network degradation occurs may jerk, be delayed or skip but picture is visible, usually no artefacts on the video.

The video over UDP when network degradation occurs and frames are lost the artefacts on the video happen.

8.2.4 Results and Observations

<u>HD video (1280x720) with average bitrate at 2 Mbps</u>

During the test from time to time the video framerate and bitrate was dropped to unexpected range, picture jerks, stops and blinking were visible. After short time the video was recovered to good quality and then again degradation occurred.

Figure 94: HD Video Streaming Stationary Test (Testbed Germany), snapshot with good quality (20 fps, 1904 kbps)

Figure 95: HD Video Streaming Stationary Test (Testbed Germany), snapshot with unexpected quality drop (2 fps, 299 kbps)

Wireshark tool network data dumps analyses of video session shows brakes in the transmission, data were not received over the network in intervals, sometimes even over 10 seconds. Detailed Wireshark analyses of network dumps for RTP stream shows 14484 packets loss of 52821 expected (27.42%).

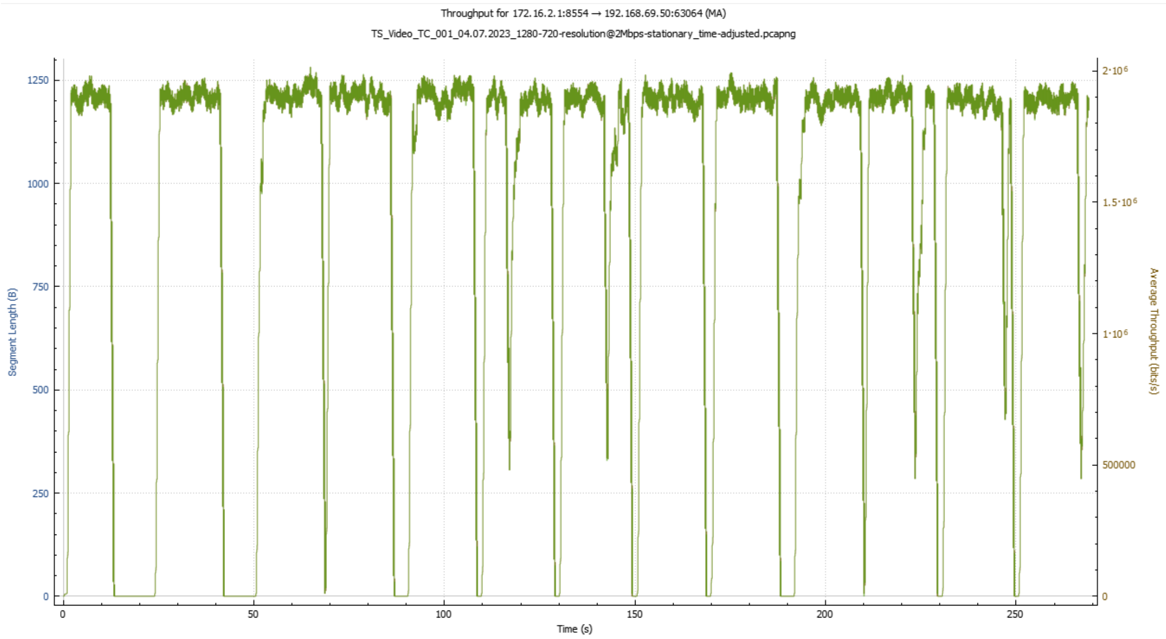


Figure 96: HD Video Streaming Stationary Test (Testbed Germany), throughput / goodput over time, Test Case No. Video_TC_001

<u>SVGA video (800x600) with average bitrate at 1 Mbps</u>

During the test from time to time the video framerate and bitrate was dropped to unexpected range, especially when the camera bitrate increased over 1 Mbps as of movements in the scene, picture jerks, stops and blinking were visible. After short time the video was recovered to good quality and then again later degradation occurred.

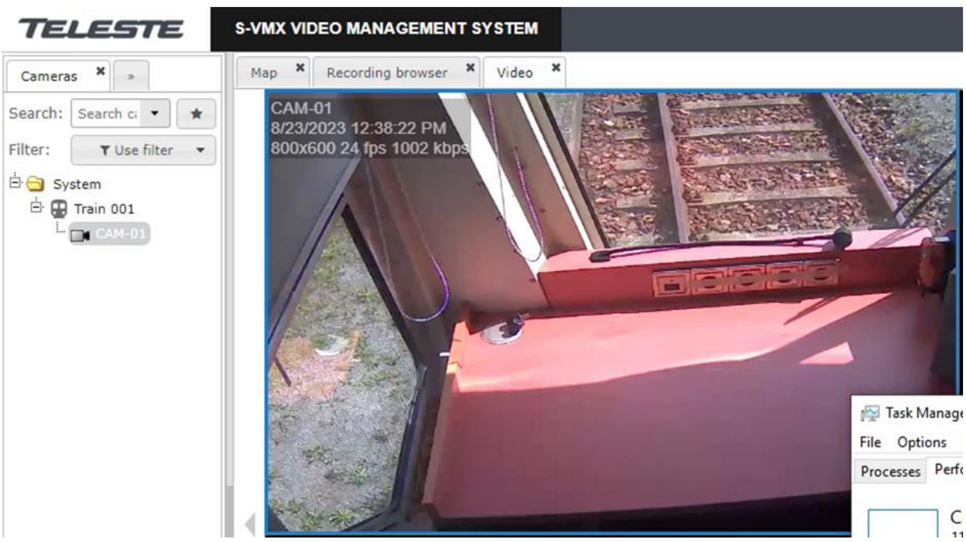


Figure 97: SVGA Video Streaming Stationary Test (Testbed Germany), snapshot with good quality (24 fps, 1002 kbps)

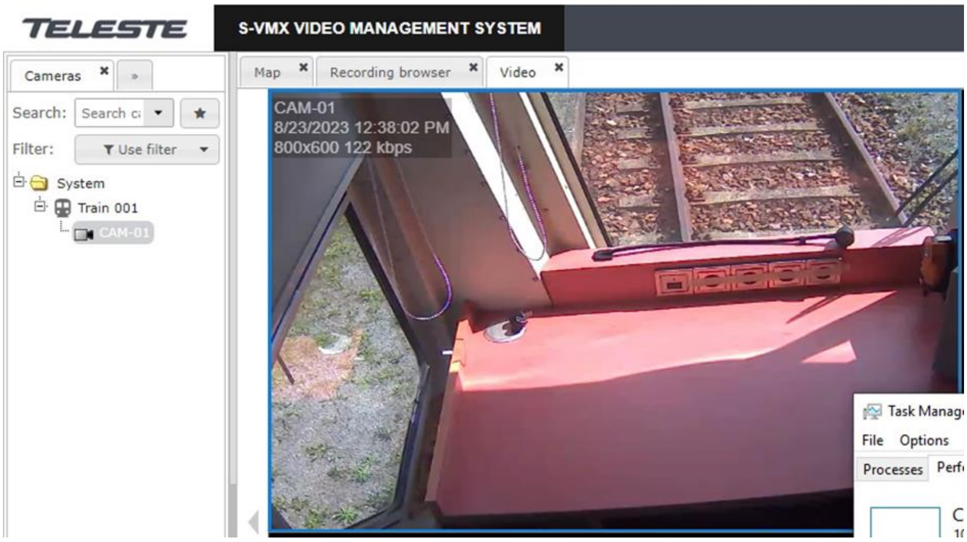


Figure 98: SVGA Video Streaming Stationary Test (Testbed Germany), snapshot with unexpected quality degradation (122 kbps)

Wireshark tool network data dumps analyses of video session shows brakes in the transmission, data were not received over the network in intervals, especially when video bitrate increases as of movements in the scene. Onboard application was buffering the data and then was sending it immediately after the network becomes stable (increased bitrate after brake). After some time of data transmission, the brake was happening again and the process continues in intervals.

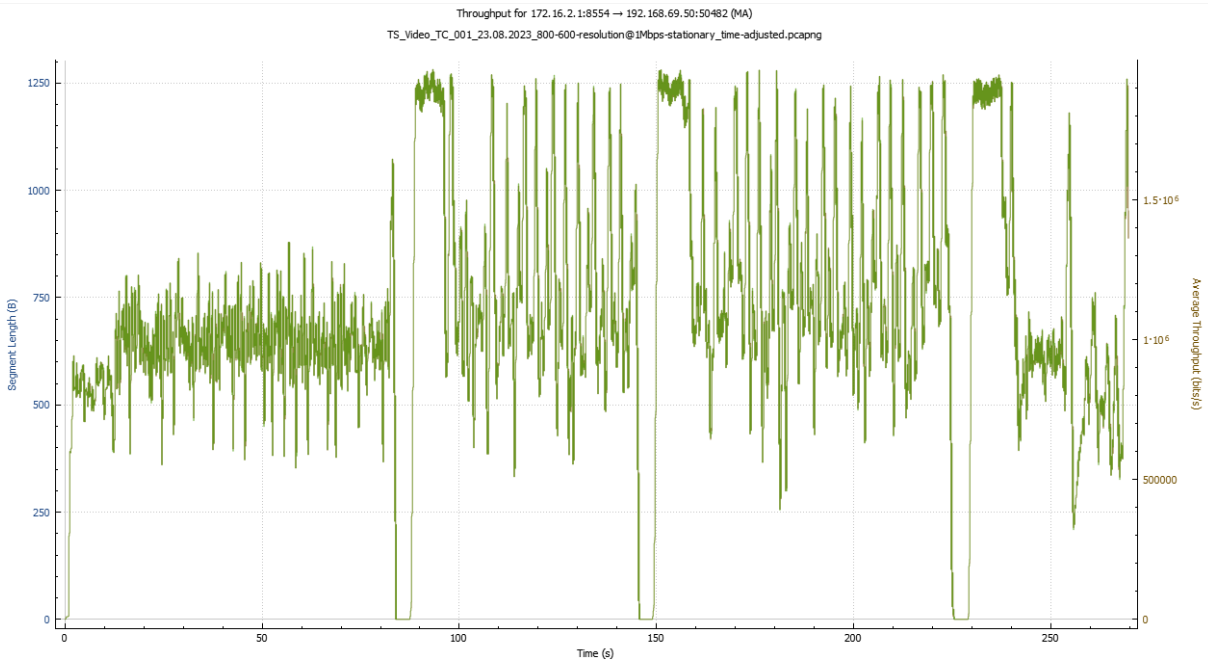


Figure 99: SVGA Video Streaming Stationary Test (Testbed Germany), throughput / goodput over time, Test Case No. Video_TC_001

Detailed Wireshark tool analyses of network dumps for RTP stream shows 12 packets loss of 28896 expected (0.04%).

VGA video (640x480) with average bitrate at 700 Kbps

During the test the visual effects of the video was good, no major jerks or picture blinking, framerate was kept within expected rage. The test was considered as successful, and this test setup and parameters were used for further testing.

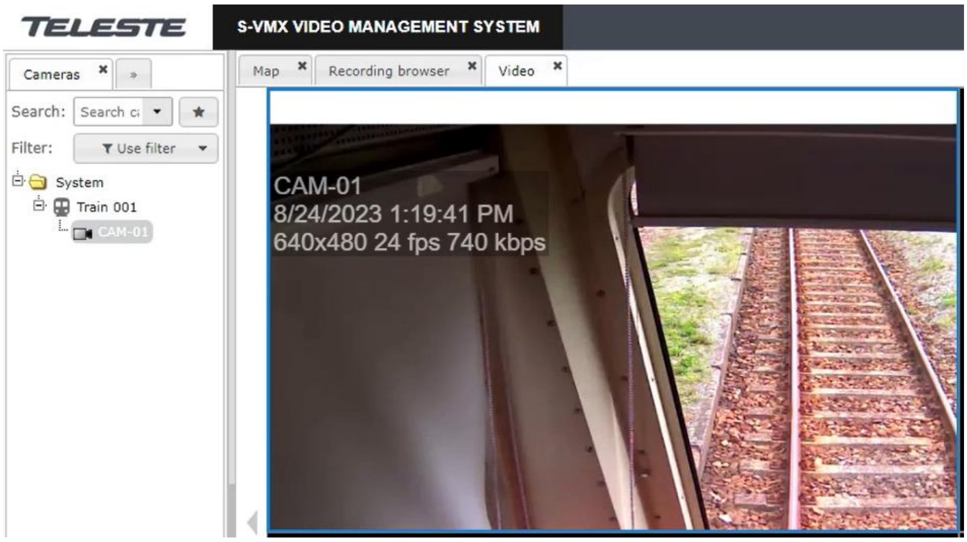


Figure 100: VGA Video Streaming Stationary Test (Testbed Germany), showing constantly good quality

Wireshark tool network data dumps analyses of video session shows no brakes in the transmission, data were received at all times.

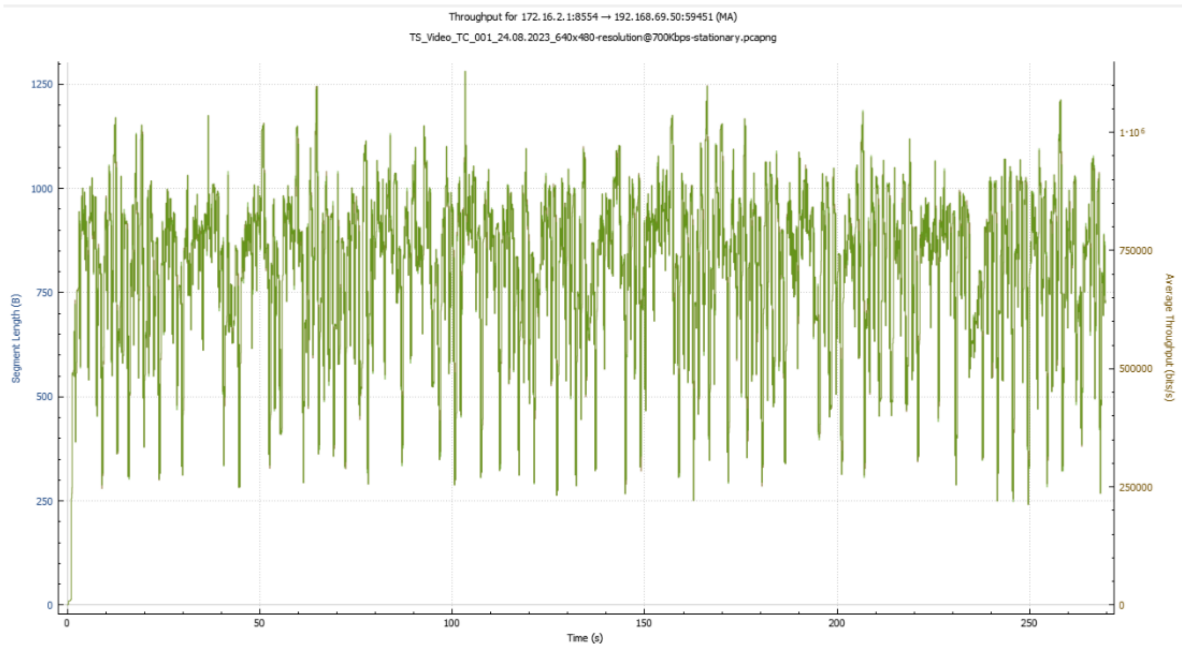


Figure 101: VGA Video Streaming Stationary Test (Testbed Germany), throughput / goodput over time, Test Case No. Video_TC_001

Detailed Wireshark tool analyses of network dumps for RTP stream shows 0 packet loss of 21094 (0.00%).

Leased Line Impact on Throughput / Video Quality

The reasons for higher RTP stream losses with HD video quality are due to an issue in the leased line configuration between the 5G RAN in the Testbed Germany and the 5G CORE, located in Budapest/Hungary. There have been QoS problems on the leased line for video transmissions with data rates higher than 1.5 Mbps. For smaller data rates the transmission over the leased line worked rather stable, which can be seen in the results of the SVGA and VGA losses in Figure 102.

The issue for HD video transmissions could be identified as one end of the line has been configured as “unmanaged leased line” with too few performance guarantees and priorities which led to buffering effects in the internet nodes between Germany and Hungary and, hence, frequent transmission interruptions that have been observed with HD video tests. The issue would have likely not occurred with a “managed leased line” on both ends and is a finding for future trials.

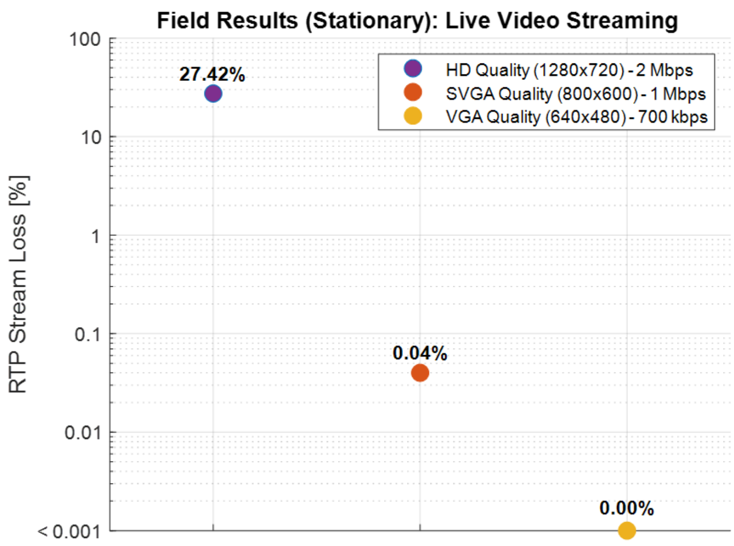


Figure 102: Comparison of different resolutions in Video Streaming Stationary Test (Testbed Germany)

Video Latency Tests

Camera, Train computer and Trackside VMS computer were NTP synchronized. Due to the environment limitations two different NTP were used, one in the trackside and one in the onboard. The time synchronization was checked with 1 second precision and the conclusion can be only indicative in such case. Camera was set to include video stream parameters and time in the picture (embedded in the video stream – top of the video display, black text on the white background) for the video latency analyses. The time embedded in the video stream to be compared with the decoder overlay time for the difference (white text on the transparent background).

The video latency was considered real-time as both the application seen on onboard computer and trackside VMS computer had the same time stamp on second level, i.e., the delay was smaller than 1 second. Unfortunately, with the given setup it is not possible to assess the difference further (e.g. on millisecond level).

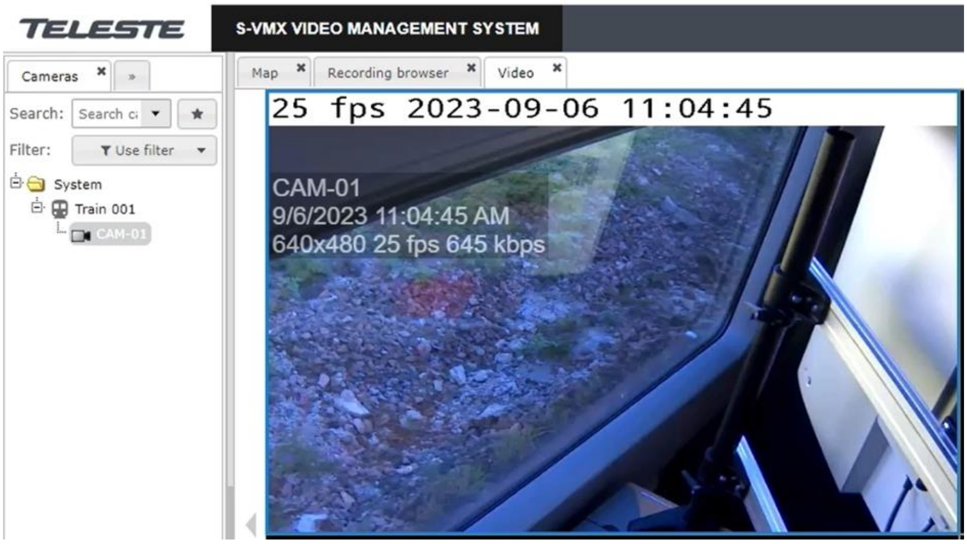


Figure 103: VGA Video Streaming Stationary Test (Testbed Germany), latency test showing same time stamps of onboard computer (transmitter side) and trackside server (receiver side), Test Case No. Video_TC_001

8.3 Streaming of video from train to trackside including BTS handover (same 5G network) (Video_TC_003)

The purpose of this test case is to test live streaming of CCTV video from the onboard video management system (Train computer) into the trackside video management system in driving conditions with intra- and inter-gNB handover situations.

8.3.1 Detailed Test Architecture

The architecture of the test case is presented below. The live view service is implemented in the FRCMS network as a loose coupled application using a MCData client which is realized in the FRMCS Onboard Gateway (TOBA box) and FRMCS Trackside Gateway. The uplink transmission test in stationary mode involves only one cell of the 5G radio access network in the German field while drive test mode involve intra- and inter-gNB handover situations over multiple cells. The used end-to-end building blocks are marked in green.

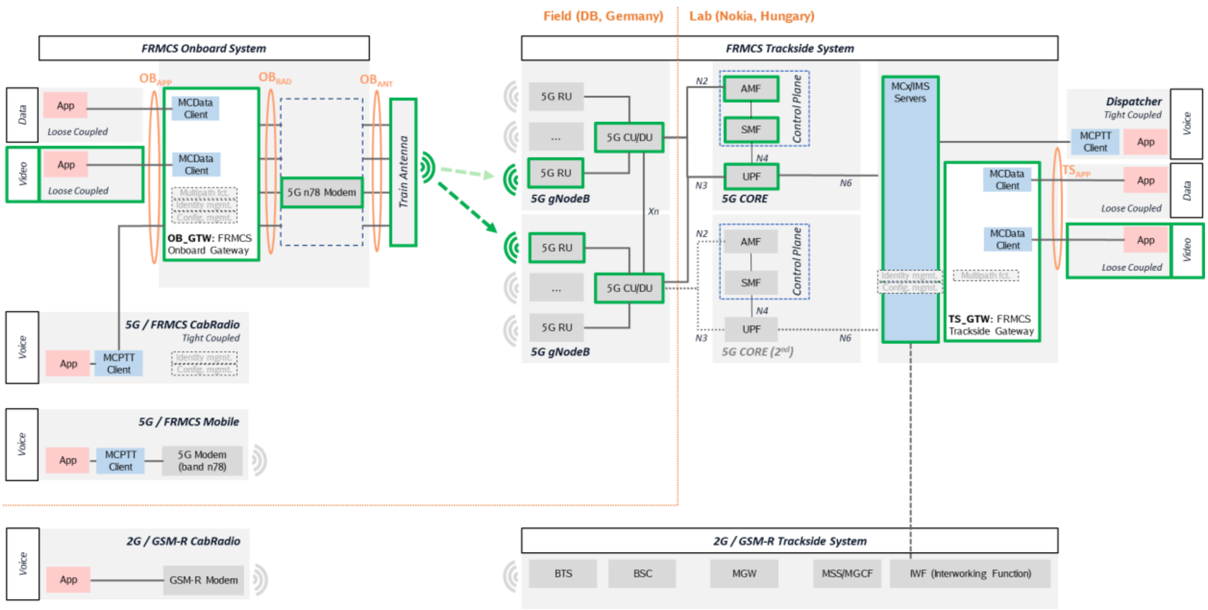


Figure 104: Architecture for test case Video_TC_003 (Testbed Germany)

8.3.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 9.4.1.4.

8.3.3 Specifics of the Test Implementation and Execution

The test was executed with VGA video resolution and 700 kbps average bitrate with the train on the move. This configuration has been derived from stationary tests with different video qualities.

Note that the camera can send higher or lower bitrate then set depending on the scene conditions. The application decoder on the trackside presents fps (frames per second) and bitrate values on the video overlay.

The live video from onboard side was connected to the Trackside VMS client decoder available on the Trackside VMS server. During the test the network data dump was performed and the screen of the Trackside VMS client decoder was recorded.

The onboard application sends video data to the trackside application over TCP. The video over TCP is considered a better choice than over UDP for unstable network conditions where network degradations may occur.

In the video over TCP, the onboard application when network degradations occur can buffer some data for a short time before the data are dropped (depends on the data rate and brake time) and send it immediately when network communication is back.

The experience and visual effects of the video over TCP is such scenarios is much better (especially for identification) then video over UDP. The video over TCP when network degradation occurs may jerk, be delayed or skip but still picture is visible, usually no artefacts on the video.

The video over UDP when network degradation occurs and frames are lost the artefacts on the video happen.

8.3.4 Results and Observations

During the test the visual effects of the video was good, no major jerks or picture blinking, framerate was kept within expected rage. At one time for a short time during the drive the degradation occurred, small picture jerk and blink, video framerate and bitrate degraded. Onboard application was buffering the data and then was sending it immediately after the network becomes stable. Then the good quality was recovered and remain stable until network coverage was available.

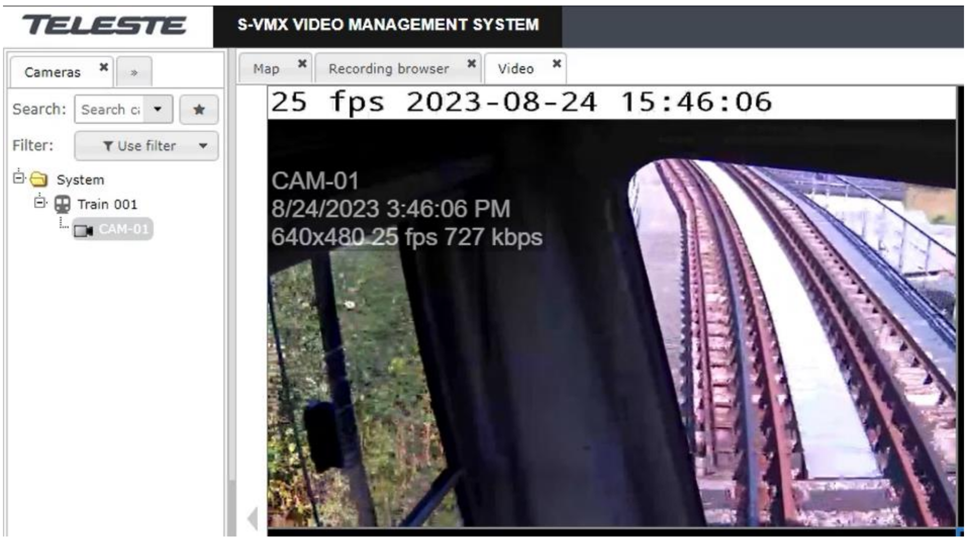


Figure 105: VGA Video Streaming Drive Test (Testbed Germany), showing good quality

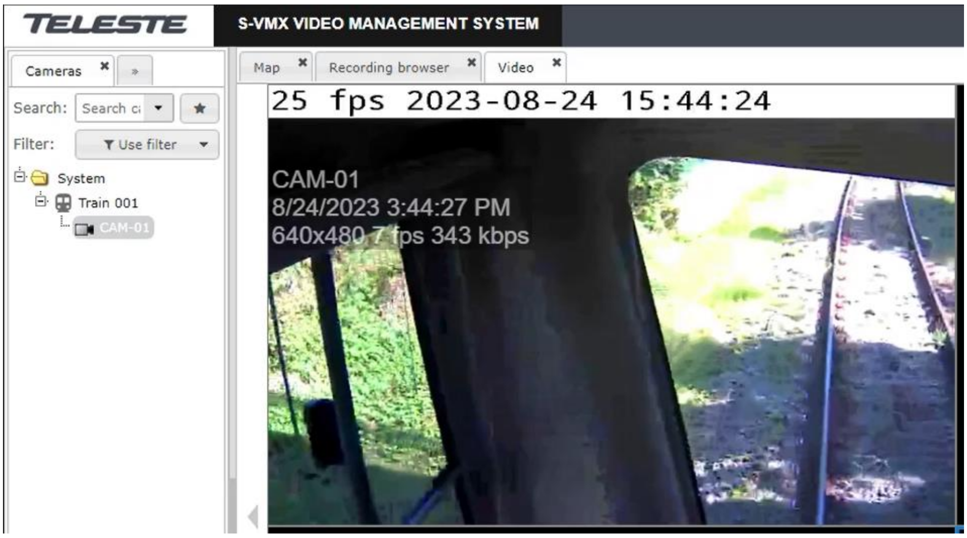


Figure 106: VGA Video Streaming Drive Test (Testbed Germany), showing short quality degradation during an inter-gNB handover situation

Wireshark tool network data dumps analyses of the video session shows stable transmission and only one small brake in the transmission.

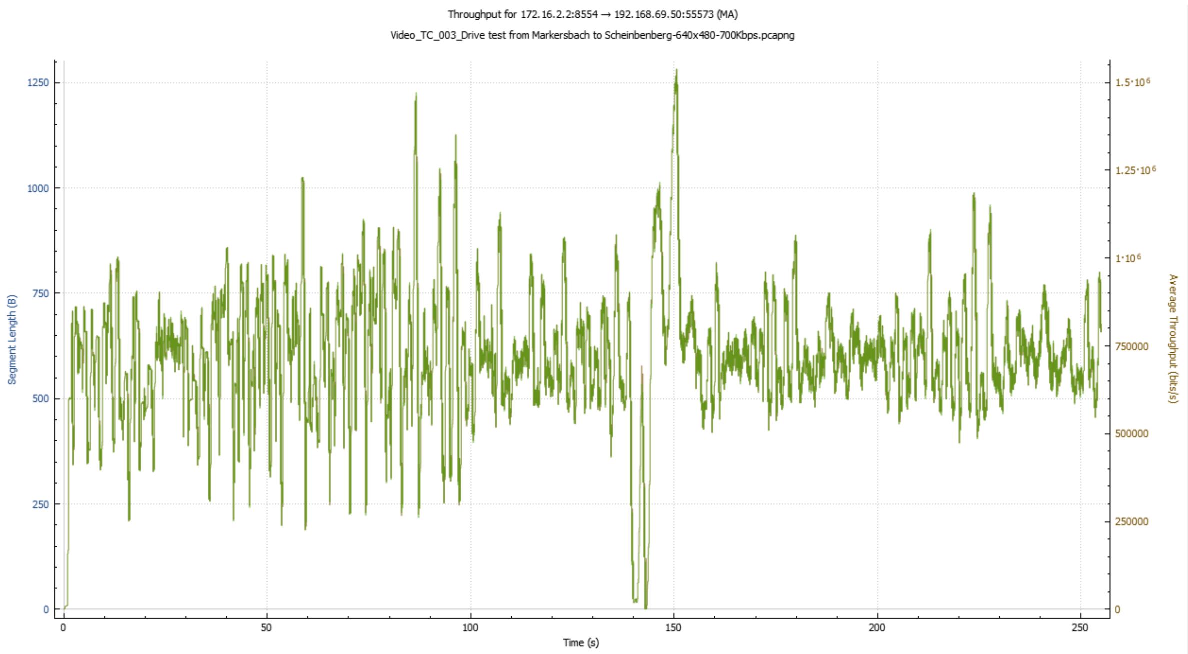


Figure 107: VGA Video Streaming Drive Test (Testbed Germany), throughput / goodput over time, Test Case No. Video_TC_003

Detailed Wireshark tool analyses of network dumps for RTP stream shows 0 packet loss of 21094 (0.00%).

Video latency test

Camera, Train computer and Trackside VMS computer were NTP synchronized. Due to the environment limitations two different NTP were used, one in the trackside and one in the onboard. The time synchronization was checked with 1 second precision and the conclusion can be only indicative in such case. Camera was set to include video stream parameters and time in the picture (embedded in the video stream – top of the video display, black text on the white background) for the video latency analyses. The time embedded in the video stream to be compared with the decoder overlay time for the difference (white text on the transparent background).

The video latency/delay that could be seen during the drive test was less than 1 second and can be considered as real-time. Unfortunately, with the given setup it is not possible to assess the difference further (e.g. on millisecond level).

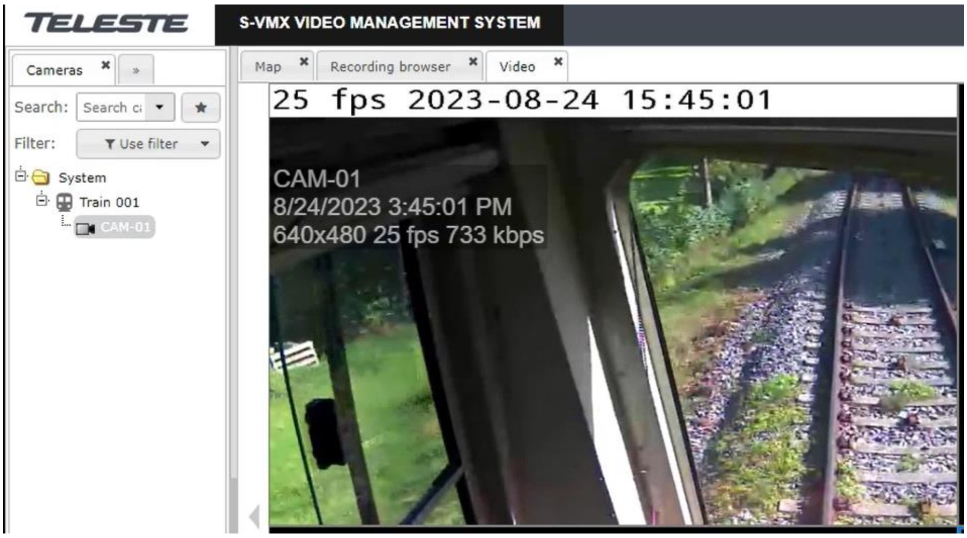


Figure 108: VGA Video Streaming Drive Test (Testbed Germany), latency test showing same time stamps of onboard computer (transmitter side) and trackside server (receiver side), Test Case No. Video_TC_003

8.4 CCTV offload from train to trackside (CCTV_TC_001)

The purpose of this test case is to test a CCTV offload system, where FRMCS provides means for transferring recorded video surveillance data between a mobile communication unit in the train and ground communication units located on train stations and alongside the predetermined route of the train.

FRMCS facilitates the communication between the mobile (onboard) and ground (trackside) communication unit. 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.

In a CCTV offload situation, the time for data transmission may be limited (e.g. to the time that the train stands on a platform or slowly moves in the station area). Hence, it is important to achieve a stable and continuous data stream of sufficient quality.

8.4.1 Detailed Test Architecture

The architecture of the test case is presented below. It is the same architecture as used for test case *Video_TC_003*. The CCTV (offload) service is implemented in the FRCMS network as a loose coupled application using a MCData client which is realized in the FRMCS Onboard Gateway (TOBA box) and FRMCS Trackside Gateway. The uplink transmission test in stationary mode involves only one cell of the 5G radio access network in the German field while drive test mode involve intra- and inter-gNB handover situations over multiple cells. The used end-to-end building blocks are marked in green.

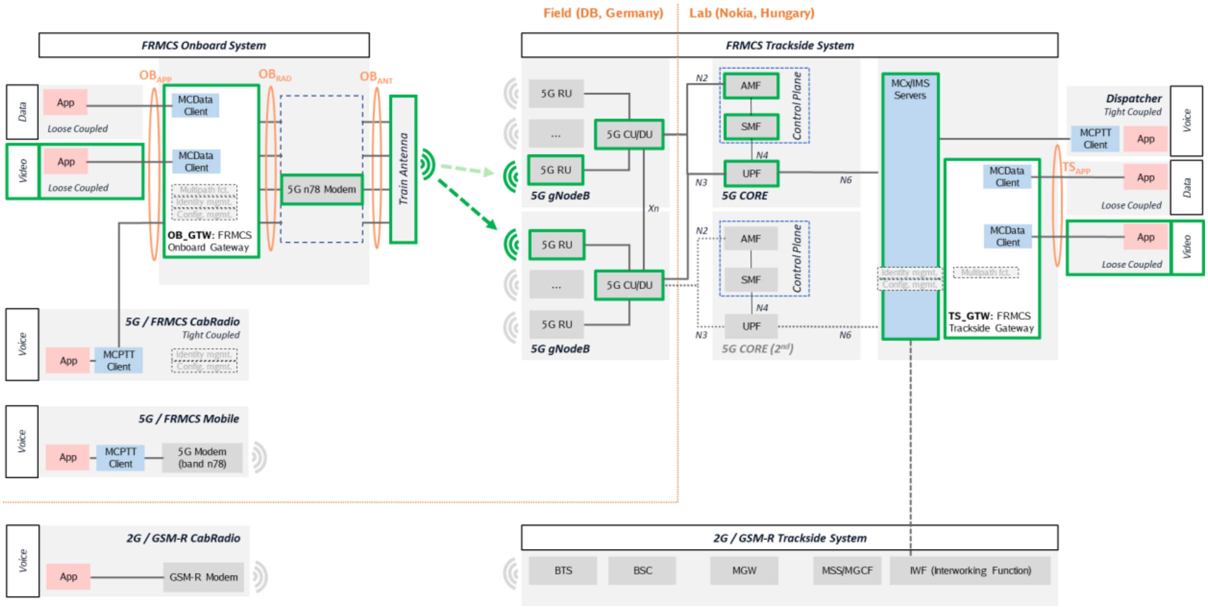


Figure 109: Architecture for test case CCTV_TC_001 (Testbed Germany)

8.4.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 9.5.1.

8.4.3 Specifics of the Test Implementation and Execution

The test was executed with different conditions both in stationary mode and drive test mode (with velocity of max. 50 km/h), with:

- full offload speed, i.e., no rate limitation has been set on application level and
- limited offload speed, i.e., a specific data rate limitation has been set on application level.

The onboard CCTV system was set to perform CCTV video offload to the Trackside VMS server, first with no limitation on the sending data rate allowing full possible speed. Since the offload process was not constant and frequent and regular breaks in the transmission occurred due to the impacts of the leased line (as described in Chapter 3.1.3), the limit on the sending data rate was applied, first 2 Mbps, then 1Mbps and 700 Kbps. With the data rate limitation a continuous application service and stabilized data transmission has been achieved.

During each test scenario the network data dump was performed.

8.4.4 Results and Observations

Achievable Peak Rates in Uplink

It was observed that the 5G network allowed UL peak rates (in good coverage zones) of up to 8 Mbps with TDD configuration 1/4 (DDDSU), using 20 MHz bandwidth within 3700-3720 MHz in TDD band n78.

Since the final FRMCS system at TDD band n101 will use 10 MHz bandwidth within 1900-1910 MHz, the observed peak results are only indicative.

Stationary Tests

It was observed that the full speed offload test was affected by some network conditions, in particular due to the leased line quality, between field environment located in the 5GRAIL DB test track in Germany (Erzgebirge) and the trackside system located in 5GRAIL Nokia lab in Hungary (Budapest). The impact is described in Section 3.1.3. Once the date rate was higher than 1.5 Mbps it could be observed brakes in the offload process and transmission (TCP data could not be send over network), that was visible in both stationary scenarios and drive test.

During the scenario for the stationary mode, full offload speed enabled, the figures below show frequent and regular breaks in the offload data transmission. The offload peak rate was around 8 Mbps.

During the scenario for the stationary mode with 2 Mbps limit on the offload speed enabled, there can be seen less frequent breaks in the offload data transmission but interruptions are still available. The offload peak rate was just below 2 Mbps as expected by the applied limitation.

During the scenario for the stationary mode with 1 Mbps and 700 Kbps limit on the offload speed enabled, no breaks in the offload data transmission were seen, i.e., the offload service was working with continuous uplink stream. The offload speed was around 1 Mbps and 700Kbps as expected by the applied limitation.

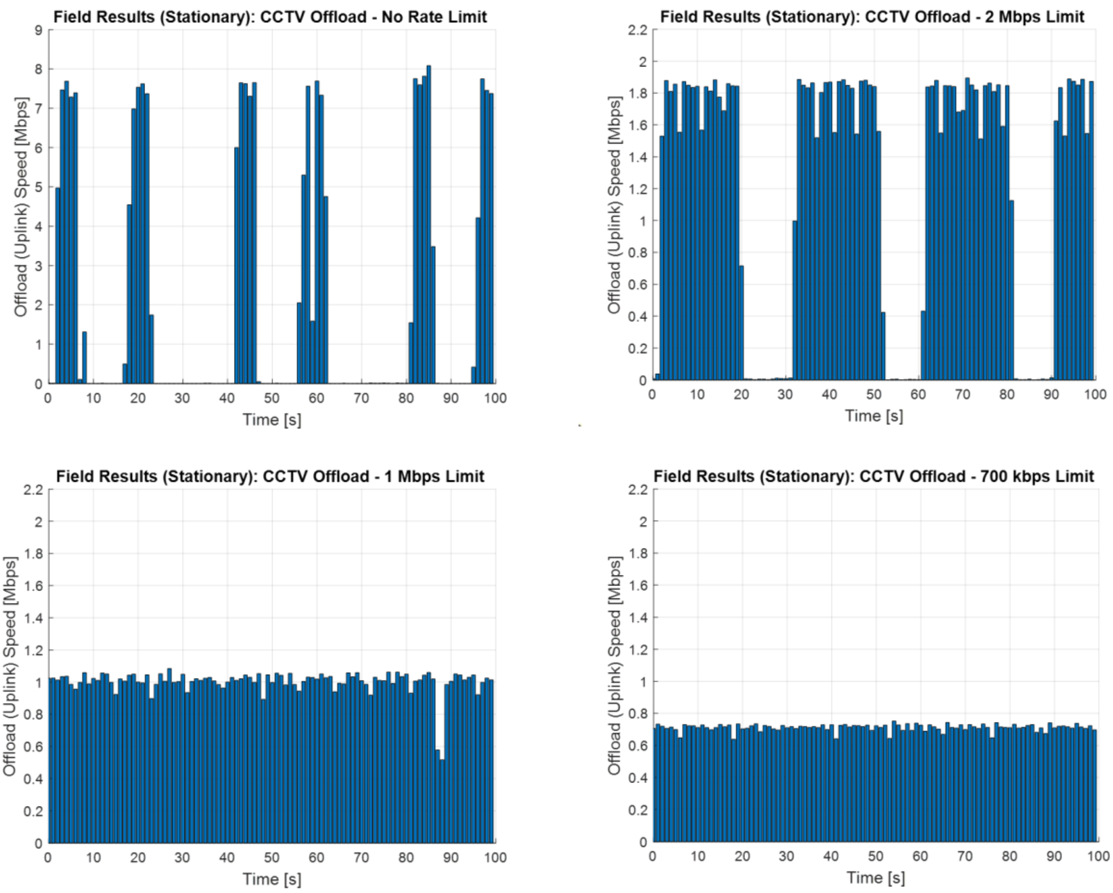


Figure 110: CCTV Offload performance in a stationary setup with different offload speed limitations, Test Case No. CCTV_TC_001

<u>Drive Tests</u>

During the scenario for the drive mode, full offload speed enabled, there can be seen frequent breaks in the offload data transmission. The offload speed varied with the changing radio conditions while driving between the different radio cells along the track, reaching just over 8 Mbps uplink peak rate in good radio conditions.

During the scenario for the drive mode with 1 Mbps limit on the offload speed enabled, there are no breaks in the offload data transmission, i.e., the offload service was working with continuous uplink stream. The maximum offload speed was around 1 Mbps as expected by the applied limitation and it was also nearly constant over the full drive between the different radio cells along the track.

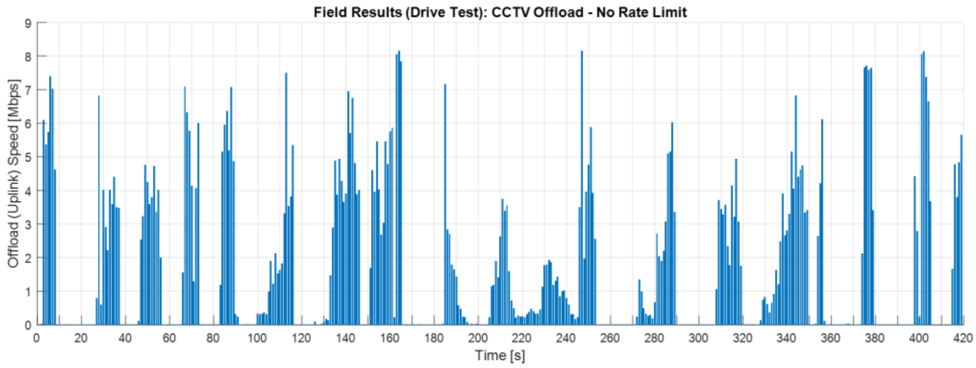


Figure 111: CCTV Offload performance in a dynamic setup (7 min drive test) without offload speed limitation, Test Case No. CCTV_TC_001

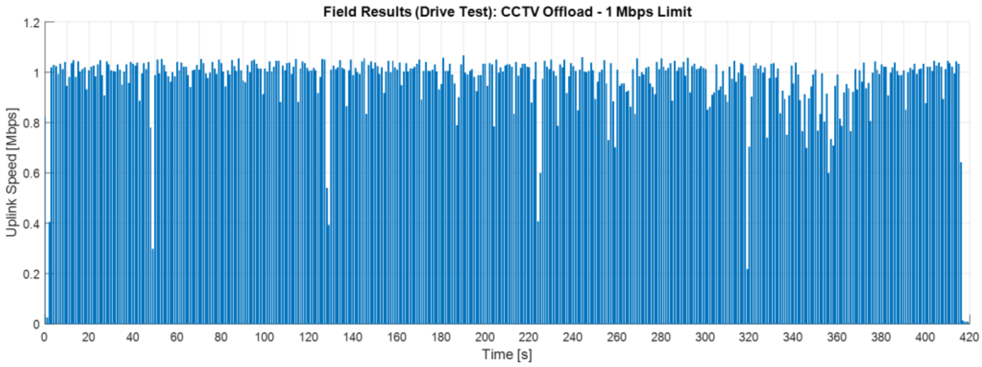


Figure 112: CCTV Offload performance in a dynamic setup (7 min drive test) with 1 Mbps offload speed limitation, Test Case No. CCTV_TC_001

9 ETCS Tests (using MCDATA) – Testbed France

9.1 List of Functional Test Cases

The following table shows the functional test cases performed in the field in accordance with Deliverable D1.1 [2]. In total, three groups of application tests have been successfully conducted. These are:

- **ETCS simulation between onboard EVC and trackside RBC**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
9.2	ETCS_WP4-WP5_TC_001 (Procedure 1) ETCS_WP4-WP5_TC_001 (Procedure 1 & 6)	OBapp Integration Test Procedures • Check the health of the link between ETCS and TOBA - The WebSocket status is correct • Check the registration and the connection status – Registration • Check the connection status
9.3	ETCS_WP4-WP5_TC_003 (Procedure 1)	Nominal communication in ETCS level 2

- **Mobility Scenarios (Transitions on ETCS App. Simulator)**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
9.4	ETCS_WP4-WP5_TC_003 (Procedure 2)	RBC handover on the same 5G network
9.5	ETCS_WP4-WP5_TC_003 (Procedure 4)	RBC & BTS handover on the same 5G network

- **Combined ETCS and ATO simulations**
  This will be elaborated in the following chapter dedicated to ATO, Section 10.7.

All tests have been performed both in static (stationary) conditions, i.e., at a fixed location in the tracks (where a coverage is granted), and in dynamic (driving) conditions, i.e., during train runs in the 5GRAIL Testbed France between the stations of *Villeneuve St. Georges* and *Juvisy* during the dynamic tests, the application continuity within intra- and inter-gNB handover situations has been tested.

9.2 OBapp Integration Test Procedures (ETCS_WP4-WP5_OBapp)

The objective of this test is to verify that OBapp and TSapp interfaces are well-integrated.

9.2.1 Test Architecture

Inheriting from Figure 39, in the following graph we only keep the involved building blocks on the architecture employed for this test.

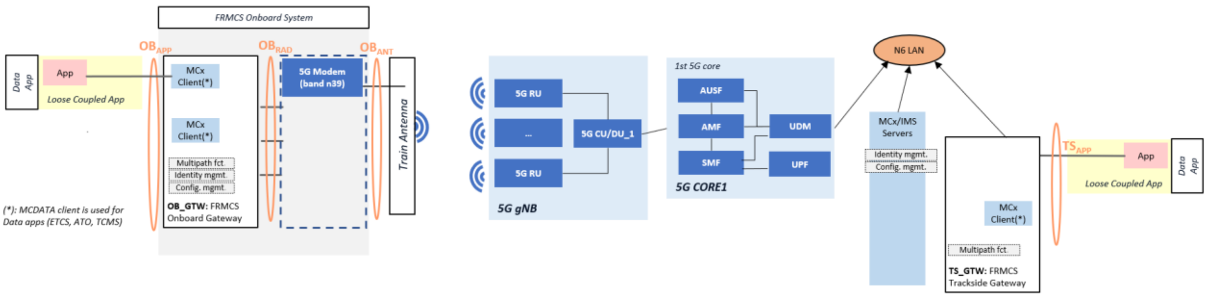


Figure 113: Involved OBapp and TSapp Interface (circled in light red) for ETCS app. integration (Testbed France)

9.2.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.2.2.1 and 8.2.2.2.

9.2.3 Specifics of the Test Implementation and Execution

Web Socket: This static test was performed on 23/05/2023. Radio signal coverage is not needed for this test as it concerns the link between the TOBA K and ETCS application.

Registration: This test was performed on 23/05/2023. After the WebSocket session establishment, the "register" message is sent by ETCS application and responded by an App UID by the TOBA K.

Connection Status: This test was performed on 23/05/2023 in two scenarios:

- The TOBA K is registered on the 5G network: the connection status is requested by ETCS application responded by TOBA K with value "connected",
- The TOBA K is not registered to the 5G network: the connection status is requested by ETCS application responded by TOBA K with value "failed".

9.2.4 Results and Observations

The tests were performed successfully, with the following observations and findings:

<u>From Infrastructure Perspective:</u>

In static area without coverage, after restart of AIM and ORC, ATO and ETCS are well registered to OB. When the train moved out of the static area without coverage, ATO and ETCS remained registered. Once the train stopped in the static area with coverage, the 5G modem has attached to the network but RIM and ORC needed to be restarted. TOBA, ATO and ETCS have been restarted. ATO and ETCS have exchanged in parallel.

From Application Perspective:

Web Socket: The test is passed. At startup of ETCS application, the WebSocket session is established automatically. Wireshark traces are saved and shows a consistent exchange. This scenario was repeated for every next ATP tests.

Registration: The ETCS application correctly sends the "register" message and responded by App UID by the TOBA K. The tests are passed both for static and dynamic tests. Wireshark traces are saved and shows a consistent exchange.

Connection Status: The ETCS application checks this status every 2 second after the ETCS application is registered. The tests are successful both for static and dynamic tests. Wireshark traces are saved. They show a consistent exchange.

9.3 Nominal communication in ETCS level 2 (ETCS_WP4-WP5_TC_003 (Procedure 1))

The objective of this test is to verify nominal data transfer test case for ETCS simulations.

9.3.1 Test Architecture

Inheriting from Figure 39, in the following graph we only keep the involved building blocks on the architecture employed for this test.

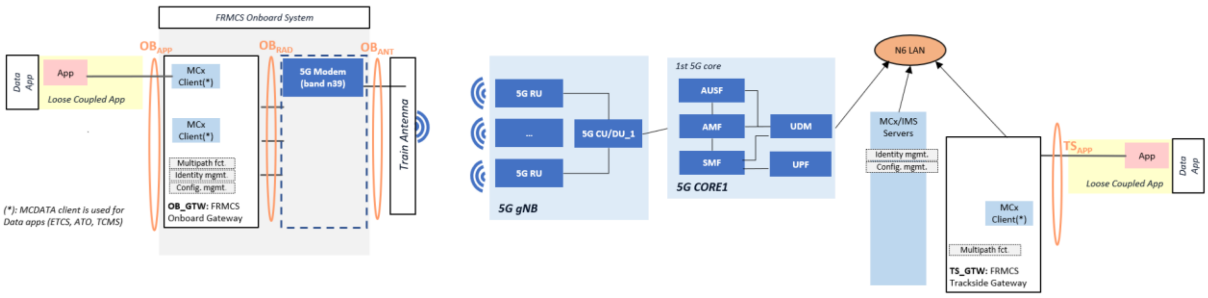


Figure 114: Involved building blocks when testing nominal communication in ETCS L2 (Testbed France)

9.3.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.2.2.3.

9.3.3 Specifics of the Test Implementation and Execution

This test was performed on 23/05/2023. After the WebSocket session establishment, the "session start" message is sent by ETCS application, and an end-to-end communication is established with a trackside simulated RBC (located in Kontron's lab).

9.3.4 Results and Observations

The tests were performed successfully, with the following observations and findings:

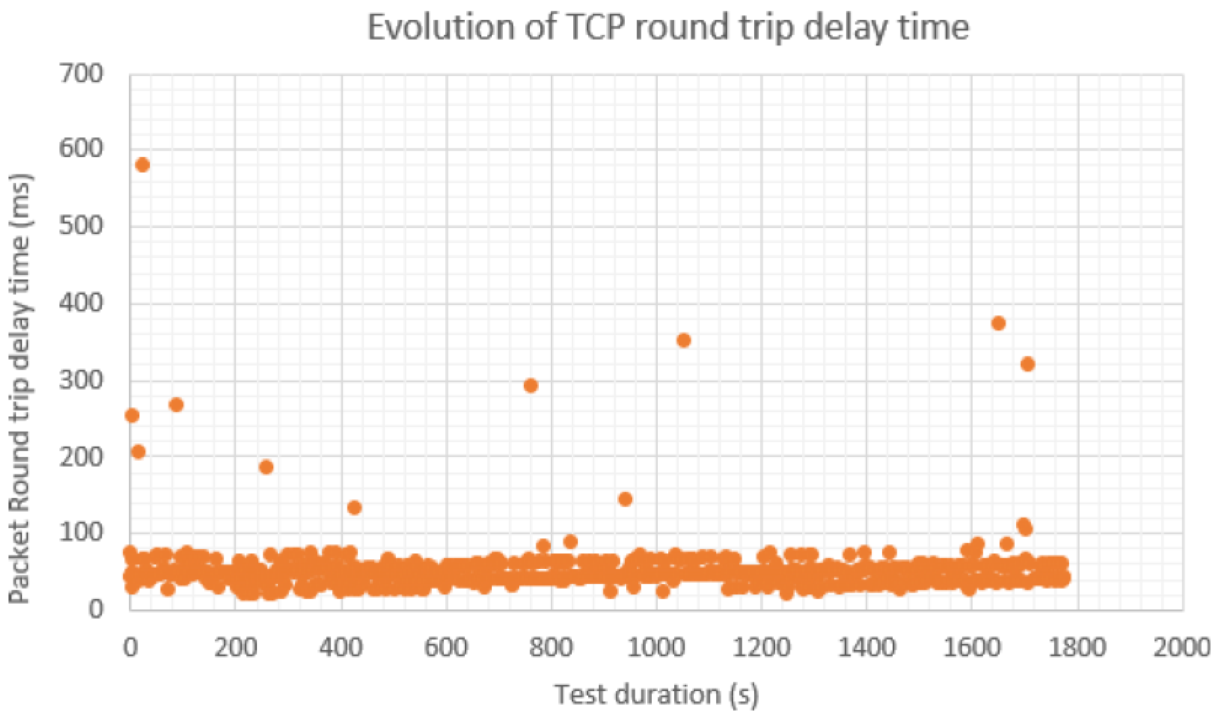
<u>From Application Perspective:</u>

The communication is established, there is no interruption (application data loss) until the loss of 5G signals. This test was passed in both static and dynamic conditions. Wireshark traces are saved and shows a consistent exchange.

The following KPIs have been measured for this test.

- Average round trip delay = 52.5 ms
- Standard deviation Round Trip Time = 35.5 ms
- The values are calculated on 681 samples.

As this test is the nominal case, those values will serve as comparison point for the following tests. Details are depicted in the following figure, where we can discuss some interesting observations.



There are some outliers. We can explain them by TCP retransmissions. Indeed, upon the deeper analysis on the impacted seconds, we noticed that the sender did not receive any ACK for the sent segment, and the timer goes off. In this case, the sender assumes that the sent segment is lost. The sender retransmits the same segment to the receiver and resets the timer.

In practice, TCP retransmissions are perfectly normal and expected if there are not too many. Usually, it should probably be less than 1% of your TCP segments that get retransmitted. In our case, we noticed 11 outliers out of 681 samples, which is far less than 1%.

9.4 RBC handover on the same 5G network (ETCS_WP4-WP5_TC_003 (Procedure 2))

The objective of this test to simulate RBC Handover (ETCS Transition) on the same 5G network (unique network).

9.4.1 Test Architecture

Inheriting from Figure 39, in the following graph we only keep the involved building blocks on the architecture employed for this test.

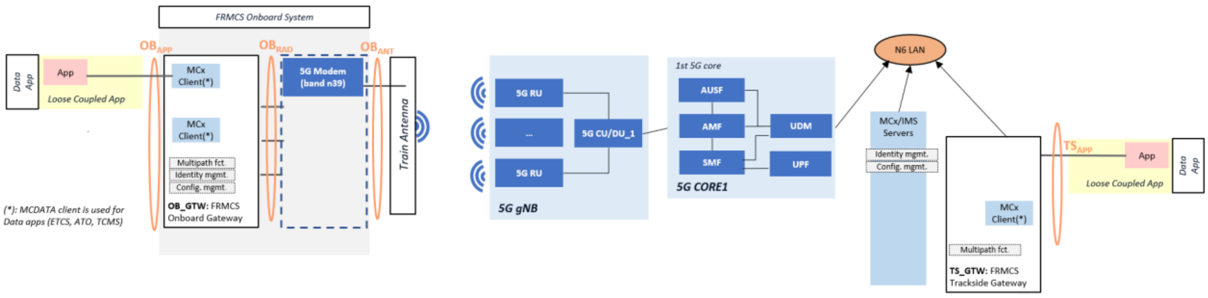


Figure 115: Involved building blocks when testing RBC HO for ETCS on same 5G network (Testbed France)

9.4.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.2.2.3.

9.4.3 Specifics of the Test Implementation and Execution

This test was performed on 06/06/2023. The trackside gateway is configured with two RBC registered. The ETCS application request the establishment of an end-to-end the first trackside simulated RBC1. Then, a balise scenario is loaded in ETCS application to trigger connection request and closure following the below sequence in a loop:

- RBC1 only
- RBC1 + RBC2 in parallel
- RBC2 only
- RBC2 + RBC1

Firstly, this looping scenario runs in static conditions. Then, the train start moving and the RBC transition are performed in dynamic conditions.

9.4.4 Results and Observations

The tests were performed successfully, with the following observations and findings:

From Infrastructure Perspective:

In static area:

- RBC/ETCS TS and OB well registered. Opening of ETCS session.
- Test RBC HO same 5G well done.

In dynamic mode:

- Several HO RBC done on the same BTS (Marin – pci 13)
- Switch of the connection over the BTS of Boubonnais (pci 12)
- RBC HO with BTS HO successfully done.

From Application Perspective:

The communication is established, there is no interruption (application data loss) until the loss of 5G signals. This test was passed in both static and dynamic conditions under a unique BTS (Marin). Wireshark traces are saved and shows a consistent exchange.

9.5 RBC & gNode-B handover on the same 5G network (ETCS_WP4-WP5_TC_003 (Procedure 4))

The objective of this test to simulate RBC Handover (ETCS Transition) and gNode-B Handover (Radio Transition) on the same 5G network.

9.5.1 Test Architecture

Inheriting from Figure 39, in the following graph we only keep the involved building blocks on the architecture employed for this test.

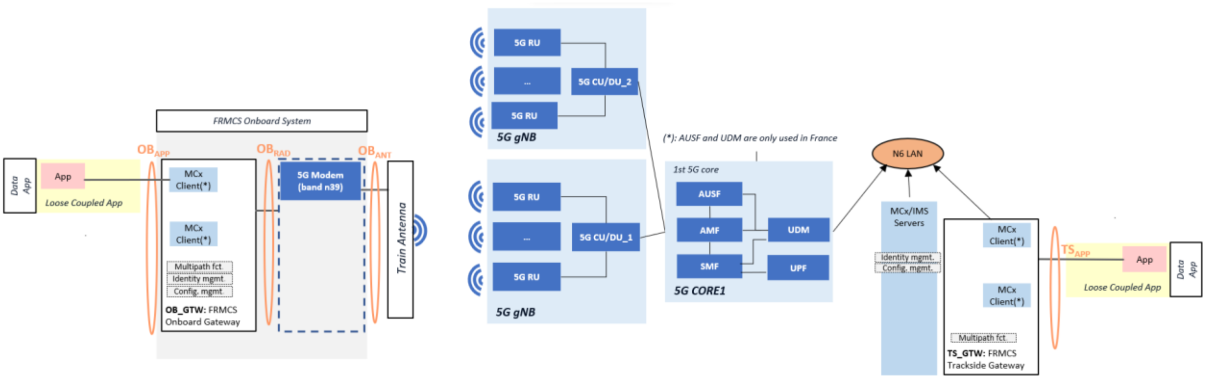


Figure 116: Involved Building Blocks when Testing RBC and intra/inter-gNode-B HO for ETCS (Testbed France)

9.5.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.2.2.3.

9.5.3 Specifics of the Test Implementation and Execution

Intra-gNodeB HO: This test was performed on 06/06/2023 in continuity of the previous test. The trackside gateway is configured with two RBC registered. The ETCS application request the establishment of an end-to-end the first trackside simulated RBC1. Then, a balise scenario is loaded in ETCS application to trigger connection request and closure following the below sequence in a loop:

- RBC1 only
- RBC1 + RBC2 in parallel
- RBC2 only
- RBC2 + RBC1

Firstly, this looping scenario runs in static conditions. Then, the train start moving and goes from BTS1 (Marin pci 13) to BTS2 (Bourbonnais pci 12) and RBC transitions are still performed in parallel.

Inter-gNodeB HO: This test was performed on 07/06/2023. The ETCS application requests the establishment of an end-to-end the first trackside simulated RBC1. The train starts moving and goes from gNB1 (Marin pci 32) to gNB2 (Bourbonnais pci 21).

9.5.4 Results and Observations

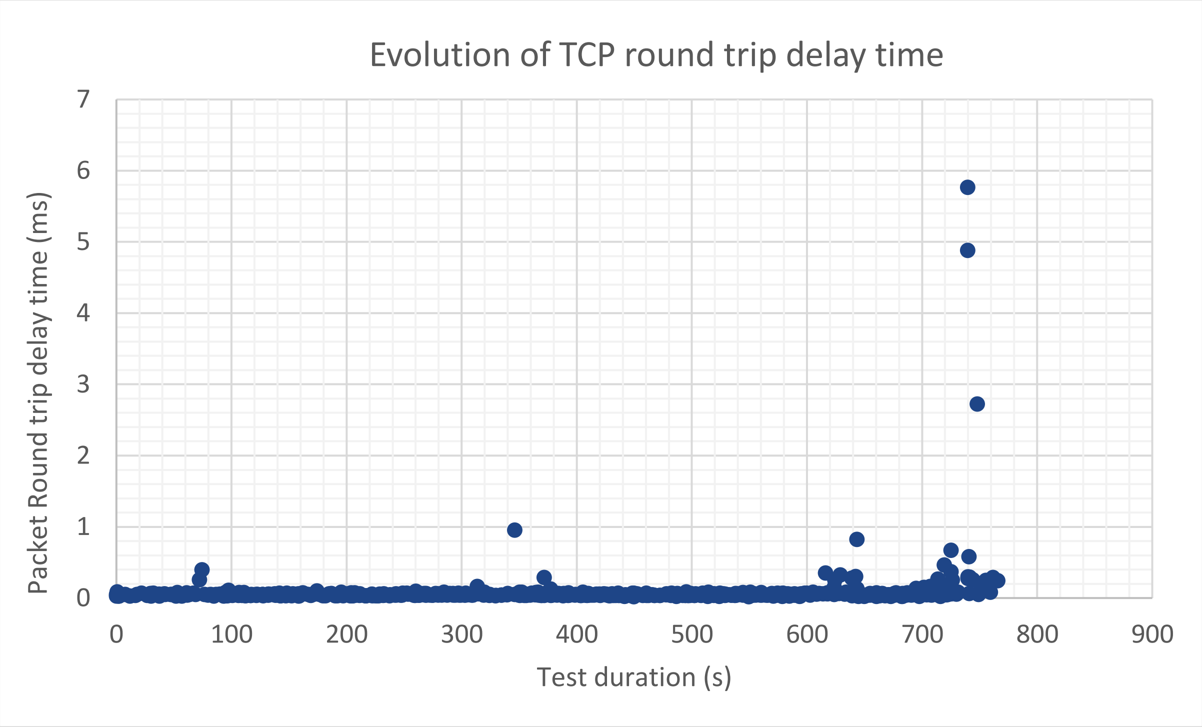
The tests were performed successfully, with the following observations and findings**:**

From Application Perspective:

Intra-gNodeB HO: The communication is established, there is no interruption (application data loss) until the loss of 5G signals. Wireshark traces are saved and show a consistent exchange.

The following KPIs have been measured for this test:

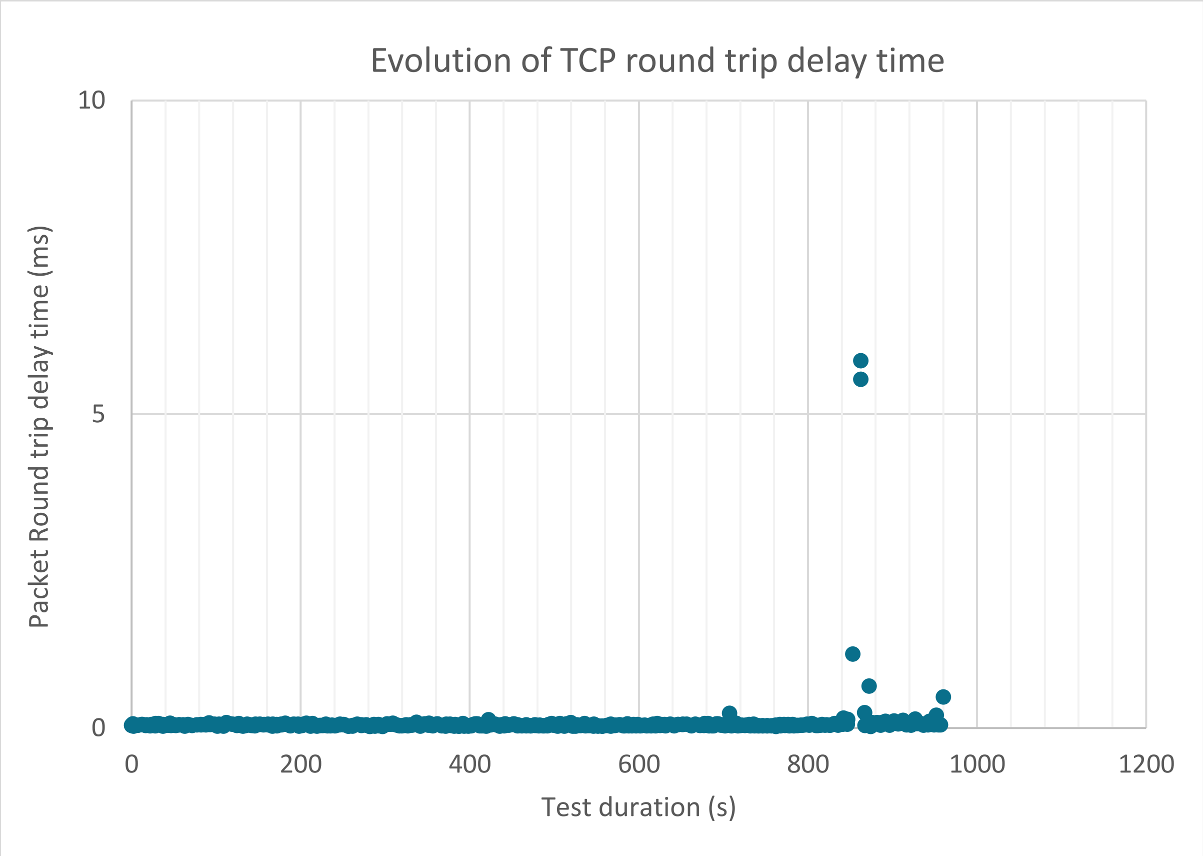
- Average round trip delay = 85.5 ms
- Standard deviation Round Trip Time = 329ms
- The values are calculated on 610 samples.



Inter-gNodeB HO: The communication is established, there is no interruption (application data loss) until the loss of 5G signals. This test was passed in both static and dynamic conditions. Wireshark traces are saved and shows a consistent exchange. During this test, both ATO and ATP were using the same network with dedicated communications in parallel.

The following KPIs have been measured for this test:

- Average round trip delay = 89,1ms
- Standard deviation Round Trip Time = 417.55ms
- The values are calculated on 377 samples.



10 ATO Tests (using MCDATA) – Testbed France

10.1 List of Functional Test Cases

The ATO test cases performed within the French WP5 trials have been selected among D1.1 chapter 8.3 [2]. This selection has been performed by WP5 consortium, according to the feasibility in the French site test, or the added value compared with lab test. The list of selected test cases for ATO in WP5 is given in the table below. In total, three groups of application tests have been successfully conducted. These are:

- **ATO simulation between onboard and trackside**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
10.2	ATO_OBapp	OBapp Integration Test Procedures • Check the health of the link between ATO and TOBA - The WebSocket status is correct • Check the registration and the connection status – Registration • Check the connection status
10.3	ATO_TC_003	Nominal communication between the ATO-onboard and the ATO-Trackside applications

- **Mobility Scenarios (Transitions on ETCS App. Simulator)**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
10.4	ATO_TC_005	ATO in nominal conditions performing intra gNodeB HO
10.5	ATO_TC_006	ATO in nominal conditions performing inter gNodeB HO
10.6	ATO_TC_007	ATO in radio degraded conditions

- **Combined ETCS and ATO simulations**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
10.7	ATO_ETCS-TC_009	ETCS on board combined with ATO application

All tests have been performed both in static (stationary) conditions, i.e., at a fixed location in the tracks (where a coverage is granted), and in dynamic (driving) conditions, i.e., during train runs in the 5GRAIL Testbed France between the stations of *Villeneuve St. Georges* and *Juvisy* during the dynamic tests, the application continuity within intra- and inter-gNB handover situations has been tested.

10.2 OBapp Integration Test Procedures (ATO_OBapp)

The purpose of this test is to check if the local binding, registration and connection status are correct between the ATO application and the FRMCS OB_{APP} Server (TOBA)

10.2.1 Test Architecture

Inheriting from Figure 39, in the following graph we only keep the involved building blocks on the architecture employed for this test.

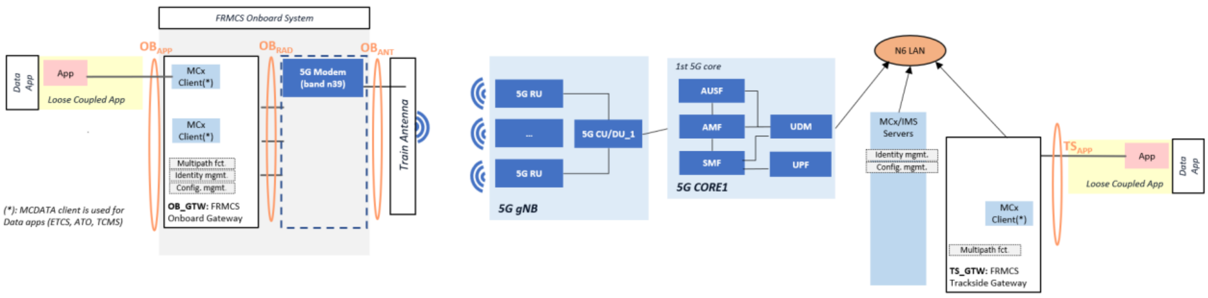


Figure 117: Involved OBapp and TSapp Interface (circled in light red) for ATO app. integration (Testbed France)

10.2.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.3.1.1 and 8.3.1.2. There are two parts:

- ATO_OBapp-TC_001: Check the health of the link between ATO and the TOBA
- ATO_OBapp-TC_002: Check the registration and the connection status.

10.2.3 Specifics of the Test Implementation and Execution

The pre-requirements for the initial state/configuration are as follows:

- The ATO equipment are installed and configured
- FRMCS Gateway is connected and configured to ATO equipment
- The ATO-Trackside equipment is connected and configured
- The ATO-onboard equipment is connected and power on in nominal state

10.2.4 Results and Observations

10.2.4.1 ATO_OBapp-TC_001: Check the health of the link between ATO and the TOBA

The tests were performed successfully, with the following observations and findings**:**

Step	Action	Expected result(s)	Compliance with selected Requirements	Obtained Result(s) in field
01	Open the WebSocket	No error returned	D2.1 TOBA Architecture Report – OBapp – Loose coupled interface	**23/05/2023** **At the ATO application level, the logs are checked to be sure there are no errors and that the local binding is correctly established.**
02	Check the status	The status indicates that the WebSocket is correctly opened		
03	Close the WebSocket			
04	Check the status	The status indicates that the WebSocket is not opened		

10.2.4.2 ATO_OBapp-TC_002: Check the registration and the connection status.

The tests were performed successfully, with the following observations and findings:

Step	Action	Expected result(s)	Compliance with selected Requirements	Obtained Result(s) in field
01	Open the WebSocket Check the status	The status indicates that the WebSocket is correctly opened	D2.1 TOBA Architecture Report -v2– OBapp – Loose coupled interface - FRMCS_GTW_REGISTER	**23/05/2023** **Logs indicates that the WebSocket is correctly opened**
02	Register the ATO-Onboard and ATO-Trackside Application	Check the registration answer with reference to the FRMCS_GTW_REGISTER function. The GTW must return a new local ID (app_uuid) unique chosen by itself if the request is succeeded. The parameter is of type ‘String’. The expected call flow will be compared with 3GPP TS33.180 Figure 5.1.1-1		**23/05/2023** **Logs indicates that the registration is properly performed**

03	Check the connection status based on the FRMCS_GTW_SERVICE_REQUEST	The connection status is OK, means that connection status = connected, in the application logs.	D2.1 TOBA Architecture Report -v2– OBapp – Loose coupled interface - FRMCS_GTW_SERVICE_REQUEST	**23/05/2023** **Logs indicates that the returned status is “CONNECTED” when the network is ready**
04	Check the duration of the registration process (i.e. from the sending of the REGISTER request until the answer to the REGISTER request), as a KPI	A value is provided based on measurements of Wireshark traces		**23/05/2023** **Duration: 17ms**

10.3 ATO in nominal conditions (ATO_TC_003)

The purpose of this test is to check that the communication between the ATO-OB and the ATO-TS is provided by the 5G network during the test.

10.3.1 Test Architecture

Inheriting from Figure 39, in the following graph we only keep the involved building blocks on the architecture employed for this test.

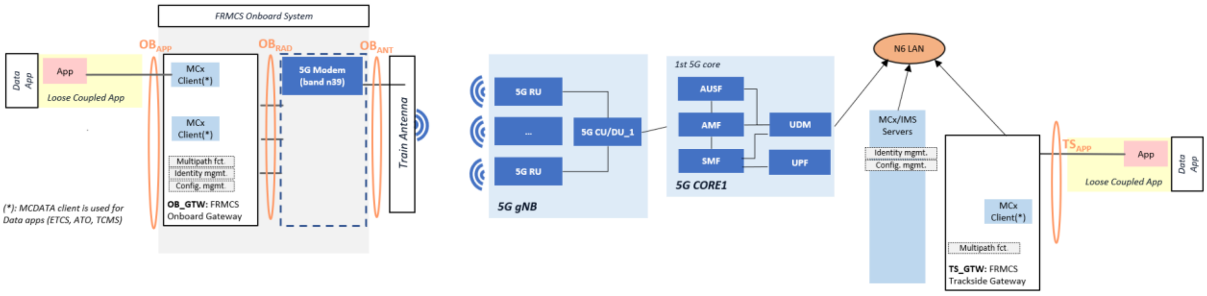


Figure 118: Involved building blocks when testing nominal communication in ATO (Testbed France)

10.3.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.3.1.3.

10.3.3 Specifics of the Test Implementation and Execution

The pre-requirements for the initial state/configuration are as follows:

- The ATO equipment are installed and configured
- FRMCS Gateway is connected to ATO equipment and configured
- The ATO-Trackside equipment is connected and configured
- The ATO-onboard equipment is connected and power on in nominal state

10.3.4 Results and Observations

The tests were performed successfully, with the following observations and findings**:**

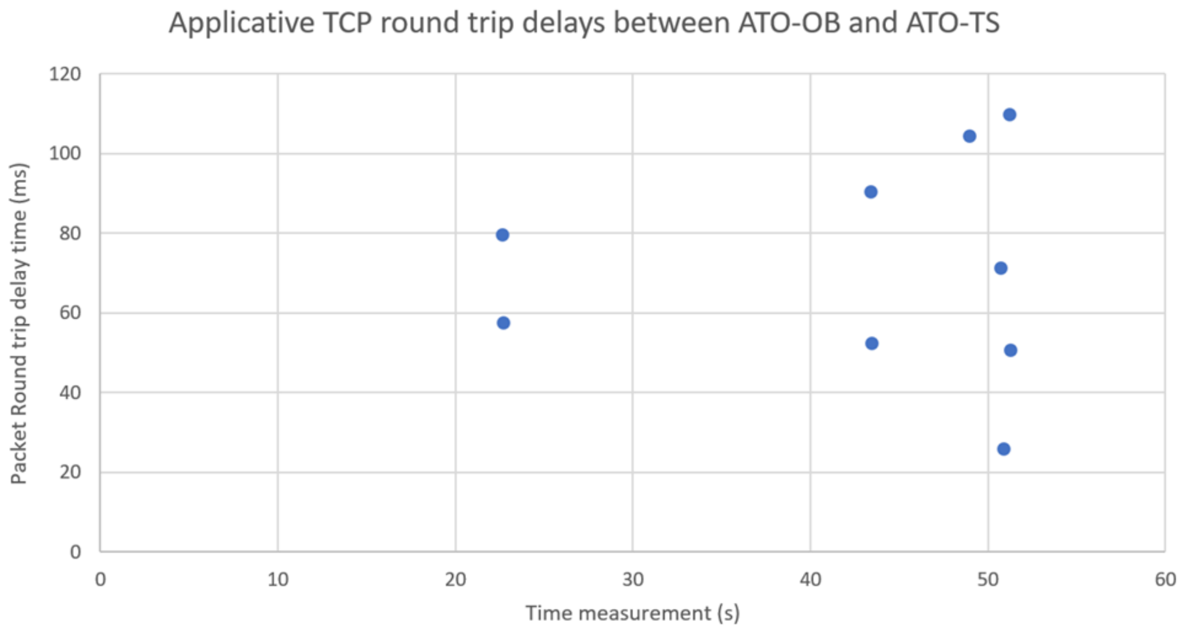
<table>
<tr><th>Step</th><th>Action</th><th>Expected result(s)</th><th>Compliance with selected Requirements</th><th>Obtained Result(s) in field</th></tr>
<tr><td>01</td><td>Establishment of a new session for communication (session start message)</td><td>The FRMCS GTW is correctly answering OK with the expected session ID</td><td rowspan="3">D2.1 TOBA Architecture Report v3– OBapp – Loose coupled interface – FRMCS_GTW_SESSION_START and FRMCS_GTW_SESSION_END</td><td rowspan="3">23/05/23

At the ATO application level, the logs are checked to ensure that:
The FRMCS GTW returns a valid session ID
The ATO polls the FRMCS GTW by sending connection status request until the returned status is “connected”
The ATO-OB and ATO-TS exchange applicative data like the HSReq, HSAck, etc.</td></tr>
<tr><td>02</td><td>Check that the FRMCS GTW is still responding to the connection status request until the session status (sent by the FRMCS GTW) is “Working”</td><td>The content of the session status “working” message (session ID) is correct</td></tr>
<tr><td>03</td><td>Check that the user plane communication is established by performing a TCP dump.</td><td>The data is properly transfer</td></tr>
</table>

The following KPIs have been measured for this test:

- Min-Max RTD: 26 ms – 110 ms
- Mean RTD: 71 ms
- Std deviation RTD: 28 ms
- Average round trip time: 89,7 ms

Further details can be observed in the following figure:


Applicative TCP round trip delays between ATO-OB and ATO-TS
Packet Round trip delay time (ms)
Time measurement (s)
0
20
40
60
80
100
120
0
10
20
30
40
50
60

10.4 ATO in nominal conditions performing intra gNodeB HO (ATO_TC_005)

The purpose of this test is to evaluate the impact of intra gNodeB HO in the performance of the ATO application. So, during the test, there would be a change of cells within the same gNode-B and simultaneously perform:

- Establishment of the communication,
- Transfer of data,
- And termination of the communication

10.4.1 Test Architecture

Inheriting from Figure 39, in the following graph we only keep the involved building blocks on the architecture employed for this test.

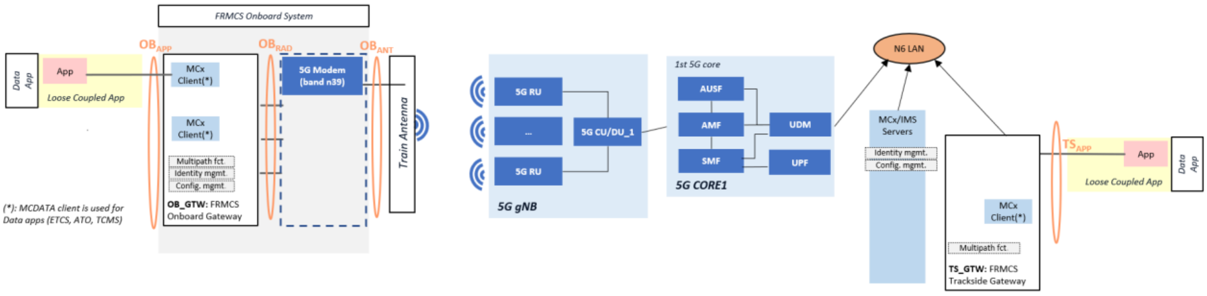


Figure 119: Involved building blocks when testing ATO during an intra gNodeB HO (Testbed France)

10.4.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.3.3.

10.4.3 Specifics of the Test Implementation and Execution

The test is performed with TOBA in band n39. The pre-requirements for the initial configuration/ state are as follows:

- The configuration set-up is presented in terms of radio is given in the figure below, with two 5G cells in n39. In case of intra gNodeB HO, one ME1210 equipment can host the 5Gcore and CU/DU managing the two Rus (two cells)
- 2nd cell is off, so that the On-board GTW is connected to the 1st cell

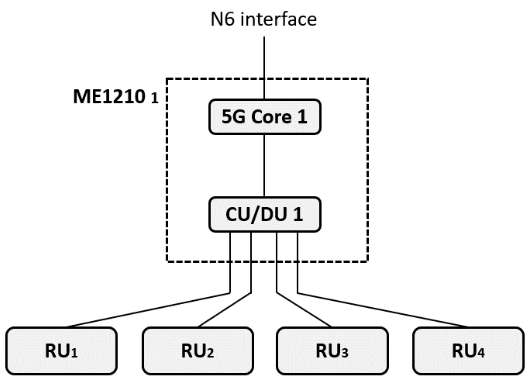


Figure 120: Configuration for intra gNodeB HO under the same 5G Core (Ref.D4.2 [10])

10.4.4 Results and Observations

The tests were performed successfully, with the following observations and findings**:**

The result is satisfactory for ATO application as the response time remained below the STR timeouts. See additional details below:

Step	Action	Expected result(s)	Compliance with selected requirements	Obtained Result(s) in field
01	Launch all softs: by opening the cmd files Start_5GRAIL_OB and Start_5GRAIL_TE	All applications are going to open (ATO_CE simulator, ATO_PROBE, SS130, SS139, SS126, ATO_SLOW, ATO_FAST, DO, ATO_REPLAY, ATO_TS)	**[FU- 7100 v5.0.0]**: 6.20.1, 6.20.2, 6.20.4, 6.20.5. 8.3.1, 8.3.2, 8.3.4, 8.3.5 8.4.1, 8.4.2, 8.4.4, 8.4.5 8.12.1, 8.12.2, 8.12.4, 8.12.5 **3GPP TR22.889 V17.4.0:** 12.9.3, 12.9.5, 12.10.2.5,	**24/05/2023** **ATO logs show that the HSReq is correctly sent to the ATO-TS** **As applicative KPI, the time between the emissions of the STRs and the receptions of the STRAcks has been measured. It is observed that this time varies between 56.682ms and 141.819ms along the whole run (which included an intra and an inter gNodeB). The mean value is 89ms and the**
02	In the scenario, an establishment of a new session is performed by sending a 'session start' message. Go to the application ATO_REPLAY and load the scenario TEST_5G.STrm then launch it	If everything is OK, ATO_On-Board will send a handshake request to the ATO trackside. If not, nothing will happen		
3	After successful establishment of the ATO-OB session and end of reception of journal	Check on the CU/DU of the gNodeB that intra-gNodeB HO has been performed		

	profile and segment profile, the 2nd 5G cell is switched on and progressively the radio power of the 1st cell is manually decreased			**standard deviation is 21ms, showing a negligeable impact on the KPI.** **(Note: these measures were filtered to remove an outlier (2502ms) occurring because of TCP retries)**
04	Compare the log with the logs of the nominal conditions test case	Verify the impact, if any, on the application KPIs, as defined in the steps of the ATO nominal conditions		

10.5 ATO in nominal conditions performing inter gNodeB HO (ATO_TC_006)

The purpose of this test is to evaluate the impact of inter gNodeB HO in the performance of the ATO application. So, during the test, there would be a change between two gNodeBs and simultaneously perform:

- Establishment of the communication,
- Transfer of data,
- And end of the communication

10.5.1 Test Architecture

Inheriting from Figure 39, in the following graph we only keep the involved building blocks on the architecture employed for this test.

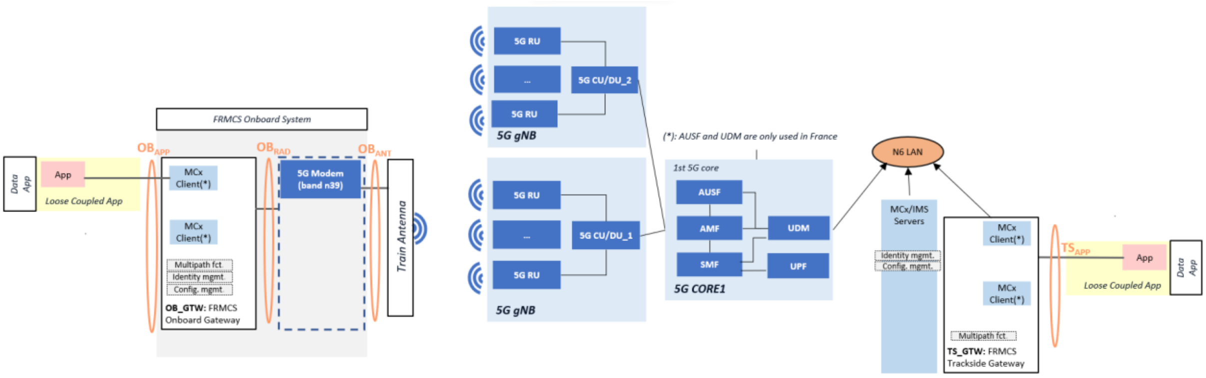


Figure 121: Involved building blocks when testing RBC and intra-/inter-gNodeB HO for ATO (Testbed France)

10.5.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.3.4.

10.5.3 Specifics of the Test Implementation and Execution

The test is performed with TOBA in n39 band. The pre-requirements for the initial state / configuration are as follows:

- The configuration set-up makes use of two 5G gNodeBs in n39 band. In case of inter gNodeB HO under the same 5Gcore, two Kontron ME1210 equipment are needed, as presented in the below figure. This is because, as explained in D4.1 and D4.2, ME1210 can host only one 5Gcore and one CU/DU together. In case a 2nd CU/DU is needed as per inter gNodeB HO, a 2nd ME1210 is required
- 2nd gNodeB is off, so that the On-board GTW is connected to the 1st gNodeB

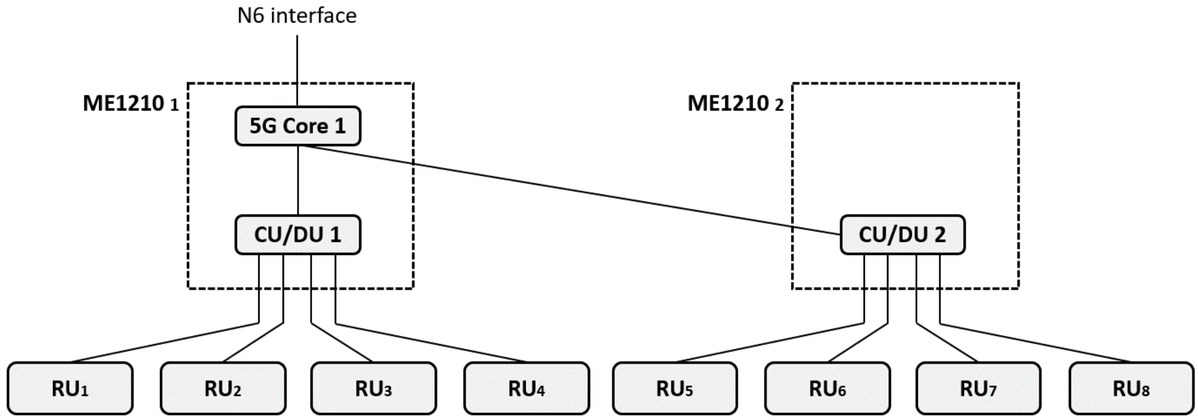


Figure 122: Configuration for inter gNode-B HO under the same 5G Core (Ref.D4.2 [10])

10.5.4 Results and Observations

The tests were performed successfully, with the following observations and findings:

The result is satisfactory for ATO application as the response time remained below the STR timeout. See additional details below:

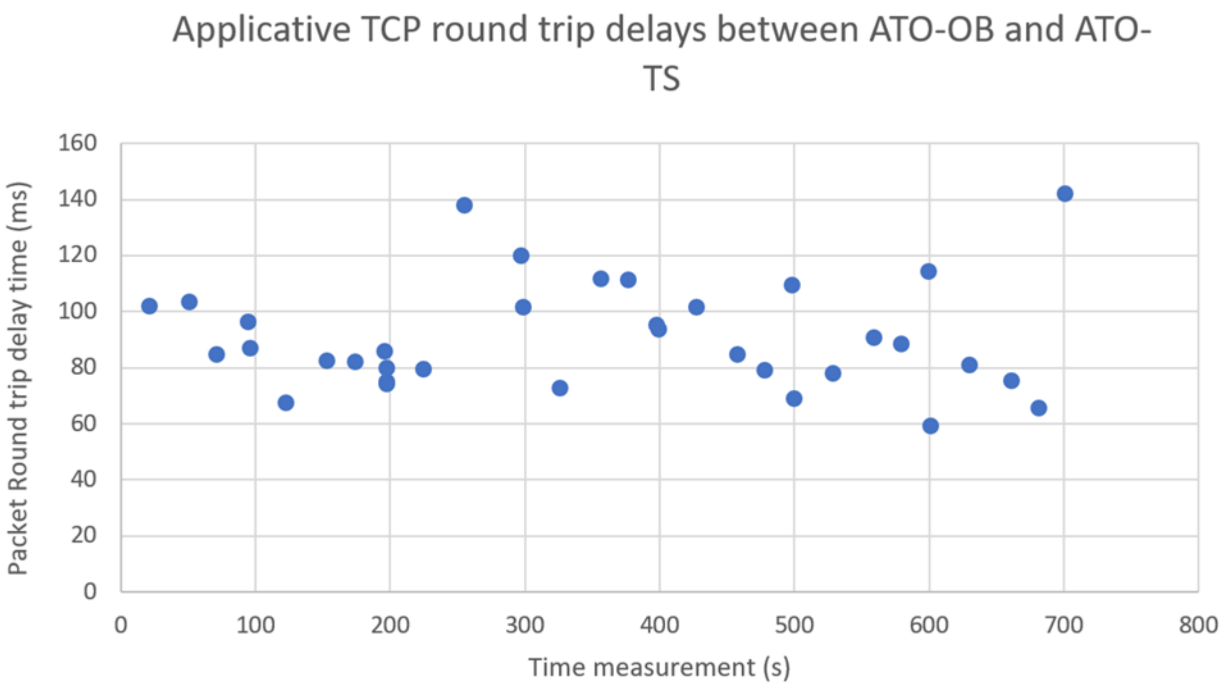
Step	Action	Expected result(s)	Compliance with selected Requirements	Obtained Result(s) in field
01	Launch all softs: by opening the cmd files Start_5GRail_OB and Start_5GRail_TE.	All applications are going to open (ATO_CE simulator, ATO_PROBE, SS130, SS139, SS126, ATO_SLOW, ATO_FAST, DO, ATO_REPLAY, ATO_TS)	**[FU- 7100 v5.0.0]**: 6.20.1, 6.20.2, 6.20.4, 6.20.5. 8.3.1, 8.3.2, 8.3.4, 8.3.5 8.4.1, 8.4.2, 8.4.4, 8.4.5 8.12.1, 8.12.2, 8.12.4, 8.12.5 **3GPP TR22.889 V17.4.0:** 12.9.3, 12.9.5, 12.10.2.5,	**24/05/2023** **ATO logs show that the HSReq is correctly sent to the ATO-TS** **As applicative KPI, the time between the emissions of the STRs and the receptions of the STRAcks has been measured. It is observed that this time varies between 56.682ms and 141.819ms along the whole run (which included an intra and an inter gNodeB).**
02	In the scenario, an establishment of a new session is performed by sending a 'session start' message. Go to the application ATO_REPLAY and load the scenario TEST_5G. STrm then launch it	If everything is OK, ATO_On-Board will send a handshake request to the ATO trackside. If not, nothing will happen		
04	During the ATO data transfer, the 2nd gNodeB is turned on and progressively the	Check that inter-gNodeB HO has been correctly performed		

	radio power of the 1st gNode B is manually decreased.			**The mean value is 89ms and the standard deviation is 21ms, showing a negligeable impact on the KPI.** **(Note: these measures were filtered to remove an outlier (2502ms) occurring because of TCP retries)**
05	Compare the log with the logs of the nominal conditions test case	Verify the impact, if any, on the application KPIs, as defined in the steps of the ATO nominal conditions		

The following KPIs have been measured for this test:

- Min-Max RTD: 57 ms – 142 ms
- Mean RTD: 89 ms
- Std deviation RTD: 21 ms

Further details can be observed in the following figure:



10.6 ATO in radio degraded conditions (ATO_TC_007)

The purpose of this test is to check that the communication between ATO on-board and ATO trackside is not operationally impacted by the degraded conditions. To compare the time between the moment, we transmit the messages from the ATO on-board to the ATO trackside in normal condition and degraded conditions.

10.6.1 Test Architecture

Inheriting from Figure 39, in the following graph we only keep the involved building blocks on the architecture employed for this test.

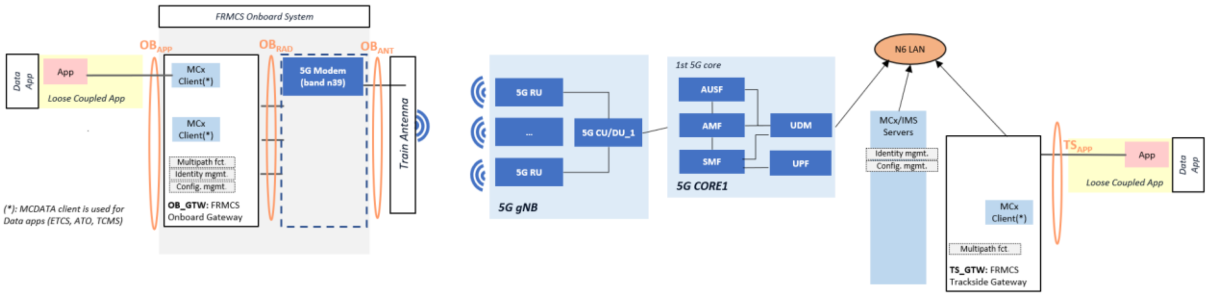


Figure 123: Involved building blocks when testing ATO in degraded radio conditions (Testbed France)

10.6.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.3.5.

10.6.3 Specifics of the Test Implementation and Execution

The test is performed with TOBA in n39 band.

10.6.4 Results and Observations

The tests were performed successfully, with the following observations and findings**:**

The result is satisfactory for ATO application as the response time remained below the STR timeout. Radio degradation would not cause the ATO to mis-operate as long as this time is lower than the related configurable timeout value.

Step	Action	Expected result(s)	Compliance with selected Requirements	Results
01	Launch all softs: by opening the cmd files Start_5GRail_OB and	All applications are going to open (ATO_CE simulator, ATO_PROBE, SS130, SS139, SS126,	**[FU- 7100 v5.0.0]**: 6.20.1, 6.20.2, 6.20.4, 6.20.5. 8.3.1, 8.3.2, 8.3.4,	**24/05/2023** **At the end of the run made the 24/05/2023, a**

	Start_5GRail_TE.	ATO_SLOW, ATO_FAST, DO, ATO_REPLAY, ATO_TS,	8.3.5 8.4.1, 8.4.2, 8.4.4, 8.4.5 8.12.1, 8.12.2, 8.12.4, 8.12.5 **3GPP TR22.889 V17.4.0:** 12.9.3, 12.9.5, 12.10.2.5,	**communication loss occurred, allowing to match the condition of this test. From the ATO logs, it was noticed that some TCP retries occurred before properly sending the STRs, leading to a KPI equal to 2502ms.**
02	In the scenario, an establishment of a new session is performed by sending a 'session start' message. Go to the application ATO_REPLAY and load the scenario TEST_5G. STrm, then launch it	If everything is OK, ATO_On-Board will send a handshake request to the ATO trackside. If not, nothing will happen		
03	Degraded conditions are created by using the Vertex tool. Check the PROBE and save the log after the end of the test scenario			
04	Compare the log between nominal and degraded conditions	Verify the impact on the application KPIs, as defined in the steps of the ATO nominal conditions		

10.7 ETCS on board combined with ATO application (ATO_ETCS-TC_009)

The purpose of this test is to check the behavior of a nominal data transfer between ETCS on board application and RBC on the same 5G network when another critical data application (e.g., ATO) is transmitting data in parallel using the same FRMCS GW. The following steps will be performed for both applications:

- Establishment of communication:
- Session start
- User plane communication
- End of communication

10.7.1 Test Architecture

Inheriting from Figure 39, in the following graph we only keep the involved building blocks on the architecture employed for this test.

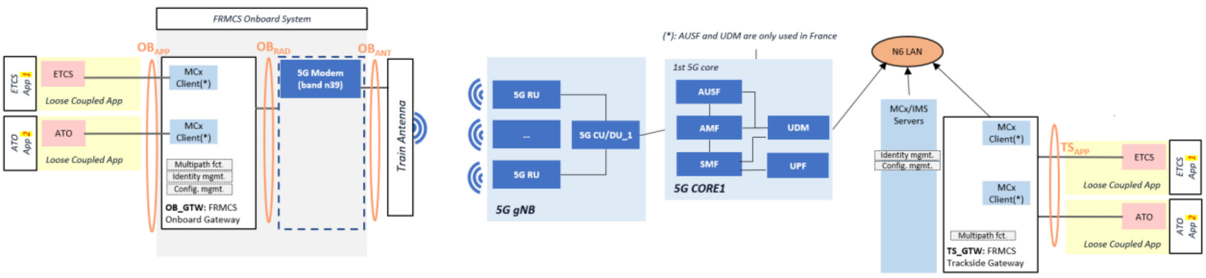


Figure 124: Involved building blocks when testing ETCS combined with ATO application (Testbed France)

10.7.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 8.3.7.

10.7.3 Specifics of the Test Implementation and Execution

The following conditions are fulfilled for both ETCS and ATO applications.

For ETCS:

- ETCS equipment are installed and configured.
- FRMCS Gateway is connected and configured to ETCS equipment and to 5G network.
- ETCS Trackside equipment are connected and configured.
- ETCS onboard and trackside equipment are connected and power on in nominal state.
- The connection status is OK.

For ATO:

- ATO is in GoA2

- ATO-onboard, ATO_REPLAY (TE) and ATO-trackside are installed and configured into the computer for rolling stock.
- FRMCS gateway is connected and configured to the ATO equipment and to the 5G network.
- ATO-onboard and ATO-trackside equipment are connected and power ON in nominal state.

Launch all softs: @ATO-Onboard, @ATO-Trackside and ATO-Replay.

The test is performed with TOBA in n39 band. The comm_profiles used (OBapp/Tsapp API parameter) are ETCS : 10 and ATO : 11.

10.7.4 Results and Observations

The tests were performed successfully, with the following observations and findings**:**

The impact of running two combined applications in average is quite negligeable, i.e., there is only slight increase in ATO round-trip delay by additional ETCS traffic.

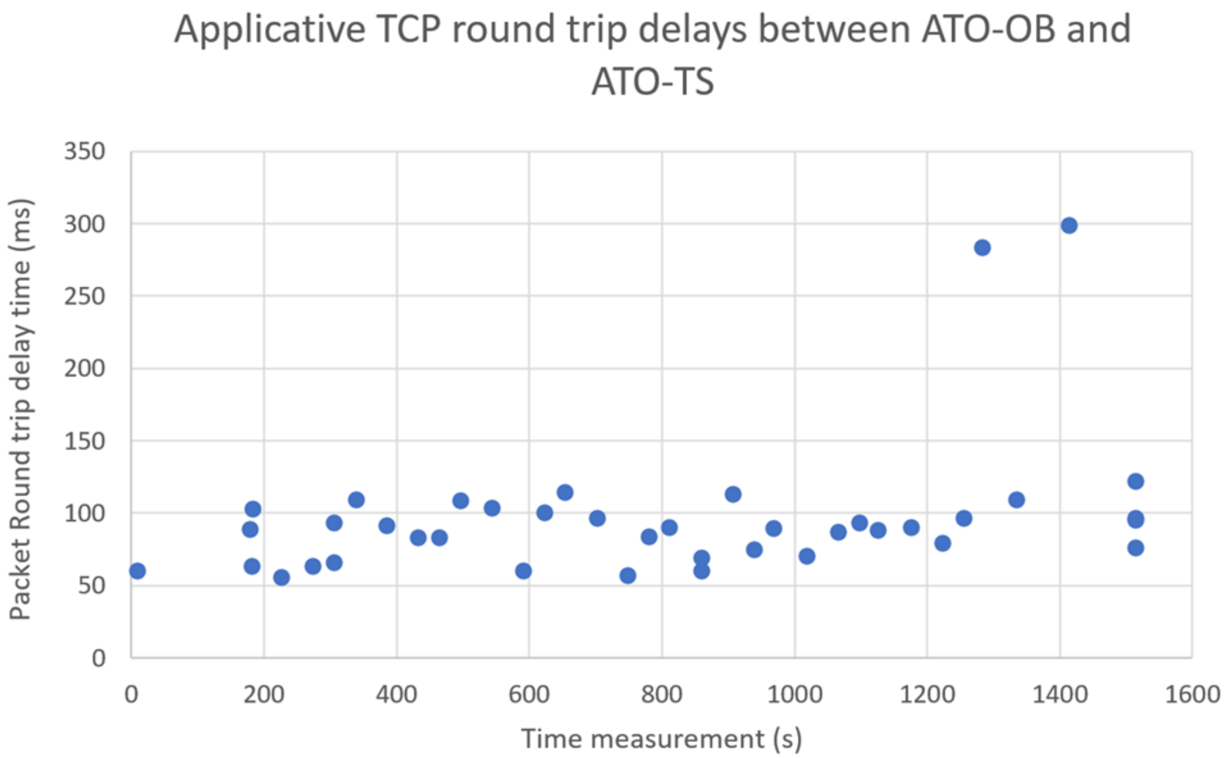
Step	Action	Expected result(s)	Compliance with selected Requirements	Obtained Result(s) in field
01	Establishment of a new session for communication between EVC and RBC (session start message)	The FRMCS GTW is correctly answering OK with the expected session ID and RBC @IP. Check that the FRMCS GTW is sending "working" notification before the timeout (12sec)	D2.1 TOBA Architecture Report– OBapp – Loose coupled interface – FRMCS_GTW_SESSION_START FRMCS_GTW_SESSION_STATUS	**07/06/2023** **ATO logs show that the HSReq, HSAck, JPReq, JP, SPReq and SP are correctly received by the ATO-OB from the ATO-TS.** **As applicative KPI, the time between the emissions of the STRs and the receptions of the STRAcks has been measured.** **It is observed that this time varies between 55.9ms and 10489ms along the whole run. The mean value is 590ms and the standard deviation**
02	Check that the user plane communication is established.	The data transfer is ongoing using the RBC IP		
03	In parallel, start ATO application. Launch all softs: by opening the cmd files Start_5GRail_OB and Start_5GRail_TE	All applications are going to open (ATO_CE simulator, ATO_PROBE, SS130, SS139, SS126, ATO_SLOW, ATO_FAST, DO, ATO_REPLAY, ATO_TS,		

04	Go to the application ATO_REPLAY and load the scenario TEST_5G. STrm then launch it	If everything is OK, ATO_onboard and ATO_Trackside will exchange the following messages: handshake request, Handshake Acknowledgment, Journey profile request and the journey profile, the segment profile request, the status report and status report Acknowledgment Cf: all the message of the nominal test case If not, nothing will happen		**is 2213ms, showing a non-negligeable impact on the KPI.** **However, these measures are due to a single outlier caused by multiple TCP retries occurring at the end of the run. After removing this single outlier, the measures are the following:** • **Min: 55.9ms** • **Max: 298.951ms** • **Mean: 95.422ms** • **Std: 49.705ms** **Therefore, the impact of the ETCS traffic on the KPI is the following:** • **Mean: +7.21%** • **Std: 136.69%**
05	Check that both applications perform properly as in nominal conditions	Check if individual KPIs of both applications in nominal conditions still been respected, or one application is impacted.		
06	Perform an end of communication for both applications (End of simulations)	Check communications are ended		

The following KPIs have been measured for this test:

- Min-Max RTD: 56 ms – 299 ms
- Mean RTD: 95 ms
- Std deviation RTD: 50 ms

Further details can be observed in the following figure:


Applicative TCP round trip delays between ATO-OB and ATO-TS
Packet Round trip delay time (ms)
0
50
100
150
200
250
300
350
0
200
400
600
800
1000
1200
1400
1600
Time measurement (s)

11 Remote Vision Tests (using MCDATA) – Testbed France

The following chapter gives a report about Remote Vision (RV) tests that have been performed in the 5GRAIL Testbed France, operated at 5G band n39. Tests have been performed in Calendar Week 25 of 2023.

The remote vision application is a sub system of the remote driving system (RDS). For the sake of integrity, we elaborate the details of the whole remote driving system which includes the remote vision application and to the remote driving desk.

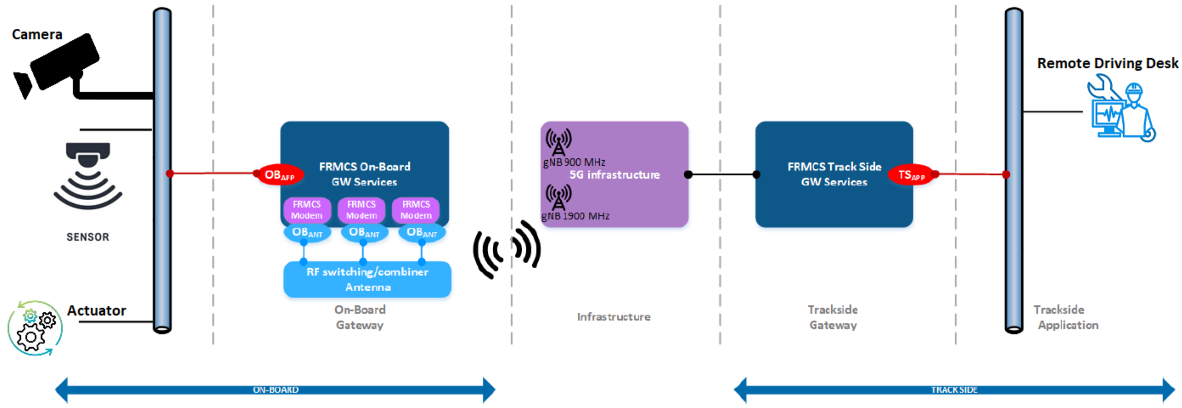


Figure 125: Global architecture of the remote driving system in the FRMCS

The RDS has two parts: (i) on-board and (ii) trackside one. The logical diagrams of the two parts are depicted in the following figures.

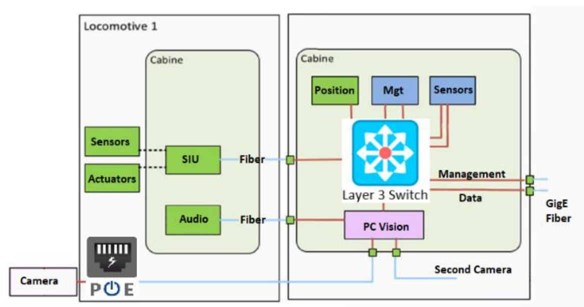


Figure 126: RDS onboard logical diagram

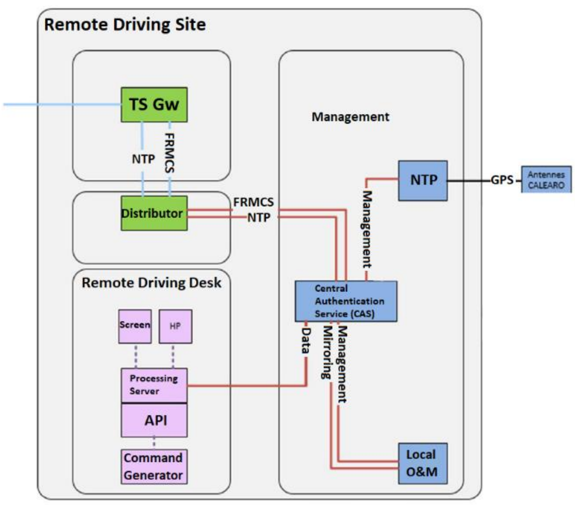


Figure 127: RDS trackside logical diagram

The onboard part includes a camera, a Power-over-Ethernet (PoE) module, a Specific Interface Unit (SIU) to concentrate sensors (Uplink: Moving Stock--Back-End) and actuators (Downlink: Back-End—Moving Stock), along to an audio input to provide a complete user-experience including video and voice.

Moreover, the SIU is connected through fiber optic cables to a Layer-3 (L3) switch, which also concentrates multiple blocks including positioning input, bidirectional management, additional sensors, and most importantly, a PC vision block. The PC vision block aggregates camera(s) inputs along to audio one and feed it to the L3 switch to transport the data and management streams using the transport stratum. This is where the remote vision application runs.

Figure 128: Frontal camera of the remote vision application (Testbed France)

On the second hand, the trackside counterpart is depicted in Figure 127. It has a distributor to separate the FRMCS flow and synchronization data using NTP to a central authentication service (CAS), where another NTP source from a GPS antenna is fed, too. The data output from this CAS is fed into the remote driving desk for control and command. See deliverable D2.1 [4] for additional details.

11.1 List of Functional Test Cases

Two kinds of application tests have been successfully conducted. These are:

- **Remote Vision Testing in different conditions**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
11.2	RV_WP5-TC_001	Remote control of Engines in different conditions: streaming of video from moving stock to trackside • under-exposure / over-exposure, • rainfall / early morning: before sunrise

- **Combined Remote Vision and ETCS simulations**

Chapter	Test Case No. (acc. to D1.1)	Test Case Label
11.3	RV_ETCS_WP5_TC_002	Combined Remote Vision and ETCS in field conditions

11.2 Remote control of Engines in different conditions: streaming of video from moving stock to trackside (RV_WP5-TC_001)

The objective of the following test cases is to validate that the FRMCS provides sufficient quality for the remote vision application. Remote vision is part of the remote control of Engine use case.

It is worthy to note that the remote control of Engine is of strategic interest for railways as it provides economic savings for the operation. For instance, it is very interesting in case of (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.

11.2.1 Test Architecture

The following figure depicts the simplified architecture showing only the building blocks involved during the test of Remote Vision application.

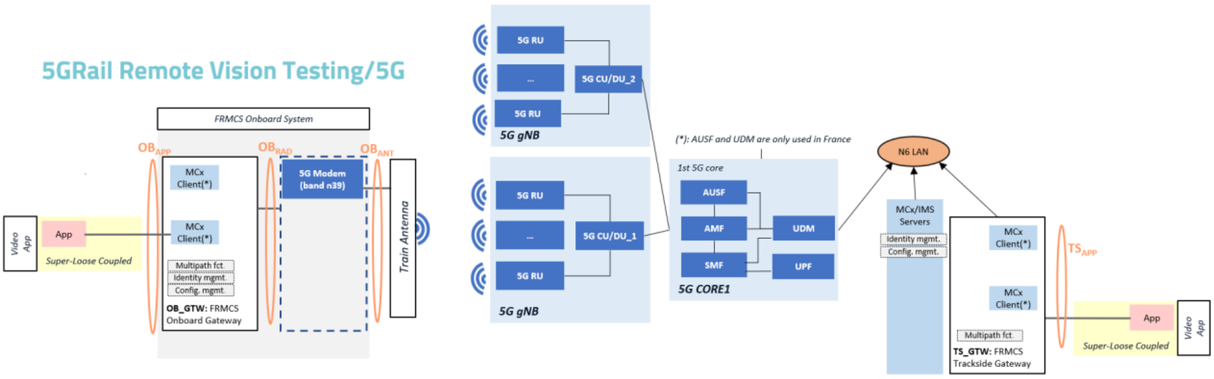


Figure 129: Involved Building blocks when testing Remote Vision as a Stand-Alone Application (Testbed France)

11.2.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 13.3.3.

11.2.3 Specifics of the Test Implementation and Execution

In this test, several scenarios were accomplished to test the remote vision application as a standalone application to be able to establish a baseline during the dynamic runs.

Moreover, the onboard codecs bitrate was adjusted from 1 Mbps to 2.5 Mbps during the runs to be able to stress the network and assess its impact. The objective was to verify if an aggressive increase of demand in term of bitrate would cause an impact on other concurrent critical applications.

11.2.4 Results and Observations

The tests were performed successfully, with the following observations and findings:

The result is satisfactory for Remote Vision application. This is confirmed because different configurations were tested including forcing higher bitrate on the onboard codecs and experimenting a further degraded radio condition during run (uncontrollable rainfall).

We report in the following table, some impressions and comments observed during each train run campaign covering different scenarios such as: under-exposure, over-exposure, uncontrollable rainfall and during early morning (before sunrise).

<table>
<tr><th>When</th><th>Parameter Settings and Comments</th></tr>
<tr><td>20/06/2023

Run 1 at 10h00

Juvisy RB →

VON GA</td><td>Video Bitrate start at 1 Mbps, then switch to 2.5 Mbps (on min. 51).
We can see the increase in term of instant bitrate on the following graph.

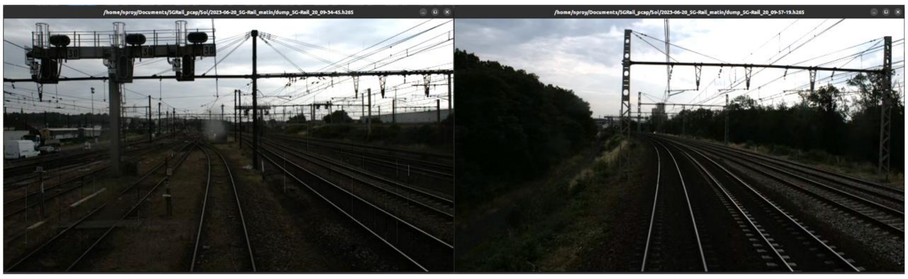



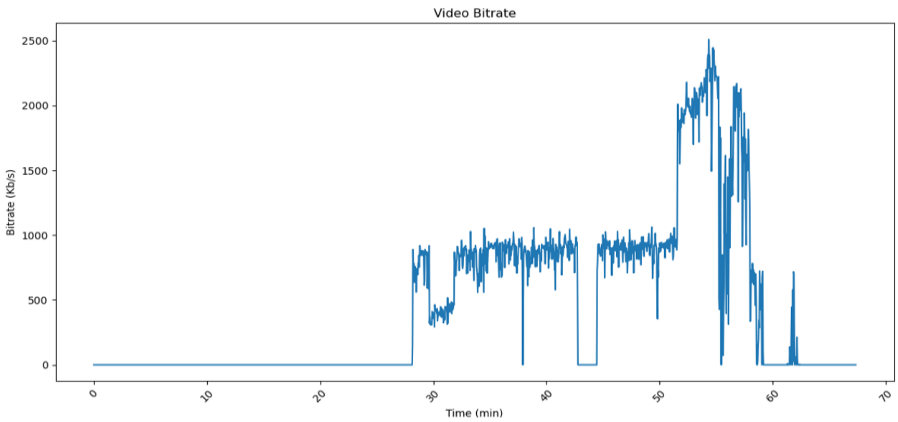
Figure 130: Impressions of remotely viewed images (under-exposure on camera)


Figure 131: Instantaneous bitrate from the RV application metrics (1 Mbps to 2.5 Mbps)

The flow was rather consistent during this attempt. Few packets were lost while the link was up and running, except for a short disruption at min. 42 above.

Later a test was conducted at 2.5 Mbps (starting min. 51), which went well until the complete network outage upon reaching the VON GA (non-covered area by 5G). The adaptive video codec took more than 2 minutes to reach the targeted 2.5Mbps due to conservative video parameters and are not linked with the actual network capacity.</td></tr>
<tr><td>20/06/2023

Run 2 at 10h45</td><td>Video Bitrate start at 2.5 Mbps</td></tr>
</table>

<table>
<tr>
<td>VON GA →
Juvisy RB</td>
<td>

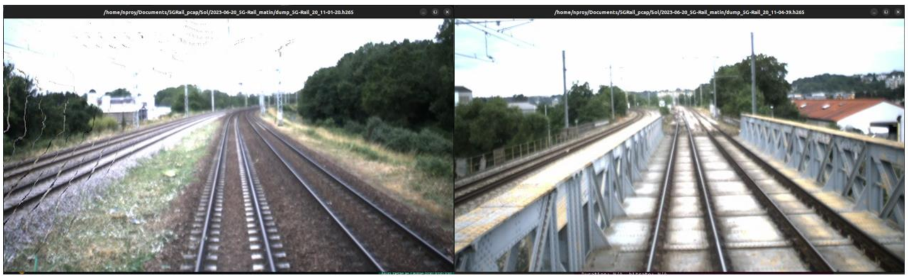


Figure 132: Impressions of remotely viewed images (Over-exposure on camera)

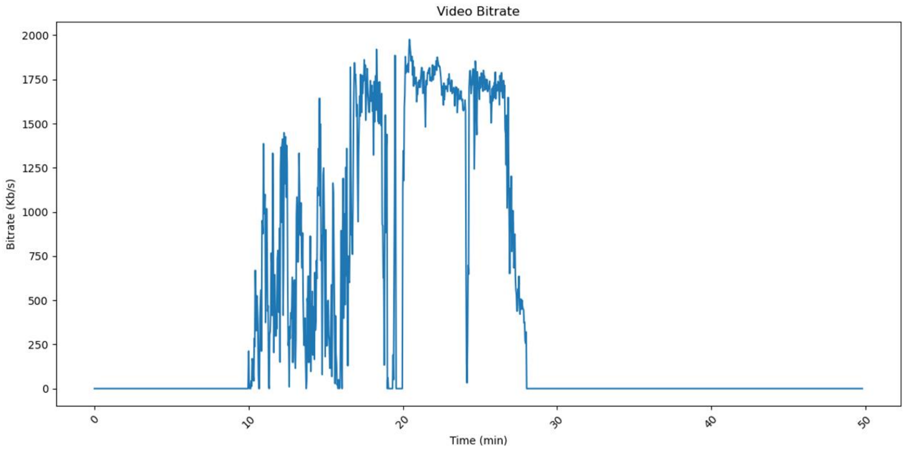


Figure 133: Fluctuating bitrate from the RV application metrics (adaptation in codecs)

The network performance was very poor in the first part of the run due to the lack of coverage. Packet losses were very high with a strong impact on video. For the second half, when under coverage (after min. 20), video stabilized. Accordingly, it is possible to obtain good video quality on the track side.

</td>
</tr>
<tr>
<td>20/06/2023

Run 3 at 11h30

Juvisy RB →
VON GA</td>
<td>

Video Bitrate over complete run at **2.5 Mbps**

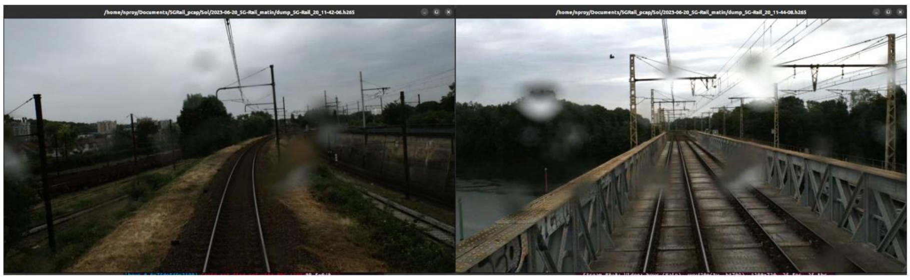


Figure 134: Impressions of remotely viewed images (rainfall) (almost no impact)

</td>
</tr>
</table>

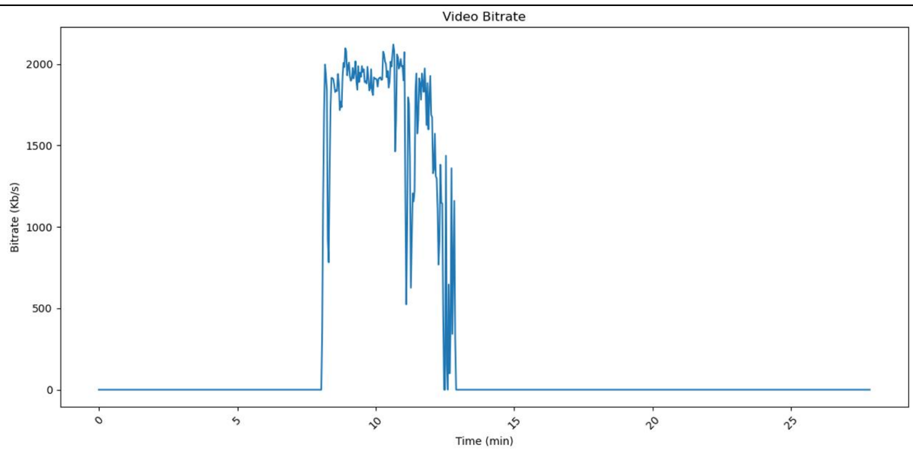
<table>
<tr>
<td></td>
<td>


Figure 135: Almost stable bitrate from the RV application metrics (decrease when out of coverage)

The first part of the run was successful with a good application bitrate. However, the network was lost during the second half of the run (when out of coverage). We can notice the rain droplets on the lenses of the frontal camera. This was one of the uncontrollable factors that affect dynamic runs and would potentially impact the radio conditions.
</td>
</tr>
<tr>
<td>
22/06/2023

Run 2 at 6h40

Juvisy RB →
VON GA
</td>
<td>
Video Bitrate start at 1 Mbps, then switching to 2.5 Mbps

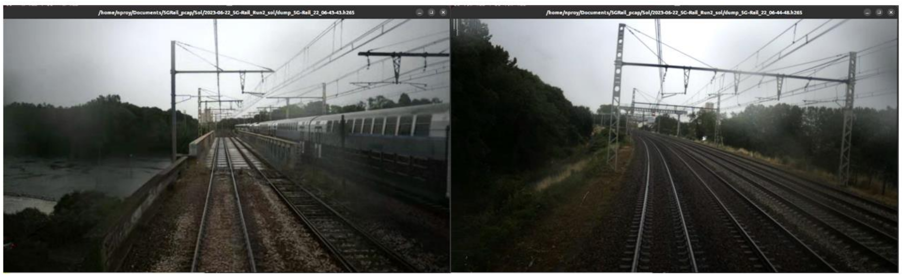


Figure 136: Impressions of remotely viewed images (early morning: before sunrise)

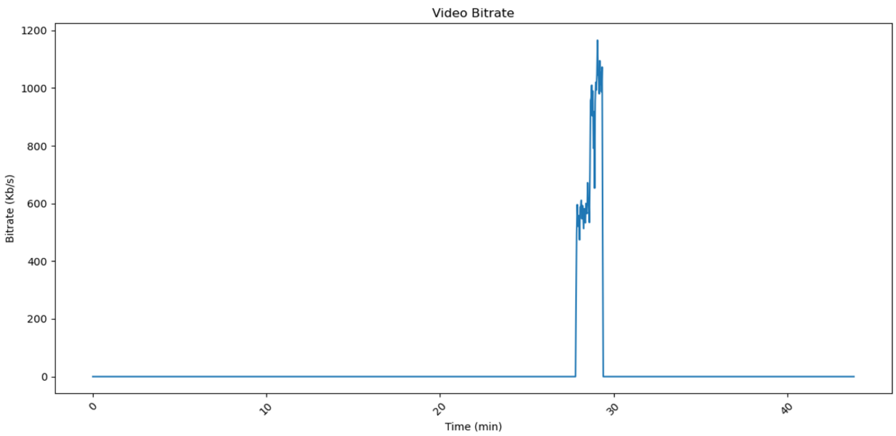


Figure 137: Instantaneous bitrate from the RV application metrics (when getting out of coverage: going beyond the 3rd and final radio site: site 3)
</td>
</tr>
</table>

	In this run, the video quality was compliant with remote driving throughout the first part of the run (when under coverage). However, it never reached the 2.5Mbps defined as target. There was a disruption starting from the second screenshot capture.

As a conclusion: Tests results are satisfactory. The performance is only impacted by the network condition and the limited coverage knowing that it is not covering the whole train run journey.

11.3 Combined Remote Vision and ETCS in field conditions (RV_ETCS_WP5_TC_002)

The objective of the following test case is to validate that the remote vision application can coexist with other critical application without impact on the quality. For this, Remote Vision application that is bitrate greedy was tested with another heterogeneous critical app that is ETCS requiring low latency but also low bitrate.

11.3.1 Test Architecture

The following figure depicts the simplified architecture showing only the building blocks involved during the test of Remote Vision application combined with ETCS.

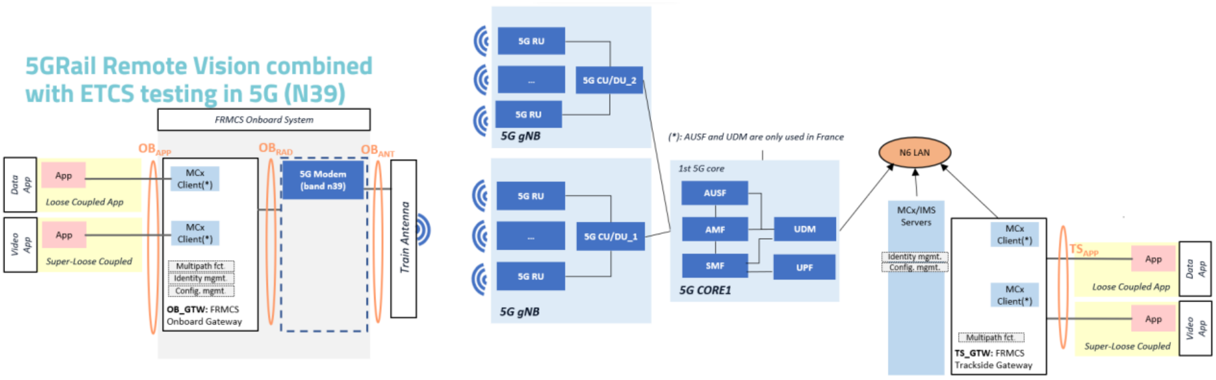


Figure 138: Involved Building blocks when testing Remote Vision combined with ETCS application (Testbed France)

11.3.2 Detailed Test Plan

The test plan is described in Deliverable D1.1v4 – Section 13.3.4.

11.3.3 Specifics of the Test Implementation and Execution

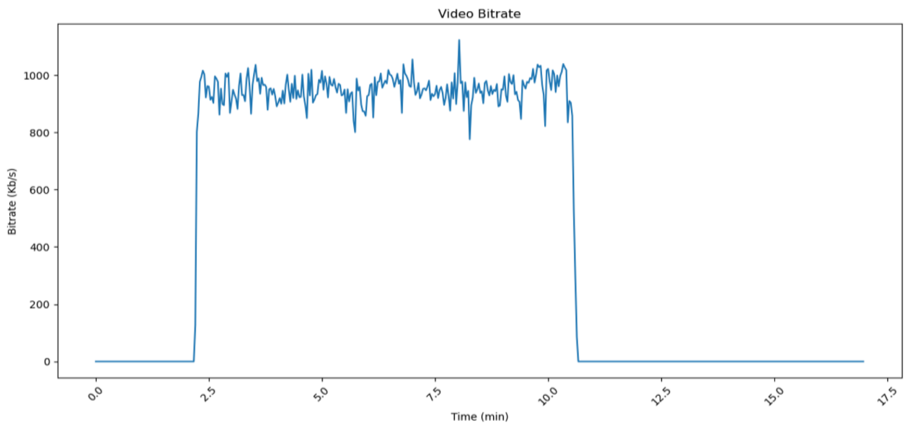
In this test, an ETCS communication is established in parallel with Remote Vision data transmission. It was performed on the 20/06/2023.

The goal is to check if both services can work in nominal case using the same network without impact on each other.

11.3.4 Results and Observations

The tests were performed successfully, with the following observations and findings**:**

RTD performance KPI remained in the same order of magnitude when combined the remote vision application with the ETCS application, we can say that the test is satisfactory.

When	Parameter Settings and Snapshots
22/06/2023 Run at 14h57 Juvisy RB → VON GA	Video Bitrate over complete run at **1 Mbps**  *Figure 139: Impression of remotely viewed images (when combined with ETCS)*  *Figure 140: Instantaneous bitrate from the RV application metrics (stable ~1 Mbps)*

<u>From Remote Vision Application Perspective:</u>

During the first part of the run, this test was the one of the best rendered video qualities on the trackside. We can say that there is no impact on the Remote Vision application performance from bitrate perspective.

<u>From ETCS Simulator Application Perspective:</u>

For this test, the Remote Vision communication was established before the ETCS communication.

From ETCS perspective, the focus is rather on the latency and not on the bitrate, unlike the remote vision app. In this context, firstly, a test is executed in static condition with two different video data rates to establish a “baseline” for the subsequent runs in dynamic conditions (where the train will move along the tracks). The ETCS communication remains active, and no applicative data is lost.

The following KPIs have been measured for this second baseline test:

- Average round trip delay = 48.3ms
- Standard deviation Round Trip Time = 216ms
- The values are calculated on 205 samples.

Then, the test is executed in dynamic conditions. The ETCS communication remains active, but we observed some data loss when approaching the Marin antenna area.

Interestingly, the following KPIs have been measured for this test:

- Average round trip delay = 67.06ms
- Standard deviation Round Trip Time = 230.13ms
- The values are calculated on 287 samples.

To analyze these results, in the following figure, we compare obtained results with nominal standalone ETCS application testing in dynamic conditions, elaborated in Section 9.3.4. We can see that the RTD for the ETCS when combined with the remote vision application remains in the same order of magnitude in both static and dynamic conditions compared to the baselines (normal conditions for ETCS in stand-alone or when combined in static conditions).

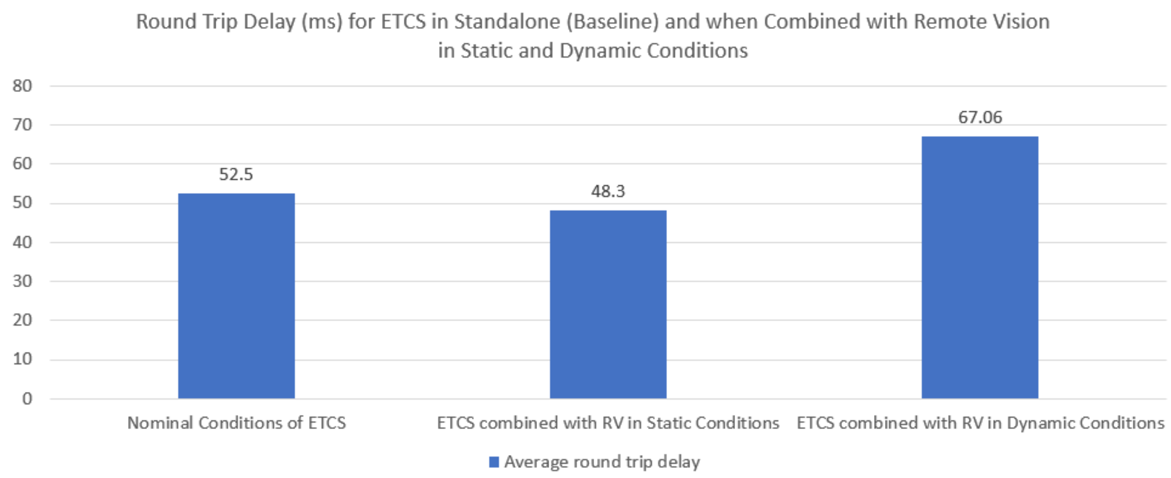


Figure 141: Average Round Trip Delay [ms] benchmarking for ETCS and Remote Vision (Testbed France)

As a bottom line: Tests results are satisfactory. The performance is only impacted by the network condition and the limited coverage knowing that it is not covering the whole train run journey.

12 CONCLUSIONS

In the 5GRAIL project comprehensive field test campaigns on FRMCS functions and performance (WP5 Task 5.2) have been performed, with 6 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 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;
- 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 the 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);

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 tests on FRMCS performance w.r.t. 5G/MCX and functional application level have been carried out as an end-to-end validation.

They were successfully performed in stationary and dynamic (drive test) modes, including intra- and inter-gNB handovers in the 5G network, for the following cases:

- **Voice calls over FRMCS/5G via MCPTT client:**
  - Point-to-Point calls between cab radio and dispatcher
  - Group calls within FRMCS groups and mixed FRMCS / GSM-R groups
  - Railway Emergency Calls (REC)

- Railway Emergency Calls (REC) with GSM-R interworking
- GSM-R (2G) to FRMCS (5G) system transition with service continuity[1]

- **Data calls over FRMCS/5G via MCData client:**
  - ETCS / ATP simulation between on-board EVC and trackisde RBC
  - ETCS / ATP simulation with RBC handover(s)
  - TCMS simulation between on-board MCG and trackside GCG
  - ATO simulation

- **Real-time and non-critical video over FRMCS/5G via MCData client:**
  - Remote vision application as part of the remote driving system (RDS)
  - Live video streaming (on-board to trackside) with different resolutions
  - CCTV file offload (on-board to trackside)
  - CCTV file offload with inter-frequency transition over two 5G bearers, incl. change of TDD patterns[1]

- **Heterogeneous applications over FRMCS/5G via multiple MCx clients**:
  - Combined voice calls and live video streaming
  - Combined ETCS and TCMS simulations
  - Combined ETCS and ATO simulations
  - Combined ETCS simulation and remote vision application

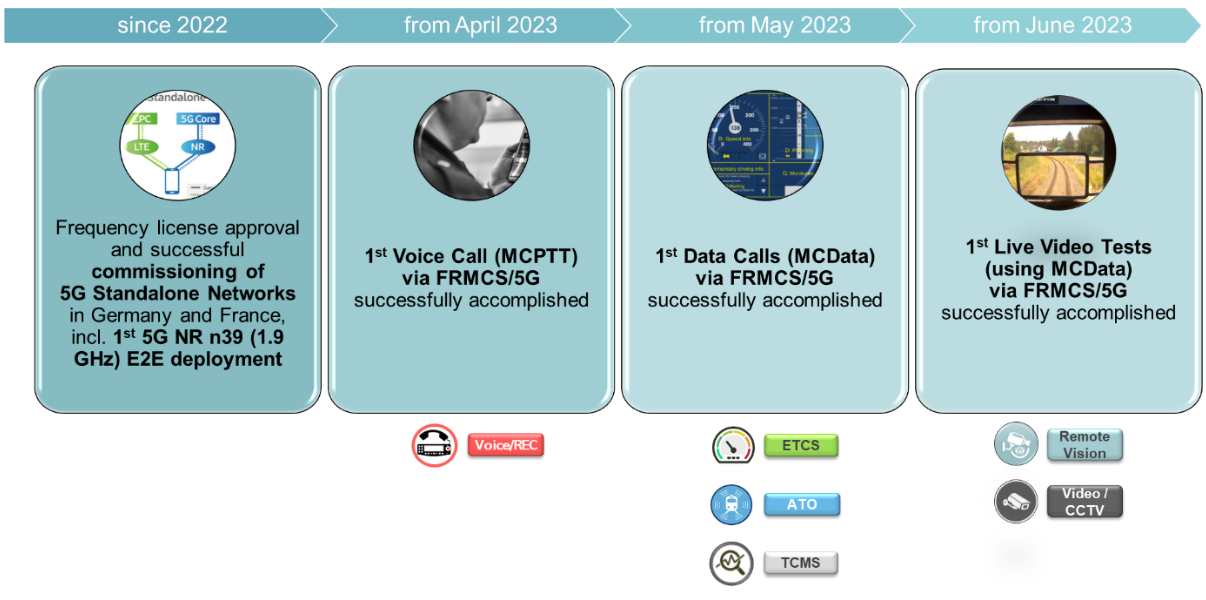


Figure 142: Timeline and achievements of WP5 field trials on FRMCS functions and performance

[1] Test case is part of WP5 Task 5.3 but listed here for completeness, see also deliverable D5.2

Figure 142 summarizes the 5GRAIL achievements in the field. For the voice and data applications with smaller bitrates (as typical for the most relevant applications in digital rail operations), the achieved latencies in the 5G TDD based FRMCS test networks and packet errors on application level have been low, allowing sufficient QoS. This was also true for combined data application scenarios.

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

The field trials 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 support to improve the upcoming FRMCS specifications and can deliver guidelines for enhanced evaluation and validation in future field experiments of FRMCS network performance and for the functional application level. The field trials do not serve as a reference for final operations or to derive final principles for radio deployment. For this, further developments on FRMCS equipment, both on 5G, MCX and application side, is needed.

13 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]	FRMCS Use Cases	UIC MG-7900 (v2.0.0)
[13]	FRMCS Principle Architecture	UIC MG-7904 (v0.3.0)
[14]	FRMCS Telecom On-board System – Functional Requirements Specification (TOBA FRS)	UIC TOBA-7510 (v1.0.0)
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[27]	Mission Critical Services Common Requirements (MCCoRe), Stage 1 (Release 17)	3GPP TS 22.280 (v17.7.0)
[28]	Mission Critical Data services, Stage 1 (Release 17)	3GPP TS 22.282 (v17.0.0)
[29]	Mobile Communication System for Railways, Stage 1 (Release 17)	3GPP TS 22.289 (v17.0.0)
[30]	Study on Future Railway Mobile Communication System, Stage 1 (Release 16 & Release 17)	3GPP TR 22.889 (v17.4.0) 3GPP TR 22.889 (v16.6.0)
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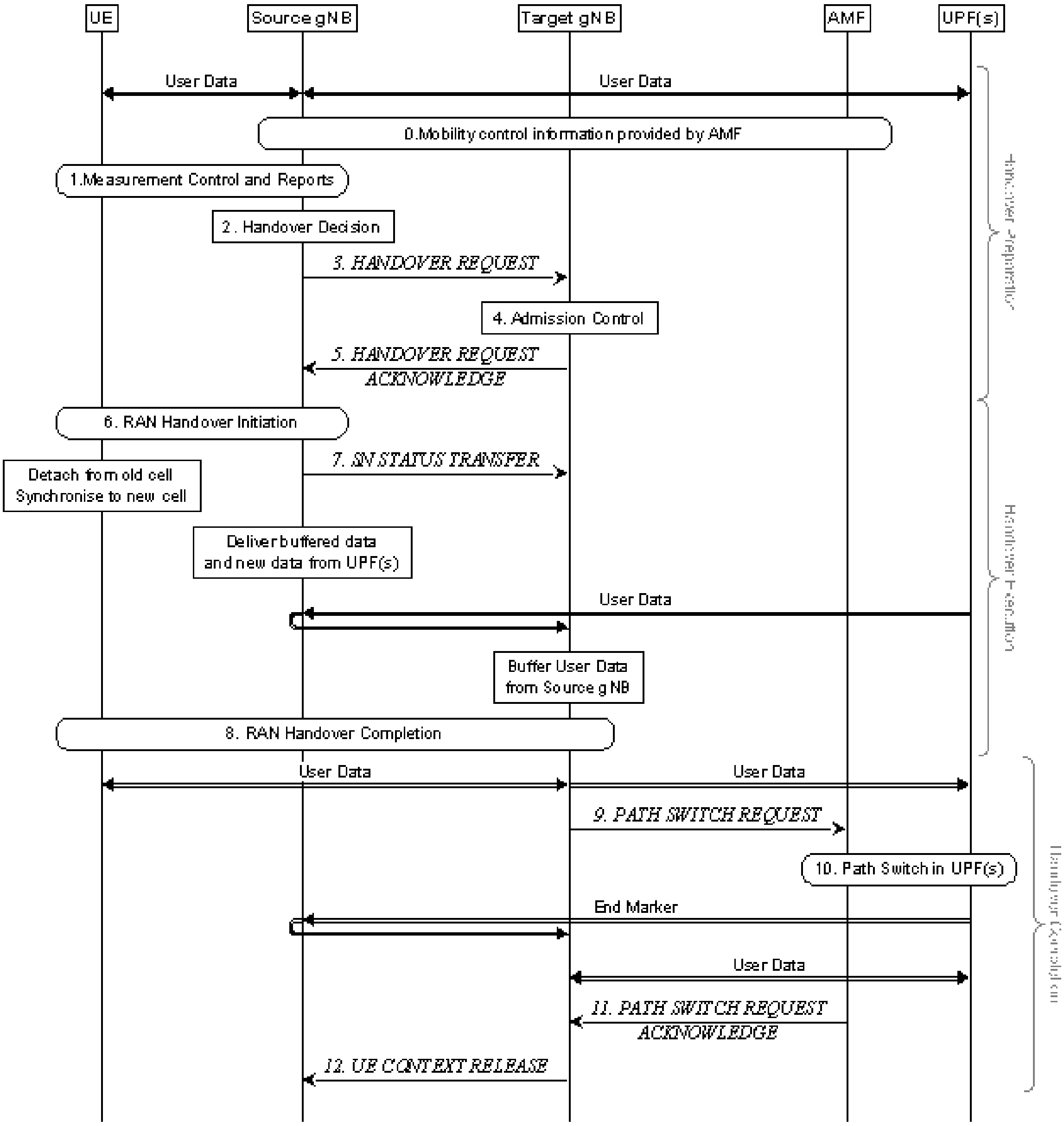
14 APPENDICES

14.1 Inter-gNB Intra-AMF Handover Scheme in 3GPP Release 15

3GPP defines the steps which are part of an Inter-gNB Inter-AMF HO procedure as follows [31]:



14.2 5G NR TDD Pattern Definition

The 3GPP NR specification provides flexible TDD frame structures. At the base station side, the number of uplink and downlink slots may be almost arbitrarily configured within the TDD frame periodicity. A guard period, when switching from downlink transmission to uplink transmission, is implemented in the special slots, which are configured with a combination of suitable uplink, and downlink symbols, interjected with a flexible number of silent symbols (or guard symbols).

The TDD frame structure configurations in NR are often described as, e.g., DDDSU or DDDSUUDDDD, where D or U indicate slots where downlink-only or uplink-only symbols are transmitted, respectively. S is the special slot which, in turn, consists of 14 symbols, and is often described as, for example, 4:6:4, which indicates that the first 4 symbols in the special slot S are downlink, the following 6 are silent, and the last 4 symbols are uplink. [36]

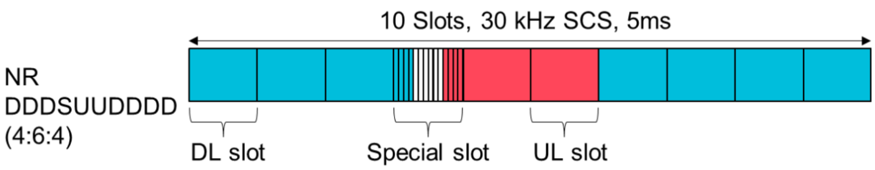


Figure 143: Example of a 5G NR TDD frame pattern with DL, UL and Special slots

Another way of describing the TDD UL-DL slot configuration is to provide the following parameters as defined in [32]:

- dl-ul-TransmissionPeriodicity
- nrofDownlinkSlots
- nrofDownlinkSymbols (in special slot)
- nrofUplinkSlots
- nrofUplinkSymbols (in special slot)

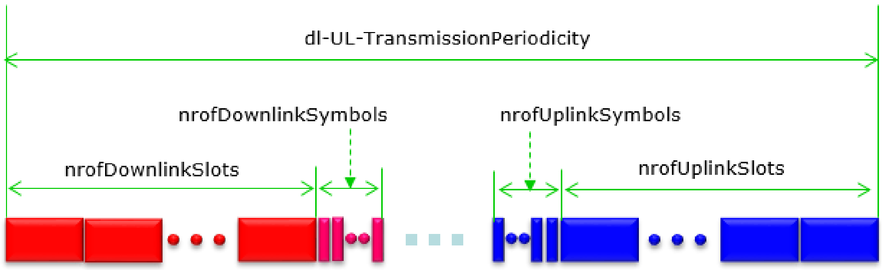


Figure 144: Definition of TDD UL-DL slot configuration by 3GPP

Grant agreement
No 951725