Deliverable D1.3

FRMCS (5G) Vision for the Future

Grant agreement No 951725

5GRAIL

5G for future RAILway mobile communication system

D1.3 FRMCS Performance measurement methodology

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Document status		
Revision	**Date**	**Description**
1.0	11/01/2024	Proposals for performance measurements based on lab and field-testing experience.
2.0	07/05/2024	- Complete re-organisation of the document with an introductive chapter §3 explaining the need for separate methodologies to evaluate each subpart of the FRMCS system (transport, service, application stratum) followed by dedicated chapters 3.1, 3.2, 3.3. - 3.1 Measurement methodologies and KPIs related to 5G network - 3.2 Measurement related to the FRMCS Gateway performance - 3.3 Measurement related to the applications performances All results endorsing the methodologies were moved to the Appendices. - 3.2.3 Bearer flex/multi-connectivity feature used for cross-border implementation - Explanations have been provided about the ETCS performances observed in WP4 lab §6.6.3 - Explanations about the HO figures of §6.3.5.1 Intra/inter gNodeB performances measured in WP3 lab

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Executive Summary

The deliverable D1.3, FRMCS Performance measurement methodology, must be also considered as an outcome of the activities performed during the Task 1.4, named Test report conclusion. The objective of the deliverable is to summarize and analyse all the performance topics of an ecosystem based on 5G and MCX, including cross-border conditions, that appeared during the lab activities of WP3 and WP4. Based on this analysis, a measurement methodology for each topic, will be provided. The suggested methodology is to be assessed and validated during the field activities, moreover, to be considered as a provider of interesting ideas for the railway's stakeholders, preparing the 5G FRMCS operational deployment in Europe.

Although, the content of the deliverable derives from the observations on the tests performed in the scope of the WP3 in Nokia's lab in Budapest/Hungary and WP4 in Kontron's lab in Montigny/France, it is worth mentioning that in most of the testing scenarios there are no target KPIs expected to be achieved. This is because the end-to-end 5GRAIL architecture is essentially constituted from prototypes, such as the gateways, applications and modems but also the performances specifications providing precise KPIs definitions still in progress, to be finalized in FRMCS V2.

D1.3 is a document in the continuation of D1.2, also providing exploitation of the test results to derive measurements methodology as an outcome of 5GRAIL, being the first FRMCS demonstrator, based on FRMCS V1 specifications.

Abbreviations and Acronyms

Abbreviation	Description
3GPP	3rd Generation Partnership Project
5GC	5G Core
5G NSA	5G Non-Stand Alone
5G SA	5G Stand Alone
aka	Also Known As
AMF	Access and Mobility Management Function
API	Application Programmable Interface
APN	Access Point Name
ATO	Automatic Train Operation
ATSSS	Access Traffic Steering, Switching & Splitting
CCTV	Closed Circuit TeleVision
COTS	Commercial Off The Shelf
CP	Control Plane
CSCF	Call/Session Control Functions
CU	Centralized Unit
DMI	Driver Machine Interface
DN	Domain Name
ETCS	European Train Control System
EU	European Union
FDD	Frequency Division Duplexing
FFFIS	Form Fit Functional Interface Specification
FIS	Functional Interface Specification
FRMCS	Future Railway Mobile Communication System
FRS	Functional Requirements Specification
GA	Grant Agreement
GoA	Grade of Automation

GTW or GW	GaTeWay or GateWay
H2020	Horizon 2020 framework program
HMI	Human Machine Interface
HSS	Home Subscriber System
IMS	IP Multimedia Subsystem
IP	Internet Protocol
IWF	Inter Working Function
KPI	Key Performance Indicators
MCX	Mission Critical, with X=PTT (Push-To-Talk forVoice) or X=Video or X=Data
MOS	Mean Opinion Score
MTU	Maximum Transmission Unit
NR	New Radio
OB	On Board
OB_GTW	On-Board Gateway
OBA	On-Board Application (e.g. ETCS on-board, ATO on-board)
OBU	On-Board Unit
O&M	Operation & Maintenance
OTA	Over The Air
OTT	Over The Top
PCC	Policy and Charging Control
PCRF	Policy and Charging Rules Function
P-CSCF	Proxy - Call Session Control Function
PPDR	Public Protection and Disaster Relief
PER	Packet Error Rate
PIS	Passenger Information System
PKI	Public Key Infrastructure
QCI	QoS Class Identifier
5QI	5G QoS Identifier

QoS	Quality Of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RBC	Remote Block Centre
REC	Railway Emergency Communication
RF	Radio Frequency
RRC	Radio Resource Control
RTP	Real Time Transport Protocol
RTCP	Real-Time Transport Control Protocol
S-CSCF	Servicing-Call Session Control Function (Correspondence IMPU - @ IP)
SDP	Session Description Protocol
SIP	Session Initiation Protocol
SMF	Session Management Function
SSH	Secure Shell
SRS	System Requirements Specification
TDD	Time Division Duplex
TE	Test Environment
TEMS	Test Mobile System
TFT	Traffic Flow Template
TLS	Transport Layer Security
TC	Test case
TCMS	Train Control Management System
TCP	Transmission Control Protocol
TOBA	Telecom On-Board Architecture
TS	Track Side
TS_GTW	TrackSide Gateway
TSE	Track Side Entity (e.g. RBC, KMC, ATO trackside)
TSI	Technical Specification for Interoperability

UE	User Equipment
UIC	Union Internationale des Chemins de fer
UP	User Plane
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)

Definitions

Term	
Application	Provides a solution for a specific communication need that is necessary for railway operations. In the context of this document, an application is interfacing with the FRMCS on-board system, through the OB_{APP} reference point, to receive and transmit information to ground systems, (for example, ETCS, DSD, CCTV, passenger announcements, etc.).
Application Coupled mode	It defines if an application is aware of the services used in the FRMCS service layer.
Application Service	Application part responsible of the UP management
Communication Services	Services enabling the exchange of information between two or more applications
Communication service availability	of the amount of time the end-to-end communication service is delivered reed QoS, divided by the amount of time the system is expected to deliver the e according to the specification in a specific area.
Communication service reliability	Ability of the communication service to perform as required for a given time interval, under given conditions.
Control Plane	The control plane carries signalling traffic between the network entities.
Data communication	Exchange of information in the form of data, including video (excluding voice communication).
End-to-End	Including all FRMCS ecosystem elements
End-to-end latency	The time that takes to transfer a given piece of information unidirectional from a source to a destination, measured at the communication interface, from the moment it is transmitted by the source to the moment it is successfully received at the destination.
"Flat-IP" Coupling Mode	This is a sub-mode of Loose-coupling type with static configuration of the requested session. Hence, flat-IP applications can only use the static session configured in FRMCS OB_GTW and TS_GTW.
GoA2	**Grade of Automation 2**: Starting and stopping are automated, but a driver operates the doors, drives the train if needed and handles emergencies.
Interworking	Interworking is the function that enables two different networks to communicate with each other, enabling services to be delivered across them
iPerf	Open source tool used to evaluate network performances in a client-server architecture, available in different operating systems.
MOS	(Mean Opinion Score) measures the perceived quality of VoIP audio on a scale from 1 to 5, with 5 being the best score. A high MOS rate indicates that the audio quality is good, while a low MOS rate indicates poor audio quality.

NG interface	The NG interface is a logical interface between an NG-RAN and 5GC. There are two interfaces under NG interface: NG-C for control plane and NG-U for user plane.
Priority service	A service that requires priority treatment based on operator policies.
PIS controller	She/he is the individual responsible for managing passenger information.
QCI (or 5QI)	A scalar that is used as a reference to a specific packet forwarding behaviour (e.g. packet loss rate, packet delay budget) to be provided to a SDF. This may be implemented in the access network by the QCI referencing node specific parameters that control packet forwarding treatment (e.g. scheduling weights, admission thresholds, queue management thresholds, link layer protocol configuration, etc.), that have been pre-configured by the operator at a specific node(s) (e.g. eNodeB)
Reliability	In the context of network layer packet transmissions, percentage value of the amount of sent network layer packets successfully delivered to a given system entity within the time constraint required by the targeted service, divided by the total number of sent network layer packets.
Service continuity	The uninterrupted user experience of a service that is using an active communication when a UE undergoes an access change without, as far as possible, the user noticing the change.
Super-loose mode	As considered by the application, can be characterized as a “flat IP”. An ‘agent’ is located between the application and the On-board Gateway, to make this mode OBapp compatible.
Transport Domain	A Transport Domain is the administrative realm of the Transport Stratum. The Transport Stratum comprises one or more access technologies controlled by a core network. A Transport Domain is uniquely identified by the PLMN-ID.
User Equipment	An equipment that allows a user access to network services via 3GPP and/or non-3GPP accesses.
User plane	The user plane (sometimes called data plane or bearer plane), carries the user/application traffic.
Voice Communication	Exchange of information in the form of voice requiring corresponding QoS treatment, regardless of the transmission method.

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1 INTRODUCTION

5GRAIL, as part of the FRMCS readiness activities has planned to provide some performance measurements methodology, together with a rough evaluation of the behavior of the tested applications within different scenarios, considering the global FRMCS that is based on 5G SA and 3GPP MCX.

In this sense, our approach is to analyze based on the experience of both labs the essential FRMCS constituents and fundamental mechanisms that influence the overall performance. Therefore D1.3 deliverable is structured as following:

- Radio 5G;
- Applications performances over 5GSA and MCX e2e network;
- Miscellaneous Performance topics, mainly related to the MCX entities and mechanisms;
- Cross-border methodology, evaluating performances related to the implementation of each lab.

The deliverable D1.3 will contribute to the next steps of FRMCS introduction, as presented in the following figure:

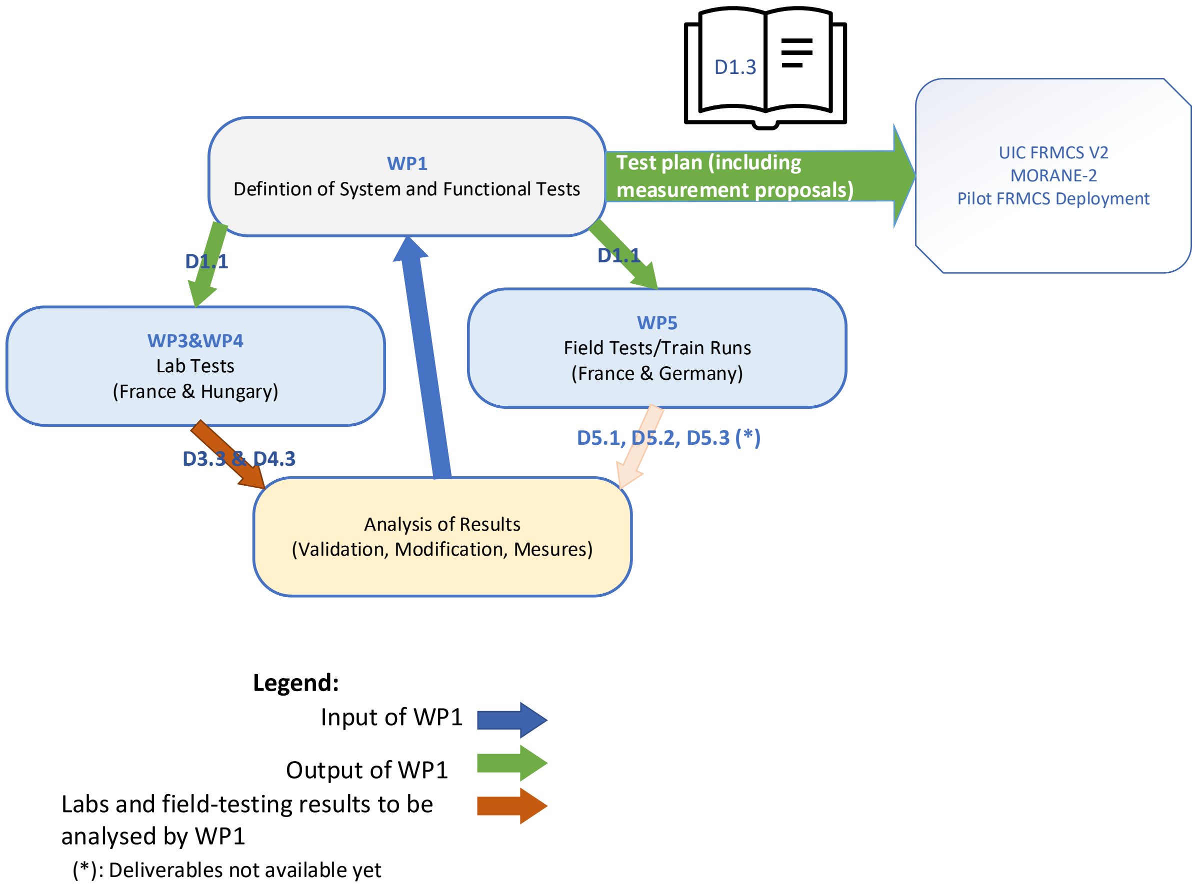
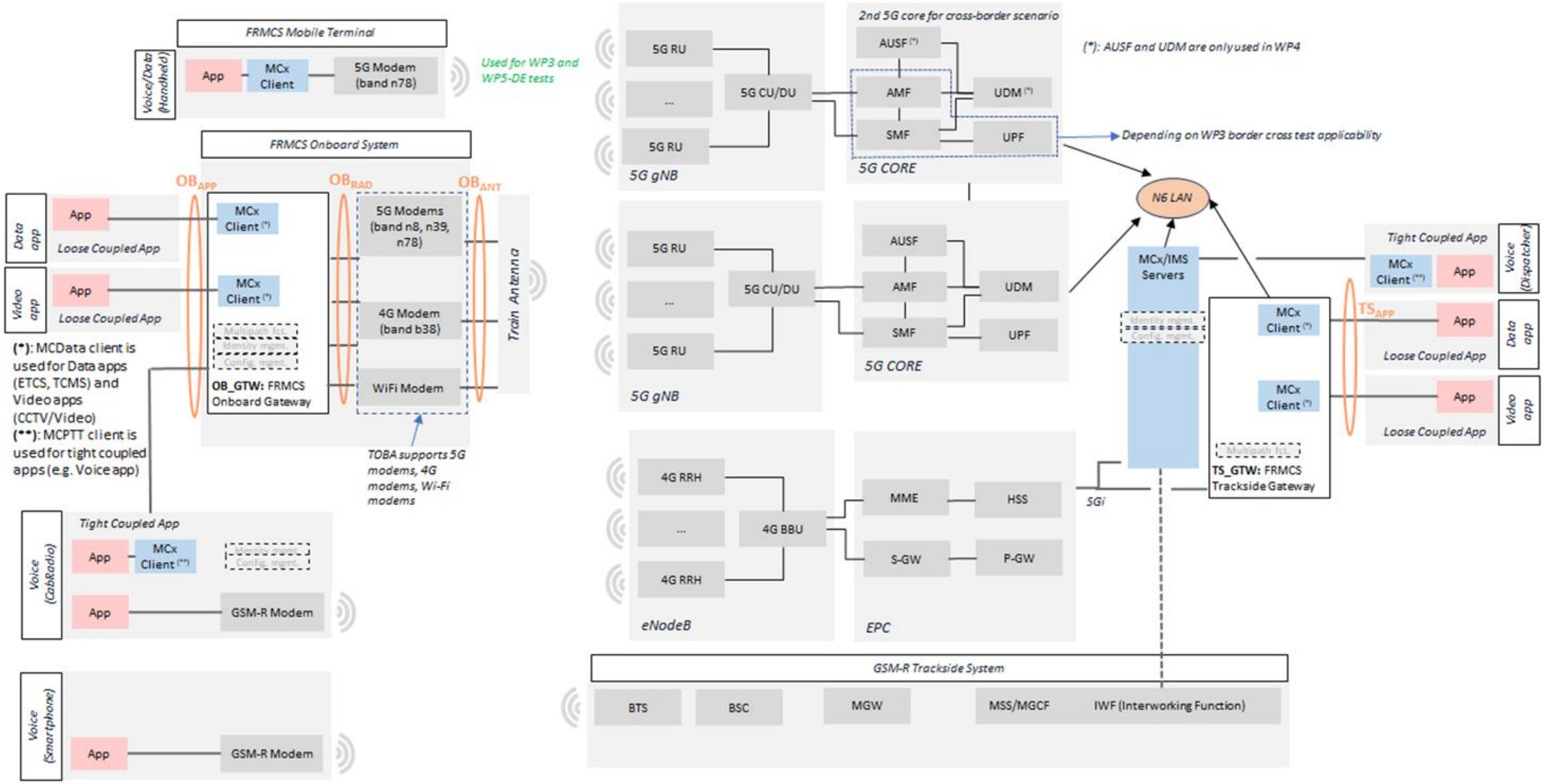


Figure 1: WP3 and WP4 performance tests analysis defines the content of D1.3 (loopback process of measurement proposals for next steps of FRMCS)

2 REMINDER OF THE GLOBAL END-TO-END ARCHITECTURE

The figure below reminds the end-to-end architecture of 5GRAIL project, which is considering the main constituents of the FRMCS ecosystem (also including the elements of the GSM-R system), that are contributing to the overall performance of the system:

Figure 2 completes the above 5GSA and MCX framework end-to-end FRMCS architecture with the D2.1 TOBA Architecture report view, which on the top of Gateways and infrastructure presents the railway operational applications in the context of 5GRAIL. The network performance is tightly related with the applications behaviour and performances, as will be explained through this deliverable:



5GRail Generic e2e Test Architecture

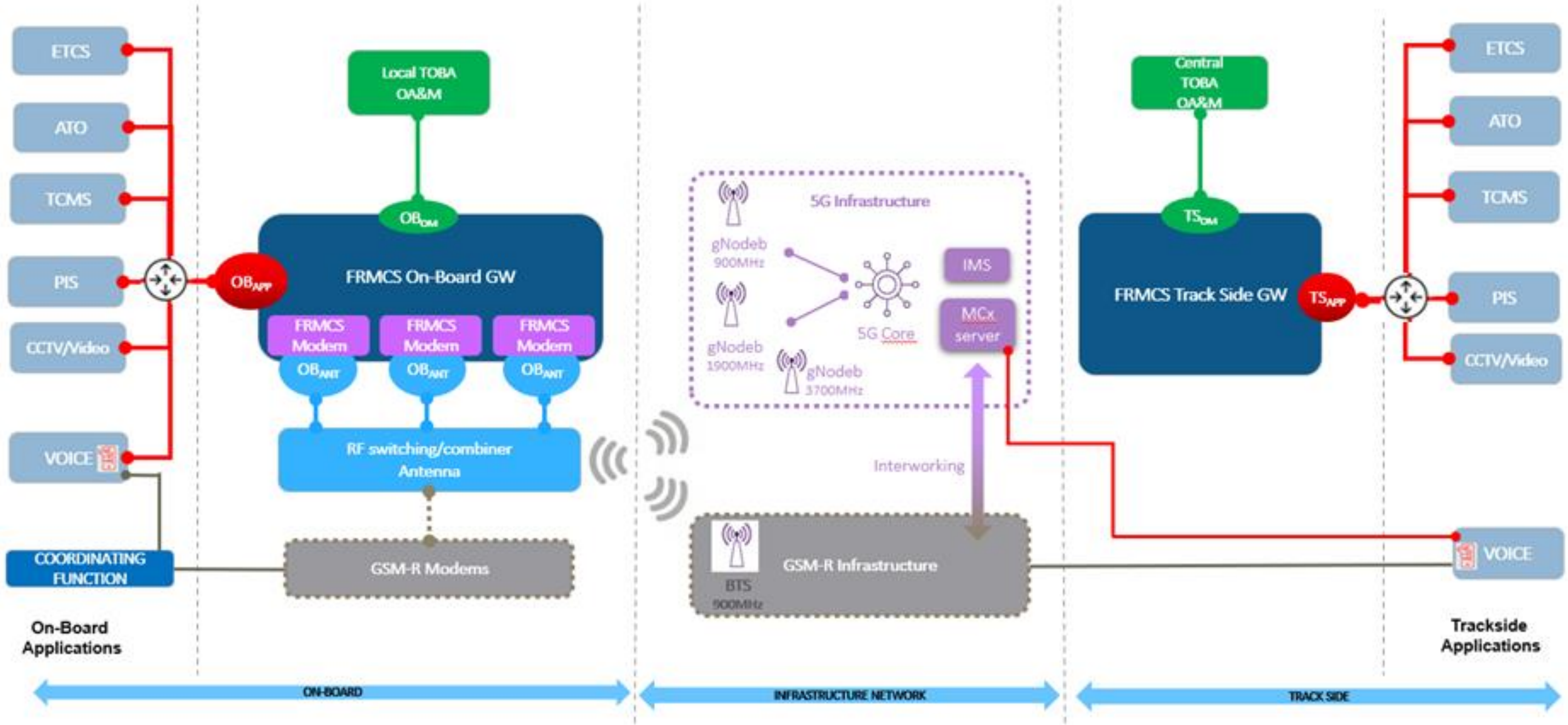


Figure 2: Architecture overview (Ref. D2.1)

3 METHODOLOGIES USED FOR MEASUREMENTS

With reference to the end-to-end architecture, including the different applications tested in the scope of 5GRAIL (cf. Figure 2), our focus was the evaluation of the network performance by proposing **end-to-end FRMCS network KPIs** (measured between the onboard interfaces OB_{APP} and trackside interfaces TS_{APP} to the application) but also **end-to-end application KPIs** (including processing in the onboard and trackside application equipment).

For the end-to-end network evaluation, particular interest and measurement analysis was given to the **5G handover KPIs** (by example of inter-gNB intra-AMF handover). In addition, **5G Radio KPIs and Metrics**, also applicable to FRMCS were proposed.

The **impact of the MCx Service level** procedures were evaluated through their time duration for loose and tight applications.

The evaluation was based on both control plane and user plane analysis.

The following figure presents all the sub-systems that are involved in the overall evaluation of the end-to-end 5GRAIL architecture:

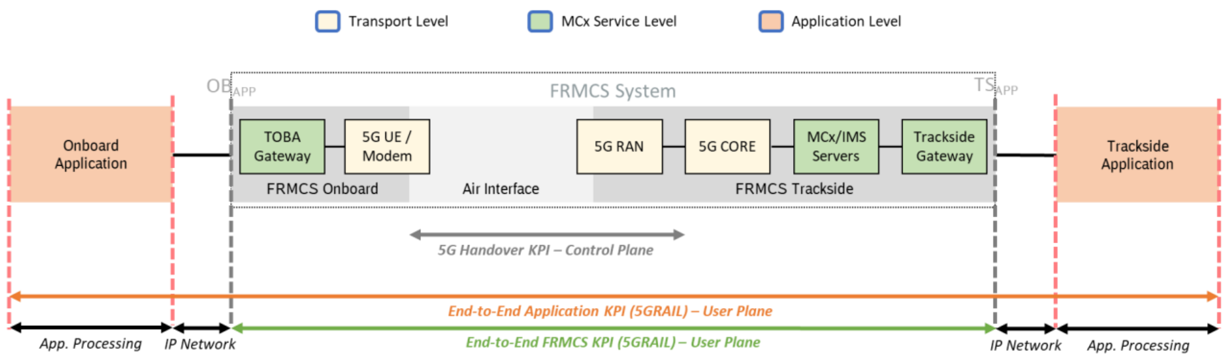


Figure 3: Performance evaluation of the end-to-end architecture of 5GRAIL (Ref.D5.3)

These topics are organized in the following sub-chapters, as following:

Description of the subject	Sub-chapter titles
End-to-end FRMCS network KPIs, 5G handover KPIs	§3.1 Measurements related to 5G network performance
Impact of the MCx Service level	§3.2 Measurements related to FRMCS Gateways
End-to-end application KPIs	§3.3 Measurements related to FRMCS applications

3.1 Measurements related to 5G network performance.

The air interface performance is mainly monitored by 5G Radio KPIs and metrics which are also valid for the FRMCS networks. These are classified into the following categories:

- Availability
- Signal and Coverage
- Interference
- Radio Link Performance
- Throughput and Latency
- Accessibility
- Integrity
- Mobility

The proposed KPIs, belonging to the above categories and their definitions are listed in the appendices §6.1.1 5GRadio Metrics and KPIs for FRMCS.

RSRP (Reference Signal Received Power) and SINR (Signal to Interference and Noise Ratio), as part of Signal and Coverage KPIs are analysed in German testbed in TDD band n78 over 7 radio cells along the test track. The analysis of these results is described in detail in D5.1.

In the following, we recall definitions of the most important 5G network KPIs and measurements methodologies that were also used in the scope of 5GRAIL. Results of these measurements per KPI are referenced in the appendices.

3.1.1 Throughput

Throughput: The rate at which packets are transmitted through the network.

Measurements methodology:

There are several ways of measuring throughput.

- Taking a trace with **capturing tool** like WireShark and using embedded tool to compute throughput at this traffic capture point.

- Using an **internal tool in one of the network devices** (e.g. gNodeB, on the Core network). For example, in 5GRAIL WP4, we could monitor real time radio throughput in RAN cell.

- Using a **call trace function** (not available in 5GRAIL) give the ability to have specific counters for a specific test user.

- Using an **external dedicated tool**: in 5GRAIL we choose to use iPerf. iPerf is composed of client and Server that are communicating together. This tool computes average throughput measured during a given test that is to be specified with iPerf commands.

- iPerf is different from WireShark method because it does not compute throughput at a specific reference point rather than loops at end-to-end approach. There is a choice in where to put client and server and this choice impact measurements. However, iPerf which is easy to use and set-up is a_good indicator of throughput KPIs. In 5GRAIL, we evaluated 5G network throughput performance by connecting the laptop with iPerf client to a 5G modem, then doing performance tests with an iPerf server installed as close as possible to the 5G core. In WP4 case we put the iPerf server in P-CSCF virtual machine.

Example of throughput results are described in the appendices §6.2.1Throughput measured in WP3 lab

3.1.2 Latency

Latency (ms): It represents the time delay between the sending and receiving of data. Latency is different from **RTD delay (RTD)** which is the time between sending a message from a source to a destination (start) and receiving the acknowledgment from the destination at the source point (end).

Measurement methodology:

Ways of measuring latency:

- In order to precisely measure latency, we can use one device (laptop, server connected at the same time at the modem and at network side of 5G core). A capturing tool runs on this device and spies all these interfaces so that we can measure the exact time between the arrival of the data packets in the network side and the departure at the 5G modem side.
- Another method consists in having two devices (laptop, server) precisely synchronized in time (NTP, GPS synchro). On both of them, we run a capturing tool and after the test we merge the two captures, so that we can compute the exact latency.

Ways of measuring RTD:

- RTD can be measured easily with a ping command that provides with the RTD value after the icmp test. The advantage of this method is that we can easily run it many times and statistically compute the results to get precise value. This is the method we've used in 5GRAIL WP4.
- RTD can also be measured with iPerf which provide RTD min, max and average values at the end of iPerf tests.

Examples of RTD observations in WP4 lab are described in the appendices §6.2.2Comparison of RTD delay in n8 and n39 band.

3.1.3 Jitter

Average Jitter (Rx) (referred to Delay variation) (ms): Jitter refers to the variation in the delay of received packets. For Rx (receive), it measures the average fluctuation in the arrival time of packets at the receiver. It is crucial for assessing the quality of real-time communication.

Average Jitter (Tx) (referred to Delay variation) (ms): For Tx (transmit), it measures the average fluctuation in the transmission of packets. Maintaining a low and consistent average jitter in transmission is essential to ensure a stable and reliable delivery of real-time data.

Measurement methodology:

- For jitter evaluation, the only measurement tool to be used is iPerf.

Examples of jitter results are described in D5.1 §3.3.3 for packets transmitted in field testbed in Germany during a voice call but also inside this deliverable D1.3 for the evaluation of TCMS performance in chapter §3.3.4.2 and as an impacting parameter in the performance of Remote Vision field application in chapter §3.3.7.

3.1.4 KPIs linked with service continuity during handover

Whenever there is a change of cell within a gNodeB (intra – gNodeB HO) or between two gNodeBs (inter-gNodeBs HO), there is obviously a service continuity that we can measure with specific KPIs, as defined in the appendices §6.3.4 5G Handover Types with KPIs.

There are different types of HO call flows, presented in appendices §6.3.2 Call flow of inter-gNodeB Xn handover in 5GSA and §6.3.3 Inter-gNodeB HO over AMF.

Measurement methodology:

In case of intra-gNodeB HO we can measure the impact of the service by:

- Using specific analyzer terminal (e.g. TEMS): The TEMS will measure all radio interface messages so that we can get the timestamps of the handover messages related to stopping and resuming User Plane data transmission. Using a protocol analyzer connected on the backhaul of the gNodeB. This analyzer will monitor all data traffic and if an uplink ftp session is running, any outage in the uplink can be monitor by this analyzer.

In case of inter gNodeB, TEMS can still be used as well as protocol analyzer but in that case, it should be put at the UPF interface.

Examples of the intra/inter-gNodeB HO are described in the appendices §6.3.5.1Intra/inter gNodeB performances measured in WP3 lab and §6.3.5.2Intra/inter gNodeB performances measured in WP4 lab

3.2 Measurements related to FRMCS Gateways performance

In this section, we focus on KPIs related to FRMCS Gateways behaviour. We can distinguish between KPIs linked to modem's performance, KPIs linked to IMS/MCX procedures (knowing that the clients are located inside FRMCS Gateways or outside in case of tight coupled applications) and KPIs linked to specific features of FRMCS Gateways like Bearer flex and multi-connectivity.

3.2.1 KPIs related to modems

3.2.1.1 Power-up On-board Gateway - 5G attach time

Once the gateway is power-up, the modem is starting to retrieve the IP address of the 5G network. In the Gateway's logs, we can evaluate the time between the moment the modem is switched on and the moment it obtains the IP address of the 5G network. The steps of this procedure are presented in the following call flow:

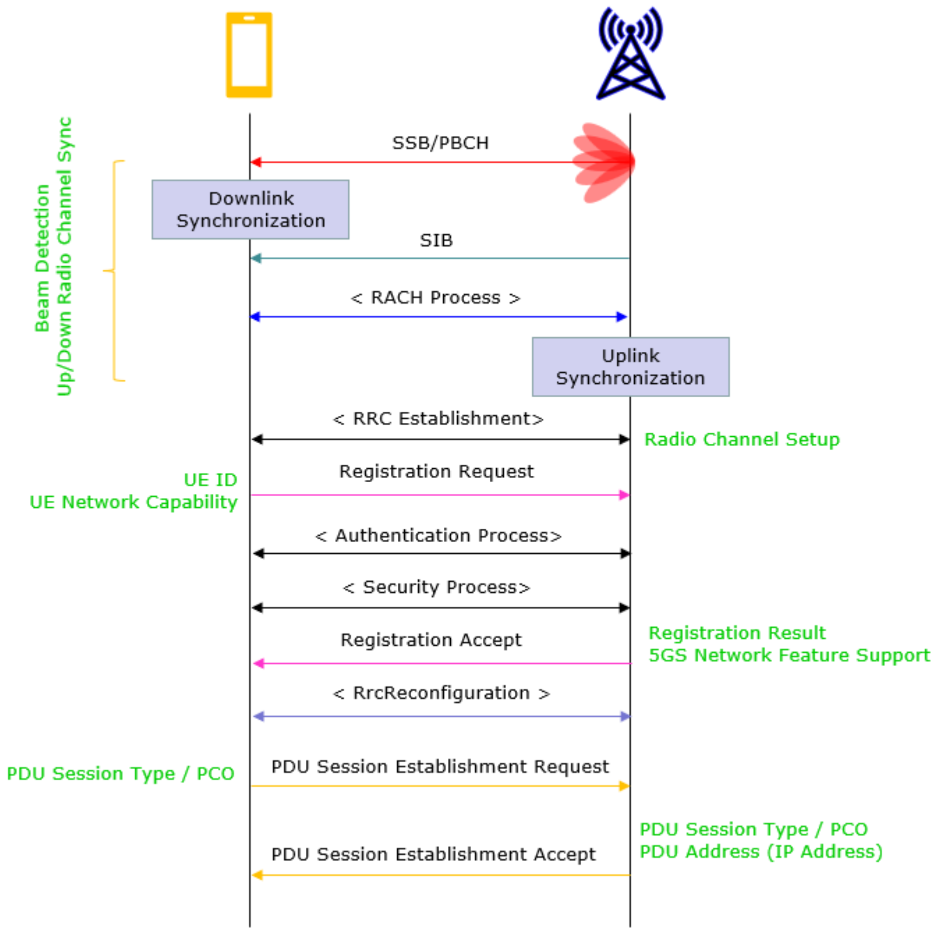


Figure 4: 5G modem attach call flow and PDU session establishment

Measurements methodology:

The KPI corresponds to the duration needed for the FRMCS Gateway to be operational. In order to measure this KPI, we must measure the time between the command to put the Gateway in service (i.e., power on) and the reception of PDU establishment accept. If we want to be quite precise, we need an external device (laptop) to be connected to the Gateway which can trigger its starting process and also spy the interface.

3.2.1.2 Loss of radio for On-board Gateway

Measurements methodology:

To evaluate the time the modem needs to recover from a complete radio outage, the radio signal emission of gNodeB is switched off. A PC equipped with WireShark is connected to the gNodeB. When gNodeB is transmitting again, the modem tries to get attached to the 5G network. We can measure in the WireShark logs, the time the modem needs to retrieve the IP address of the 5G network.

Example of Modem Time recovery: The above methodology is applied in WP4 lab, where some tests have been executed with TOBA-K to evaluate performance of modem time recovery in case the radio signal is completely lost. The purpose of this test was to simulate the situation in very degraded radio conditions in field, for example at cell edge, with attenuation around 105dB.

The procedure used is to send a continuous ping from TOBA-K to P-CSCF. Significantly increasing the RF attenuation, the radio signal is completely lost for a given time period (x seconds). Considering what was expected for field testing, x took the values of 10s, 30s and 1min. Two timestamps of the ping were considered:

- **t1**: Attenuation is reduced to come back to the previous state.
- **t2**: When ping traffic resumes.

t2-t1 is the duration modem needs to recover from the total loss of signal. The resulted recovery time, t2-t1, was less than 35s in all the cases.

3.2.2 MCX and IMS clients' procedures

The MCX registration/deregistration KPIs are described in the appendix §6.5.1 Service registration and deregistration performance and are used in the following paragraph to evaluate some MCX performance procedures for loose and tight coupled applications.

The procedures performed by the MCX client to obtain access to FRMCS services are:

- MCX authentication (to the identity management of the MCX server)
- SIP registration (to the IMS)
- MCX service authorization (to the MCX server, through IMS)

These procedures will be detailed in the following sub-chapters, also presenting relevant KPIs to be measured.

3.2.2.1 MCX authentication and authorisation

Once the IMS client is authenticated, MCX client can start authentication and authorisation procedure. It consists in:

- An authentication exchange with IdMS entity (part of the MCX common entities)
- SIP/IMS Registration
- An exchange with the MCX application server in order to get authorized for specific service

These procedures and the order of them, as performed by the MCX client, can be summarized in the following figure:

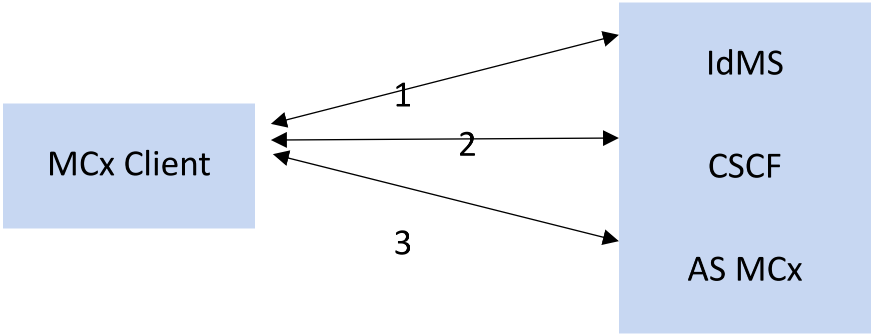


Figure 5: Order of procedures performed by MCX client for Authentication, Authorisation and SIP/IMS registration

The first phase (authentication with IdMS) consists in the sending of https ‘IdMS authentication request’ message and the related answer ‘IdMS authentication response’.

The 2nd step is the SIP/IMS registration, as described in §3.2.2.2

The third step referring to the MC service authorization, the method used is the one with SIP PUBLISH message, as defined in 3GPP TS33.180 and presented in the following figure:

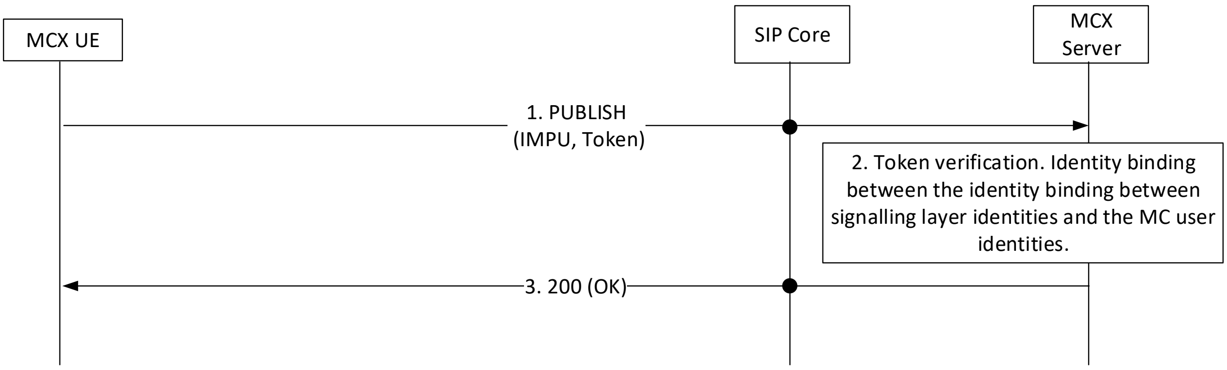


Figure 6: MCX User Service authorization using SIP PUBLISH message

For this third step, the information used is the one provided during the authentication phase with IdMS.

Measurement methodology: The way to measure the duration of the authentication procedure is by analysing the WireShark logs in the Gateway entre https ‘IdMS authentication’ message and the related answer ‘IdMS authentication response’.

Another important KPI reflecting the global procedure can be calculated between the 1st authentication message ‘IdMS authentication request’ and the last message of authorisation step 3 ‘200 OK’.

3.2.2.2 SIP/IMS registration

SIP Registration is achieved using the REGISTER method in 5GRAIL.

SIP registration is a 2 steps procedure:

- In the first step, SIP client sends a REGISTER message that is sent to P-CSCF. HSS provides authentication information to S-CSCF and a “401 Unauthorized” message is sent back to the client.
- Using challenge information contained in the “401 Unauthorized” message and its secret key, SIP client replies with a new REGISTER message that contains the result from computation. If this result matches the result stored in S-CSCF, Registration is accepted and S-CSCF will ask HSS for user profile download.

An example of SIP registration call flow is presented in the following figure:

Figure 7: SIP Registration call flow (Ref. D3.3v2)

Measurement methodology: The way to measure the IMS registration time is by analysing the logs WireShark in the Gateway: the duration is the difference between times of reception of following messages:

- 1st SIP REGISTER message
- SIP 200 OK message

3.2.2.3 Registration/authentication performances for loose coupled applications

In the following state diagram, we can distinguish three timers, as defined for loose coupled applications. Measuring these timers constitutes an appropriate methodology to evaluate an important MCX procedure, as registration and session_start are, for loose coupled applications:

T1: start of application,

T2: start of MCX client and

T3: start of session

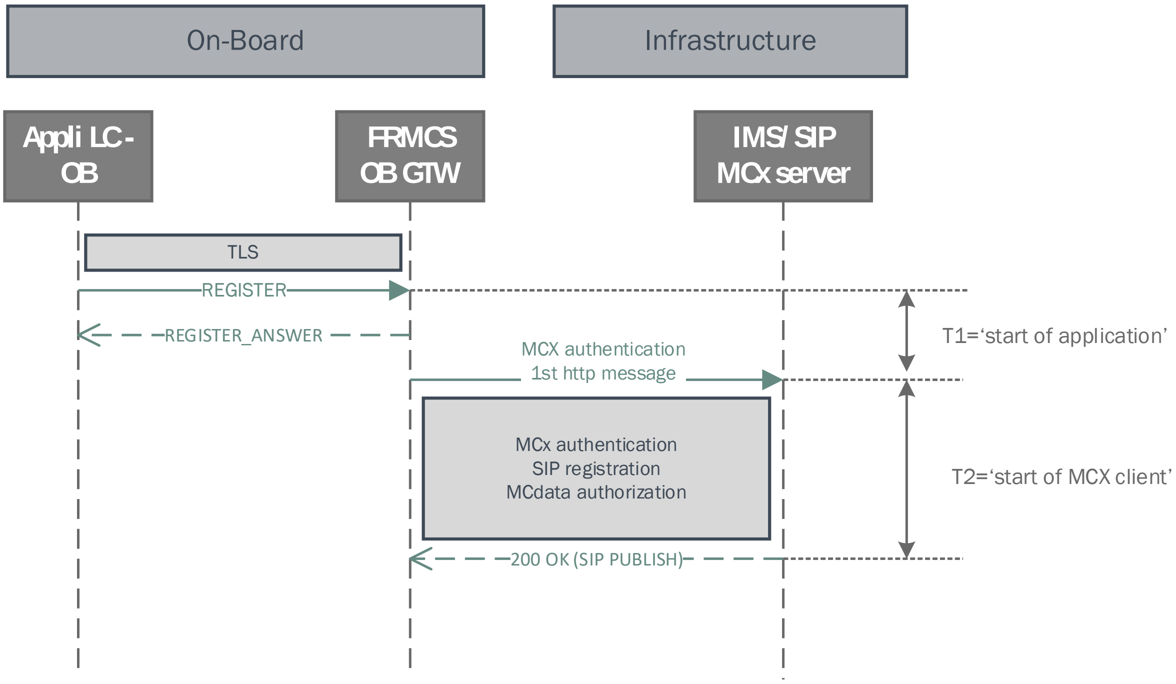


Figure 8: Definition of T1 and T2 intervals in loose coupled applications

T1 and T2 interval is the time between reception of the register request (through OBapp API) and the moment when the MCX/SIP authentication, registration and authorization are finished (i.e., the moment when the OB GW receives a 200 OK answer to the SIP PUBLISH request)

Considering several WP4 captures with ETCS, ATO and PIS applications using TOBA-A, the measurement is generally between 600ms and 1s. There are few cases with higher values, but these were not considered as they refer to the situations where the MCX server faces difficulties due to several registrations in parallel.

This time is a good indicator for registration to FRMCS service servers, it takes into account the MCX/SIP transactions over the radio link, reaction time of the MCX/SIP servers and the FRMCS GW. It does not consider the train network time (which is anyway lower than 600ms).

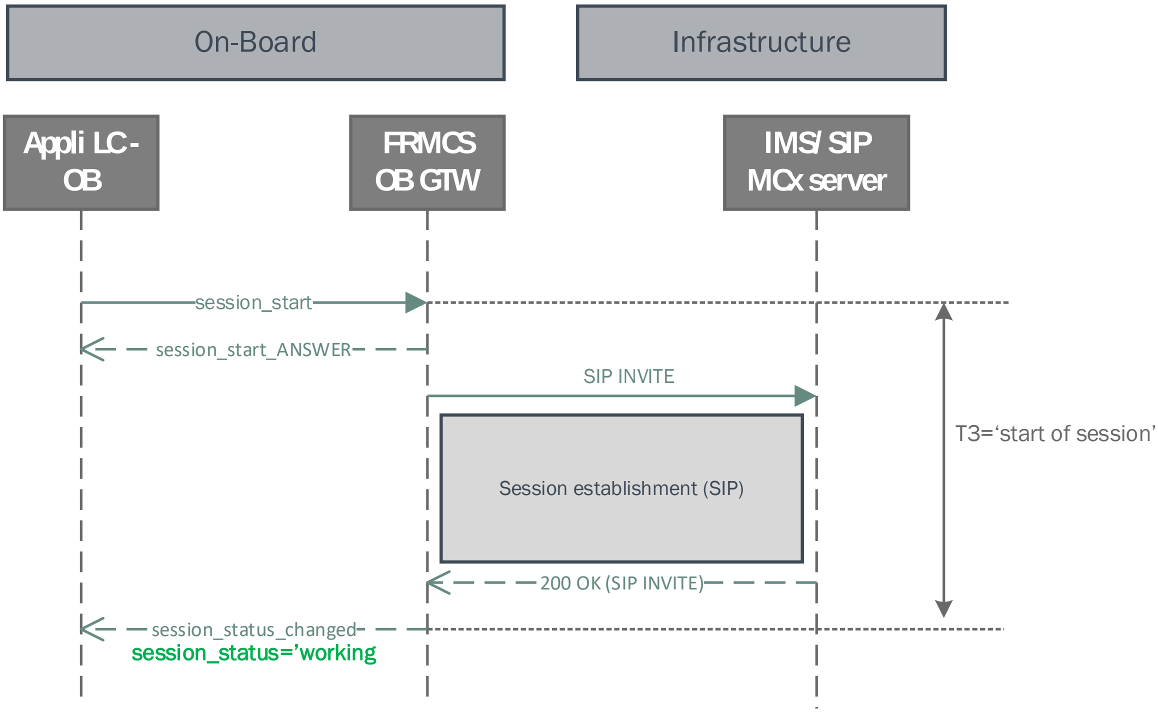


Figure 9: Definition of T3 interval for loose coupled applications

T3 is the time between reception of the session_start request (through OBapp API) and the moment when the corresponding session_status = "working" is sent to the application (through OBapp API).

Considering several WP4 captures with ETCS, ATO and PIS applications using TOBA-A, the measurement is generally around 200ms (no differences between applications) under normal conditions.

This time is a good indicator for session establishment performance, it considers the SIP transaction over the radio link, reaction time of the MCX server and the FRMCS GW. It does not consider the train network time (which is anyway lower than 200ms)

3.2.2.4 Registration/authentication performances for tight coupled applications

In the following state diagram, we can distinguish three timers, as defined for tight coupled applications. With the below methodology, we are evaluating registration and session_start in the context of tight coupled applications:

T1: start of application,

T2: start of MCX client and

T3: start of session.

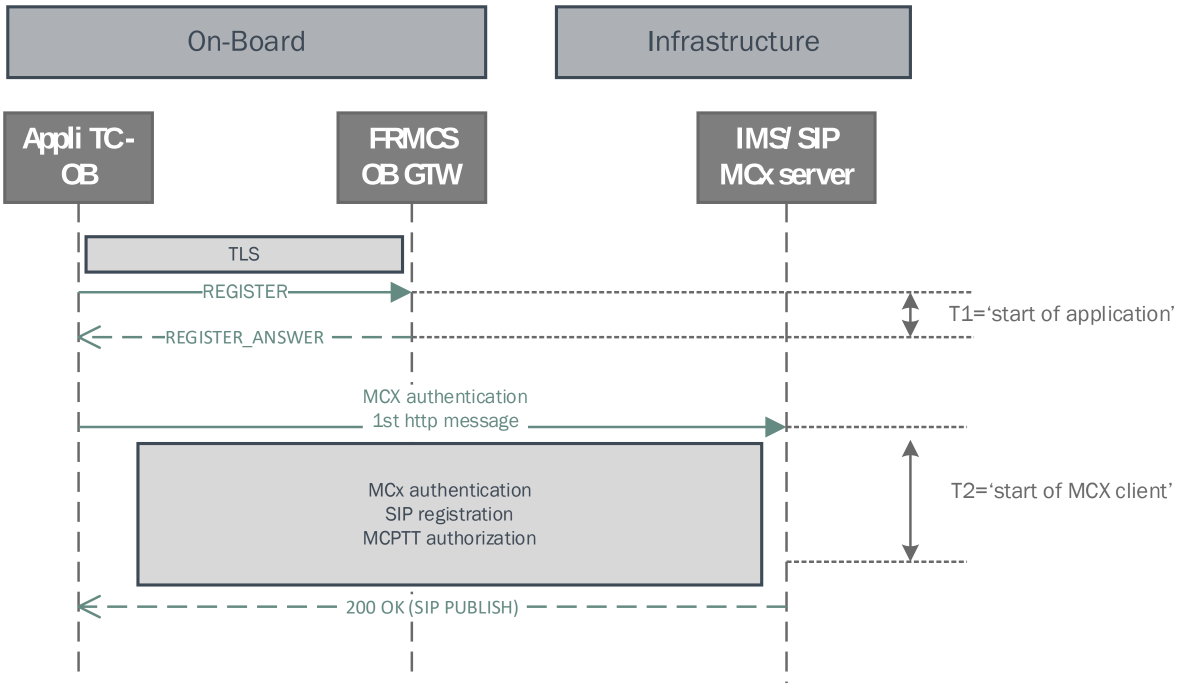


Figure 10: Definition of T1 and T2 intervals in tight coupled applications

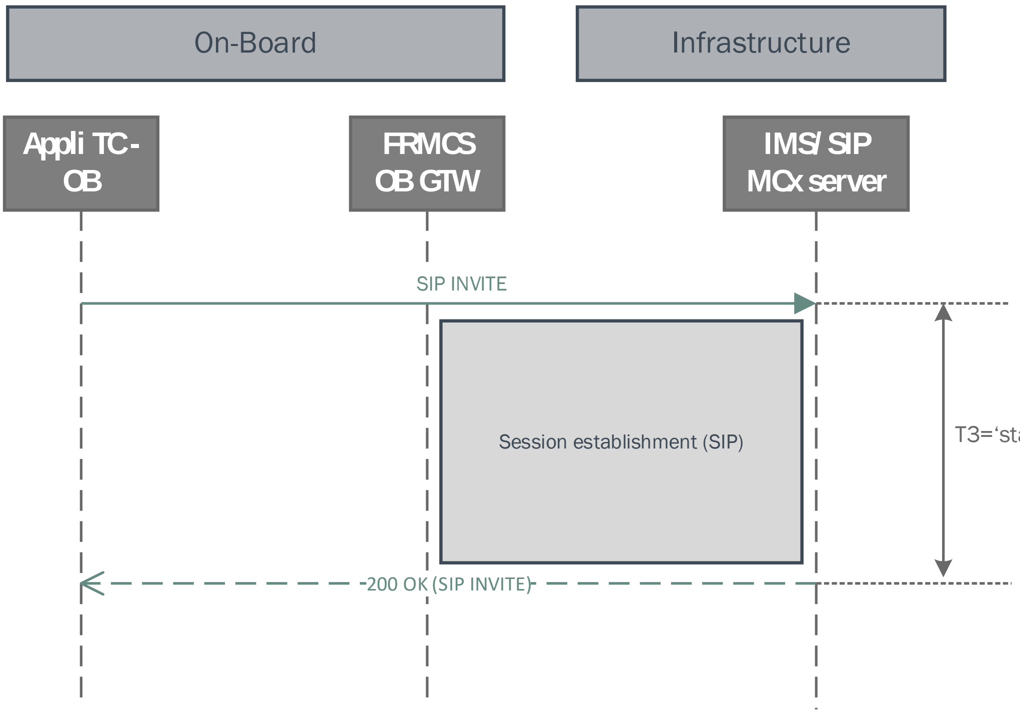


Figure 11: Definition of T3 interval for tight coupled applications

Example of SIP registration: In the framework of WP3 lab, as an example the Cab radio SIP registration time was measured, equal to 40ms.

3.2.3 Bearer flex/ multi-connectivity

The bearer-flexibility feature enhances the independency between the applications and the transport technologies. Bearer flexibility is realised by means of FRMCS Multipath. As described in the FRMCS specifications, FRMCS Multipath enables the (sequential or simultaneous) use of Data Paths over multiple Radio Modules on the same or different (transport) domains.

FRMCS gateways support this feature which facilitates the network transition, by using multi-connectivity (the ability of simultaneous usage of two bearers) and bearer flexibility (ability to use several bearers and changing from one to another). In the framework of WP4, it was a great opportunity to have two flavours of FRMCS gateways (with Kontron and Alstom, as providers) with two different implementations of border crossing:

- TOBA-A: Bearer flexibility with only one path active at the same time (Primary and Secondary link)
- TOBA-K: Multi-connectivity with both paths active at the same time. Based on the MPTCP protocol.

The following sections present the performances of cross-borders implementations using the above features with ETCS application, which requires service continuity.

The bearer-flex/multi-connectivity features are the ones used for the cross-border implementations. The challenges of the cross-border implementations during 5GRAIL timeframe but also the specifications guidelines were described in the appendices 6.7.1 Specifications guidelines for network transition (cross-border topic).

3.2.3.1 Cross-border with TOBA-A using 2UEs

The test set-up consists in putting two 5G n8 modems in TOBA-A and move from one 5G network to another with an overlapping zone.

5G modem A is configured to attach only on first network while 5G modem B can only use network B. In the overlapping zone, modem B will attach to the second 5G network. A priority rule is also added so that whenever modem A is attached, it must be used (preferred or primary link).

In the following some performance KPIs will be described to demonstrate the cross-border impact for the usage of TOBA-A with two 5G modems. In the figures below the two different 5G networks are named (‘blue’ network) and (‘red’ network). As a reminder, the cross-border implementation is relying on the multipath function of TOBA-A to switch from a first 5G network to the second 5G network.

The RTD (Round Trip Time) is a relevant indicator for ETCS applicative data, which is the main KPI used by ETCS to qualify the FRMCS communication, as explained in §3.3.2.1 Performance methodology used in 5GRAIL for ETCS.

The scatter plot below displays all the RTD for the applicative frames sent from EVC side (on-board) to RBC side (trackside) through FRMCS sessions established between TOBA-A and TS-GTW-A. The abscissa corresponds to the time where the TCP ACK of the packet is received (which is considered to compute the RTD). The first plot shows the full picture of the test, the second plot is a zoom around the key moments of the border-crossing, i.e., the change of network to carry the applicative data.

- Initial conditions:

T0 of the graphic below corresponds to the initiation of the "end to end" TCP connection between EVC and RBC. It means that the FRMCS session has already been requested to TOBA-A through OBapp API, and TOBA-A has already sent a notification to the ETCS applications (both OB and TS) to notify the availability of the underlying session.

From TOBA-A point of view, two tunnels have been established in parallel to transport the applicative data:

- Tunnel 0xdbb168db through 5G modem 1, connected to 5G network A ("Blue" 5G network)
- Tunnel 0x17754811 through 5G modem 2, connected to 5G network B ("Red" 5G network)

There is a primary/backup policy configured for the two modems. Modem 1 ("Blue" network) is the primary link, Modem 2 ("Red "network) is the backup link. At T0, TOBA-A is under coverage of both networks (Blue and Red) and the two tunnels 0xdbb168db and 0x17754811 are working. **But all the ETCS applicative data is carried by tunnel 0xdbb168db**.

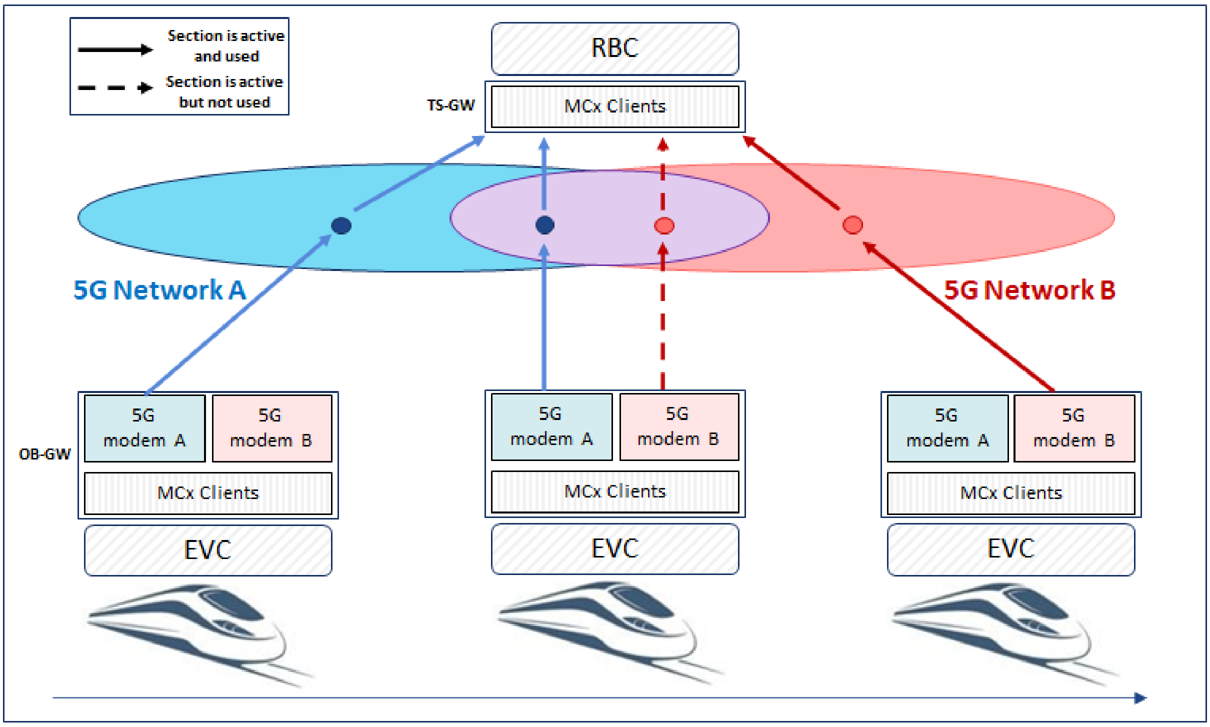


Figure 12: Cross-border steps with TOBA-A (Ref. D4.3v2)

The change of network made by TOBA-A to carry ETCS applicative data has strictly no impact on the RTD seen by the application. The RTD just before and just after the transition is approximately the same **(48.8ms vs 45.3ms)**.

3.2.3.2 Cross-border with TOBA-K using 2UEs

As explained in D4.3v2, it was not possible to install two 5G UEs prepared for field tests in n39 with -31dBm inside TOBA-K, due to heating and room constraints (both caused by the n39 radio module booster). Moreover, we haven't n8 frequencies available on French test track. That is why the testing scenario for cross-border was adapted to the usage of one 5GUE and one 4G UE, moving from a 5G only area to a 5G+4G area, as per French testbed set-up, however the principle remains the same, identical as if two 5G UEs were used.

In TOBA-K's implementation, the main difference with TOBA-A implementation is the simultaneous usage of both links and the application of MPTCP protocol, as presented in following figure:

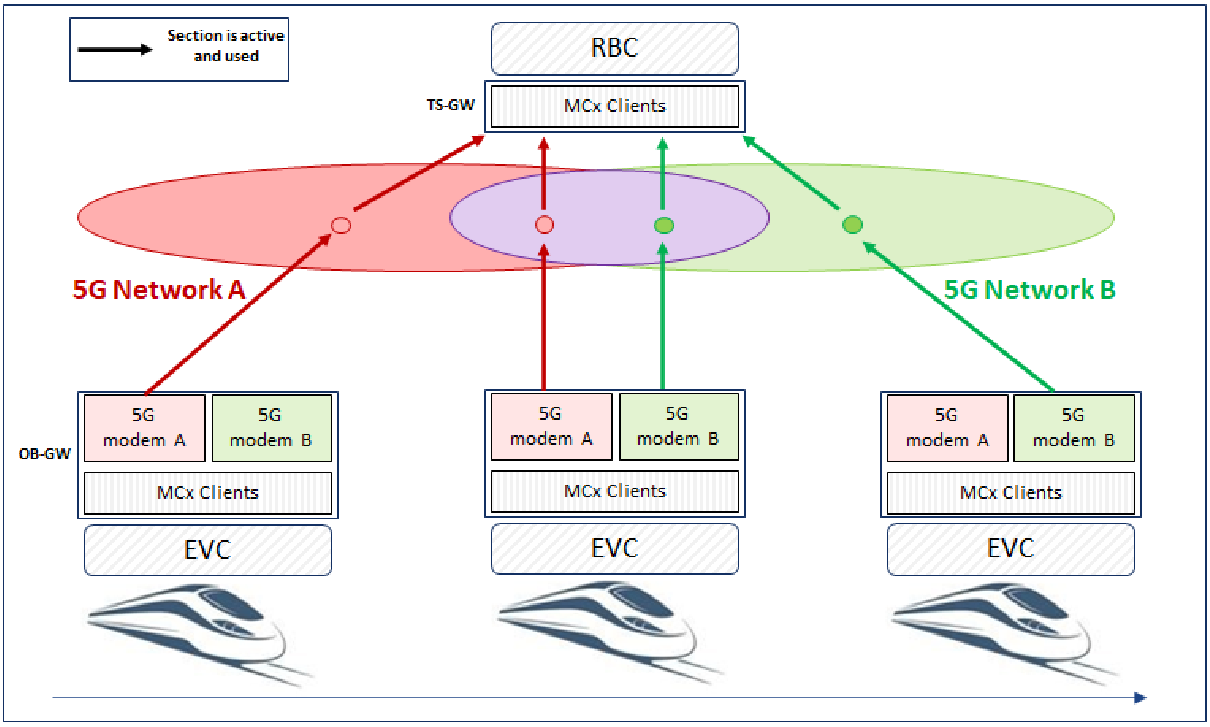


Figure 13: Cross-border steps with TOBA-K (Ref. D4.3v2)

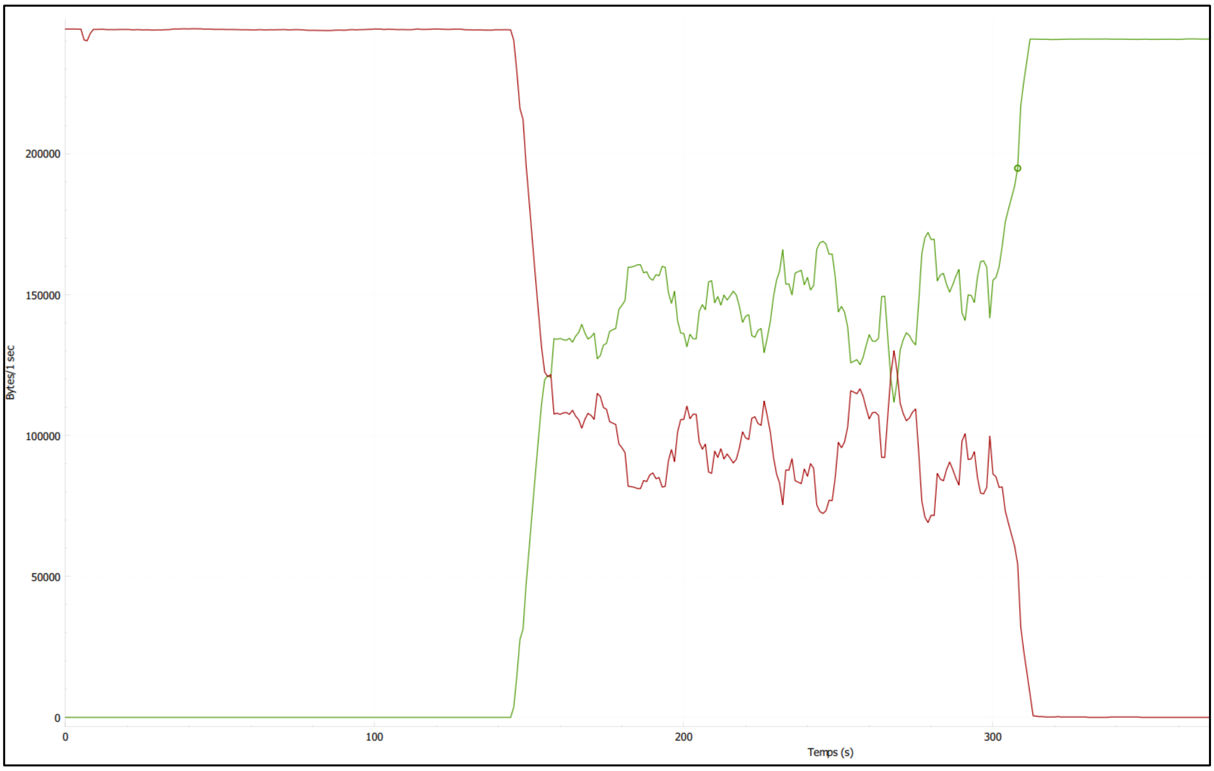


Figure 14: Cross-border evaluation test with TOBA-K (Ref. D4.3v2)

As per WP4 testing outcome, the traffic initially carried by 5G UE under 5G only coverage, is distributed to the 4G and 5G UE when in overlapping coverage and in only 4G UE, when under 4G coverage.

As it can be observed in the above graph, when one data traffic decreases (e.g. 4G) the other data traffic increases (e.g. 5G) or splitted in both bearers, as a conclusion it remains the same, consequently service continuity is ensured for critical railway applications.

3.3 Measurements related to FRMCS applications performance

During the timeframe of 5GRAIL, FRMCS KPIs were not defined yet in the specifications, except MCPTT KPIs which were clearly defined in 3GPP specifications. The MCPTT KPIs were briefly reminded in §6.6.1 MCPPT KPIs.

For the loose coupled applications which are using MCData, KPIs described in §3.1 and in the appendices §6.6.2 MCData KPIs are used to evaluate their performance.

3.3.1 VOICE

3.3.1.1 Voice performance using MCPTT KPIs

A set of MCPTT KPIs with their definitions are presented in the appendices §6.6.1 MCPPT KPIs among them KPI1 and KPI2 for which the definitions are reminded in the following figure:

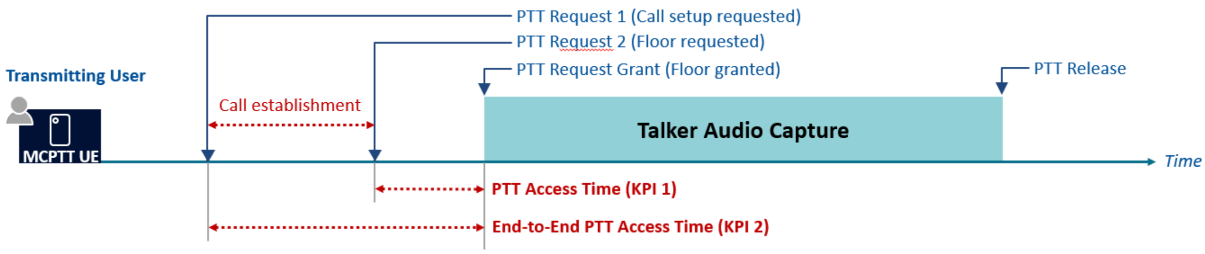


Figure 15: Overview of MCPTT KPI1 and KPI2

Referring to MCPTT KPI2, a performance view of the REC calls in WP3 lab was presented in the following figure. The performance was completely fulfilled in both directions from cab radio to dispatcher and vice-versa. However, higher values are observed in the dispatcher to cab radio direction due to the additional processing time at the receiving CAB radio.

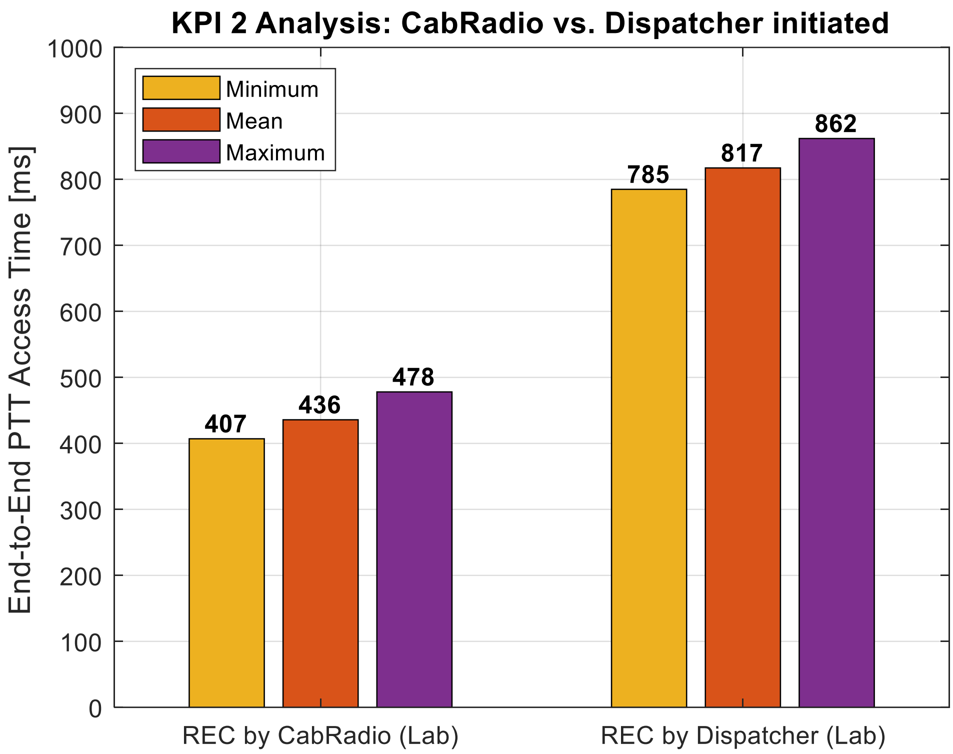


Figure 16: Comparison of MCPTT KPI2 values Cab radio versus dispatcher initiated for REC calls (Ref. D3.3v2)

3.3.1.2 Voice MCX procedures performance and comparison with GSM-R

As per D3.3v2 outcome for voice & CAB radio the following measurements have been done for comparison between GSM-R KPIs and 5GRAIL KPIs, summarized as a reminder in the following table:

KPI Voice	Value EIRENE SRS/FRS	5GRAIL measured over 5G
CAB Functional Address registration	< 30 sec / 5 number	60 ms per alias
CAB / Dispatcher REC / Group Call	<4 sec e2e, considering network call processing time < 2.5 sec	KPI 2: 400-800 ms

Table 1: Comparison between GSM-R and 5GRAIL KPIs (Ref. D3.3v2)

Some explanations to understand the above comparative table are:

- The GSM-R standard requires the registration of Functional Number (5 numbers) below 30 sec.

3.3.2 ETCS

ETCS is a critical railway signalling application, a key component of the ERTMS.

As such, ETCS performance requirements are listed in a document called ETCS Subset 093 v4 §5 [24], and the measurements methods in a document called O-2475 v4 ERTMS/GSM-R Quality of Service Test Specification §5[44]. Below, current QoS values captured in SS-093:

Table 2 Summary of QoS requirements (PS mode)

QoS Parameter	Value
PS Service Setup delay (PS-SS) (refer to chapter 6.7.2)	≤35s (99%) (see note to „Network Registration Delay")
GPRS Attach Delay (GPRS-AD) (refer to chapter 6.7.3)	≤ 5s (99%)
PDP Context Activation Delay (PDP-CAD) (refer to chapter 6.7.4)	≤ 3s (99%)

Table 2: Extract of SS-093 v4 for QoS requirements (PS mode)

Within 5GRAIL, to ensure the current functioning and at least the current performance of ETCS, a new ETCS application has been developed, as part of the EVC, to enable the interface with the FRMCS on-board system (OBapp) which allows to communicate with the ground system RBC via the FRMCS infrastructure. CAF and Alstom, as ETCS applications providers in the scope of 5GRAIL have modified the ETCS application to make it compliant with the FRMCS specifications.

The following figure reminds the ETCS implementation from CAF over the FRMCS ecosystem, as used in the framework of WP3 lab:

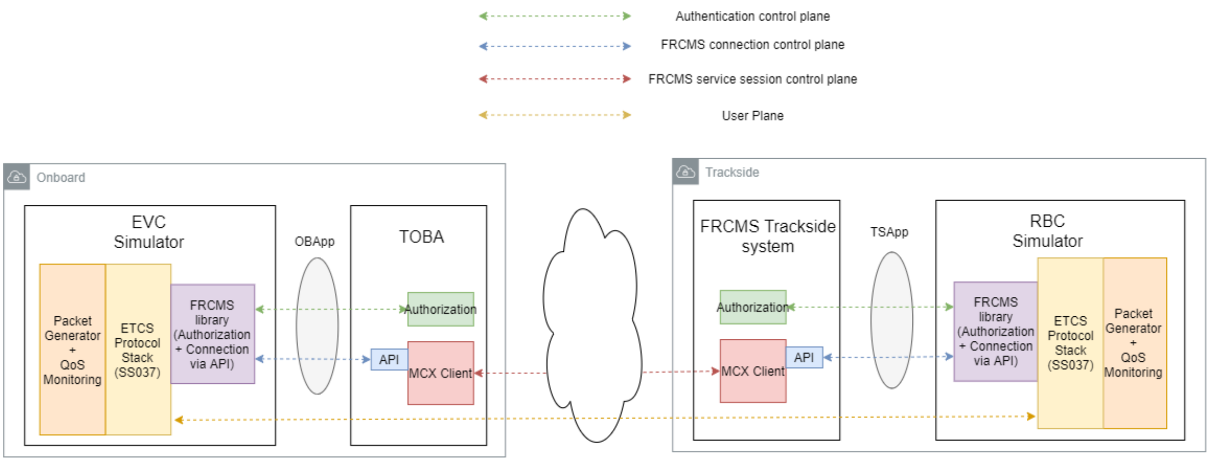


Figure 17: Overview of ETCS compatible FRMCS, as implemented by CAF in WP3 lab (Ref. D3.3)

ETCS from Alstom is implemented as following in WP4 lab:

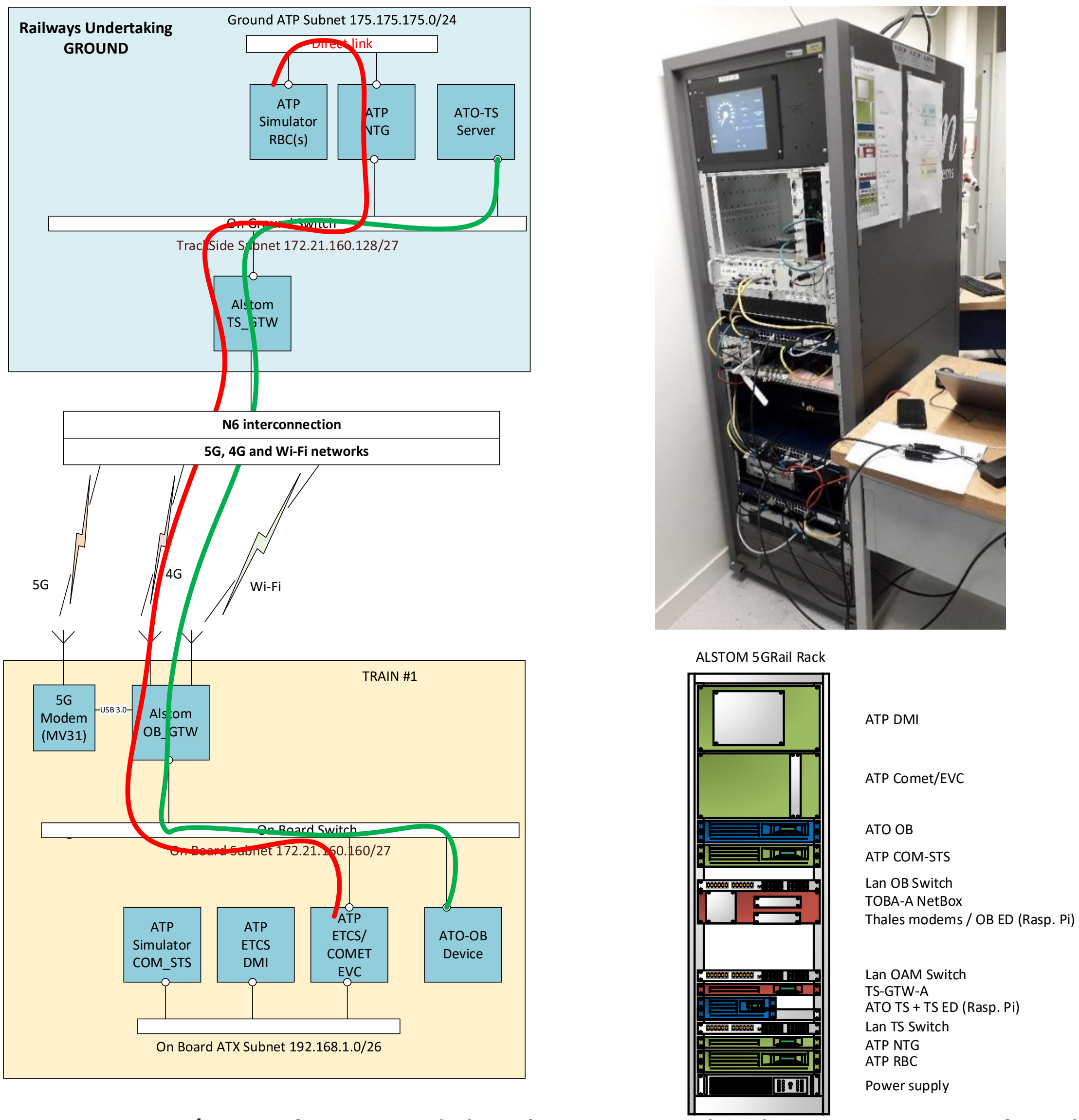


Figure 18: ETCS/ATO configuration and Alstom's equipment rack in the test environment of WP4 lab (Ref. D4.2, D4.3)

3.3.2.1 Performance methodology used in 5GRAIL for ETCS

The analysis of the data collected during the lab and field tests have been performed using Wireshark traces. The traces have been captured on both sides (EVC and RBC) to have the complete end-to-end view of the packets exchanged between the applications. The parameters that have been analysed are RTT delay (RTD) which is reflecting latency, packets sent/received, retransmissions and sent/received data rate.

- **RTT delay (RTD, reflecting latency)**

The latency is probably the most complex parameter to be measured because the processing times of the end devices are part of the measurement. As Euroradio protocol stack is relying on TCP, the analysis is based on the sequence numbers and the timestamp values from Wireshark.

For the case of ETCS, the number of packets transmitted is low and there is no delay for the acknowledgement sending. Therefore, for every TCP packet sent there is an acknowledgement packet reception (except if it is lost in the communication system).

Assuming that sequence number “x” is sent at time “t” and the acknowledgement of the sequence number “x” is received at time “t + i", it can be assumed that the RTD is equal to “i”. However, the value of “i” includes the processing time of the receiver of the packet with the sequence number “x”. The processing time can be derived from the Wireshark of the receptor of the sequence number “x”, that is why is vital to have the Wireshark of both ends. Assuming that the time of reception of the sequence number is “t”, and the time of sending the acknowledgement is “t + j”, the processing time is “j”.

Concretely, for every TCP packet sent by the EVC there is an acknowledgement packet coming from the RBC. The RTD is calculated between the time of sending the EVC packet and receiving the corresponding acknowledgement. Any network latency will be highlighted by a higher RTD value.

Below, a diagram to show the TCP exchange and how the times are used to calculate the RTD:

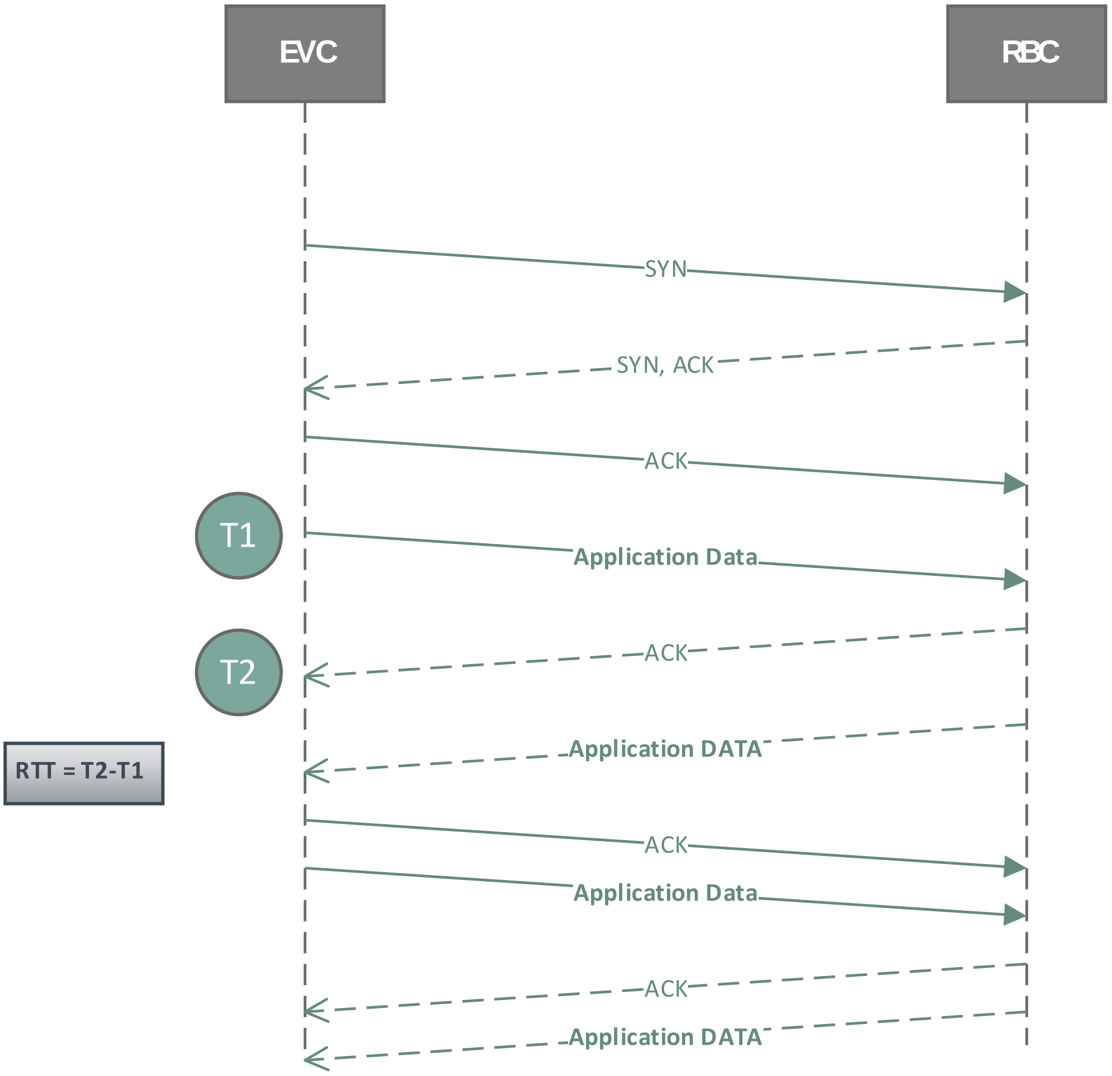


Figure 19: ETCS data exchange used to measure the RTD

__Note__: The processing time may vary depending on the moment when the packet is received and the priority of the protocol stack on the operating system at such moment.

- __Packets Sent/Received__

The procedure to obtain the packets sent or received by each entity is easier than the computation of the RTD. In this case, as Euroradio protocol is relying on TCP, and the ETCS packets are lower than the maximum MTU size of TCP (1500 bytes), each TCP packet was composed of an application message. Therefore, the TCP source and destination ports have been used to identify the number of packets sent and received.

- __Retransmissions__

The TCP protocol already implements a flow control mechanism. Therefore, it is easy to identify the packet losses from the application traces considering the number of retransmissions.

However, it is not possible for the application to detect "where" these packets are lost (gateway data overflow, air gap, 5G core...). To detect those losses, it is necessary to have traces in each of the boundaries.

- **Sent/Received data rate**

The data rate can be easily calculated from the application side. The first step is to filter the packets using the source and destination ports, and then use Wireshark tool to calculate the values for the whole traces. For example, for the EVC, the destination port 7911 would be the "sent" data rate, and the source port 7911 would be the "received" data rate.

Example of ETCS observations applying the above-mentioned methodologies in WP3:

The following table summarizes the ETCS performances in the different 5GRAIL test conditions, using the previously explained KPIs:

Test conditions	Average RTD (ms)	Packet retransmission	Average Sent/received Data rate (bits/s)
Nominal conditions	81,3	0	2694/2694
Degraded radio conditions	111,6	3	2698/2695
Increase data rate up to 4Kb/s	86,7	0	5028/5028
ETCS combined with TCMS application	91,1	0	5028/5028

Table 3: ETCS performance measured in WP3 lab

The above table reminds that only in degraded radio conditions some delays were observed in the RTD where in the nominal test case the value was always below 120ms, in degraded conditions this threshold was often overpassed, and therefore few packet retransmissions were observed at TCP level.

In the multiple applications scenarios with ETCS and TCMS, the performance parameters prove that there is no impact on the ETCS and that the On-bord FRMCS Gateway can handle in parallel multiple applications, since light difference was observed in the RTD in that case.

The performances of ETCS in WP3 lab are summarized in the following:

- **Low latency** (around 40-60ms) compliant with SS093 clause 6.7.5.2 GPRS (<2.6 s)
- **Low packet retransmissions** at user level only under dynamic or degrade condition when handover was made without remarkable effect.

- No impact in QoS in **combined ETCS/TCMS** scenario (prioritization).

Example of ETCS observations applying the above-mentioned methodologies in WP4 lab:

Two significant results, using the above methodology, were performed in WP4 lab and are presented in the Appendix 6.6.3: a) ETCS application with TOBA-A, as On-Board FRMCS gateway, applying bearer flexibility/multi-connectivity feature in degraded conditions generated by the simultaneous iPerf traffic. and b) ETCS application with TOBA-K, as On-Board FRMCS gateway, performing RBC and gNodeB handover in degraded fading and varying speed radio conditions, simulated by Vertex tool. The observations were commented in Appendix 6.6.3:

3.3.3 ATO

The ATO functioning has the same behaviour as the train driver when a mission is assigned to him. It is the timetable: with this information, the driver knows when he must pass a given station. The driver can then adapt the traction and braking of the train, to be on time. The ATO (Automatic Train Operation), has the same objective. It must respect the timetable assigned to it. For that, the ATO can rely on a first input provided to it: the **Journey Profile**, which is the set of information, enabling to know the theoretical route and the stations to pass.

The characteristics of the tracks on which the train will circulate are in the **Segment Profile**. The Segment Profile contains information enabling the ATO to know precisely how to manage the traction and braking of the train, so to save energy. This information is the maximum speed of the line, gradients and curves.

At the end of the mission, a **status report** is exchanged.

The following figure is summarizing the ATO over FRMCS set-up, as tested in WP4 lab:

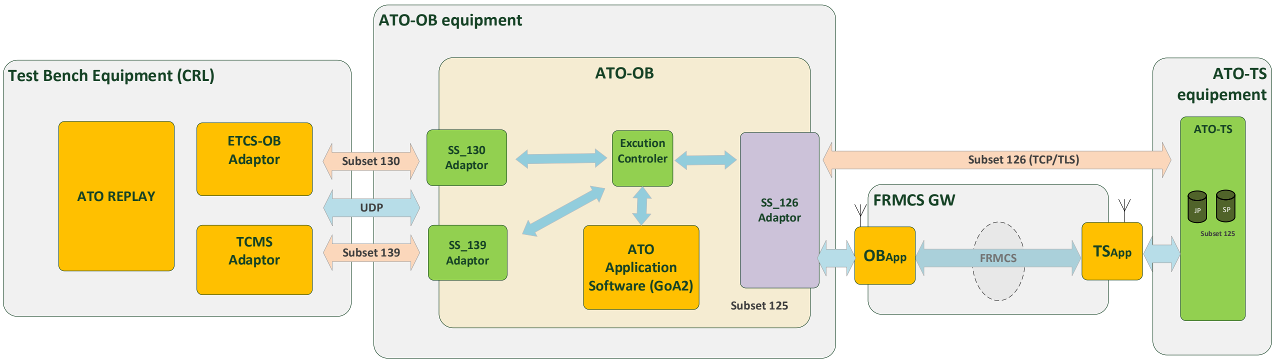


Figure 20: ATO configuration tested in 5GRAIL.

Measurements methodology:

To evaluate the ATO performance, a KPI referring to the round-trip delay of status report, sent periodically from ATO-OB to ATO-TS, is used.

The methodology used to measure this RTD of the status report consist in using WireShark traces either On-board or trackside and based on the logs timestamp of the report, the RTD can be calculated.

The following graphs show the performance of ATO based on this KPI, in nominal and degraded conditions, using iPerf traffic simultaneously in uplink or downlink with TOBA-A, as On-Board FRMCS gateway:

- ATO in nominal and perfect lab conditions:
  - Status report **RTD Mean: 65.26 ms**.
  - Status report **RTD Standard deviation: 16.77ms**

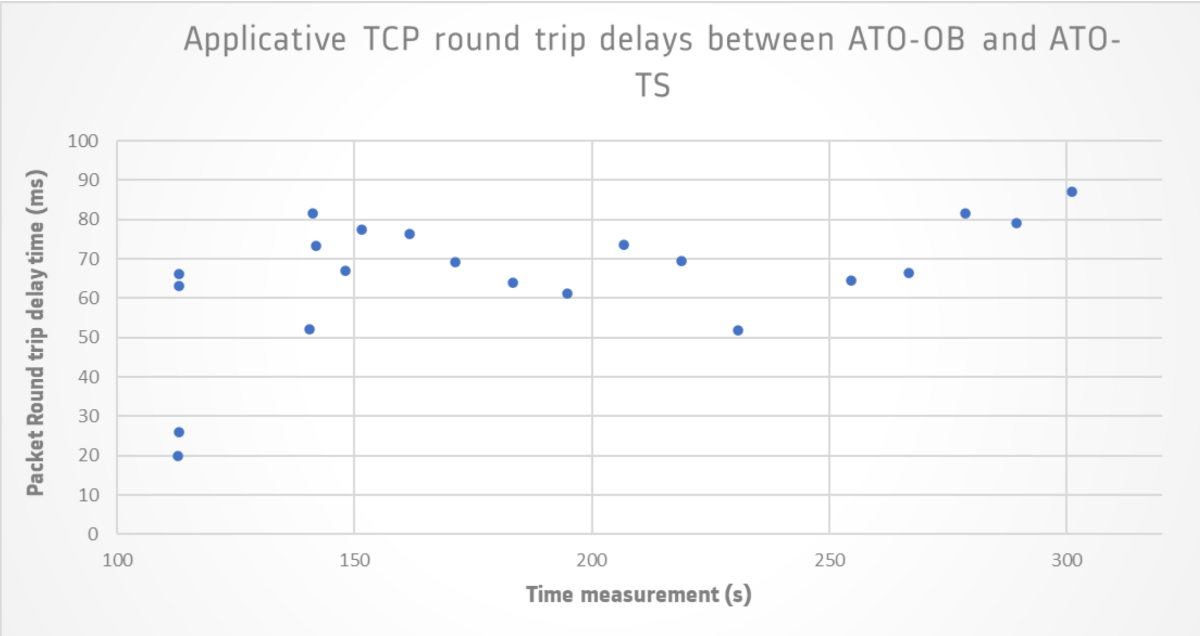


Figure 21: RTD delay of ATO status report in nominal lab conditions with TOBA-A.

- ATO in parallel with high uplink traffic generated by iPerf.
  - Status report **RTD Mean: 63.42 ms**
  - Status report **RTD Standard deviation: 14.81ms**

The above nominal results can be compared with the failover from 5G to 4G and vice-versa (bearer-flex) results of ATO using TOBA-A.

The measured values are:

- Status report **RTD Mean: 69.52 ms,** if we do not consider the high values obtained during link switch.
- The switch between links (5G to 4G or 4G to 5G) may increase the RTD obtained for regular status report. The maximal delay obtained during these test cases is **2.536s** (compared with the nominal mean delay which is around 65ms)

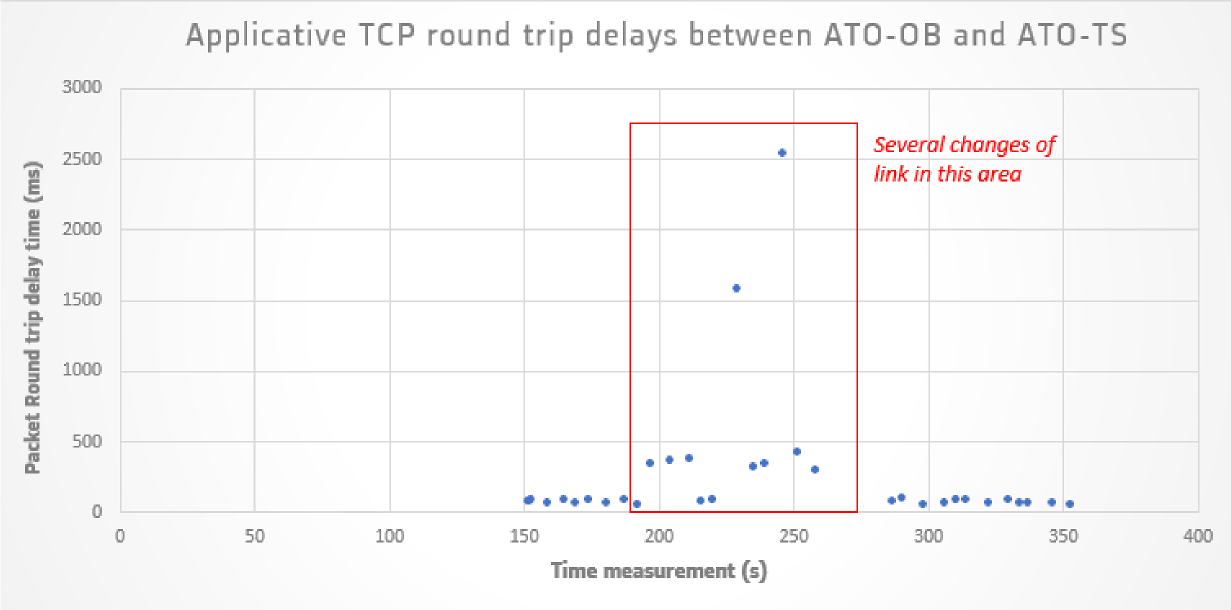


Figure 22: RTD delay of ATO status report in bearer-flex (failover 5G/4G) conditions with TOBA-A.

3.3.4 TCMS

The two use cases considered for TCMS non-critical application in WP3 lab are:

a) On-train telemetry communications (initiated by the MCG on board)

b) On-train remote equipment control (HTTP request initiated by the GCG on trackside)

The following figure shows the overview architecture of the TCMS application compatible FRMCS, where the TCMS Mobile Communication Gateway (MCG) interacts with the On-board FRMCS Gateway, and the Ground Communication Gateway (GCG) interacts with the FRMCS Trackside System.

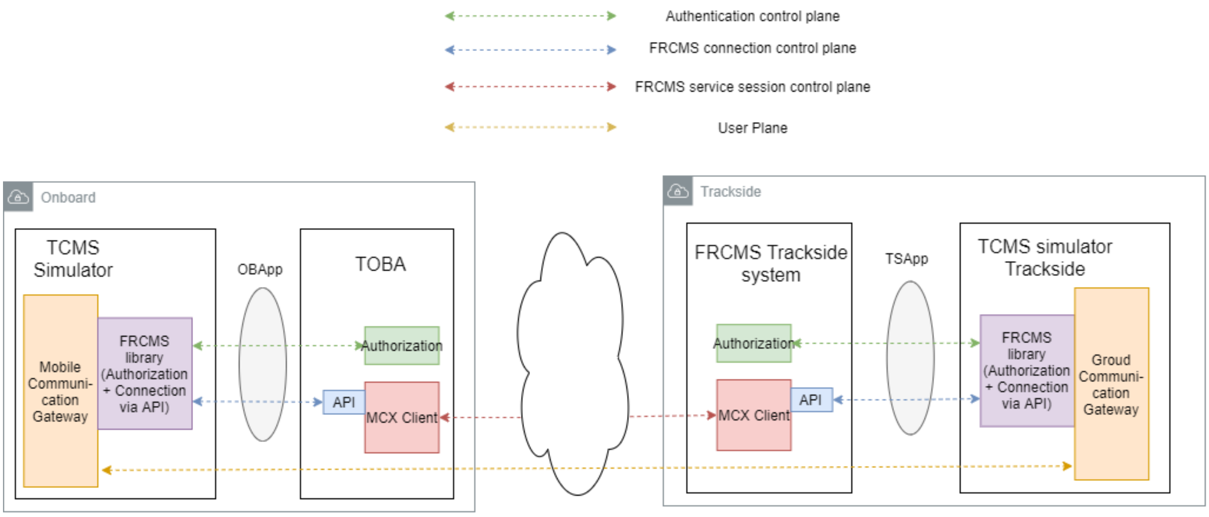


Figure 23: TCMS implementation over FRMCS end-to-end architecture

3.3.4.1 Performance methodology used for TCMS

The analysis of the data collected during the lab and field tests have been performed using Wireshark traces and application traces. The traces have been captured on both sides (TCMS on-board and TCMS trackside) to have the complete end-to-end view of the packets exchanged between the applications. The parameters that have been analysed are latency, packets sent/received, retransmissions and sent/received data rate similarly to the ETCS use case.

This manner it is easier to compare results and performance of the services. This was carried out for the field tests. During laboratory tests, application traces were used since Wireshark traces were logged in the GWs and consequently latency could not be measured using Wireshark traces. However, the methodology was updated for the field test.

- **Latency**

The latency is probably the most complex parameter to be measured. In the lab test campaigns the traces were obtained between the GWs and thus the end-to-end latency could not be obtained from there, but from the application traces. Latterly, to harmonize the performance analysis, the captures were logged with Wireshark traces, similarly to ETCS §3.3.2.1Performance methodology used in 5GRAIL for ETCS.

- **Packets Sent/Received**

The procedure to obtain the packets sent or received by each entity is easier than the computation of the RTD. In this case, as TCMS protocol is relying on TCP, and there was not any fragmentation as than the maximum MTU size of TCP (1500 bytes), each TCP packet was composed of an application message. Therefore, the TCP source and destination ports have been used to identify the number of packets sent and received.

- **Retransmissions**

The TCP protocol already implements a flow control mechanism. Therefore, it is easy to identify the packet losses from the application traces considering the number of retransmissions.

However, it is not possible for the application to detect "where" these packets are lost (gateway data overflow, air gap, 5G core...). To detect those losses, it is necessary to have traces in each of the boundaries.

- **Sent/Received data rate**

The data rate can be easily calculated from the application side. The first step is to filter the packets using the source and destination ports, and then use Wireshark tool to calculate the values for the whole traces. For example, for the TCMS, the destination port 1883 would be the "sent" data rate.

3.3.4.2 TCMS Performance

For the TCMS performance, the **jitter** of the received packets will be used because it is a one-way application that is used. In the figure below, the upper picture shows the transmitted packet time difference meanwhile the bottom one the time difference of the transmitted packets. The expected behaviour in an ideal network is having the same shape. However, packets are suffering different delays over the network. More precisely the standard deviation over the mean will be used which should be approximately 500ms (increased data rate test case). but based on the different scenario conditions, this varies from 26,4ms to 10,1ms in degraded radio conditions, which is not impacting the application.

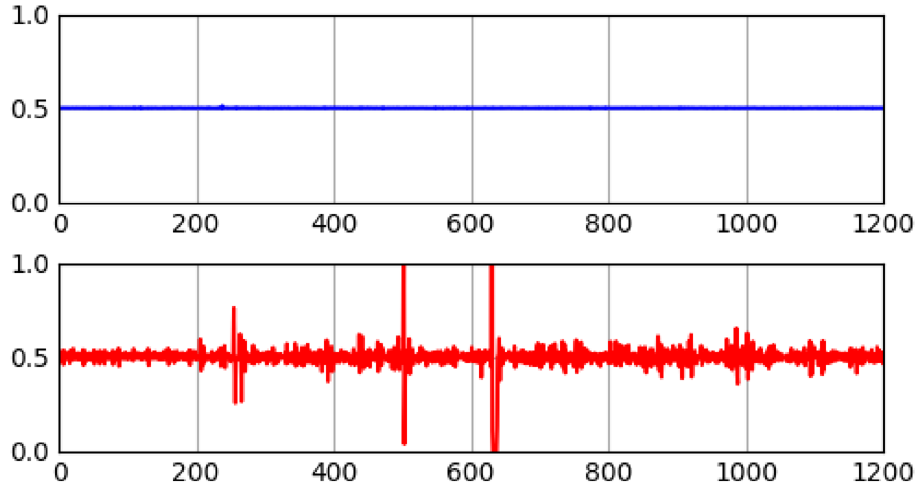


Figure 24: Time difference between consecutive packets

3.3.5 PIS

PIS application has been tested only on lab environment in WP4 activity. Nevertheless, the performance measurement methodology applied in the lab environment can be applied on real railways environment.

Generally, in railway project, user requirement on PIS application performance is defined as a **delay between PIS trackside and on-Board display. This delay should be less than 7 seconds.** (Note that 6 seconds are allowed for sub-system radio link trackside-on-Board).

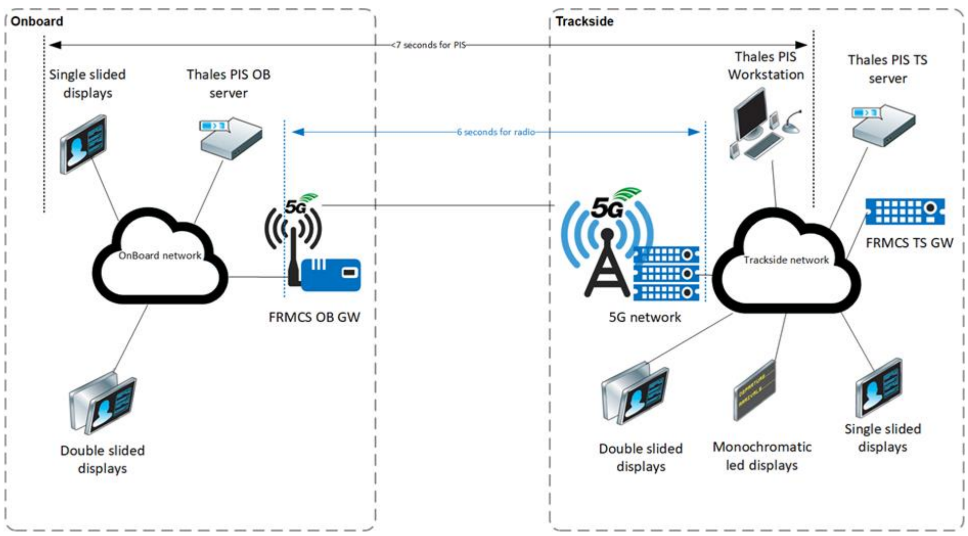


Figure 25: PIS system User requirement performance overview

To measure this performance, Thales used 2 different information:

- PIS internal timestamps logs to identify when PIS message is sent and displayed on the screen.
- Wireshark capture on both sides (On-Board and Trackside) to follow application packets.

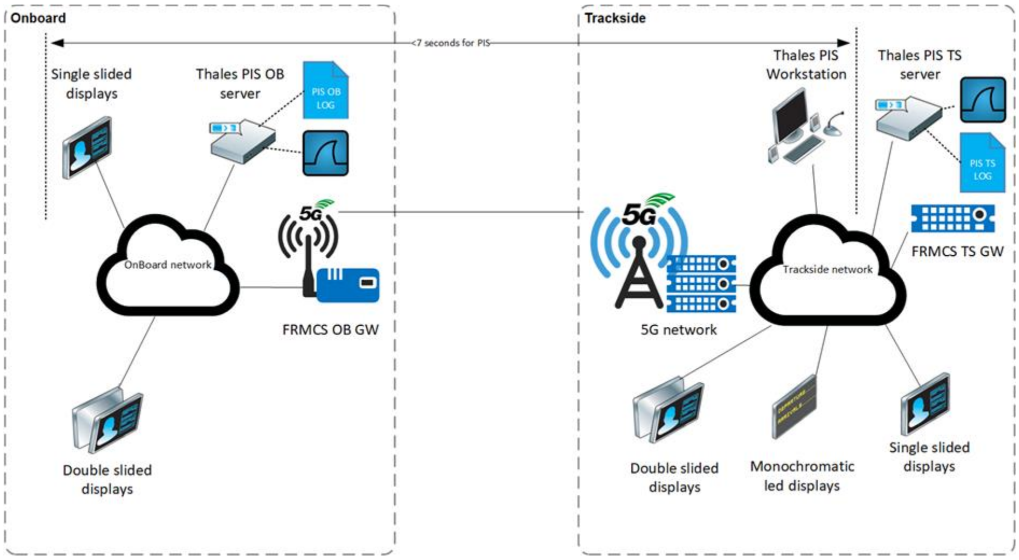


Figure 26: PIS performance capture overview

PIS performance details result for each test are available in D4.3 Second Lab Test Report. The following table gives some performance figures did during WP4 activity.

Test Title	Message received when session is not opened	Message received when session is already opened
Send text message with a normal priority to trains	4,75 s	2,64 s
Send text message with a high priority to trains	5,05 s	2,75 s
Send text message with a normal priority in degraded conditions – 5G radio link is overloaded	6,90 s	5,67 s
Send text message with a high priority in degraded conditions – 5G radio link is overloaded	6,97 s	5,53 s

Table 4: PIS performance KPI

Note: Performance value is compliant to user requirement (less than 7s). Session opening delay in OBapp and TSapp could be improved in the future.

3.3.6 VIDEO

3.3.6.1 Video performance

The following figure is showing the CCTV/Video common architecture for nominal testing, which corresponds to CCTV/video from the on-board video management system (Train computer) to the trackside video management system. In particular, the below figure corresponds to the field set-up at German testbed with remote connection to WP3 lab in Budapest:

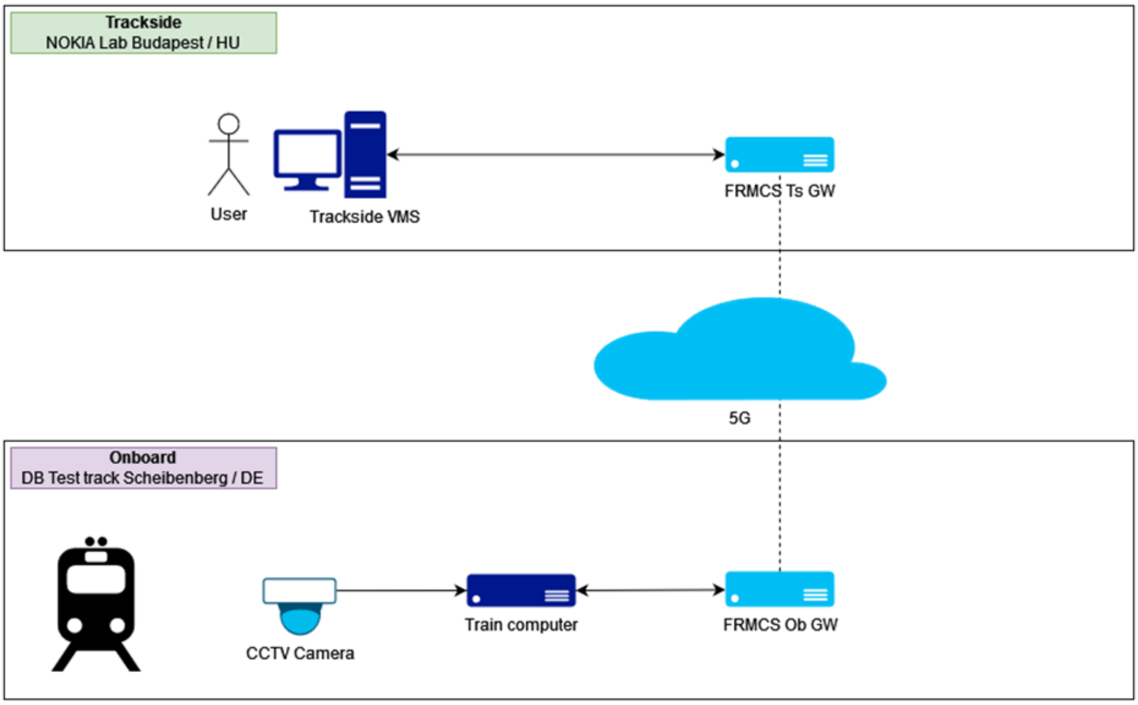


Figure 27: CCTV video - Test Architecture (Ref. D5.1)

The On-board application sends video data to the trackside application over TCP. The video over TCP is considered a better choice than over UDP when network degradations may occur.

The experience and visual effects of the video over TCP in such scenarios is much better (especially for identification) than video over UDP. The video over TCP when network degradation occurs may jerk, be delayed or skipped but picture is visible, however for video over UDP, when network degradation occurs, frames are lost.

To evaluate the impact on video with degraded radio conditions, different speeds 50Km/h, 120Km/h, 175Km/h and doppler effects have been simulated in the WP3 lab.

The following figures are reminding the results in the different scenarios:

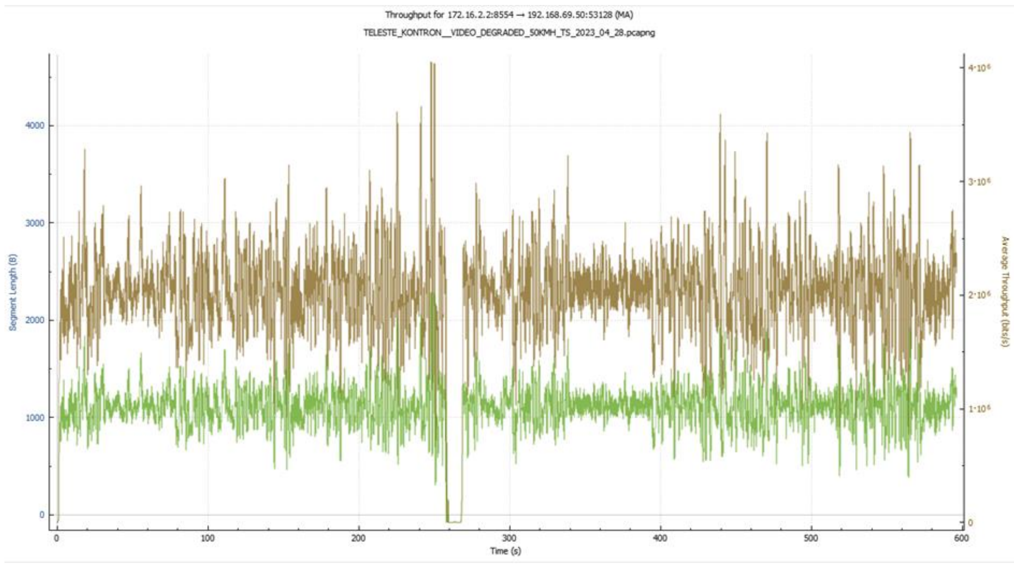


Figure 28: Video streaming at simulated train speed of 50 km/h– – throughput/goodput (Ref. D3.3v1)

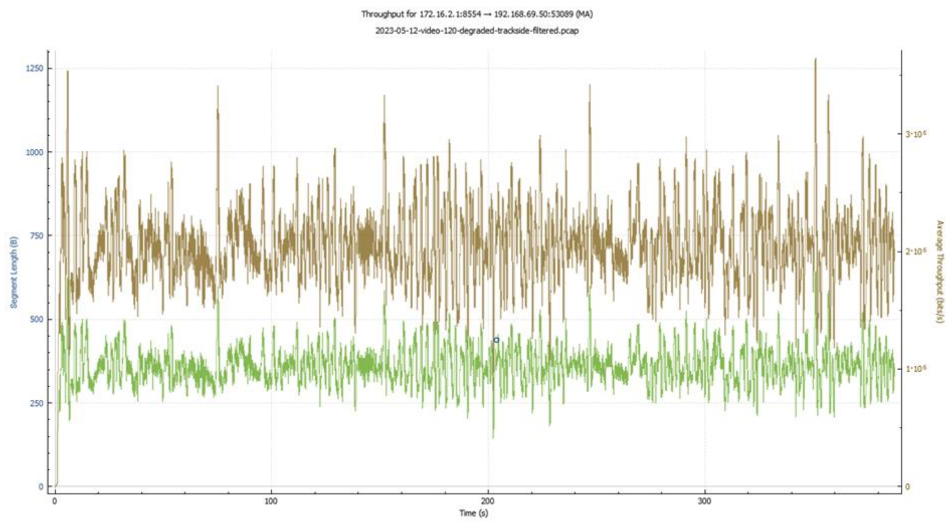


Figure 29: Video streaming at simulated train speed of 120km/h– – throughput/goodput (Ref. D3.3v1)

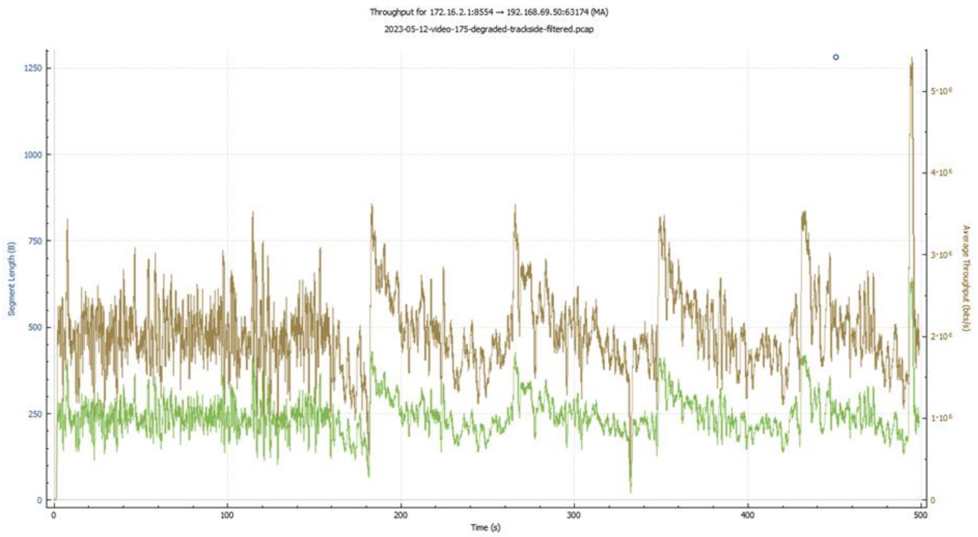


Figure 30: Video streaming at simulated train speed of 175km/h– – throughput/goodput (Ref. D3.3v1)

The observations demonstrated that up to 120Km/h, there were no major impacts in video quality but in 175Km/h, frequency was dropping from 25fps to 15fps or more and bit rate was dropping from 1000Kb/s to 600Kb/s or more.

3.3.6.2 Offload speed of CCTV using two subbands of n78 TDD with different frame structure

Different frame structure was used to demonstrate the impact with two subbands of n78 with CCTV offload test case. This is presented in the following figure where bearer-flexibility set-up is considered as an inter-frequency Xn handover between Cell1 (track) to Cell2 (station), using different subbands of n78, in that way the multi-access variant of the bearer-flexibility feature was demonstrated:

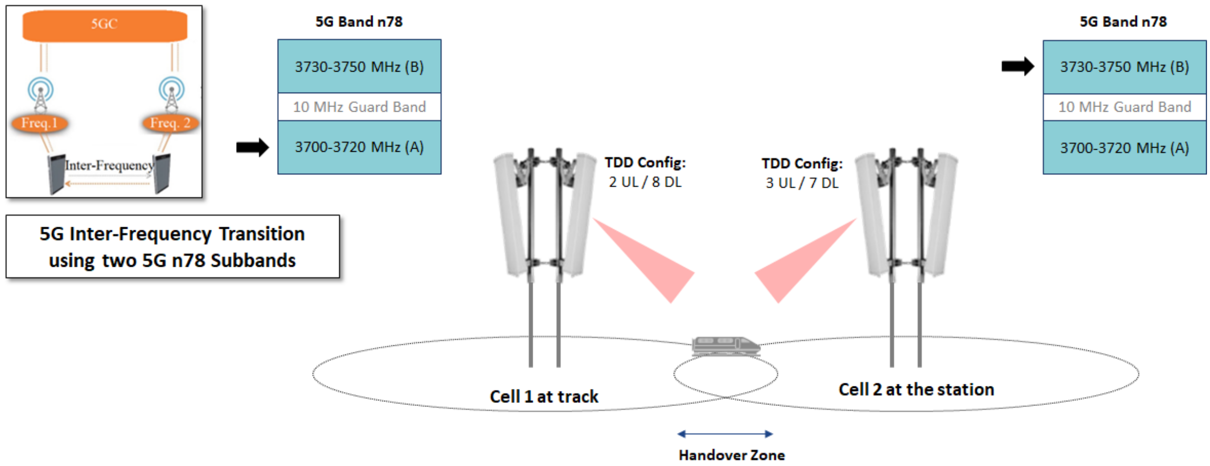


Figure 31: Bearer flex set-up (Ref. D3.3, D5.1)

Cell1 represents 5G coverage at track while Cell2 represents 5G coverage at the train station.

When performing CCTV offload, which consist in uploading data from train to trackside, where uplink data slots are used in the TDD frame structure. In Cell1 the 1 / 4 ratio means that there are 2 uplink and 8 downlink data slots out of 10 time slots, however in Cell2 the 3 / 7 ratio means that there are 3 uplink and

7 downlink data slots for the same. So, in Cell2 there is 1,5x larger bandwidth available (3 data slots instead of 2 data slots in uplink) for data upload, which ensures a higher offload speed, as presented in the following comparison figure for lab performances of CCTV offload:

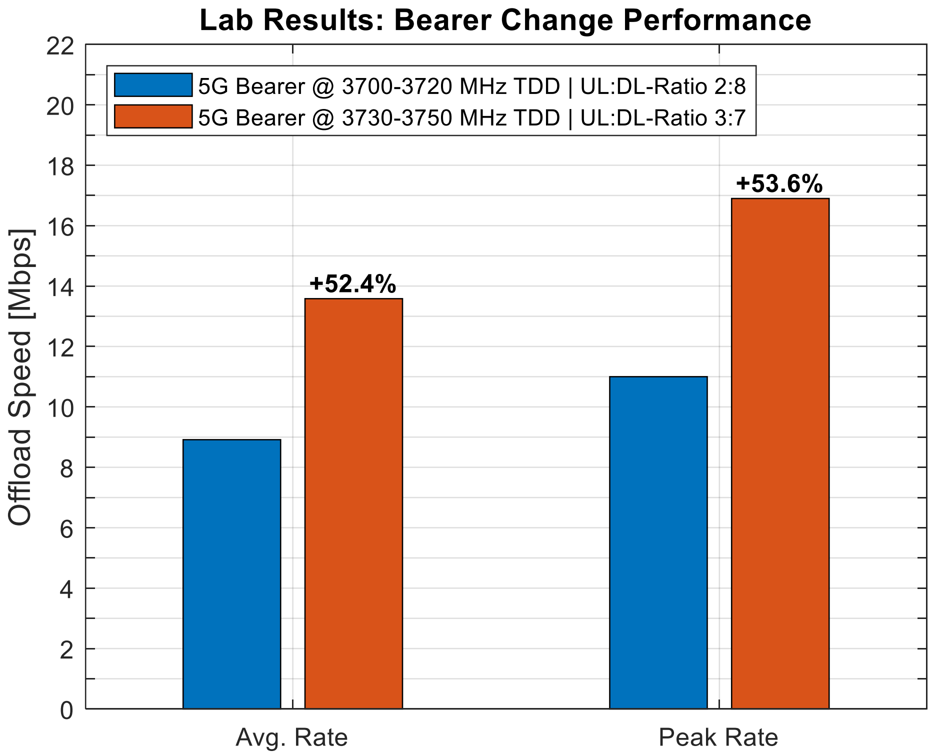


Figure 32: Impact of Bearer Change in CCTV offload performance (Ref. D3.3v2)

Precisely, at the beginning of the test, the CCTV offload, mainly the upload of CCTV video surveillance data was transferred in Cell1 at about 11 Mbps, almost constantly, without any issue. Then background traffic was generated in Cell1, which lowered the bandwidth of CCTV offload to about 6 Mbps. After 2 minutes, the CCTV offload moved from Cell1 to Cell2, when suddenly the bandwidth of the CCTV offload increased to about 17 Mbps in Cell2 due to the higher UL frame structure.

The performances of this test in the WP3 lab are presented in the following figure:

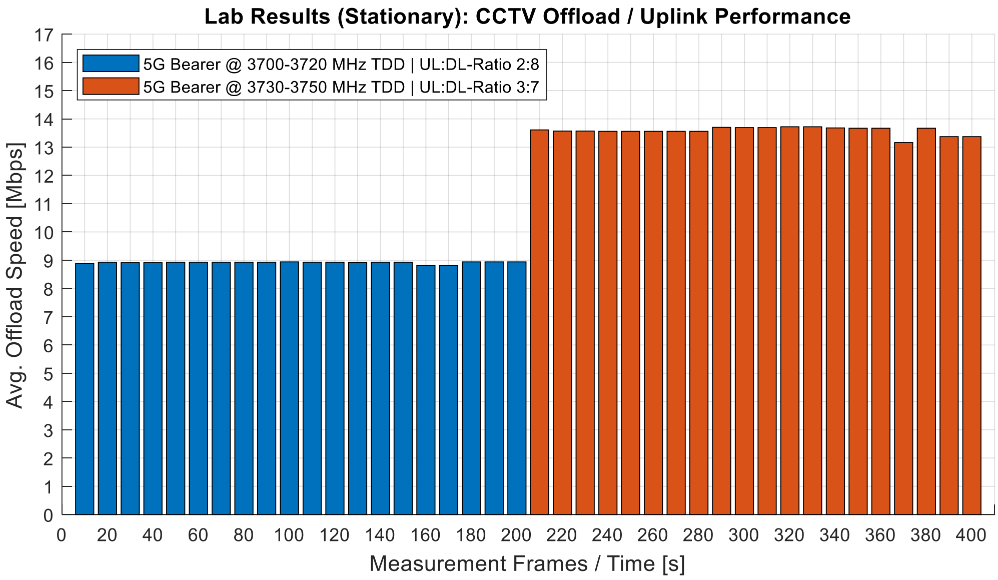


Figure 33: CCTV offload performance using Bearer flex feature (Ref. D3.3v2)

3.3.7 REMOTE VISION

Remote vision is an application used by SNCF in a remote operation context for technical centre manoeuvre, 1st and last daily journey and recovery in case of incident. The requirements of this application are video latency as low as possible, video stability for safety and comfort. The video quality can be achieved through adaptable bit rate, latency is related to network reliability and stability is related to advanced codecs. The application was tested in French testbed and pre-tested in WP4 lab to safely prepare the field activities.

For remote vision as well, the TDD frame structure in n39 is validated in WP4 lab that it is impacting, as for CCTV application, the performance of remote vision when using 4TSs instead of 2TSs in the uplink. This was the configuration of remote vision used during the field tests in the French testbed.

The following figure is showing the application constituents, On-Board and Trackside:

Figure 34: Presentation of remote vison Video chain (Ref. D5.1)

Depending on the quality of network coverage, the remote vison application takes longer timer to increase from 1Mb/s to 2.5Mb/s but due to coverage issues related to the presence of PMNO's interferer, the application never reached the 2.5Mb/s.

The following figure shows the test run with the more stable higher quality.

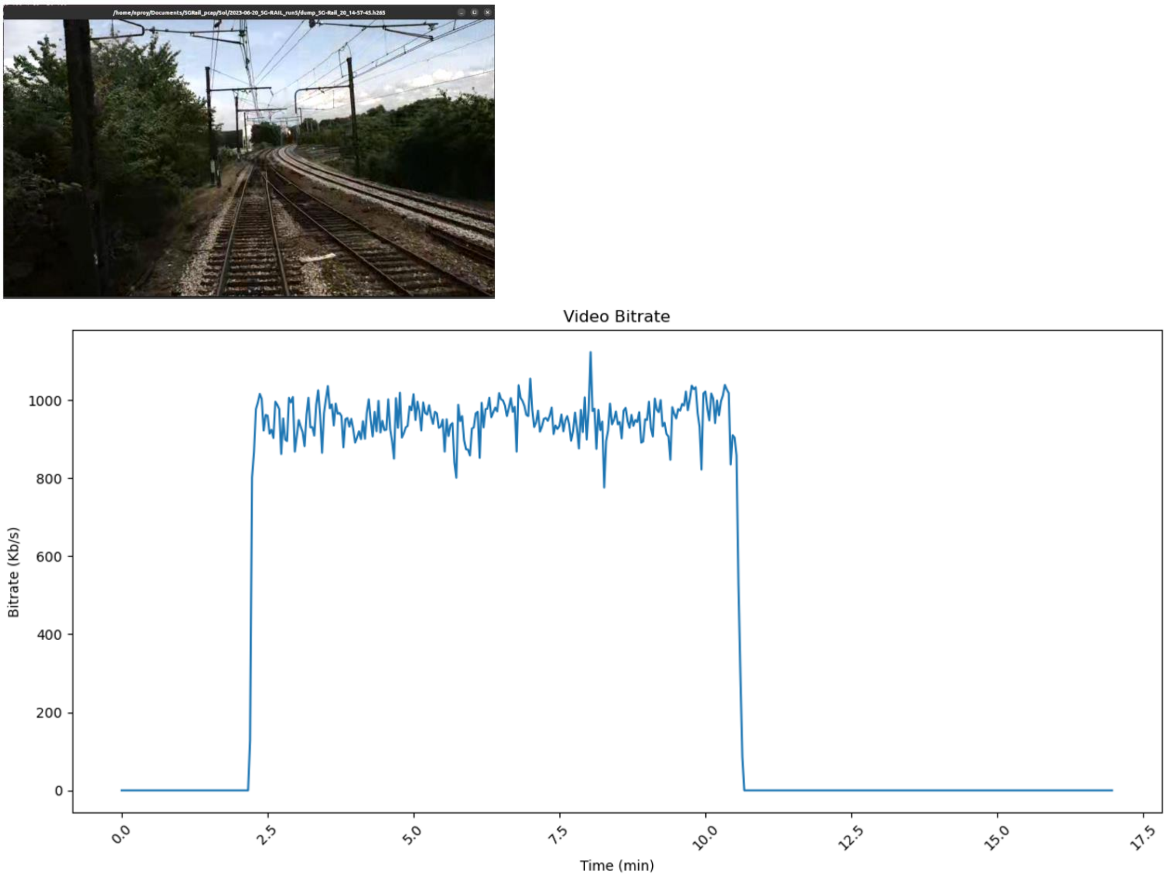


Figure 35: Highest quality performance of remote vision, without packet losses and jitter (Ref. D5.1)

3.3.7.1 Measurement methods for remote vision

The following KPI measurements can be used for the video application layer:

1-Throughput: Throughput is measured based on the number of packets received per second on the machine's network using a specified protocol, in our case, it is RTP, for which we chose the packet size.

2- Received Video Packets: The number of received packets is the sum of all RTP packets received over the network.

3- Lost Packets: The number of lost packets is measured based on the seqNum of RTP packets. A difference is calculated between the received packet and the one received just before it. If there is a gap of more than one packet, it means that these packets are lost, and the indicator is incremented.

4- Late Packets: Late packets are packets that arrive later due to network loss and have been buffered. As video implies a fixed delay between images, if the packets to decode a precise image arrive after its decoding time, these are discarded, and the KPI is incremented.

5- Latency: Latency is measured end-to-end by comparing the timecode embedded inside the video multiplexed stream and the machine time on the decoding computer. To ensure accurate time synchronization between the two machines, both on-board and ground video computers use a GPS sensor to get GPS time. The video application provides a latency with a millisecond precision, relevant for the use-case.

4 CONCLUSIONS

The purpose of D1.3 was to elaborate / propose a performance measurements methodology derived from the lab and field-testing experience that can be considered for future FRMCS trials and pilot deployments.

Through this deliverable, our approach was to identify the main items of the FRMCS end-to-end architecture where performances need to be evaluated. Moreover, some proposal of relevant KPIs per topic have been presented, together with the measurement methods applied during the lab and field testing of 5GRAIL, as well as with the first results of these tests.

These are considered as an added value of 5GRAIL for the on-going specifications discussions for FRMCS testing strategy, e.g. related to QoS measurements in different scenarios. It is also a valuable indication for railway stakeholders as well as for measurement tools providers to efficiently prepare FRMCS testing framework.

5 REFERENCES

id	DOCUMENT TITLE	REFERENCE, VERSIONS
[1]	FRMCS User Requirements Specification,	FU-7100
[2]	FRMCS Use cases	MG-7900
[3]	FRMCS Functional Requirement Specification (FRMCS FRS)	FU- 7120
[4]	System Requirements Specification (FRMCS SRS)	AT- 7800
[5]	Study on Future Railway Mobile Communication System, Stage 1 (Release 16 & Release 17)	3GPP TR22.889 V17.4.0 3GPP TR22.889 V16.6.0
[6]	Technical Specification Group Services and System Aspects, Mission Critical Services over 5G System, Stage 2 (Release 17)	3GPP TS 23.289 V1.0.0
[7]	Technical Specification Group Services and System Mission Critical Services Common Requirements (MCCoRe) Stage 1 (Release 17)	3GPP TS 22.280 V17.4.0
[8]	Technical Specification Group Services and System Aspects Mission Critical Push to Talk (MCPTT) Stage 1(Release 17)	3GPP TS 22.179 V17.0.0
[9]	Technical Specification Group Services and System Aspects Mission Critical Data services Release 16	3GPP TS22.282 V16.4.0
[10]	Group Services and System Aspects Security of the Mission Critical (MC) service (Release 17)	3GPP TS 33.180 V17.2.0
[11]	Technical Specification Group Services and System Aspects System architecture for the 5G System (5GS) Stage 2(Release 17)	3GPP TS 23.501 V17.0.0
[12]	Technical Specification Group Services and System Aspects. Mobile Communication System for Railways Stage 1(Release 17)	3GPP TS22.289 V17.0.0

[13]	Technical Specification Group Services and System Service requirements for the 5G system Stage 1 (Release 18)	3GPP TSTS22.261 V18.2.0
[14]	ETSI- Study on FRMCS System Architecture	ETSI TR 103 459 V1.2.1 (2020-08)
[15]	ETSI-GSM-R/FRMCS Interworking	ETSI TR 103 768 V0.0.4 (2021-062)
[16]	D2.1 TOBA Architecture report	REV3 – 31/01/2023
[17]	D3.1 First Lab Integration and Architecture Description	13/09/2021 – v1 31/03/2022 – v2
[18]	D4.1 Second Lab Integration and Architecture Report	14/09/2021 – v1 25/03/2022 – v2
[19]	Grant Agreement number: 951725 — 5GRAIL — H2020-ICT-2018-20 / H2020-ICT-2019-3	
[20]	D3.2 First Lab Setup Report	28/02/2022 - v1 30/06/2022 – v2
[21]	D4.2 Second Lab Setup Report	25/02/2022 – v1
[22]	Functional Interface Specification	FIS – 7970
[23]	Form Fit Functional Interface Specification	FFFIS-7950
[24]	ERTMS/ETCS GSM-R Bearer Service Requirements	Subset 093 – v4.0.0
[25]	Radio Transmission FFFIS for EuroRadio	V13.0.0
[26]	Subset-037	v3.2.0
[27]	Functional architecture and information flows to support Mission Critical Push to Talk (MCPTT); Stage 2 - (Release 17)	3GPP TS 23.379 v17.8.0
[28]	Mission Critical Push To Talk (MCPTT) media plane control; Protocol specification	3GPP TS 24.380 v17.6.0

[29]	Subset 126 – Appendix A	Issue: 0.0.10
[30]	D1.1 Test plan	RV4
[31]	D4.3 Second Lab Test report	RV2
[32]	Technical Specification Group Services and System Mission Critical Services Common Requirements, Stage 2 (Release 17)	3GPP TS23.280 v17.9.0
[33]	Technical Specification Group Core Network and Terminals Mission Critical Data (MCData) signalling control Protocol specification (Release 17)	3GPP TS24.282 v17.9.0
[34]	Technical Specification Group Core Network and Terminals. Mission Critical Push To Talk (MCPTT) call control; Protocol specification (Release 17)	3GPP TS24.379 v17.11.0
[35]	Technical Specification Group Services and system Aspects; Policy and charging control framework for the 5G System (5GS) Stage 2 (Release 17)	3GPP TS23.503 v17.9.0
[36]	Cross-Working Group Work Item: Network Reselection Improvements (NRI) – 5GAA Automotive Association Technical Report	V1.0
[37]	D3.3 First Lab Test report	RV2
[38]	Ericsson White Paper	GFTL-22:000375 Uen March 2022
[39]	FRMCS metrics/KPIs	VIAVI Solutions
[40]	K. Alexandris, N. Nikaein, R. Knopp, C. Bonnet, Analyzing x2 handover in lte/lte-a. In:	2016 14th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), pp. 1–7 (2016). IEEE
[41]	Shift2Rail – X2Rail-3: Advanced Signalling, Automation and Communication System (IP2 and IP5) – Prototyping the future by means of capacity increase, autonomy and flexible communication.	
[42]	FRMCS Border Crossing.	5GRAIL Final Conference Presentation by Sara Akbarzadeh.

[43]	Procedures for the 5G System (5GS); Stage 2 (Release 17)	3GPP TS23.502 v17.11.0
[44]	ERTMS/GSM-R Quality of Service Test Specification	UIC/ERA O-2475 4.0.0

6 APPENDICES

6.1 Appendix A.1: Inputs referred in the 5G network performance part (5GRadio Metrics)

6.1.1 5GRadio Metrics and KPIs for FRMCS

For the proposed radio KPIs, only definitions are provided, values cannot be provided at that step, because FRMCS specifications are on-going with reference to that topic and the experience of tool measurement providers is based on the PMNO 5G networks (cf. §5 [39]).

Category	RF KPIs	Definition
Availability	**5G-NR Network Ratio**	The ratio of 5G New Radio (NR) network resources used for data transmission compared to the total available resources.
Signal and Coverage	**Serving SS-RSRP**	The power of the received reference signal in the serving cell
	Serving SS-RSRQ	The quality of the received reference signal in the serving cell.
	Serving SS-SINR	The ratio of the signal power to the interference plus noise power in the serving cell.
Interference	**Wideband CQI**	Definition: An indicator of the quality of the radio channel between the user equipment and the serving cell.
	NR-RSSI	The received signal strength indicator for the New Radio signal
Radio Link Performance	**UL MCS (Avg)**	The average modulation and coding scheme used for uplink transmission.
	DL MCS (Avg)	The average modulation and coding scheme used for downlink transmission
	Average RLC DL BLER	The average rate of downlink blocks with errors in the Radio Link Control layer.
	RLC DL Retx_Rate	Radio Link Control Downlink Retransmission Rate
	RLC UL Retx. Rate	Radio Link Control Uplink Retransmission Rate
Throughput and Latency	**PDSCH Throughput**	The average throughput of the physical downlink shared channel
	RLC DL Throughput	The average throughput on the downlink at the Radio Link Control layer
	PUSCH Throughput	The average throughput of the physical uplink shared channel.

	RLC UL Throughput	The average throughput on the uplink at the Radio Link Control layer.
Accessibility	**RACH Attempt Success Rate**	The rate of successful attempts to access the network through the Random Channel
	Attach Success Rate	The rate of successful attachment of the UE to the network
	RRC Setup Success Rate	The rate of successful Radio Resource Control setups for communication
	Initial Attached Time	The time taken for the initial attachment of the user equipment (UE) to the network.
	RRC Connection Setup Time	The time required to set up the Radio Resource Control (RRC) connection for communication between the UE and the network
	Call Setup Success Rate	The rate of successful call setups.
Integrity	**Service Call Drop Rate**	The rate at which service calls are dropped within the network.
	RRC Connection Drop Rate	The rate at which Radio Resource Control (RRC) connections are dropped within the network.
Mobility	**Inter-gNodeB Xn Success Rate**	The rate of successful handovers between gNodeBs in the Xn interface.
	Inter-gNodeB Xn HO Duration (Avg)	The average duration of handovers between gNodeBs in the Xn interface.
	Inter-gNodeB Inter AMF Success Rate	The rate of successful handovers between gNodeBs that are not connected to the same AMF.
	Inter-gNodeB Inter AMF HO Duration (Avg)	The average duration of handovers between gNodeBs that are not connected to the same AMF.
	Intra-gNodeB HO Success Rate	The rate of successful handovers within the same gNodeB
	Intra-gNodeB HO Duration (Avg)	The average duration of handovers within the same gNodeB

Table 5: Monitoring Mandatory Metrics and KPIs for FRMCS

6.2 Appendix A.2: Inputs referred in the 5G network performance part (Throughput, RTD)

6.2.1 Throughput measured in WP3 lab

In the scope of WP3 lab, a test was performed to compare the maximum data throughput between n78 and n8 band with the required radio configuration. The tool used for this throughput measurement was iPerf. Applying the same configuration of iPerf, uplink throughput measurement test was performed both on n78 and n8 band.

Both bands performed a maximum throughput around 10Mb/sec without differences during the test comparison, as described in the below figures:

```
[  5]  20.00-21.01  sec  1.12 MBytes  9.42 Mbits/sec
[  5]  21.01-22.00  sec  1.12 MBytes  9.46 Mbits/sec
[  5]  22.00-23.00  sec  1.12 MBytes  9.47 Mbits/sec
[  5]  23.00-24.01  sec  1.12 MBytes  9.31 Mbits/sec
[  5]  24.01-25.01  sec  1.12 MBytes  9.44 Mbits/sec
[  5]  25.01-26.00  sec  1.12 MBytes  9.57 Mbits/sec
[  5]  26.00-27.01  sec  1.12 MBytes  9.31 Mbits/sec
[  5]  27.01-28.01  sec  1.12 MBytes  9.49 Mbits/sec
[  5]  28.01-28.44  sec   512 KBytes  9.65 Mbits/sec
```

Figure 36: iPerf throughput result on n78

```
[  4] 262.00-263.01 sec  1.25 MBytes  10.4 Mbits/sec
[  4] 263.01-264.00 sec  1.27 MBytes  10.8 Mbits/sec
[  4] 264.00-265.00 sec  1.24 MBytes  10.4 Mbits/sec
[  4] 265.00-266.01 sec  1.19 MBytes  9.90 Mbits/sec
[  4] 266.01-267.01 sec  1.30 MBytes  10.9 Mbits/sec
[  4] 267.01-268.01 sec  1.25 MBytes  10.5 Mbits/sec
[  4] 268.01-269.00 sec  1.31 MBytes  11.0 Mbits/sec
[  4] 269.00-270.00 sec  1.27 MBytes  10.7 Mbits/sec
[  4] 270.00-271.00 sec  1.19 MBytes  9.99 Mbits/sec
```

Figure 37: iPerf throughput result on n8

6.2.2 Comparison of RTD delay in n8 and n39 band.

FRMCS networks will be operated over two different RF bands: RMR 100 band (900 MHz) and RMR101 band (1900 MHz). These two bands will of course have different behaviours because of radio propagation differences when radio frequency increases. Moreover, RMR 100 will use FDD mode whereas RMR 101 will be in TDD mode, which also introduces some differences.

5GRAIL experiments were using n8 (900 MHz) and n39 (1900 MHz) bands, also respectively in FDD and TDD mode. Consequently, test set-up could already give some insights about RMR 100 and 101 bands expected differences.

The main point appears to be the influence on round trip delay, as the usage of TDD mode has clearly an impact on it (modem shall wait for an uplink slot to be able to transmit uplink data, same effect on downlink side). This test is performed by pinging the P-CSCF, as it is the entry point of many procedures impacted by this delay (e.g., IMS registration).

We noticed a difference of RTD in WP4 evaluation tests of On - Board Gateways as RTD was measured around 30ms with TOBA-A in n8 while around 40ms with TOBA-K in n39. However, the modems that are used (ES1 for n8 and ES3 for n39) are quite different and it is then difficult to reach any conclusion at that stage. However, **this RTD difference should be something to be considered in future FRMCS tests as it may have an impact on some procedures that require several exchanges between UE and the network, such as IMS registration.**

6.3 Appendix A.3: Inputs referred in the 5G network performance part (Handover)

6.3.1 5G Handover types

There are different kind of 5G handovers (change of cell within the same gNodeB, changing gNodeB with or without Xn interface, changing gNodeB and AMF, changing gNodeB and UPF…), as presented in the below non-exhaustive figure:

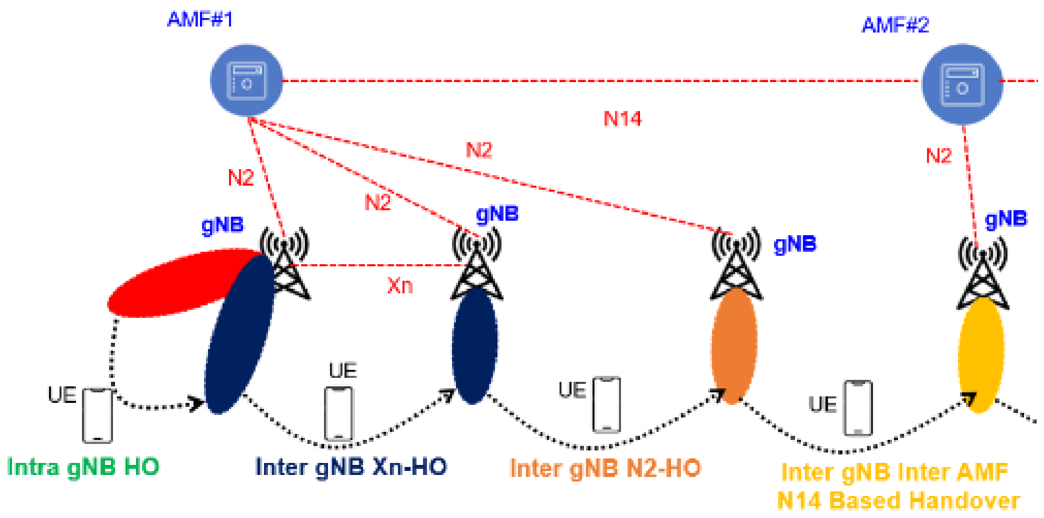


Figure 38: 5G Handovers - Connected Mode Mobility - TelcoSought

In the following, we are providing definitions of the above categories for a better understanding of the complexity that implies each one:

- **Intra-gNB (intra-AMF/intra-UPF)**: 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/intra-UPF):** The serving and target gNBs share the same AMF and UPF. The handover procedure could occur on gNB level if interface Xn exists. If Xn doesn't exist, the control messages could be also exchanged via NG interface.
- **Inter-gNB (intra-AMF/inter-UPF)**: The serving and target gNBs share the same AMF but different UPFs. The handover procedure could be achieved on gNB level if interface Xn exists. If Xn doesn't exist, the control messages could be also exchanged via NG interface.
- **Inter-gNB (inter-AMF/inter-UPF)**: Since the AMF and UPF are not the same for serving and target gNBs, the handover procedure is handled in NG level between two AMFs.

- **Inter-gNB (inter-AMF/intra-UPF):** The handover procedure is handled in NG level between two AMFs, while the UPF remains the same for gNBs.

6.3.2 Call flow of inter-gNodeB Xn handover in 5GSA

The following figure is presenting the 5G nodes involved in the inter-gNodeB Xn handover:

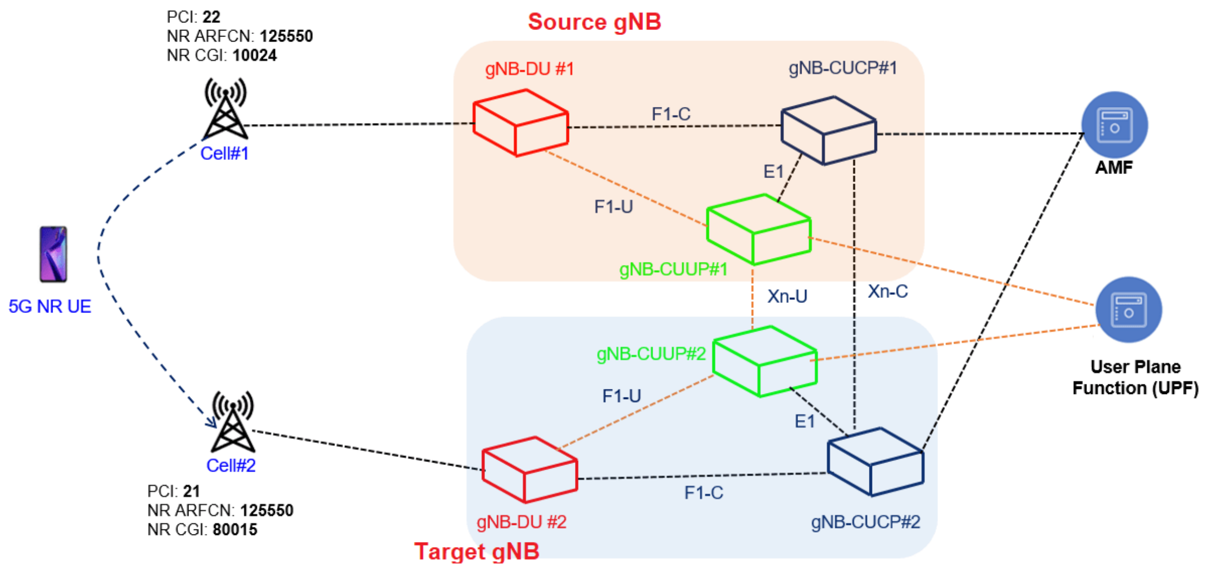


Figure 39:5G SA Inter gNB Xn Handover – (techplayon.com)

Based on the received measurements, Source gNodeB initiates the handover through Xn interface. Target gNodeB provides a new RRC configuration and performs admission control. Source gNodeB forwards the Handover Request Acknowledge message to the UE, along with cell ID, access information, and beam-specific information.

UE moves to RRC connected state with Target gNodeB and sends the RRC Reconfiguration Complete message.

Xn handover does not include AMF and User Plane Function (UPF) in the handover procedure. In case they are included (e.g., in Next-Generation (NG) Handover), the procedure consists of additional steps, further increasing the complexity and the delay required by the process.

The following figure is presenting the inter-gNodeB handover call flow:

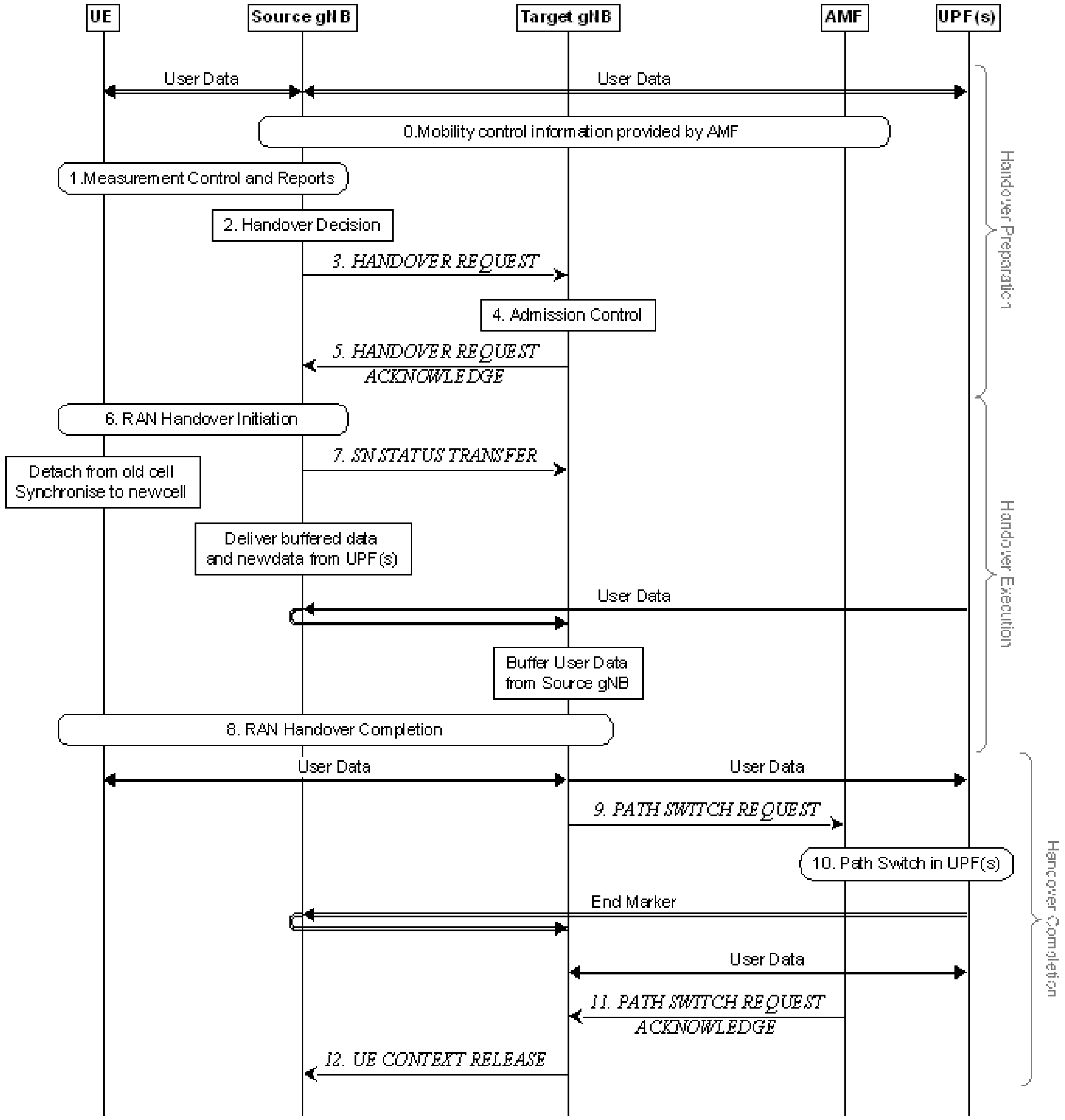


Figure 40: 5GSA Inter-gNB Handover – Xn Handover (Intra AMF/UPF Handover)

6.3.3 Inter-gNodeB HO over AMF

The following figure summarizes the inter-AMF HO set-up:

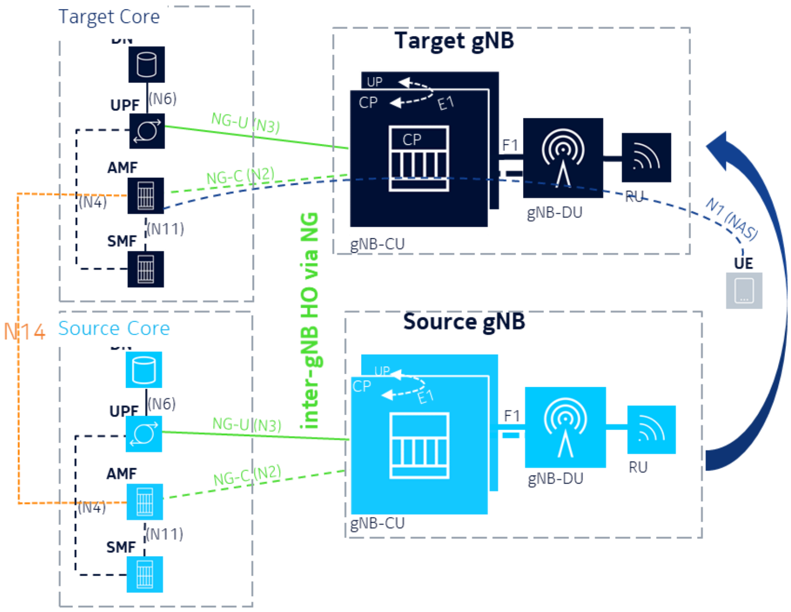


Figure 41: Inter gNodeB/Inter-AMF HO Setup via NG(N2) interface (Ref. D3.3v2) The sequence of procedures and the call flow is as following:

BTS-1 on CMU-1 asks for handover → CMU-2 sends HO request for BTS-2 → BTS-2 sends back the 'HandoverNotify' to CMU-2 → CMU-1 asks BTS-1 for 'UEContextReleaseRequest' →BTS-1 sends back 'UEContextReleaseComplete' to CMU-1

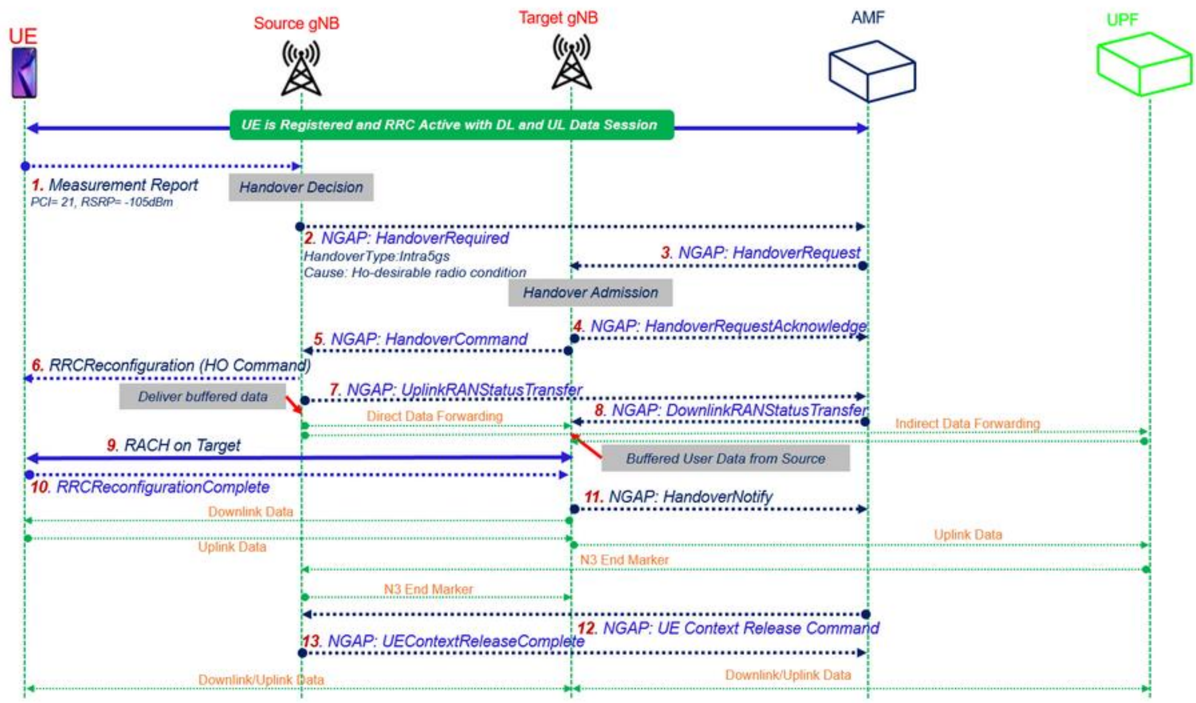


Figure 42: Call flow for inter-AMF HO set-up

The handover interruption time can be considered between **HandoverRequired** and **HandoverNotify** message, which is estimated around **154 ms**.

Based on the above diagram, we provide few explanations about these two steps:

- **Step#2-Handover Required**: Based on source gNodeB HO decision it trigger an N2 handover and sends an **N2 Handover Required** message to **AMF**. The message contains the UE RAN NGAP-ID, AMF-NGAP-ID, Target gNB ID, **Handover Type**, Handover Cause and information about the PDU Sessions to be handed over.
- **Step#11-HandoverNotify**: The target gNodeB then sends a Handover Notify to AMF and by this the target gNodeB considers the handover successful. This message includes UE-NGAP_IDs for both RAN and AMF to identify the UE context and UE location information mean under which **Tracking Area** (TAC) UE is being served.

The Inter-AMF handover has been tested with voice. Data flow was performed between Cab radio and Train controller (CAB→DISP) and the observations performed were based in the cab radio's logs, as presented in the following figure.

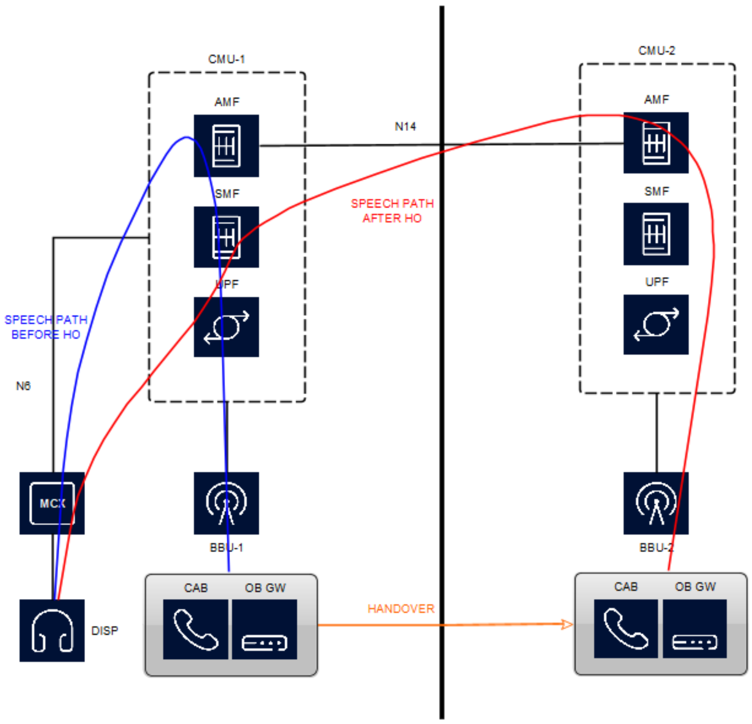


Figure 43: Voice Call flow during Inter-AMF HO (Ref.D3.3v2)

After the handover, call flow is moved to the target AMF, however session management remains in the source CMU (SMF, UPF, UDM) unit.

During the testing, it has been noticed that:

1. Cab radio towards Train controller speech path is continuous during handover, short crackling was hearable without any loss.
2. Train controller towards Cab radio speech path is not continuous during handover, ~1 sec voice gap is hearable.

6.3.4 5G Handover Types with KPIs

In 5G Standalone (SA) networks, several types of handovers facilitate seamless mobility for user equipment (UE). Some key handover types in 5G SA are:

Intra-gNB Handover: Supports handovers between different cells served by the same gNB (gNodeB) in a 5G SA network.

Inter-gNB Handover: Enables handovers between cells served by different gNBs, ensuring uninterrupted service as the UE moves across different coverage areas.

Inter-system handover: This occurs between a 5G gNB and an eNodeB.

Here are some example KPIs that can be used to assess the handover performance in a 5G network for:

- **Intra-gNodeB Handover Time:** Intra-gNodeB handover time refers to the duration required to transfer the connection of a user equipment (UE) from one cell to another within the same gNB (gNodeB) in a 5G network.
- **Inter-gNodeB Handover Time:** Inter-gNodeB handover time refers to the duration required to transfer the connection of a UE from one cell to another, between different gNBs (gNodeBs) in a 5G network.
- **Inter-AMF Handover Time: I**nter-AMF handover time pertains to the duration required to transfer the session of a UE from one Access and Mobility Management Function (AMF) to another in a 5G network.
- **Handover Success Rate**: The percentage of successful handovers over the total number of attempted handovers.
- **Average Handover Duration**: The average time taken for a successful handover to complete.
- **Intra-gNodeB Handover Interruption Time**: The time taken for the UE to regain stable communication after an intra-gNodeB handover.
- **Inter-gNodeB Handover Interruption Time**: The time taken for the UE to regain stable communication after an inter-gNodeB handover.
- **Inter-AMF Handover Success Rate**: The percentage of successful AMF handovers over the total number of attempted AMF handovers.

The additional below KPIs can evaluate the efficiency and reliability of handover procedures in a 5G network, ensuring a seamless and uninterrupted user experience during mobility across different cells and mobility management functions. Adjusting these thresholds can be done based on specific network requirements and the desired quality of service for end-users:

- Handover Success Rate
- Handover Latency
- Xn/NG Handover Success Rate
- Inter-Frequency Handover Success Rate

6.3.5 HO inter/intra gNodeB

Based on the 5G handover types, as presented in appendix § 6.3.1, less impacting one being clearly the change of cell within the same gNodeB because it does not need the exchange of lots of preparation messages between nodes to be set-up.

If the handover management is achieved via the Xn interface between serving and target gNodeBs but without the involvement of network function, then it is called Xn-based. The Xn-based handovers are considered as classic handover, supported by one single core. If the AMF, UPF and other functions are involved, the control messages are sent via NG interface and the handover is kind of NG based or network based §5 [43]. It was shown that the handover delay in **interface-based (Xn) method is up to six times smaller than that of network-based (NG),** on the condition that the X2/Xn interface exists §5[41].

When it comes to measuring the real impact of handovers, following indicators, linked to the duration of the radio transmission outage, are relevant: Loss of packets, retransmissions, impact of data rate and jitter at the application level.

To better characterize them, a specific FTP application like iPerf can be used, handover being performed with iPerf application doing an uplink or a downlink transfer. This kind of tool will automatically compute jitter and data rates. However, to assess the impact on end user applications (ATO, ETCS, voice…) it is better to directly use the application during the test, with a statistical approach (i.e., repeating the test scenario many times). In that case, the relevant KPI of the application should be used (MOS voice quality, number of ETCS packets dropped…); iPerf will only give an idea of the impact but each application obviously reacts differently to it. It should also be noted that some smartphone embedded applications might also be used to better measure the handover duration by tracing handover control messages but, once again, this is different from end user impact analysis.

Regarding lab tests, it is also important to set the radio level conditions close to what is expected on field for that situation, that it to say, cell edge power level. This would better reflect the on-site behaviour. Velocity and multi-path may also be added by a simulation tool to consider the speed of the train and the urban or rural landscape.

6.3.5.1 Intra/inter gNodeB performances measured in WP3 lab

In the WP3 lab set-up environment, there are two configurations to simulate handover conditions either using Vertex channel Emulator which accurately simulates signal fading but also complex effects of wireless transmissions, such as multipath and Doppler effects. So, it is an equipment used to simulate in principle degraded radio conditions but can also be used for handover only. When using it to only simulate handover, this can happen by simply modifying signal strength of source and target cells. This method was used for mobility scenarios (inter/intra gNodeB HO) with voice application (MCPTT), or two applications in parallel voice and video (MCData) applications. In that case, the set-up is as following:

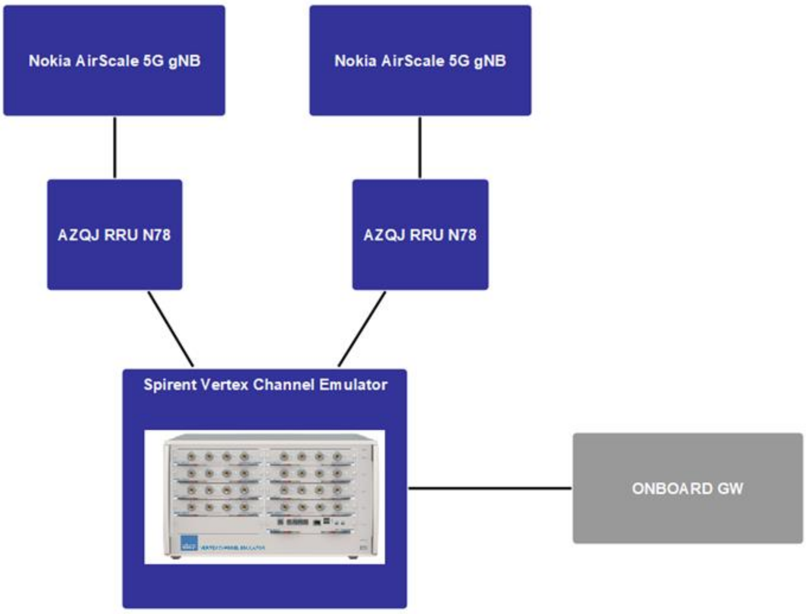


Figure 44: 5G Handover and/or radio degraded conditions set-up with Vertex Channel Emulator (Ref. D3.3)

Or using the HYTEM 6x6 FULL FAN OUT Attenuation Matrix (6x6 - 93/110 dB - 3 to 6 GHz), which was the case for the different MCData only applications scenarios. The set-up of this equipment is presented in the following figure:

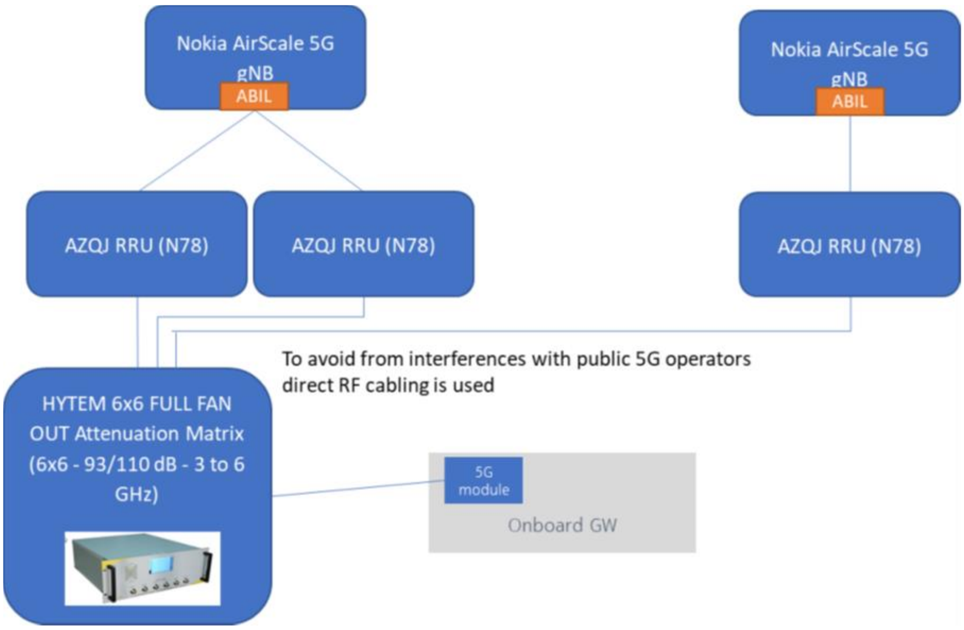


Figure 45: 5G Handover only RF configuration with HYTEM attenuator

<u>**NOTE**</u>: WP3 decided to focus on two 5G frequencies:

- N8 band, 900 MHz FDD (UL: 880 – 915 MHz, DL: 925 – 960 MHz)
- N78 band, 3300 – 3800 MHz TDD

In the following we will provide some indications of the impact of HO in the applications tested in WP3 lab with TOBA-K:

- **ETCS-CAF**

Test conditions	Average RTD (ms)	Packet retransmission	Average Sent/received Data rate (bits/s)
Nominal conditions	81,3	0	2694/2694
With inter and intra gNodeB HO, around every 2min	86,3	1	2694/2696

Table 6: Impact on ETCS performance due to inter/intra gNodeB HO measured in WP3 lab

So very slight increase was observed in the RTD without impact in the application's behaviour.

- Comparison of inter-gNodeB (Intra-AMF/Intra-UPF) Handover in lab conditions (n78 vs n8)

The below figures are mainly referring to the test case Voice_019 described in the D1.1 Test plan, where the purpose was to evaluate the impact of mobility conditions in a point-to-point voice communication from the train driver to the responsible dispatcher. Due to the mobility conditions, HO performances have been evaluated in different frequency bands (n78 and n8), as the same test was repeated in both bands. During the test, inter-gNode B, intra frequency Xn handover occurred.

Based on the call flow presented in Figure 40 of the Appendices §6.3.2Call flow of inter-gNodeB Xn handover in 5GSA, the Xn handover involves a signalling time over three phases: HO preparation, HO execution and HO completion. The duration of these three phases is presented for the Voice_019 test in n78 and n8 in §Figure 46. 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.

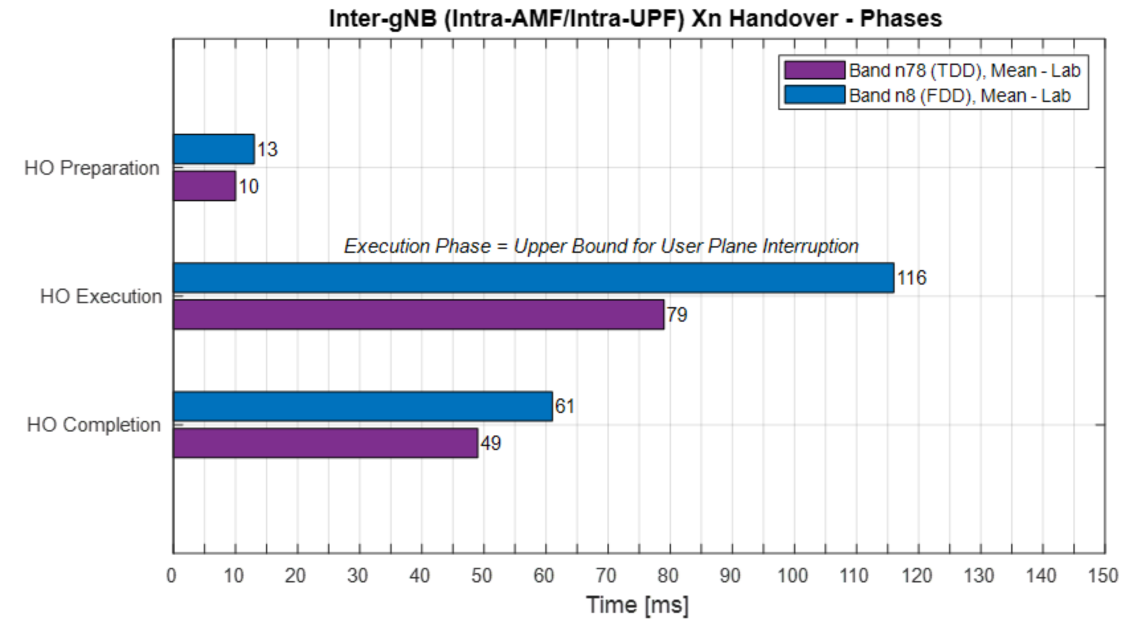


Figure 46: Comparison of Inter-gNodeB (Intra-AMF/Intra-UPF) Handover -Xn Phases in lab conditions (n78 vs n8) (Ref. D3.3v2)

The Figure 47 presents the overall Xn handover time of the same test in the two band n78 and n8.

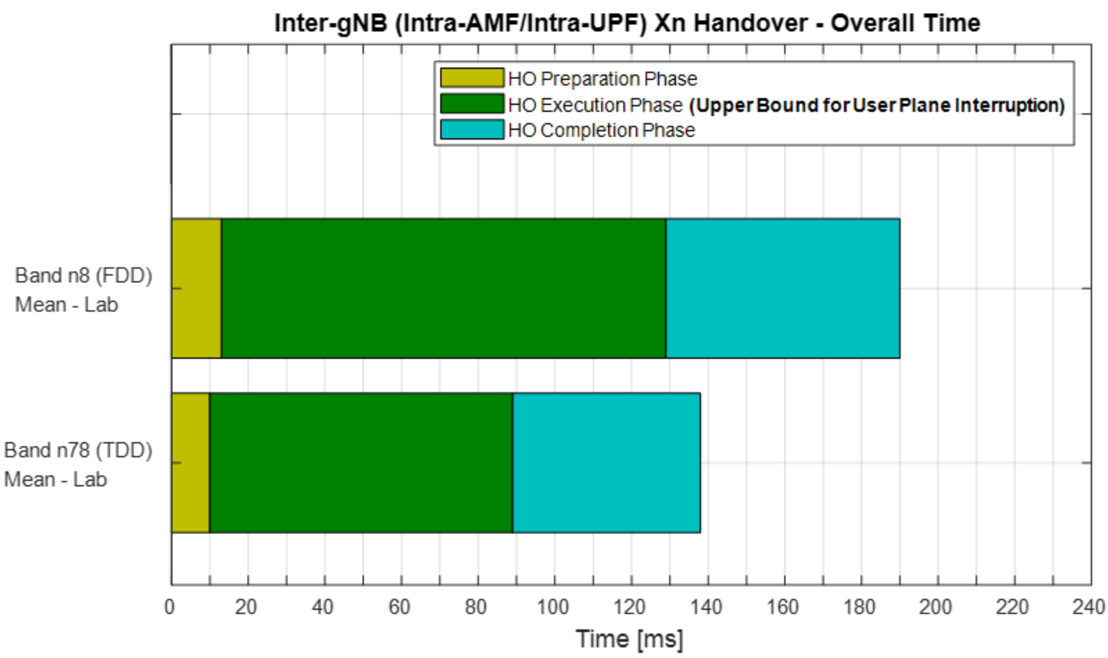


Figure 47: Comparison of Inter-gNodeB (Intra-AMF/Intra-UPF) Handover -Xn Overall Time (n78 vs n8) (Ref.D3.3v2)

The logs of WP3 lab below demonstrate the same overall Xn-handover values, as in Figure 47.

Handover time on n78:

17650 *REF*	10.104.6.93	10.104.6.92	XnAP	598	HandoverRequest
17654 0.010	10.104.6.92	10.104.6.93	XnAP	778	HandoverRequestAcknowledge
17655 0.014	10.104.6.93	10.104.6.92	XnAP	158	SNStatusTransfer
17664 0.089	10.104.6.92	10.88.89.211	NGAP	146	PathSwitchRequest
17689 0.138	10.104.6.92	10.104.6.93	XnAP	102	UEContextRelease

Figure 48: Handover time on n78

Handover time on n78 band is 138 ms.

Handover time on n8:

9705 *REF*	10.104.6.90	10.104.6.91	XnAP	554	HandoverRequest
9711 0.013	10.104.6.91	10.104.6.90	XnAP	770	HandoverRequestAcknowledge
9714 0.018	10.104.6.90	10.104.6.91	XnAP	146	SNStatusTransfer
9722 0.129	10.104.6.91	10.88.89.211	NGAP	142	PathSwitchRequest
9778 0.188	10.88.89.211	10.104.6.91	NGAP	166	SACK (Ack=0, Arwnd=131072) , PathSwitchRequestAcknowledge
9780 0.190	10.104.6.91	10.104.6.90	XnAP	98	UEContextRelease

Figure 49: Handover time on n8

Handover time on n8 band is 190 ms.

The above observations conclude that **the HO in TDD band is faster than the one of FDD band**.

The above results observed during one voice test case, were consolidated by HO Xn observations in N78 TDD band versus N8 FDD band for different applications (e.g. ETCS, TCMS, Video), in the scope of WP3 lab, where although there is no significant statistical volume, we can deduce a certain behaviour. These are presented in the below tables:

N78 Xn HO time	
Mean	0,320625
Standard Error	0,0592
Median	0,177
Mode	0,179
Standard Deviation	0,529497
Sample Variance	0,280368
Kurtosis	14,51987
Skewness	3,954793
Range	2,444
Minimum	0,128
Maximum	2,572
Sum	25,65
Count	80
Confidence Level(95.0%)	0,117834
Upper CI	0,438459
Lower CI	0,202791

N8 Xn HO time	
Mean	0,197533
Standard Error	0,008929
Median	0,19
Mode	0,198
Standard Deviation	0,034583
Sample Variance	0,001196
Kurtosis	6,031175
Skewness	2,219756
Range	0,135
Minimum	0,168
Maximum	0,303
Sum	2,963
Count	15
Confidence Level(95.0%)	0,019151
Upper CI	0,216685
Lower CI	0,178382

Table 7: Comparison of Xn HO time in n78 TDD and n8 FDD bands

In the above table, we can observe that the highlighted in green median values of TDD band are lower than the ones of FDD band.

6.3.5.2 Intra/inter gNodeB performances measured in WP4 lab

In the framework of WP4 TOBA-K with n8 and n39 are available as well as TOBA-A with n8. N101 (1900-1910 MHz) TDD band dedicated to FRMCS (which is a n39 sub band) is considered to be used for the safety critical railway applications because this band is first allocated in Europe for FRMCS exclusively, and second seems achieving 5G NR latency, reliability and user throughput, required by these applications. TOBA-K in n39 was used in field tests in French testbed this is the reason why the mobility tests (intra/inter gNode B HO) have been evaluated in this band.

The below set-up for intra gNodeB HO was used up to a path-loss of 105 dB, before the complete loss of communication which represents the worst-case scenario at cell edge in field. So, the HO has to be triggered before this lower threshold of path loss.

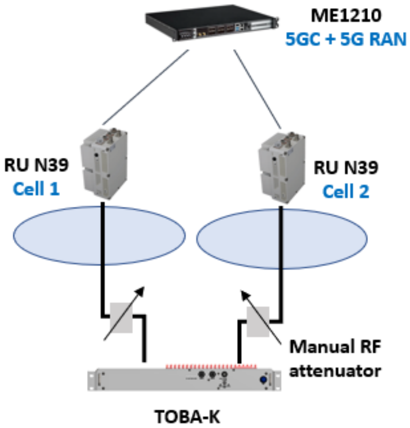


Figure 50: TOBA-K intra gNodeB HO test setup (Ref. D4.3v2)

The following set-up was used for the inter gNodeB HO evaluation:

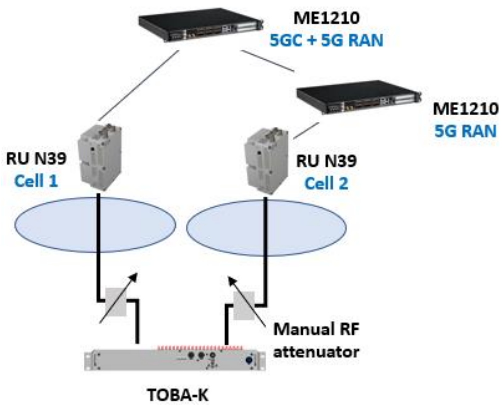


Figure 51: TOBA-K inter-gNodeB HO test setup (Ref. D4.3v2)

The above tests without application presence were only performed to identify the behaviour at cell edge, to prepare the worst-case scenario in field conditions.

In below figure, the impact of intra-gNodeB HO and inter-gNodeB HO as observed in WP4 lab in France was presented for ETCS application of Alstom:

- ETCS with TOBA-K with RBC and gNodeB handover on the same 5G network in lab conditions:

In lab conditions also, even though slight degradation was observed in the RTD delay with 121.3 ms and standard deviation Round Trip Time = 450.7ms with gNodeB handover versus 119.89 ms in nominal conditions and standard deviation Round Trip Time = 452.45ms, this was without impact in the application

The TCP retries have been excluded because they are not impacting data exchange although they are increasing the standard deviation value.

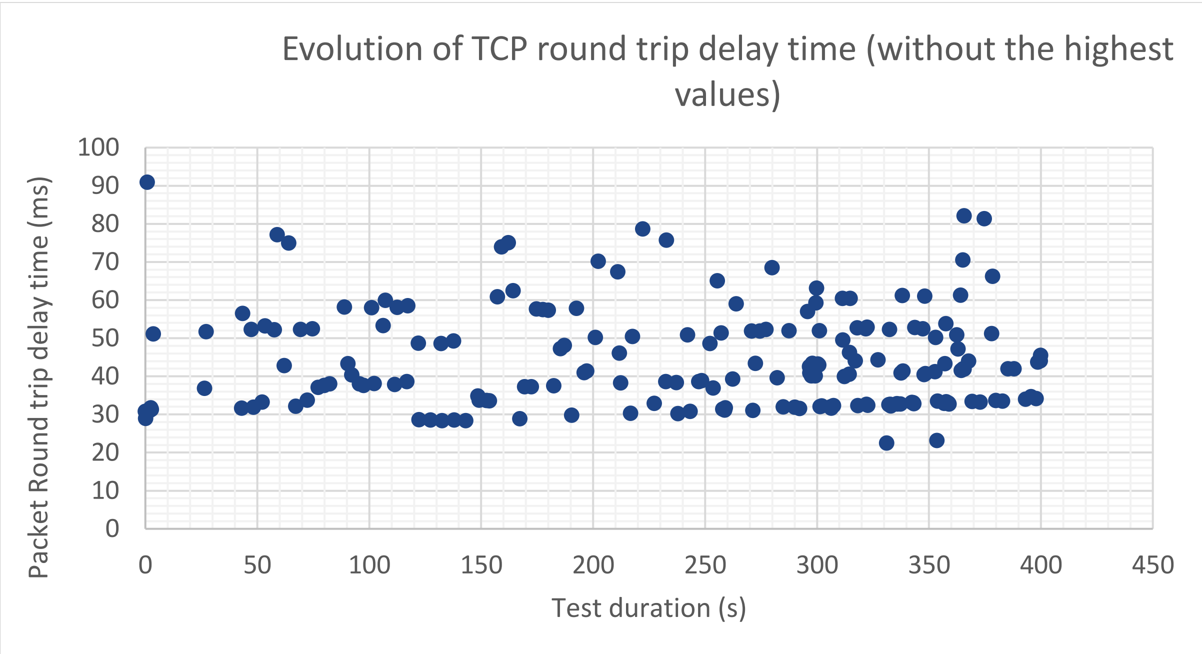


Figure 52: RTD delay of ETCS application with RBC and gNodeB handover in the same 5G network.

The is to be compared with the nominal case below:

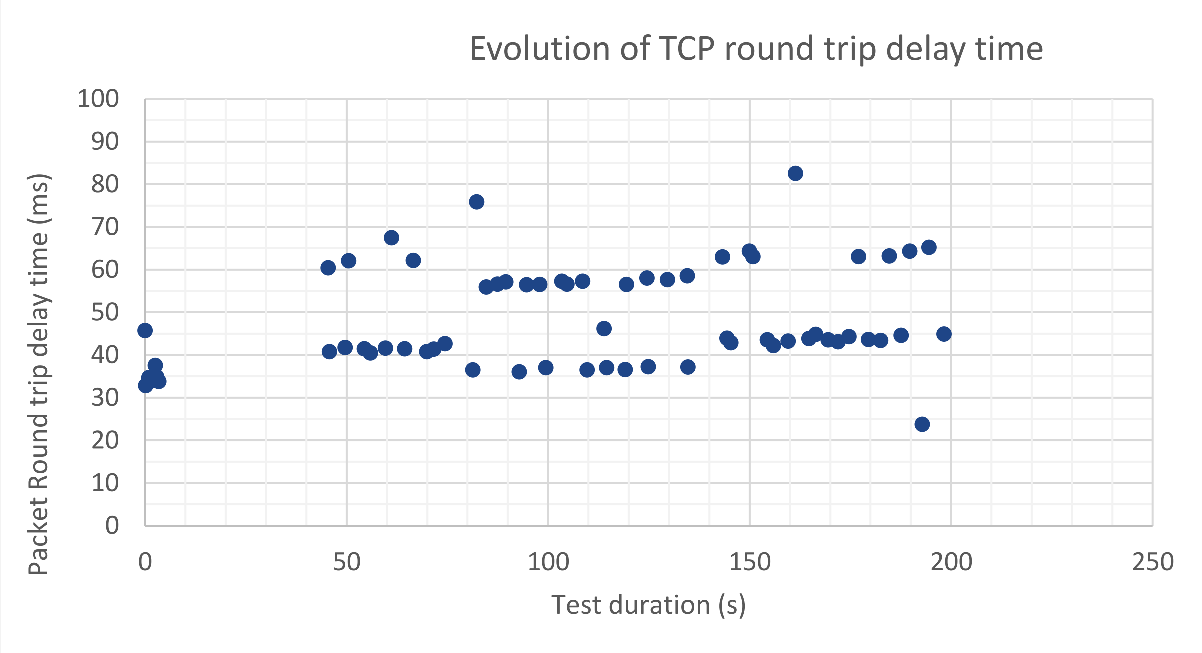


Figure 53: RTD delay of ETCS application in nominal lab conditions.

6.4 Appendix B.1 Measurements related to FRMCS Gateways performance (KPIs related to modems)

6.4.1 Modem in cross-border conditions

Using specific AT commands helps 5G modem to select the initial network. The command to be used is:

- At+cops=1,2, « 208xx» allows to select the initial network

When in border-crossing conditions, manual selection is the most appropriate mode:
- AT^SET_PLMN - Select PLMN Manually

Sometimes it takes about 10 seconds to attach specific PLMN network. Moreover, when inserting different SIM cards or restarting device, the setting is lost. So, the above command was the most efficient to perform handover in less than 10sec.

- Usually the modem, especially in field is attached in 4G/5G coverage but it is not able to retrieve the IP address.
- At+cgatt=1
- At+cgact=1,1 (the second 1 points to PDN: cmnet) that has to be configured by default in the modem. This command allows to retrieve the IP address immediately after execution.

6.5 Appendix B.2 KPIs of MCX procedures

6.5.1 Service registration and deregistration performance

The below KPIs can be used to measure service registration and deregistration performance. This kind of KPIs can be monitored at IMS/N6 level:

Category	KPIs Name	Definition
Accessibility	**(De)Registration time**	The (de)registration time is the time period between the (de)registration request of the service and being (de)registered to the server
Accessibility	**(De)Registration Failure rate**	(De)Registration failure ratio is the probability that (De)Registration is abnormally released

Table 8: Application registration and deregistration performance KPIs

6.6 Appendix C.1 Inputs referred to FRMCS applications performance

6.6.1 MCPPT KPIs

The voice performance through the different tests is evaluated thanks to MCPTT KPIs, KPI1 and KP2, as defined in §5 [8]. In the following, we remind the definition of these two standardized KPIs. Also, some other MCPTT KPIs were defined which were not used in the scope of 5GRAIL.

Definitions:

- **MCPTT Access time (KPI 1)**: The time between when an MCPTT User request to speak (normally by pressing the PTT button) and when this user gets a signal to start speaking. This time does not include confirmations from receiving users.
  Optimal thresholds: MCPTT Access time (KPI 1) is less than 300ms for private calls and group calls for 95% of all MCPTT requests, however for MCPTT Emergency Group Calls and Imminent Peril Calls, the KPI 1 is less than 300ms for 99% of all MCPTT requests.
- **End-to-end MCPTT Access time (KPI 2):** 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.

  Optimal threshold: 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.

For the measurement logging of SIP messages in the UE and Server will be used, alternatively the dedicated Wireshark monitoring PC attached to Onboard and Trackside

Both CAB Radio as well as Nokia UE will support detailed logging capabilities. In the following the measurement task are described based on Nokia UE for KPI 1:

The above measured KPIs together with KPI4 are considered as accessibility KPIs. As a reminder the definition of KPI4 §5[40] is provided, also not measured but interesting for future projects.

- **KPI4 Late Entry Call**: Time to enter an ongoing MCPTT Group call measured from the time that a user decides to monitor such an MCPTT Group Call, to the time when the MCPTT UE's speaker starts to play the audio.

  Optimal threshold: 150 ms for 95% of calls without application layer encryption < 350 ms for 95% for application layer encrypted calls

  Other KPIs considered in the in the integrity category for voice are:
- **KPI3 Mouth -to-Ear Latency**: Time between an utterance by the transmitting user, and the playback of the utterance at the receiving user's speaker.

  Optimal threshold: < 300 ms for 95% of all voice bursts.
- **MOS**: Quality **M**ean **O**pinion **S**core for calls during the measurement interval >= 3.0 within one MCPTT system. The monitoring is performed at IMS level. Even though there were no tools available to measure this KPI in WP3 lab but it can be considered for future FRMCS projects.
- **Packet failure rate**: Number of packets identified as lost / Number of packets received at the monitoring point.
  Optimal threshold: <0.1% considering Payload: <256 Bytes and Throughput: < 300kbps.

6.6.2 MCData KPIs

In the following, some MCData KPIs recommended for FRMCS §5[40], as well, will be presented:

NOTE: Whenever possible with the measurement tools and procedures, these KPIs were used with the applications tested in 5GRAIL's labs and field testbeds. These were mainly measured at IMS/N6 interface level.

Category	KPIs Name	Definition
Accessibility	**Access time**	The MCDATA Service access time is the delay between transmission of data and the request.
Integrity	**Packet latency**	The MCDATA One-way Latency Key Performance Indicator is the time interval between the emission of a packet by the client up to its reception by the receiver.
Integrity	**Packet failure rate**	Number of packets identified as lost / Number of packets received at the monitoring point.

Table 9: Proposal of MCData KPIs for FRMCS

6.6.3 ETCS performance in WP4 lab

a.1)ETCS and iPerf UDP test. ETCS on 5G, iPerf UDP on 4G. TOBA moves from 4G/5G area to 5G only area. iPerf & ETCS traffic continue on 5G

The RTT values are as following:

- Average Round Trip Time = 25.55ms
- Standard deviation Round Trip Time = 19.07ms

The value is calculated with 43 samples.

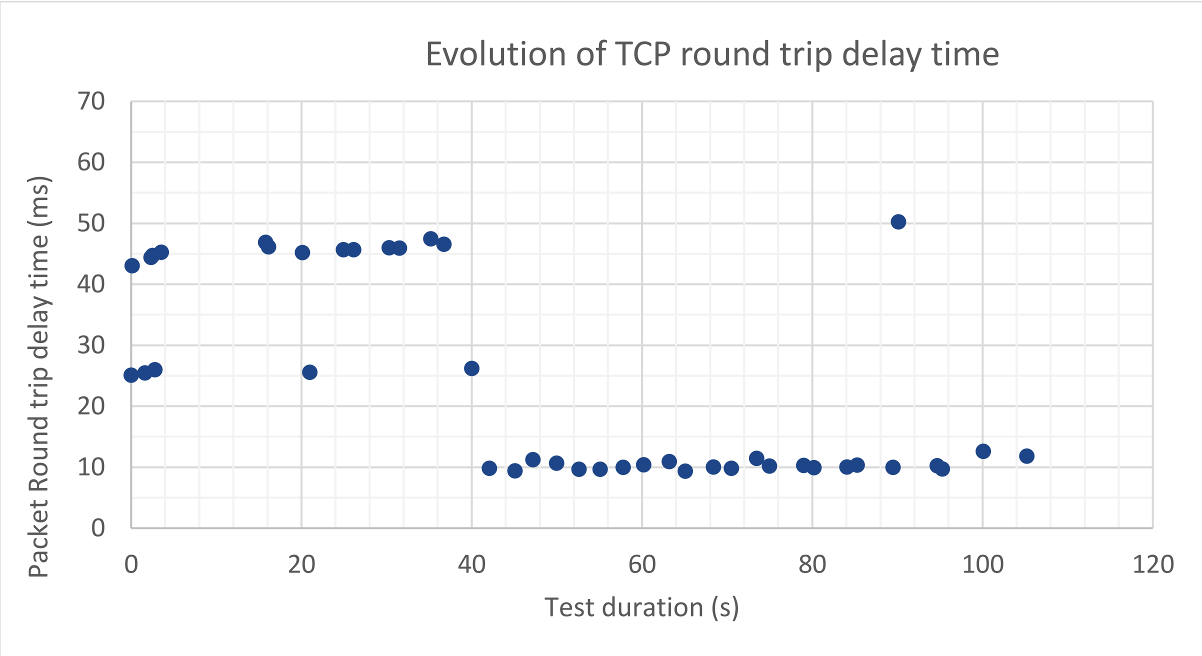


Figure 54 – Evolution of the RTD delay of ETCS with iPerf traffic in parallel, when moving from a 5G/4G area to an only 5G coverage with TOBA-A (Ref. D4.3v2)

Observations:

Based on the test configuration, TOBA-A is using the two modems (5G and 4G). ETCS is configured to use 5G modem as primary link, and iPerf (disturbing flow) is configured to use 4G modem as primary link. TOBA-A is connected to both bands 4G and 5G. In the first part of the figure, we have higher latency values due to the 4G coverage, while in the second part of the figure, 5G coverage is only present with lower latency values, as expected, and less impacting iPerf traffic, since iPerf in mainly using 4G modem.

a.2) ETCS and iperf UDP test. ETCS and iperf UDP on 5G. TOBA moves from 5G only area to 4G/5G area. ETCS traffic continue on 5G and UDP iperf on 4G

The RTT values are as following:

- Average Round Trip Time = 18.24ms
- Standard deviation Round Trip Time = 15.34ms

The value calculated on 163 samples.

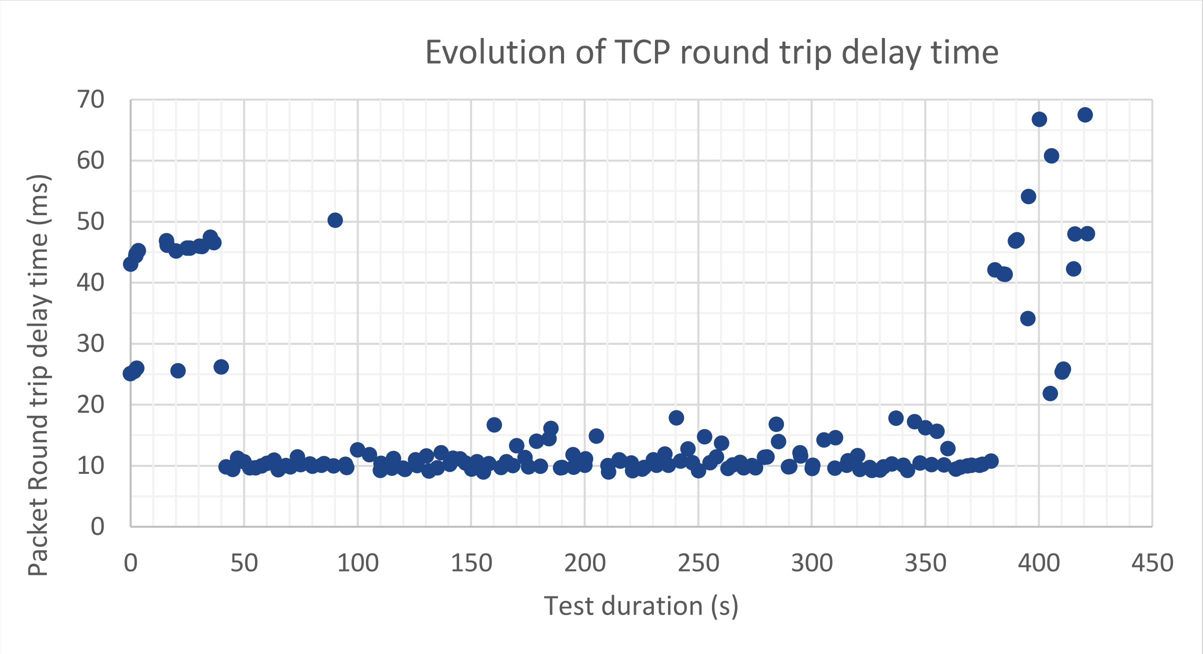


Figure 55 – Evolution of the RTD delay of ETCS when moving from 5G only area to 4G/5G coverage with TOBA-A. ETCS continues on 5G and iPerf on 4G (Ref. D4.3v2)

Observations:

The previous explanation is also valid for the above graph, corresponding to similar test configuration. In the above case, TOBA-A is starting with a short period where a 4G/5G coverage are both available, continuing with a sudden change to 5G only coverage and again a 4G/5G coverage. In the first part of the graph, again the 4G coverage explains the higher latency values where in the second part the 5G coverage justifies lower values of latency, as expected. Moreover, the disturbing flow from iPerf also contributes to the high latency values, whenever under 4G/5G coverage.

Note: The above test scenarios are also proving that the On-board Gateway can handle the transition from aggregated networks (4G and 5G) to a 5G only area and vice-versa without interruption on the ETCS application communication, only a slight increase of the RTD value due to the disturbing flow presence.

b) RBC and gNodeB handover on the same 5G network using Vertex tool with fading and varying speed

Using TOBA-K as On-board FRMCS gateway, a test scenario was created where RBC handover is likely to occur at the same time as a BTS handover, although the network planning usually prevents from these situations, but still an interesting worst case scenario. Besides that, degraded radio conditions with Vertex tool, have been added. The corresponding RTT values are presented in the following:

- for the connexion with RBC1 = 51.7ms
- for the connexion with RBC2 = 54.52ms

Standard deviation Round Trip Time = 19.56ms

The value calculated on 120 samples.

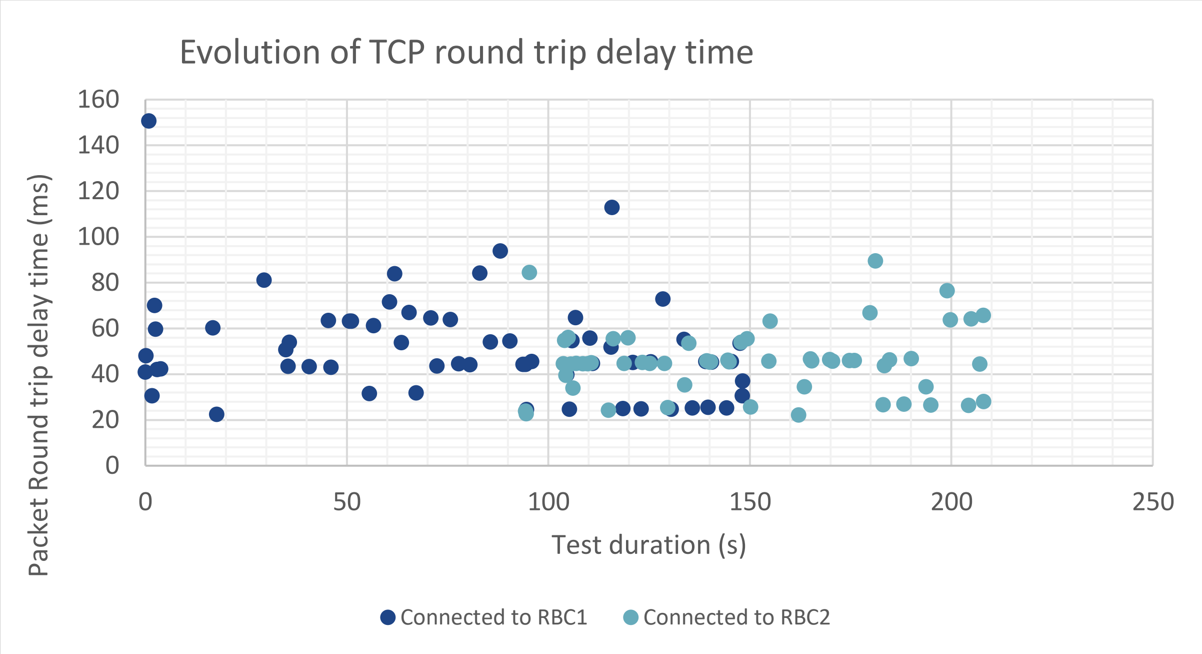


Figure 56 – Evolution of the RTD delay of ETCS with RBC and gNodeB handover in degraded environment created by Vertex tool (D4.3v2)

Although all the above cases are referring to ETCS performance in degraded radio conditions, the RTD still in the order of milliseconds, lower than 2.6s, as per SubSet'93 GSM-R KPIs.

6.7 Inputs referenced in the Cross-border measurements.

6.7.1 Specifications guidelines for network transition (cross-border topic)

The following considerations endorsed by the UIC specifications are very important to understand the complexity of the cross-border topic §5[42]:

- All the **active modem(s)** on the train **are shared among all OB applications.** There is no application-dedicated modem in FRMCS.
- The **Inter-FRMCS-Domain transition cannot be triggered by any application,** while all applications' requirements (e.g., w.r.t functional needs or continuity requirements) shall be satisfied during the transition.
- The solution **shall not impose any common or interdependent configurations among FRMCS Domains** which impacts the whole per IM deployments, e.g., no European-wide identities / IP addresses is required.
- At the current state, a solution using **2 active UEs shall be defined in FRMCS V2 for ETCS trains** to prevent being impacted by the uncertainties about the performance of 3GPP solutions.
- The **performance** of the FRMCS solution(s) for border crossing will be further tested during MORANE 2 project.

Grant agreement
No 951725

White Paper

FRMCS (5G) Vision for the Future

Grant agreement
No 951725

5GRAIL

The precursor for the railways FRMCS (5G) Vision for the Future

Abstract

This whitepaper aims to give an indication of FRMCS next implementation steps and of the benefits expectation form this 5G system, based on 5GRail prototypes results of Lab and Field testing. FRMCS will offer continuity and enhancement of GSM-R services and will enable digitalization.

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

CONTENT

1. Railways current usage for telecom

Railways have a need to use radio systems to connect Train Drivers and Controllers, the train equipment with the track-side ones, as well as other Rail traffic participants.

The technology used in Europe (and quite largely also out-of-Europe) is GSM-R.

GSM-R is fully specified in the EIRENE FRS and SRS specifications, complemented with MORANE interface specifications. These specifications can be consulted on: UIC GSM-R specifications

GSM-R is a 2G technology, becoming obsolete soon, which supports:

Voice calls, including Point-to-Point, Group and Broadcast Calls between Train Drivers and Controllers, this includes shunting and maneuver.

Railway Emergency Calls, connecting in few seconds the necessary controllers and all relevant train drivers, situated in the danger area. This application is considered as major safety improvements, stopping trains directing to the danger zone when all other systems have failed.

GSM-R also supports the European Train Control System – **ETCS.**

GSM-R enables a limited number of non-critical however very useful applications e.g. line side telephones, or passenger Information system.

In Europe, there are some 130.000 km of track is covered with GSM-R, with more than 90.000 Cab Radio's activated. These figures might not seem much, compared to any PMNO network, however it represents most of the trains in Europe.

2. FRMCS

FRMCS (Future Railways Mobile Communication System) based on 3GPP 5G Mission Critical (MCX) technology with dedicated RMR (Railway Mobile Radio) spectrum for interoperable applications, [1] which is UIC and Railways answer for two major challenges:

- Replace GSM-R
- Enable digitalisation

Being the GSM-R successor, the FRMCS shall enable at minimum the same applications with at least the same performances.

However, the aim is to improve these applications and also to enhance the train-performance real-time information with new applications e.g. by limiting the number of trains stopped in case of a Railway Emergency Call for instance by excluding trains going in the opposite direction of the danger zone, allow merging of various communication, etc., or for example allowing more data to be added to ETCS inteligence, for instance informing the system on a critical alarm of element of the train like e.g., the Hot Axle box detector etc. , all this with the aim to improve the Railway System performance.

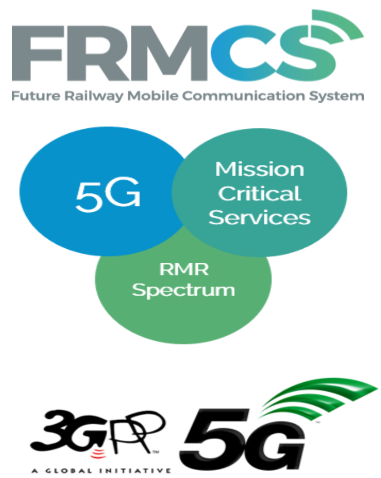


Figure 57: FRMCS is a 3GPP 5G MCX System

[1] Interoperable applications (e.g., ATP, ATO, REC, driver-controller voice communication), in the sense of railway border-crossing conditions.

3. FRMCS relies on 3GPP 5G MCX

One key element of this new architecture is the introduction of the On-Board FRMCS equipment in the end-to-end communication chain, as well as the decoupling between railway applications and telecommunication network - which allows the transport layer to evolve e.g., to a new radio technology without impacting the application layer. FRMCS is based on 3GPP 5G technology:

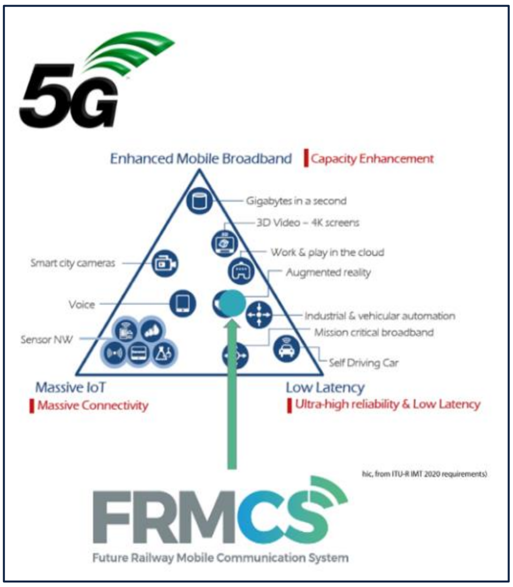


Figure 58: FRMCS as a 5G technology

Below some 5G and MCX principles that we follow to define, build and implement FRMCS:

- 5G Stand Alone (SA) Architecture
- 5G New frequency bands (FRMCS 900 and 1900 MHz, now 3GPP n100 and n101 standardized bands)
- Performance enhancements for 5G in High-Speed Mobility scenarios
- Critical communications (5QI QoS flows mechanism)
- Mission Critical (MC) Services

The FRMCS Use Cases and Requirements are part of 3GPP 5G service requirements: 3GPP TR22.989

Resource Sharing (e.g. providing transport services for multiple applications of any category using the same FRMCS on-board system considering the individual QoS requirements of the application and possibly priorities among applications).

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

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

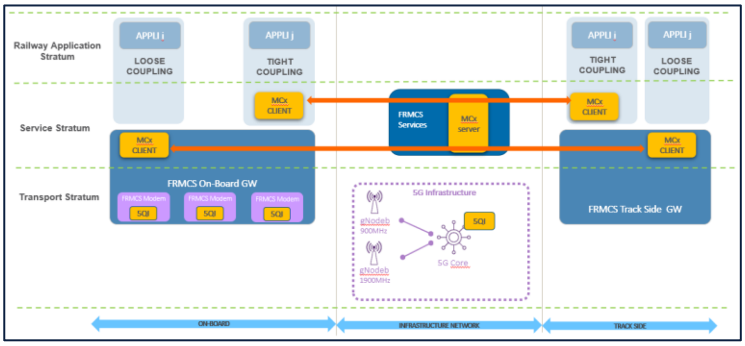


Figure 59: FRMCS is a 5G and MC based system, supporting applications with various QoS requirements

4. 5GRAIL contributes to the FRMCS program

FRMCS is planned to be introduced in Europe in 2027. Until the moment of writing this paper, we have reached some critical milestones, listed below:

- Obtained dedicated frequencies for FRMCS, listed in ECC (20) 02.
- Incorporated most of FRMCS needed features and mechanisms in 3GPP R15, 15, 17, and currently in R18 and R19, where 5GRAIL outcomes has impacted.
- Started specifying FRMCS solutions in ETSI Technical Committee for railways Telecom, using also 5GRAIL's experience.

- Finalize FRMCS v1 specifications which were included in 2023 CCS TSI: [2023 CCS-TSI FRMCS specifications]

One important step to introduce FRMCS 1st Edition, is 5GRAIL, the first FRMCS demonstrator, which validated the first set of FRMCS specifications.

4.1 5GRAIL objectives

5GRAIL is a project cofounded by DG CONNECT that reunites 18 members, coming from various telecom and railways sectors.

The purpose of this project is to:

- Develop a test plan based on relevant Use Cases to validate FRMCS features.
- Build the first FRMCS prototypes, especially for the On-Board equipment, and for the main applications.
- Test the prototypes in Lab conditions, in France and Hungary, in multivendor environment.
- Further validate the prototypes in two field testbeds, with trains under real radio conditions, in multi-vendor environment, in France and Germany.
- Feedback the observations of these tests to FRMCS and other standards' groups.

4.2 5GRAIL results in lab and field testbeds applying the FRMCS architecture

5GRAIL applied the principles, described in chapters §2 and §3 - see the subsystems highlighted in red in the below end-to-end architecture of the project; tested them in lab and field testbeds, to validate the compliancy of all prototypes with the FRMCS v1 specifications, using 5G and MCX features:

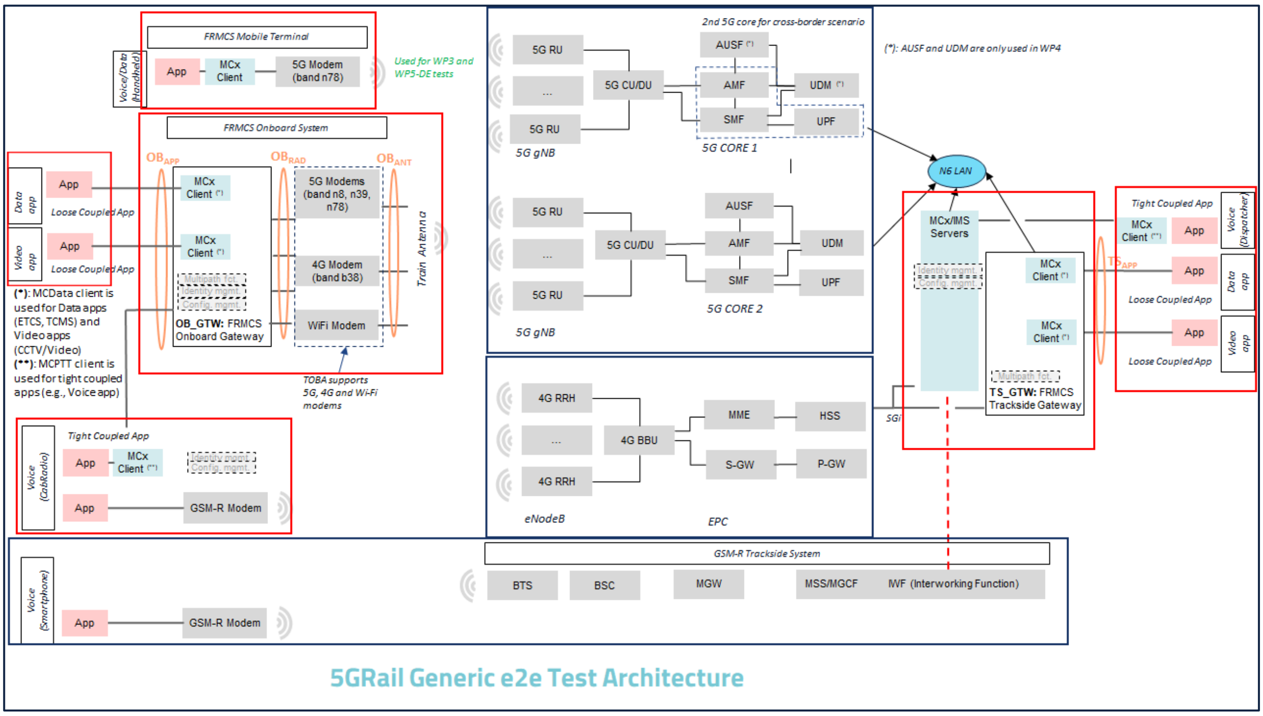


Figure 60: 5GRail end-to-end architecture. Elements in red have been developed by the project

Performance tests have been executed in both labs, for critical and non-critical applications, in nominal and simulated degraded radio conditions, also considering multiple applications over the same On-board FRMCS[2], to demonstrate resource sharing and QoS capabilities, as well. These applications were:

- Voice, including Group Calls with FRMCS and GSM-R participants (IWF)[3](Mission Critical Push-To-Talk (MCPTT), tight coupled application).
- Video (MCData, loose-coupled application) with bearer flexibility/multi-access concept.
- ETCS, ATO (MCData, Loose-coupled application)
- TCMS (MCData, Loose-coupled application)
- Railway Emergency Call (Voice, MCPTT, tight coupling application), including interworking with GSM-R.

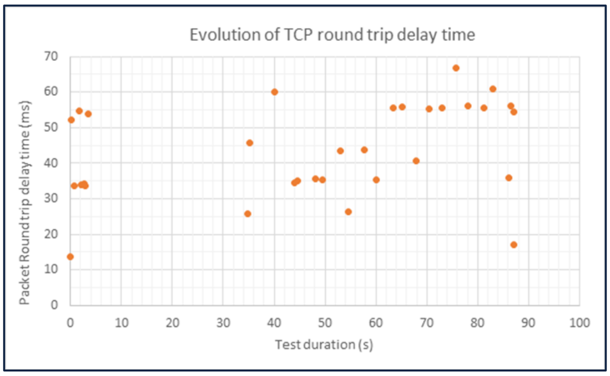


Figure 62: Communication in level 2 between ETCS On-Board application and RBC, using RTD5 as performance KPI

For comparison with GSM-R, where KPIs for ETCS (and ATO) over GPRS requires 2.6s maximum for end-to end delay of a standard packet, it can be noted as seen in **Figure 62** and **Figure 63**, that with 5G we have obtained delays within 100 ms (with an

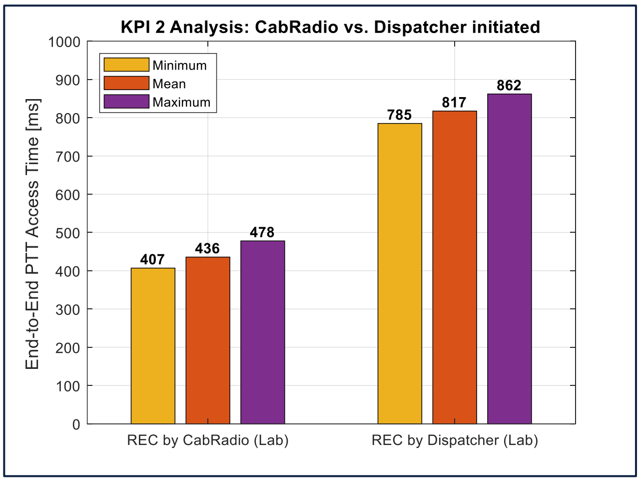


Figure 61: REC MCPTT KPI 24 results

experimental set-up). We can note similar improvement for voice applications (see **Figure 61**).

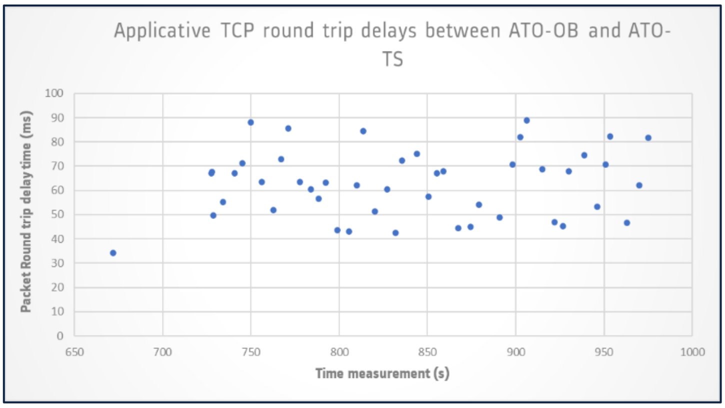


Figure 63: ATO status report 6 in parallel with highly disturbing uplink iPerf traffic, using RTD as performance KPI (QoS validation).

[2] Where in GSM-R, one radio is used for each communication type.

[3]IWF: Interworking Function enables FRMCS and GSM-R network to communicate with each other, enabling services to be delivered across them.

[4] MCPTT KPI2 (3GPP TS22.179) < (less than 1000 ms for MCPTT Group calls): 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.

[5]RTD (Round Trip Delay): which is the time between sending a message from a source to a destination (start) and receiving the acknowledgment from the destination at the source point (end). RTD at application level is an indication of the network latency, as well.

[6] ATO status report: Response to the 'journey profile' by On-board client

A subset of testing scenarios has been repeated in field testbeds to validate the protypes in real 5G radio environment and compare with the lab performances. Field tests demonstrate the usability of 5G to answer railway needs using railway applications and application simulators. Some results are presented in the following:

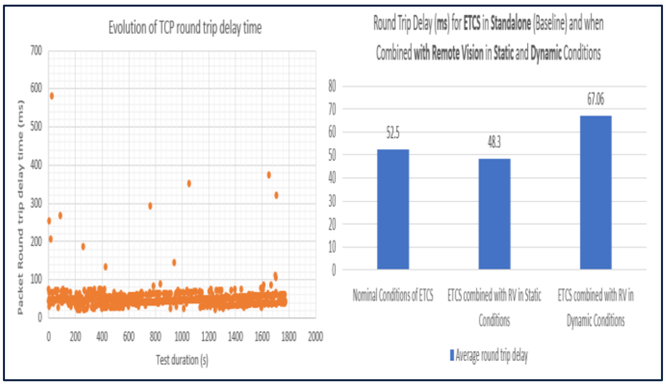


Figure 64: Field test results, confirming Lab figures

4.3 Cross Border implementation and testing

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

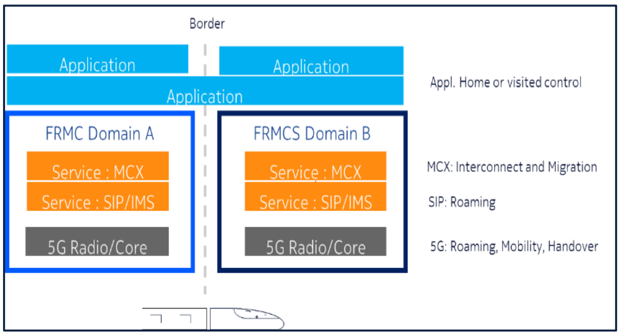


Figure 65: Cross-border principles in FRMCS and 5GRAIL challenges

4.3.1. FRMCS to GSM-R Cross

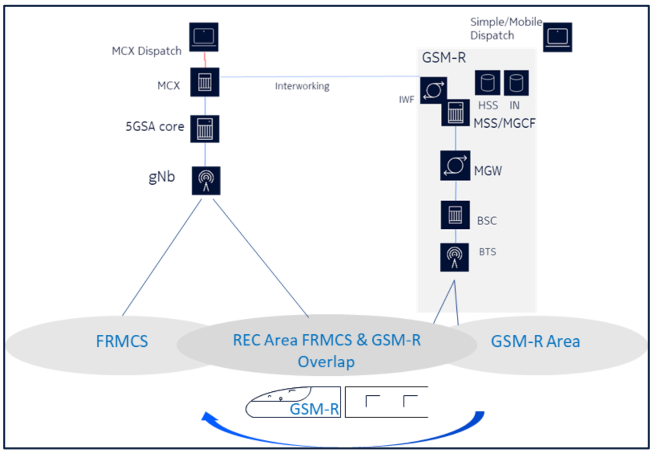


Figure 66: GSM-R to FRMCS network transition with REC voice

GSM-R to FRMCS Border Crossing was tested with REC voice application, as a representative use case of the coexistence period, with above set-up (see **Figure 66**).

4.3.2. 5G FRMCS Border Crossing

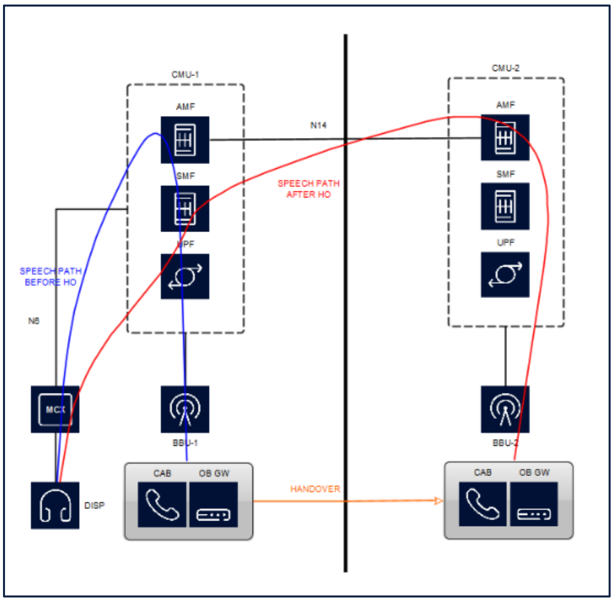


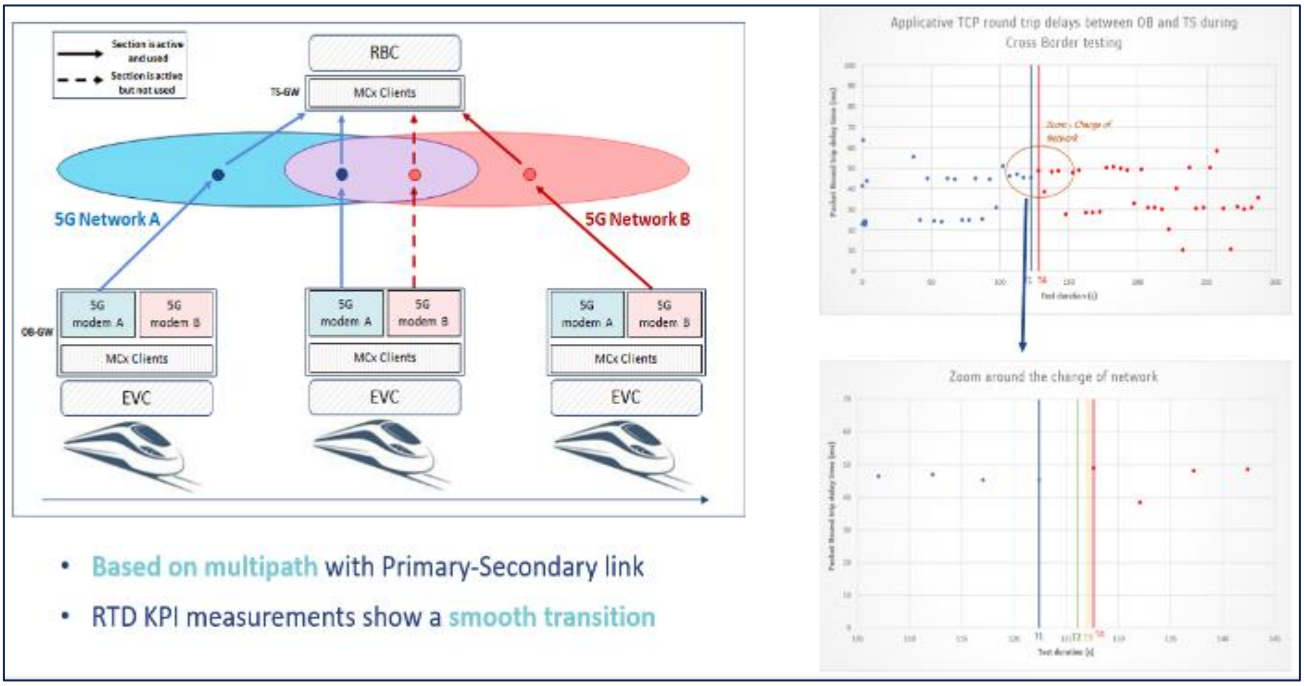
Figure 67: 5GRAIL border crossing with voice & video, using one UE implementation

FRMCS-to-FRMCS Border Crossing with one UE [7] was tested with voice and video in lab conditions, in Hungary, applying inter gNB / Ng based handover over AMF [8] (using N14 interface), where an interruption of 150ms was observed on signaling level, which is in the range of results of other ICT053 projects, as presented in

Figure **67**. MCX/UPF have remained in 'home network'. This allowed to evaluate the two mains steps out of the three needed for a border crossing with one UE.

4.3.3 FRMCS 2UE's Border Crossing (Application Level)

Figure 68: Border crossing in French lab with two UEs in TOBA-A[9] and ETCS application



Two On-bord FRMCS Gateways from two different providers have been tested in the lab in France, applying two different flavors of Bearer-flex/multi-connectivity feature.

We have tested this Border Crossing mode as it is important for Railways: we cannot do for now a 5G MCX one UE service continuity due to lack of MCX existing mechanisms. However, these are under development in 3GPP where they have reached CT1 stage.

We intend to use this model for ETCS only, as a service continuity Border Crossing, and we wish to apply MCX Interconnection and Migration mechanisms.

4.4 5GRAIL reached its target and received innovation EU recognition

[7] UE is to be understood as RM (Radio Module)

[8] AMF: Access and Mobility Management Function of 5GS

[9] TOBA- A: On-board FRMCS Gateway provided by Alstom

5GRAIL has proven:

- **The FRMCS principles**, as a 5G MCX system is fit-for-purpose and works, ensuring future proofness, and the usage of one On-board FRMCS equipment for all applications (voice, data, video).
- **FRMCS prototypes** can progress to industrialisation phase and become **products.**
- **5G NR Spectrum** (n8 (900MHz FDD), and n78 (3.7GHz TDD), as an example of PMNO band and also a first radio module prototype been compatibe with FRMCS 1900 MHz band).
- **QoS:** tested for both MCPTT and MCData, with current available products and mechanisms.
- **Cybersecurity:** Local binding (OBapp) and e2e TLS (TOBA and ATO application).
- **Cross-border:** Two solutions considered, including the two 5GUEs implementation which is included in FRMCS v2 specifications. Major building blocks of the one 5GUE solution have been successfully tested in lab in Hungary.
- **Bearer flexibility** tested both as multi-connectivity and multi-access.

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

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

4.5 5GRAIL's contribution to the specifications

5GRail have offered valuable inputs to FRMCS specifications groups but also to 3GPP/ETSI by introducing features, such as

- 3GPP Ad Hoc group call based on initiator's location to establish a REC with less impact to the traffic.
- 3GPP enhancement of Functional Identities
- 3GPP enhancement of MC interconnection and migration procedures
- UIC FRMCS specifications: 2 UE implementation of border crossing with service continuity for ETCS
- UIC FRMCS specifications: Bearer flex/multi-connectivity, also applicable to border-crossing
- UIC FRMCS specifications: Direct connection of Dispatcher to the MC server (Tctl) interface already tested.
- UIC FRMCS specifications: Enhancement of OBapp/TSapp interfaces for Gateways and Applications

4.6 5GRAIL lessons learnt

5GRAIL was a successful first step, with valuable lessons learnt that will be considered within future pilot trials:

- **A more efficient one UE cross-border concept** validating the progress of 3GPP specifications with not only inter-PLMN handover as a transport feature but also including MCX migration and interconnection, expected to be made available within Rel.18. This will bring efficiencies and is expected to expand service continuity also to voice.
- **Better knowledge of KPIs** that will allow optimum planning of the future FRMCS networks.
- **Impact of high-speed (300 km/h) in the performance of the end-to-end system** which was not possible in the current field testing.

- Study **monitoring tools** adapted to the FRMCS context.
- **Cybersecurity** topics need to be further investigated with different architectures and evaluate more solutions. First trends were provided with the 5GRAIL testing.
- **Deepen on authentication, authorization rules** for the FRMCS with efficient storage and update of credentials.
- **Further multivendor end-to-end testing for On-board and Trackside.**

5. What Next, FRMCS Vision for the Future

5.1 Next steps of FRMCS introduction

With the finalization of the FRMCS V1 specification and their inclusion in the CCS-TSI, and with the finalization of 5GRail testing phase, we have closed phase 1 – see below planning representation.

Next steps for the introduction of FRMCS 1st Edition are:

Finalization of FRMCS V2 specification published by ERA as technical opinion by the end of 2024.

Launch of the **FRMCS European Trial**, called MORANE-2, middle 2024.

With the finalization of this trial, create and deliver v3 of FRMCS specifications, and include these in 2027 CCS TSI.

FRMCS 1st Edition will be the first FRMCS equipment that railways can procure, to start the national trials.

FRMCS 1st Edition is planned as GSM-R successor. Enhancements will follow in FRMCS 2nd Edition, and further-on.

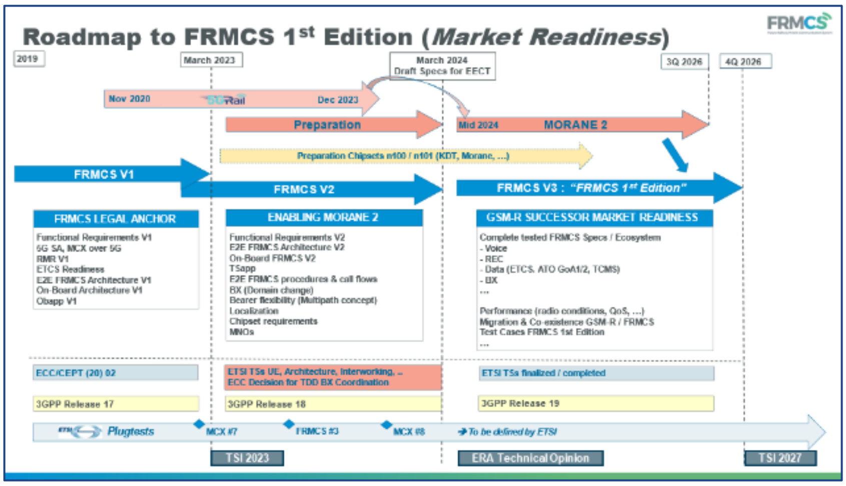


Figure 69: Roadmap to FRMCS 1st Edition (source UIC)

Migration from GSM-R to FRMCS will last until somewhere 2035.

Following the FRMCS introduction in 2023 CCS TSI, Railways have started to plan the migration. We expect that this will start in 2027, studies have already been launched by the early implementers, including national strategy plans and initial budget estimations for track side and on-board equipment.

5.2 5G FRMCS Benefits

The replacement of GSM-R- with FRMCS – is vital; train operations including signaling system are based on it.

However, railways need capacity and performance upgrades, dictated by increasing number of passengers, with new security, comfort, and higher punctuality expectations.

Building new tracks is not feasible, due to high cost and complexity.

The envisaged way forward is therefore to have more trains on same tracks, however with an improved reliability, to achieve the targeted increase of performance (A stopped train means that all trains behind will also stop).

To achieve this upgrade, to improve operations and to increase train performance,

punctuality and safety & security, the trains need:

- Automatic Train Operations
- Telemetry capabilities
- Video (e.g. for front train video, catenary video, bridges flooding camera's, etc.)
- Improved positioning and localization
- Wireless track side telephones
- Wireless level crossing camera's
- IoTs to prevent accidents e.g. land slip sensors, etc.

5G will allow the introduction of these types of applications, in a safe and affordable way. We expect an increase of these applications demand once FRMCS 1st Edition will be made available.

One of main challenges that we have considered for the FRMCS 1st Edition is to plan and develop a system that will allow all known improvements, without changing the TOBA, for which the Train Operating Companies have a minimum of 10 -12 years life cycle expectation.

We expect that when the first new 'Train Performance' applications, are introduced, the appetite for such digitalization will simply grow.

This will take advantage of technological continuous improvement done through 3GPP.

With the introduction of 5G in European trains, we are opening the way for the long wished Intelligent Train, that will allow a more affordable, yet more performant railway.

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