5G key technology enableRs for Emerging media COntent pRoDuction services

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Abstract

The document describes the final integration stage of different media and 5G components into the testbeds. It also includes an update on the test results carried out to validate and improve the project components in the different use cases. The document also highlights the updates in the 5G infrastructures and describes the added features to achieve the required KPIs. The use cases described in the documents are live audio production, multiple camera wireless studio, and live immersive media production.

[1] CO = Confidential, only members of the consortium (including the Commission Services)

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Keywords

5G components, integration, measurement, monitoring tools, testing, test-bed infrastructure

Disclaimer

This 5G-RECORDS D4.2 deliverable is not yet approved nor rejected, neither financially nor content-wise by the European Commission. The approval/rejection decision of work and resources will take place at the Final Review Meeting, after the monitoring process involving experts has come to an end.

Executive Summary

The document describes the final integration stage of different media and 5G components into the testbeds. It also includes an update on the test results carried out to validate and improve the project components in the different use cases. The document also highlights the updates in the 5G infrastructures and describes the added features to achieve the required KPIs. The use cases described in the documents are live audio production, multiple camera wireless studio, and live immersive media production.

Use case 1: live audio production has focused on the integration of audio equipment to the 5G network from one side, and the integration of the 5GC and the 5G RAN into the EURECOM infrastructure in Sophia Antipolis, France. EURECOM has modified the 5G network to achieve reliable ultra-low latency. This Use case has executed 1 test session until the writing of the deliverable, in which they focused on measuring packet latency and packet loss, while they have run several bilateral sessions for the integration process.

Use case 2: multiple camera wireless studio with its two scenarios, i.e., integrated production and remote production, has focused on testing and integrating different media components (e.g., encoders and decoders) into the 5G infrastructure provided by Ericsson. The integrated production scenario has utilized the URLLC network provided by Ericsson to test time synchronization performance along with other features such as QoS and MEC. The remote production scenario has focused on testing network slicing and bonding to verify the PNI-NPN functionality. This use case has executed 3 test sessions using the 5G test network in Aachen, Germany.

Use case 3: live immersive media production has focused on integration the developed version of the FVV system with the 5G network, MEC, and delivery cloud. In a first stage, the systems were integrated with the 5G and MEC systems deployed in the trial site in Segovia, Spain, over a public network (in a pilot deployment). The second phase covered the integration with a compact Non-Public Network deployment in Madrid, Spain. This second integration were used for the validation of the final version of the systems, and the measurements of Key Performance Indicators.

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List of Acronyms and Abbreviations

5GC	5G Core
AES	Advanced Encryption Standard
AF	Application Function
API	Application Programming Interface
AVC	Advanced Video Coding
ANT	Audio Network Interface
BB	Baseband Unit
CI/CD	Continuous Integration/ Continuous Development
CNF	Cloud-native Network Function
COTS	Commercial Off-The-Shelf
CPE	Customer-Premises Equipment
CU	Centralized Unit
CUPS	Control and User Plane Separation
DL	Downlink
DN	Data Network
DNS	Domain Name System
DSCP	Differentiated Services Code Point
DU	Distributed Unit
E2E	End to End
ELK	Elasticsearch, Logstash and Kibana
ETSI	European Telecommunications Standards Institute e-MBB enhanced Mobile Broadband
EPC	Evolved packet Core
FDD	Frequency Division Duplexing
FPS	Frames Per Second
FTTH	Fiber To The Home
FW	Firmware
GOP	Group Of Pictures
GPS	Global Positioning System
GPU	Graphics Processing Unit
GTP	GPRS Tunneling Protocol
HARQ	Hybrid Automatic Repeat Request
HLS	HTTP Live Streaming
HTTP	Hypertext Transfer Protocol
HW	Hardware
ICMP	Internet Control Message Protocol
IEEE	Institute of Electrical and Electronics Engineers IEM In-Ear Monitor
IP	Internet Protocol
IRU	Indoor Radio Unit
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
MG	Media Gateway
MEC	Mobile Edge Computing
MIMO	Multiple-Input Multiple-Output
mmW	millimeter Wave
MOCG	Media Orchestration Control Gateway
NAT	Network Address Translator
NB-IoT	Narrow Band Internet-of-Things
NR	New Radio
NSA	Non-Standalone
NSM-AF	Network Slice Manager Application Function

NTP	Network Time Protocol
NUC	Next Unit of Computing
OAI	OpenAirInterface
OCXO	Oven-controlled Cristal Oscillator
ONAP	Open Network Automation Platform PCF Policy Control Function
PDCP	Packet Data Convergence Protocol PER Packet Error Ratio
PNF	Physical Network Function PPS Pulse Per Second
PTP	Precision Time Protocol QoE Quality of Experience QoS Quality of
Service	
PPS	Pulse Per Second
RAN	Radio Access Network
RD	Radio Dot
RF	Radio Frequency
RGB	Red, Green and Blue
RTCP	Real Time Control Protocol RU Remote Unit
SA	Standalone
SAS	Shared Access Server
SBA	Service Based Architecture
SCReAM	Self-Clocked Rate Adaptation for Multimedia
SCS	Subcarrier Spacing
SDAP	Service Data Adaptation protocol
SDI	Serial Digital Interface
SDN	Software Defined Network
SDP	Session Description Protocol
SIM	Subscriber Identity Module
SMPTE	Society of motion picture and Television Engineers SSH Secure Shell
Protocol	
SUT	System Under Test
SW	Software
TCP	Transport Control Protocol
TDD	Time Division Duplexing
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink
UM	Unacknowledged Mode
UP	User Plane
UPF	User Plane Function
URLLC	Ultra Reliable Low Latency Communications VNF Virtual Network
Function	
USB	Universal Serial Bus
WMI	Web Managed Interface
VPN	Virtual Private Network

1 Introduction

1.1 Scope

The present document describes the final stage of integrating 5G and media components into the use cases infrastructure. It provides a documentation of the procedures to integrate several components, verify the development of individual components and testing the whole system over the provided infrastructure for the three use cases: live audio production, multiple camera wireless studio and live immersive media production.

The document also describes the tools used to verify and test the agreed Key Performance Indicators (KPIs) and provide feedback to WP3 for improvement.

Moreover, the document describes the work done by the infrastructure providers to update the networks with features that can achieve the requirements defined in D2.1 [1].

The document is considered as a breakdown for the high-level plan described in D4.1 [2] and provides a summary of the effort done by each component provider to bring the whole end-to-end (E2E) solution together.

1.2 Objectives

The objectives of the deliverable are as follows:

1. Provide a step-by-step description of all the efforts and procedures for integrating different 5G and media components.
2. Provide a comprehensive study of the validation steps for each component within the use cases.
3. Report the results from integrating multiple components and verify its compliance with the use case expected output.
4. Provide an update on the testing tools used in the project.
5. Report the results for the testing and validating different KPIs introduced in other deliverables.
6. Report on the latest updates and configured features in the project infrastructures.

1.3 Structure

The document is divided into three sections (Section 2, 3 and 4), each one describing the integration, testing and infrastructure update for each of the following use cases: live audio production, multiple camera wireless studio, and live immersive media production, respectively. These sections also include:

a. Integration of different 5G components
b. Measurements of individual components and update on tools
c. Tests and results including End-to-End integration
d. Infrastructure update and added features

2 Live audio production

2.1 Updates on integration of 5G components

2.1.1 CU and core network

The SA-GUI gives a web-based user interface for managing 5G Core. gNB configurations, Operators, Network Slices, Subscribers, and 5GLAN group settings can be managed. GUI is developed based on Cumucore Network Configuration (CNC) management REST API. In addition to the above, there is a possibility of user management. The user management menu gives access to manipulate user accounts with different privileges as shown in Table 1.

Table 1. User management

GUI Tabs that can be accessed\Role	Admin	Network Engineer	Subscriber Manager
Home Page	Yes	Yes	No
gNB Configuration	Yes	Yes	No
Operator	Yes	No	No
Slice Manager	Yes	Yes	No
Subscriber	Yes	No	Yes
5G LAN	Yes	Yes	No
Status	Yes	No	No
User Management	Yes	No	No

The home pages display the gNBs and subscribers. The status of gNB and users are indicated by their color. Each gNB added will be assigned a different color, which at first would be dimmed because the GUI did not receive the setup message. The gNB with a brighter color will be displayed after the mobile core receives a setup message from the gNB which indicates the gNB is active.

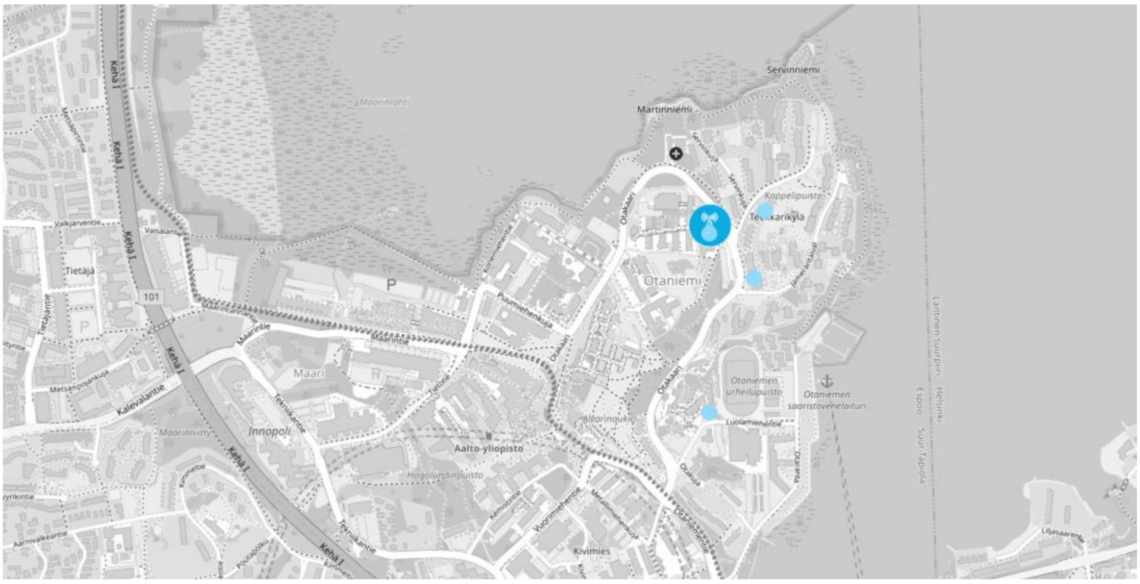


Figure 1. GUI Home Page

The first step in the GUI is to add gNB to the system. It can be done by selecting the location in a geographical map in the home tab. The map can be zoomed in and out to choose the exact position of the gNB. If you click on the map area, a new dialog form will be displayed to fill in the information about the gNB. After filling the required information and pressing the "Add" button, it will register to the network (please ensure the TAC ID matches with the values in the gNB configuration).

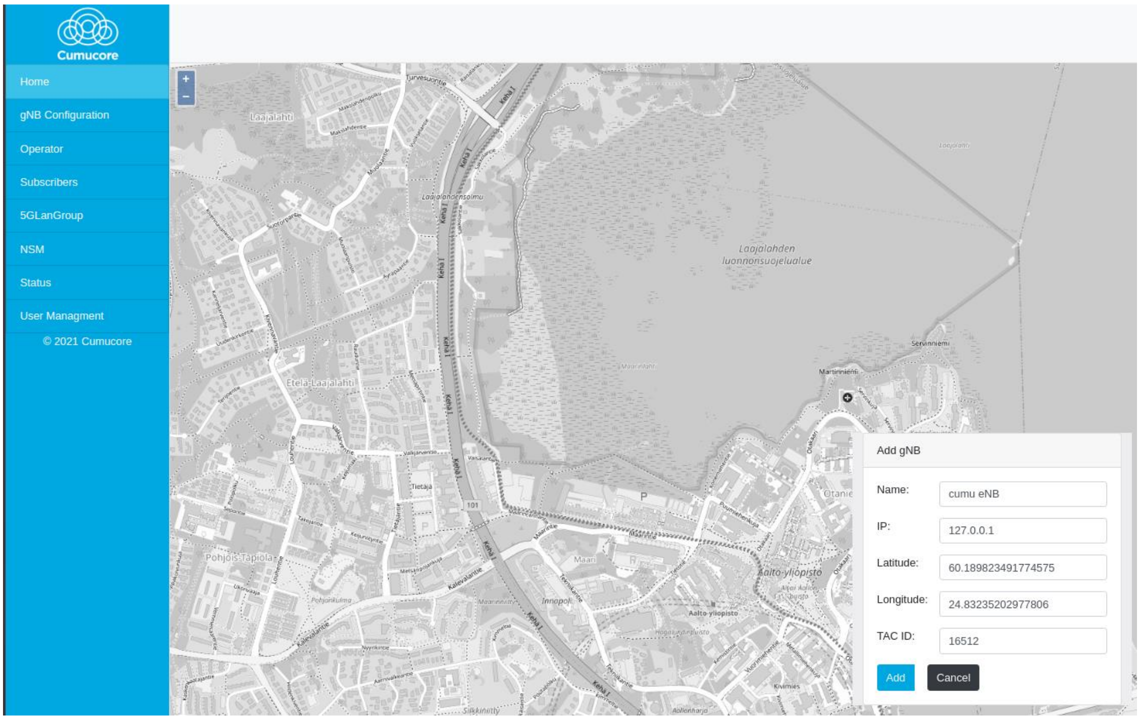


Figure 2. gNB Configuration

A list of gNBs can be obtained in the gNB configuration tab. When the gNB is connected, it is indicated by the message "gNB is running". In gNB Configuration menu, gNB values can be edited/deleted.

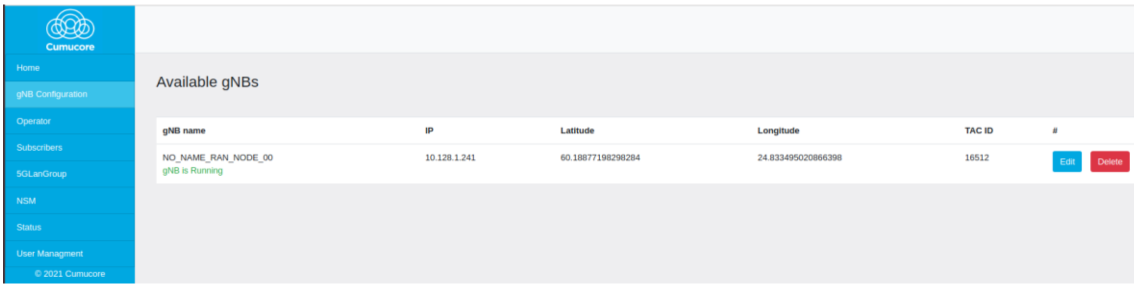


Figure 3. gNB Configuration Tab

2.1.2 CU and OAI DU

The Interoperability between Accelleran CU and OAI DU has been successfully validated for the control and user-plane over F1 interface. As shown in Figure 4, the Accelleran CU is composed of two blocks: the CU-CP and the CU-UP. The CU-CP is responsible for the control plane functionality and the corresponding configuration and message exchanges with the OAI DU over F1-C interface to support the UE connection with the 5G network. The CU-UP is responsible for the User plane traffic transfer, as well as the flow control procedures between the CU and the DU. The configuration of the CU-UP from CU-CP takes place over the E1 interface.

The interoperability between Accelleran CU and Cumucore 5GC using the NG-C (N2) and NG-U (N3) was pre-validated earlier in Accelleran labs with a different 3rd party DU/RU. The integration of Cumucore 5GC with Accelleran CU and OAI DU is in progress.

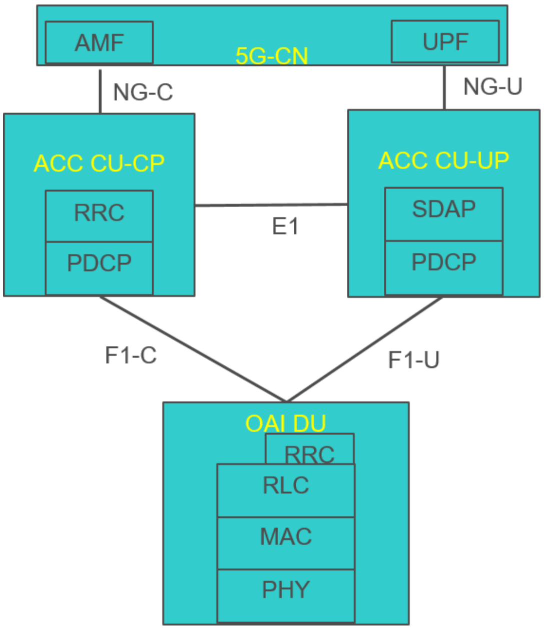


Figure 4. CU/DU Split architecture

Figure 5 shows the topology of the CU deployment at the EURECOM OpenShift cluster.

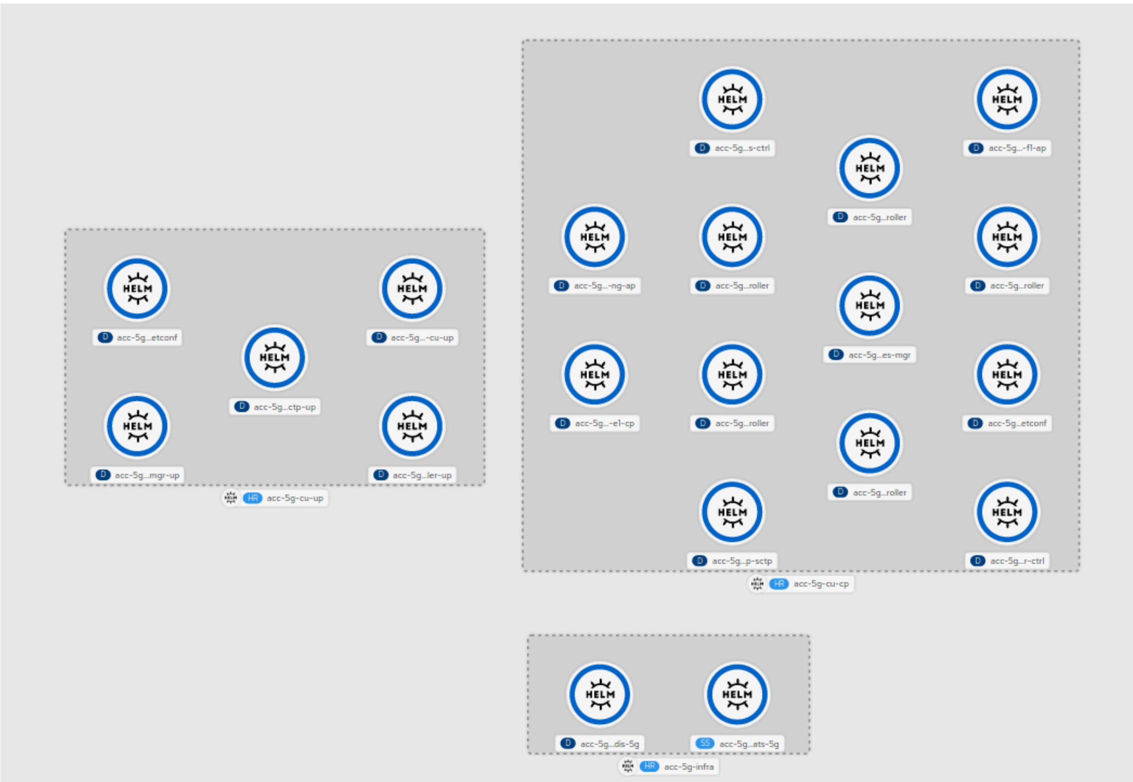


Figure 5. The topology in the CU deployment

2.1.3 Mic / In-Ear monitor and 5G UE

The interface between audio network interface (ANT) devices and the 5G UEs is an Ethernet/IP-connection. The 5G UEs consist of a small PC in combination with a M2 or USB connected 5G modem unit. As such, the ANT device is not part of the 5G sub-network but is attached via the modem PC acting as an IP-gateway. Integration between the ANT device and the 5G UE was made by configuring the small IP-network between the two devices and the gateway service in the modem PC. The integration and the correct routing were tested with ping-tests between the attached ANT device and the 5G UPF in the 5G network.

2.1.4 Local audio processing and timing server and core network

Cumucore 5G NC supports the N9 interface that enables connecting local servers directly to UPF.

MEC has many advantages in NPN use cases:

MEC is connected directly to UPF. Direct connection minimizes the delay.

- MEC can be used without access outside the network, this provides an additional layer of security.
- MEC provides additional flexibility for IP planning because the network is controlled by one author, there is no need for a NAT.
- MEC enables it to run heavy applications (e.g., high-definition video-based applications) without expensive backhaul.

Video analytics are under very strict data privacy regulations, and they might also be delay sensitive. These requirements can be met with MEC implementation.

Cumucore network can work without connection to the Internet. If MEC is used instead of public Cloud, the network will stay operational even when connection to the Internet is lost.

Classic IoT/IT networks are not mobile, and they are low in bandwidth. Modern mobile networks can provide lower latency and are inexpensive and reliable in the high-definition video use case.

NPN with MEC is the optimum solution for low latency, high bandwidth, and secure communication needs. Radio interface is interference free; network utilizes state of the art radio technology and MEC provides low latency, secure and high-performance computing platform that enterprise has full control over.

2.1.5 Core configuration service with network slice manager

The Network Slice Management provides multiple functions that are crucial for E2E service delivery and E2E closed-loop automation (zero-touch network). It provides the following functions:

- Integrates 5G network layer, possibly different domain orchestrators, to fulfill the request on the resource level.
- Network Slice Catalog to list all the instantiated and activated services.
- Closed-loop automation for service remediation

Figure 6 presents the Network Slicing Lifecycle.

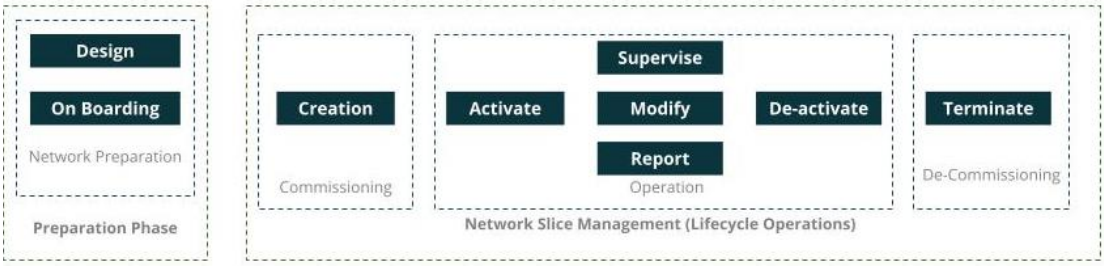


Figure 6. Network Slicing Lifecycle

Dataflow Application Function (AF)

Dataflow application function is used for the scenarios where an external application is controlling or requesting additional dataflow creation for the UE. Typically, this kind of scenario is found in industrial use cases.

API architecture

Following example diagram illustrates the architecture of the dataflow application function environment.

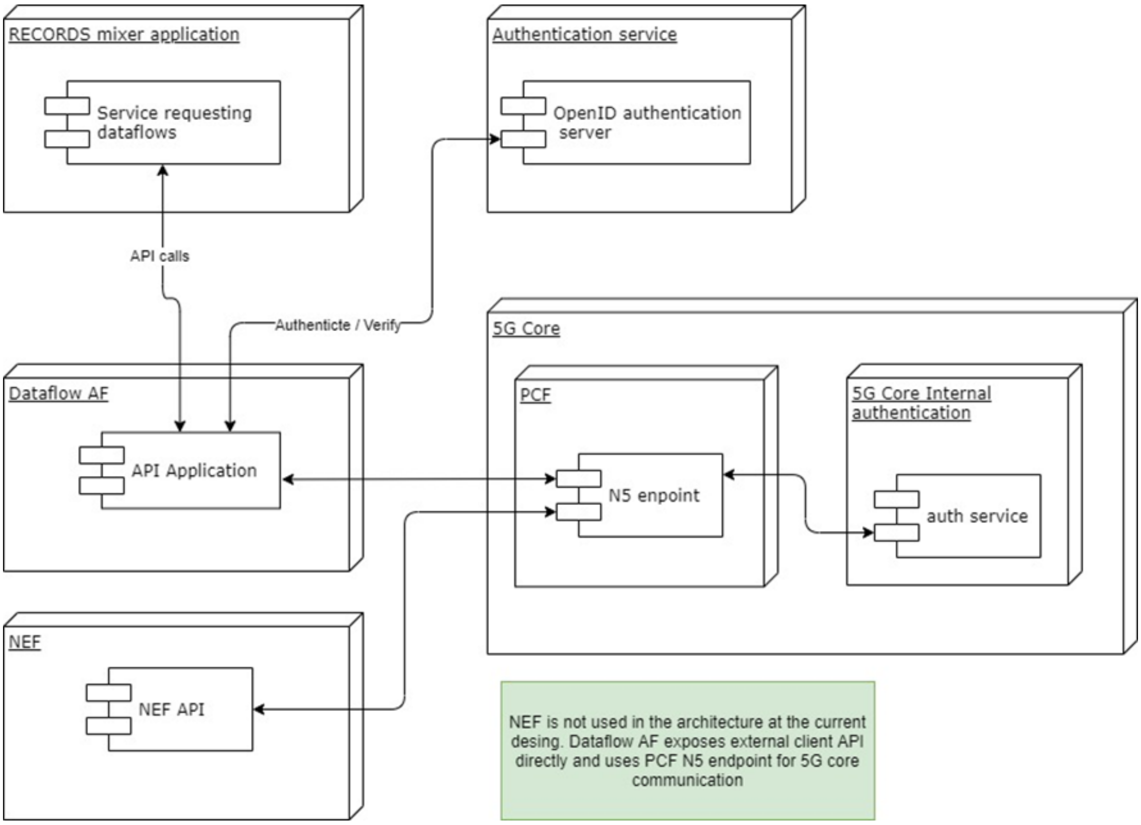


Figure 7. API environment

Interfaces

Dataflow AF will use PCF N5 endpoint for creating application sessions and dataflows for the subscriber. N5 interface is specified in the following specification TS 29.514 [3].

Dataflow AF will implement a north-bound API for external applications to request dataflows for subscribers. Example use case is 5G-RECORDS is the program mixer table controlling dataflows for 5G enabled microphones.

Dataflow AF will use an external OpenID Connect authentication service for authenticating external applications accessing the Dataflow API. After authentication access token is used for API communication messages

2.1.6 Shared access client and shared access server

Accelleran cloud-native Shared Access client communicates with RED Technologies Shared Access server using an HTTP/TLS-based transport with JSON-based protocol message encoding as per WINNFORUM specifications. By means of this protocol Accelleran Shared Access client obtains dynamically the spectrum configuration allowed on a particular geographical location from RED Technologies Shared Access server according to the spectrum leases defined in that server (Dynamic Spectrum Access). The Shared Access client uses the information from the requests of the Shared Access server to drive the operational logic and RF parameters configuration in Open RAN DU/RU. The most important parameters are related to the transmission power, bandwidth and carrier frequency derived from the maxEirp allowed by the Shared Access server on the leased blocks of spectrum.

The architecture of this dynamic spectrum access system is described in Figure 8.

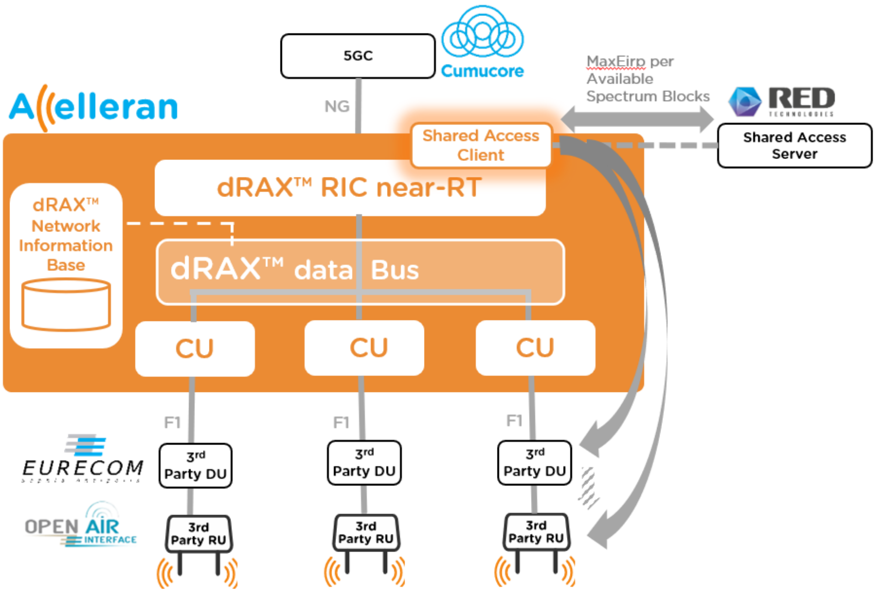


Figure 8. Dynamic spectrum access system architecture

2.1.7 End-to-end integration

At the current stage, the missing elements for an end-to-end integration are primarily the Cumucore 5GC and the dynamic spectrum access component. The Cumucore 5GC is fully integrated into the EURECOM infrastructure and is functional with the OAI gNB (monolithic mode) and the combined solution of Accelleran CU and OAI gNB-DU. However, the end-to-end establishment of a 5G service with the COTS UE is still not fully functional. There are some unexpected minor differences in the slicing features between the OAI gNB implementation and Cumucore 5GC. The differences will be resolved by end of June 2022. This does not impact the end-to-end configuration when the gNB-CU from Accelleran is used but the use of the OAI monolithic gNB is an important validation step and used as a reference configuration for latency measurements.

The integration of the RED technologies dynamic spectrum access client via the Accelleran gNB-CU is underway during the summer months of 2022. This entails adding a NETCONF server to the OAI gNB (and gNB-DU) and specifying YANG models for the gNB. This will be tested with the rest of the end-to-end demonstration in early August 2022.

2.2 Measurement and monitoring tools

This subsection describes the tools used in the integration and testing of Use Case 1, as well as the KPIs employed to measure and monitor the performance of its components prior to their use in trials.

2.2.1 KPIs update

D4.1 [2] initially selected the KPIs that are relevant in the context of Use Case 1 and could be measured with the tools available within the consortium. This section provides an update on such KPIs for the final stage of integration and testing.

1. ***Mouth-to-ear latency:***

Defined as the maximum application latency tolerated by a live performer between the analogue audio source (wireless microphone) and the analogue audio output (IEM). It includes two times the network latency plus the audio processing time. It is assumed that 2 ms are used for audio processing within the mixing console. The total mouth-to-ear latency is expected to be below 4 milliseconds.

2. ***5G network latency:***

This is the latency from the application layer on the UE side to the application layer on a device connected via the UPF to the 5GC (or vice versa). It includes the transfer interval (periodicity of packet transfers). The 5G network latency shall be lower than 1 millisecond.

3. ***Synchronicity:***

It is the absolute difference between any synchronised clock in the network and the time master, which shall be lower than 500 nanoseconds.

4. ***Packet error ratio****:*

The packet error ratio (PER) of the system for a packet size corresponding to 1 ms of audio data. Moreover, a consecutive minimum continuous error-free duration ≥ 100 ms must be ensured. This is because, to make packet errors inaudible, error concealment is used at application level. Every concealment is capable of handling one specific kind of error distribution. This KPI shall be lower than 10^{-6}.

2.2.2 Tools update

The following measurement tools have been used in the context of Use Case 1.

1. ***Analog audio latency measurement tool***

This tool is a dedicated hardware device that can measure mouth-to-ear latency by generating analogue test tones, capturing analogue audio and calculating the propagation delay between those analogue signals. To measure for example the latency from a microphone through a processing system to an IEM, the measurement tool can be connected into the same interfaces replacing the microphone and IEM. The device can achieve a measurement precision better than 100 µs.

Related KPI: *Mouth-to-ear latency*

2.3 Tests

This subsection describes the tests performed to guarantee the proper integration of the components and the fulfilment of the expected KPIs.

2.3.1 Testing of individual components

1. ***Centralized Unit (CU):***

Accelleran fully cloud native CU-CP and CU-UP microservices are developed and tested following strict CI/CD development practices and deployed in Kubernetes via Helm charts. These components undergo extensive unit testing, TTCN testing and wraparound testing with commercial testing solutions in addition to other tools enabling coverage analysis, profiling, debugging and optimization of the code such as PCLint, Valgrind, etc. All the tools are integrated to enable full regression testing on the code developed in an Agile environment.

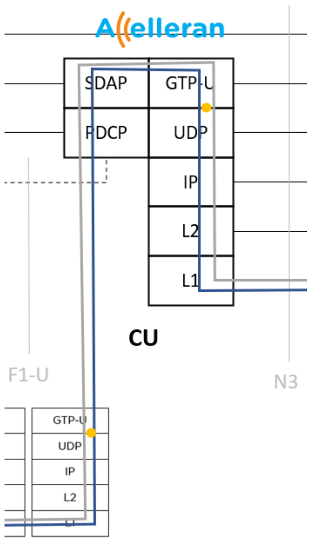


Figure 9. User plane protocols for CU

One of the important phases related to this project was the optimization of the threading model of the CU-UP protocol components and interfaces used to achieve the lowest latency possible in the processing of the packets from the ingress/egress interface points at F1 and NG-U (N3) interfaces. Figure 9 shows the specific protocols involved in the CU-UP processing between F1-U and NG-U (N3) interfaces. The demarcation points for measuring the processing latency are indicated with orange dots considering the SAP of the networking UDP protocol normally part of the networking stacks of the system.

To measure the processing delay in the CU-UP from UDP SAP to UDP SAP in both the uplink and downlink, Wireshark traces were used to catch the time difference between the packets, while the Ping tool was used to ping from UE to an external server behind the 5GC. In Figure 10 you can see that the processing delay in the CU-UP in UL is 54 µs (Ping Request in the UL), while in the DL it is 37 µs (Ping Reply in the DL) for a ping packet of 1400 bytes.

0.413388	10.80.11.2	10.244.0.14	GTP <GTP>	1382	T-PDU
0.000054	10.45.0.2	4.2.2.2	GTP <ICMP>	1386	Echo (ping) request id=0x13ff, seq=1/256, ttl=64 (reply in 49055)
0.022463	4.2.2.2	10.45.0.2	GTP <ICMP>	1386	Echo (ping) reply id=0x13ff, seq=1/256, ttl=55 (request in 49054)
0.000037	10.244.0.14	10.80.11.2	GTP <GTP>	1397	T-PDU
0.000390	10.80.11.2	10.244.0.14	GTP	66	T-PDU

Figure 10. Wireshark trace of ping packet through CU-UP

2. OAI Distributed Unit (DU):

The verification of this component is discussed in detail in Section 1.

3. 5GC and network slicing manager:

The slicing manager is an AF that is integrated with 5GC over N5 and N33 interfaces. These interfaces are between two network elements delivered by Cumucore.

Network slicing manager integration with 5GC was verified in Cumucore premises. Test cases cover the life cycle of a network slice (creation, modification, reporting and removal) and dynamic creation of dataflows into the specific network slice. Data flow creation request is done by using network slicing manager API.

4. Time Service:

Time service and related time synchronization functionality in the audio network devices / local audio processing were verified by using dedicated Ethernet connections to exchange PTP packets (see Figure 11). PPS signals from each device were measured to evaluate alignments of clocks.

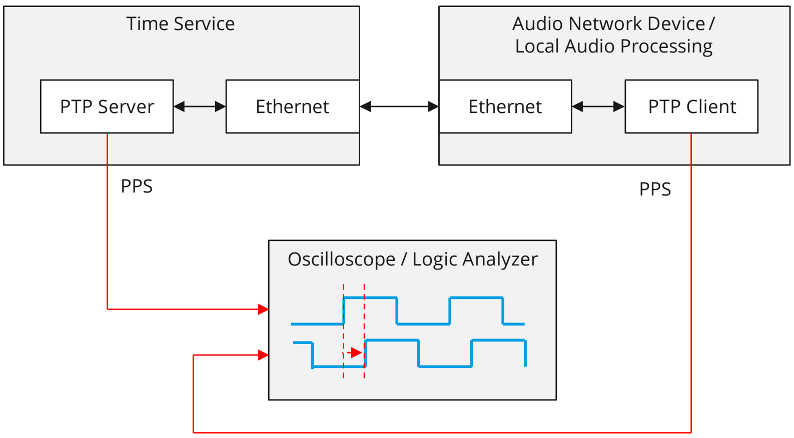


Figure 11. Setup to verify time synchronization service

The measurements showed that it was possible to achieve clock alignments better than +/- 30 ns with wired Ethernet connections. Figure 12 shows an exemplary measurement.

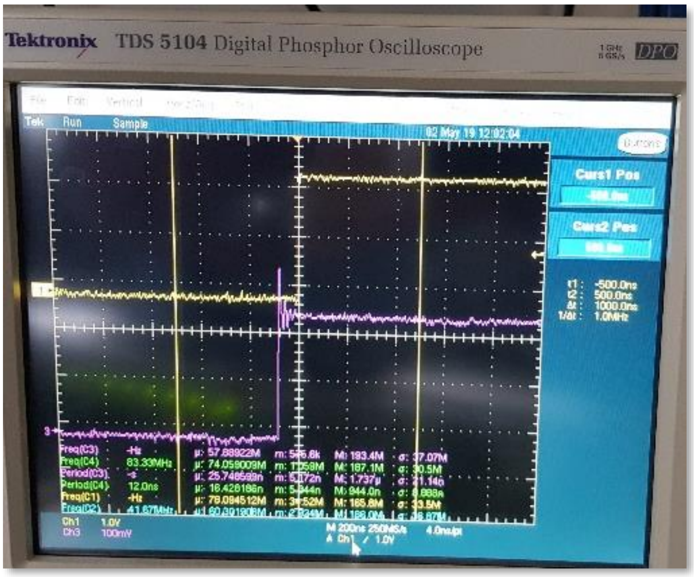


Figure 12. Exemplary measurement of PPS signal alignments

5. *Microphone IEM:*

The delay portion of the audio application in the user terminal is deterministic and known due to a dedicated hardware implementation. It is smaller than 170 µs from network packet reception to analogue audio output and vice versa. Depending on the configured network packet periodicity in the sender (microphone) an additional delay for the collection of multiple audio samples for network transfer is required. If for example, the network packet periodicity is 500 µs the same delay must be added.

To verify the implementation of the network streaming, the setup shown in Figure 13 was used. This is the baseline for the one-way network transmission latency measurement. The actual audio streaming was realized with dedicated Ethernet connection. The results of the measurement using the “Packet-based application latency measurement tool” are shown in Figure 14. It is shown that the pure network transmission in a direct network connection is in the single-digit microsecond range for every packet as expected.

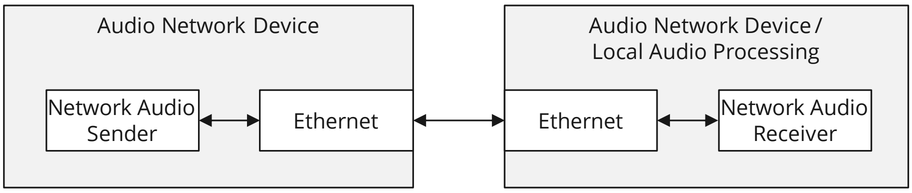


Figure 13. Setup for verification of audio network devices

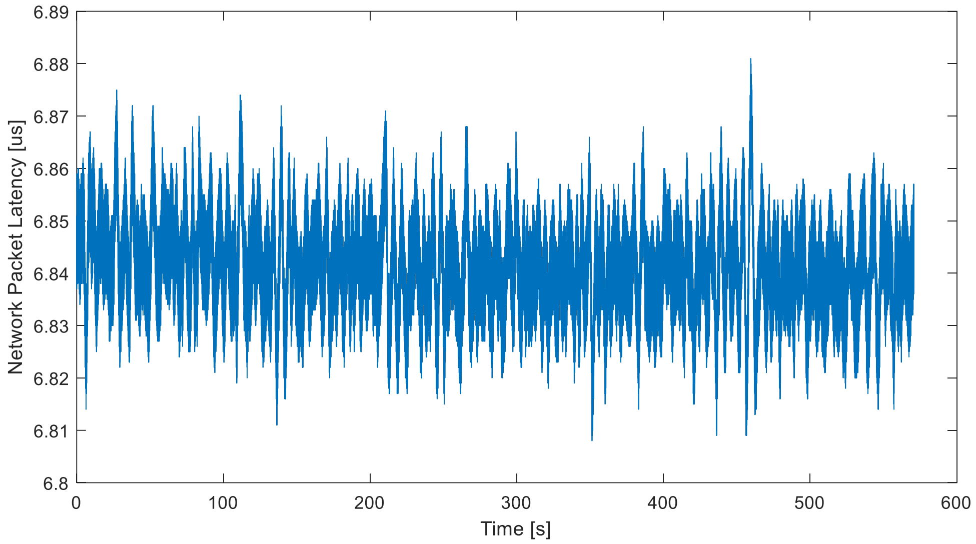


Figure 14. Latency of audio network packets in a direct connection of audio devices

6. Local audio processing

The latency of the local audio processing device consists of two portions. First, the network transmission-related handling and processing. This section is similar to the processing in the user terminal application, it is deterministic and known to be smaller than 50 µs from network packet reception to availability of individual digital audio samples and vice versa. Second, the audio-related processing, filtering, and mixing. This latency has a large portion of algorithmic audio delay and can vary between one and tens of milliseconds depending on the applied filtering and effects. In the 5G network evaluation, we assume that the audio data is looped back, omitting the algorithmic audio delay. Again, when sending audio packets from the local audio processing the network transfer periodicity must be added to the latency

Since the local audio processing device is based on the same hardware and software platform as the user terminal the verification measurement described in Figure 13 and Figure 14 is also valid for this device.

7. Core configuration service:

The REST-API calls of the core configuration service are verified by manual evaluation with Wireshark.

8. Shared access client:

In line with the Accelleran practice indicated in heading 1 for the CU, the Accelleran Shared Access client has also been developed and tested as a cloud native microservice following strict CI/CD development practices. This particular component undergoes extensive unit testing and TTCN testing. Additionally, this component has also been tested in isolation using Winnforum's Test Harness, which is the official test harness to demonstrate, by means of different testcases, CBSD (SAC) to SAS protocol conformance required by FCC Part 96 (CBRS). Figure 15 shows how the Winnforum`s Test Harness is used to emulate Shared Access server behavior while the SUT is the

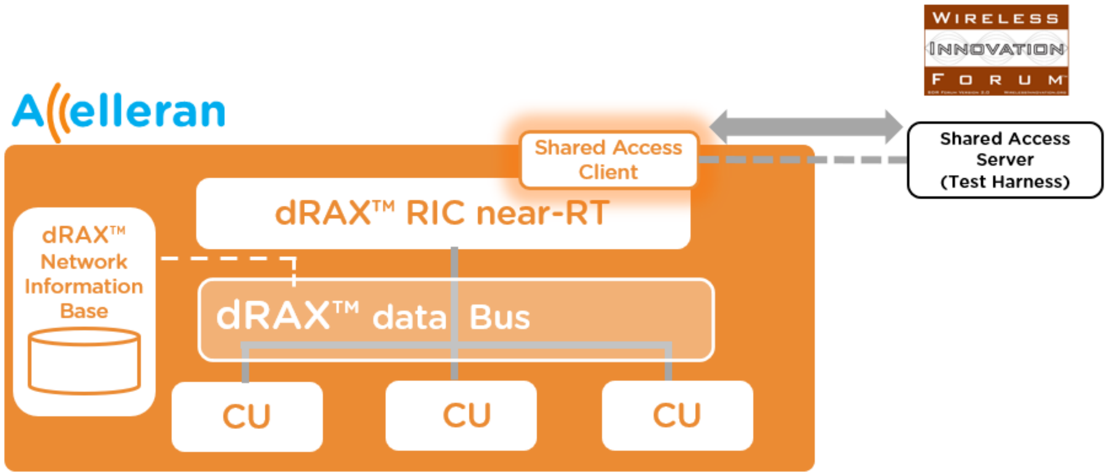


Figure 15. Conformance testing of Accelleran SAC as SUT

Shared Access client.

9. ***Shared access server:***

The validation of the protocol (registration, spectrum inquiry, Grant) was performed by executing tests in Python: the Python code sends an HTTP request to the Shared Access Server and verifies that the HTTP response is identical as the expected response.

The validation of the lease creation and of the synchronization with the lease database was performed manually (by using the web interface of the Shared Access Server).

2.3.2 Interoperability test

1. ***Accelleran CU – OAI DU interoperability tests:***

Control plane validation over F1-C

Figure 16 shows a trace captured at CU-CP with the exchanges over F1-C (with the OAI DU) and N2 (with the OAI AMF) interfaces for a successful UE registration and PDU Session establishment. The F1-C exchanges between the Accelleran CU and the OAI DU are based on ASN1.0 F1AP messages integrated as per 3GPP 38.473, Rel. 16. These messages can be grouped in the following:

- F1 setup messages between the CU and the DU, as well as their configuration updates
  - Configuration exchanges between CU and DU after the SCTP association
  - System Information transfer between DU and CU
- F1 DL/UL RRC message containers for transparent transfer of RRC/NAS messages between the CU and the UE through the DU
- F1 UE context management messages
  - Supporting the establishment of SRBs/DRBs
  - Transfer of RRC cellgroup configuration updates from the DU to the CU

Establishment of GTP-U tunnels between the CU and DU, required for enabling user-plane traffic transfer over F1-U.

ngap || f1ap

No.	Time	Source	Destination	Protocol	Length	Info
53	5.019566	192.168.18.113	192.168.18.90	F1AP	268	F1SetupRequest, MIB, SIB1
60	5.032352	192.168.18.90	192.168.18.113	F1AP	84	F1SetupResponse
69	5.036246	192.168.18.90	192.168.18.92	NGAP	376	NGSetupRequest
71	5.037372	192.168.18.92	192.168.18.90	NGAP	576	NGSetupResponse
75	5.042326	192.168.18.90	192.168.18.113	F1AP	96	GNBCUConfigurationUpdate
76	5.042575	192.168.18.113	192.168.18.90	F1AP	96	SACK , GNBCUConfigurationUpdateAcknowledge
210	15.934181	192.168.18.113	192.168.18.90	F1AP/NR RRC	224	RRC Setup Request
215	15.945073	192.168.18.90	192.168.18.113	F1AP/NR RRC	224	SACK , RRC Setup
216	16.019145	192.168.18.113	192.168.18.90	F1AP/NR RRC/NAS-5GS/NAS-5GS	216	SACK , RRC Setup Complete, Registration request, Registration request MAC=0x00000000
220	16.025269	192.168.18.90	192.168.18.92	NGAP/NAS-5GS/NAS-5GS	204	InitialUEMessage, Registration request, Registration request
221	16.026552	192.168.18.92	192.168.18.90	NGAP/NAS-5GS	304	DownlinkNASTransport, Identity request
224	16.030459	192.168.18.90	192.168.18.113	F1AP/NR RRC/NAS-5GS	128	SACK , DL Information Transfer, Identity request MAC=0x00000000
225	16.039138	192.168.18.113	192.168.18.90	F1AP/NR RRC/NAS-5GS	144	SACK , UL Information Transfer, Identity response MAC=0x00000000
228	16.042172	192.168.18.90	192.168.18.92	NGAP/NAS-5GS	148	UplinkNASTransport, Identity response
229	16.061736	192.168.18.92	192.168.18.90	NGAP/NAS-5GS	608	DownlinkNASTransport, Authentication request
232	16.064593	192.168.18.90	192.168.18.113	F1AP/NR RRC/NAS-5GS	168	SACK , DL Information Transfer, Authentication request MAC=0x00000000
239	16.354059	192.168.18.113	192.168.18.90	F1AP/NR RRC/NAS-5GS	132	UL Information Transfer, Authentication response MAC=0x00000000
243	16.357531	192.168.18.90	192.168.18.92	NGAP/NAS-5GS	136	UplinkNASTransport, Authentication response
244	16.358606	192.168.18.92	192.168.18.90	NGAP/NAS-5GS	440	DownlinkNASTransport, Security mode command
247	16.361521	192.168.18.90	192.168.18.113	F1AP/NR RRC/NAS-5GS	148	SACK , DL Information Transfer, Security mode command MAC=0x00000000
248	16.369031	192.168.18.113	192.168.18.90	F1AP/NR RRC/NAS-5GS/NAS-5GS	200	SACK , UL Information Transfer, Security mode complete, Registration request MAC=0x00000000
251	16.372032	192.168.18.90	192.168.18.92	NGAP/NAS-5GS/NAS-5GS	204	UplinkNASTransport, Security mode complete, Registration request
252	16.373862	192.168.18.92	192.168.18.90	NGAP/NAS-5GS	1184	InitialContextSetupRequest, Registration accept
256	16.377705	192.168.18.90	192.168.18.113	F1AP	152	SACK , UEContextSetupRequest
257	16.378068	192.168.18.113	192.168.18.90	F1AP	232	SACK , UEContextSetupResponse
264	16.581204	192.168.18.113	192.168.18.90	F1AP/NR RRC	104	Security Mode Complete MAC=0x8f746cb0
268	16.586147	192.168.18.90	192.168.18.113	F1AP/NR RRC/NAS-5GS	288	SACK , RRC Reconfiguration, Registration accept MAC=0x7060283b
270	16.654105	192.168.18.113	192.168.18.90	F1AP/NR RRC	120	SACK , RRC Reconfiguration Complete MAC=0x33714b66
274	16.657563	192.168.18.90	192.168.18.113	F1AP	108	SACK , UEContextModificationRequest
275	16.657612	192.168.18.113	192.168.18.90	F1AP/NR RRC/NAS-5GS	132	SACK , UL Information Transfer, Registration complete MAC=0xbed705d9
278	16.660535	192.168.18.90	192.168.18.92	NGAP/NAS-5GS	120	UplinkNASTransport, Registration complete
284	16.861202	192.168.18.113	192.168.18.90	F1AP	204	UEContextModificationResponse
288	16.864244	192.168.18.90	192.168.18.92	NGAP	84	InitialContextSetupResponse
310	18.064085	192.168.18.113	192.168.18.90	F1AP/NR RRC/NAS-5GS	188	UL Information Transfer, UL NAS transport, PDU session establishment request MAC=0x19eacc4f
315	18.068700	192.168.18.90	192.168.18.92	NGAP/NAS-5GS	192	UplinkNASTransport, UL NAS transport, PDU session establishment request
316	18.075822	192.168.18.92	192.168.18.90	NGAP/NAS-5GS	304	PDUSessionResourceSetupRequest, DL NAS transport, PDU session establishment accept
323	18.090639	192.168.18.90	192.168.18.113	F1AP	196	SACK , UEContextModificationRequest
324	18.091144	192.168.18.113	192.168.18.90	F1AP	252	SACK , UEContextModificationResponse
331	18.101241	192.168.18.90	192.168.18.113	F1AP/NR RRC/NAS-5GS	420	SACK , RRC Reconfiguration, DL NAS transport, PDU session establishment accept MAC=0x49686ed1
333	18.159073	192.168.18.113	192.168.18.90	F1AP/NR RRC	132	SACK , Measurement Report MAC=0xf8e9f141
340	18.365198	192.168.18.113	192.168.18.90	F1AP/NR RRC	104	RRC Reconfiguration Complete MAC=0x1f1feca1
345	18.368653	192.168.18.90	192.168.18.113	F1AP	108	SACK , UEContextModificationRequest
346	18.368962	192.168.18.113	192.168.18.90	F1AP	232	SACK , UEContextModificationResponse
349	18.372134	192.168.18.90	192.168.18.92	NGAP	104	PDUSessionResourceSetupResponse

Figure 16. F1AP and NGAP exchanges over F1 and N2 interface for UE registration and PDU Session establishment

User plane validation over F1-U

```
nrmodule1@nrmodule1:~$ ping -I 12.2.1.15 172.21.10.5
PING 172.21.10.5 (172.21.10.5) from 12.2.1.15 : 56(84) bytes of data.
64 bytes from 172.21.10.5: icmp_seq=1 ttl=63 time=9.17 ms
64 bytes from 172.21.10.5: icmp_seq=2 ttl=63 time=7.40 ms
64 bytes from 172.21.10.5: icmp_seq=3 ttl=63 time=10.5 ms
64 bytes from 172.21.10.5: icmp_seq=4 ttl=63 time=9.03 ms
64 bytes from 172.21.10.5: icmp_seq=5 ttl=63 time=7.53 ms
64 bytes from 172.21.10.5: icmp_seq=6 ttl=63 time=10.5 ms
64 bytes from 172.21.10.5: icmp_seq=7 ttl=63 time=9.04 ms
64 bytes from 172.21.10.5: icmp_seq=8 ttl=63 time=6.52 ms
64 bytes from 172.21.10.5: icmp_seq=9 ttl=63 time=10.5 ms
64 bytes from 172.21.10.5: icmp_seq=10 ttl=63 time=8.99 ms
64 bytes from 172.21.10.5: icmp_seq=11 ttl=63 time=7.09 ms
64 bytes from 172.21.10.5: icmp_seq=12 ttl=63 time=9.97 ms
64 bytes from 172.21.10.5: icmp_seq=13 ttl=63 time=9.94 ms
64 bytes from 172.21.10.5: icmp_seq=14 ttl=63 time=7.55 ms
64 bytes from 172.21.10.5: icmp_seq=15 ttl=63 time=5.52 ms
64 bytes from 172.21.10.5: icmp_seq=16 ttl=63 time=9.53 ms
64 bytes from 172.21.10.5: icmp_seq=17 ttl=63 time=8.05 ms
64 bytes from 172.21.10.5: icmp_seq=18 ttl=63 time=6.52 ms
64 bytes from 172.21.10.5: icmp_seq=19 ttl=63 time=9.03 ms
64 bytes from 172.21.10.5: icmp_seq=20 ttl=63 time=7.54 ms
```

```
nrmodule1@nrmodule1:~$ iperf3 -B 12.2.1.14 -c 172.21.10.5 -b 8M -u -t 300 -l 1024 -R
Connecting to host 172.21.10.5, port 5201
Reverse mode, remote host 172.21.10.5 is sending
[  5] local 12.2.1.14 port 38048 connected to 172.21.10.5 port 5201
[ ID] Interval           Transfer     Bitrate         Jitter    Lost/Total Datagrams
[  5]   0.00-1.00   sec   980 KBytes  8.03 Mbits/sec  1.549 ms  0/980 (0%)
[  5]   1.00-2.00   sec   977 KBytes  8.00 Mbits/sec  1.516 ms  0/977 (0%)
[  5]   2.00-3.00   sec   976 KBytes  8.00 Mbits/sec  1.507 ms  0/976 (0%)
[  5]   3.00-4.00   sec   977 KBytes  8.00 Mbits/sec  1.531 ms  0/977 (0%)
[  5]   4.00-5.00   sec   976 KBytes  8.00 Mbits/sec  1.505 ms  0/976 (0%)
[  5]   5.00-6.00   sec   977 KBytes  8.00 Mbits/sec  1.536 ms  0/977 (0%)
[  5]   6.00-7.00   sec   976 KBytes  8.00 Mbits/sec  1.612 ms  0/976 (0%)
[  5]   7.00-8.00   sec   977 KBytes  8.00 Mbits/sec  1.546 ms  0/977 (0%)
[  5]   8.00-9.00   sec   976 KBytes  8.00 Mbits/sec  1.560 ms  0/976 (0%)
[  5]   9.00-10.00  sec   976 KBytes  8.00 Mbits/sec  1.598 ms  0/976 (0%)
[  5]  10.00-11.00  sec   975 KBytes  7.99 Mbits/sec  1.649 ms  0/975 (0%)
[  5]  11.00-12.00  sec   964 KBytes  7.90 Mbits/sec  1.653 ms  13/977 (1.3%)
[  5]  12.00-13.00  sec   963 KBytes  7.89 Mbits/sec  1.627 ms  13/976 (1.3%)
[  5]  13.00-14.00  sec   978 KBytes  8.01 Mbits/sec  1.638 ms  0/978 (0%)
[  5]  14.00-15.00  sec   975 KBytes  7.99 Mbits/sec  1.626 ms  0/975 (0%)
[  5]  15.00-16.00  sec   978 KBytes  8.01 Mbits/sec  1.585 ms  0/978 (0%)
[  5]  16.00-17.00  sec   973 KBytes  7.97 Mbits/sec  1.762 ms  0/973 (0%)
[  5]  17.00-18.00  sec   978 KBytes  8.01 Mbits/sec  1.670 ms  0/978 (0%)
[  5]  18.00-19.00  sec   975 KBytes  7.99 Mbits/sec  1.704 ms  0/975 (0%)
[  5]  19.00-20.00  sec   977 KBytes  8.00 Mbits/sec  1.736 ms  0/977 (0%)
[  5]  20.00-21.00  sec   976 KBytes  8.00 Mbits/sec  1.700 ms  0/976 (0%)
[  5]  21.00-22.00  sec   975 KBytes  7.99 Mbits/sec  1.848 ms  0/975 (0%)
[  5]  22.00-23.00  sec   977 KBytes  8.00 Mbits/sec  1.828 ms  0/977 (0%)
[  5]  23.00-24.00  sec   967 KBytes  7.92 Mbits/sec  1.863 ms  9/976 (0.92%)
[  5]  24.00-25.00  sec   977 KBytes  8.00 Mbits/sec  1.825 ms  0/977 (0%)
[  5]  25.00-26.00  sec   976 KBytes  8.00 Mbits/sec  1.879 ms  0/976 (0%)
[  5]  26.00-27.00  sec   977 KBytes  8.00 Mbits/sec  1.835 ms  0/977 (0%)
^C[  5]  27.00-27.58  sec   575 KBytes  8.07 Mbits/sec  1.533 ms  0/575 (0%)
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Jitter    Lost/Total Datagrams
[  5]   0.00-27.58  sec  0.00 Bytes  0.00 bits/sec  0.000 ms  0/0 (0%)  sender
[  5]   0.00-27.58  sec  26.3 MBytes  7.99 Mbits/sec  1.533 ms  35/26939 (0.13%)  receiver
```

Figure 17. DL iPerf

```
Accepted connection from 172.21.10.2, port 41439
[  5] local 172.21.10.5 port 5201 connected to 172.21.10.2 port 47441
[ ID] Interval           Transfer     Bitrate         Jitter    Lost/Total Datagrams
[  5]   0.00-1.00   sec   602 KBytes  4.93 Mbits/sec  1.965 ms  0/602 (0%)
[  5]   1.00-2.00   sec   609 KBytes  4.99 Mbits/sec  1.936 ms  0/609 (0%)
[  5]   2.00-3.00   sec   611 KBytes  5.00 Mbits/sec  2.066 ms  0/611 (0%)
[  5]   3.00-4.00   sec   611 KBytes  5.01 Mbits/sec  1.970 ms  0/611 (0%)
[  5]   4.00-5.00   sec   610 KBytes  5.00 Mbits/sec  1.826 ms  0/610 (0%)
[  5]   5.00-6.00   sec   609 KBytes  4.99 Mbits/sec  1.967 ms  0/609 (0%)
[  5]   6.00-7.00   sec   613 KBytes  5.02 Mbits/sec  1.830 ms  0/613 (0%)
[  5]   7.00-8.00   sec   608 KBytes  4.98 Mbits/sec  2.262 ms  0/608 (0%)
[  5]   8.00-9.00   sec   610 KBytes  5.00 Mbits/sec  1.878 ms  0/610 (0%)
[  5]   9.00-10.00  sec   612 KBytes  5.01 Mbits/sec  1.869 ms  0/612 (0%)
[  5]  10.00-11.00  sec   609 KBytes  4.99 Mbits/sec  1.752 ms  0/609 (0%)
[  5]  11.00-12.00  sec   611 KBytes  5.00 Mbits/sec  1.942 ms  0/611 (0%)
[  5]  12.00-13.00  sec   611 KBytes  5.01 Mbits/sec  1.809 ms  0/611 (0%)
[  5]  13.00-14.00  sec   612 KBytes  5.01 Mbits/sec  1.874 ms  0/612 (0%)
[  5]  14.00-15.00  sec   610 KBytes  5.00 Mbits/sec  1.688 ms  0/610 (0%)
[  5]  14.00-15.00  sec   610 KBytes  5.00 Mbits/sec  1.688 ms  0/610 (0%)
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Jitter    Lost/Total Datagrams
[  5]   0.00-15.00  sec  9.46 MBytes  5.29 Mbits/sec  1.817 ms  0/9684 (0%)  receiver
```

Figure 18. NR-User plane protocol GTP-U extension header for DL User Data

```
183… 4.358009   172.21.10.9     172.21.16.120   GTP <GTP>     252 T-PDU
183… 4.358045   172.21.16.120   172.21.10.9     GTP            68 T-PDU
183… 4.358978   172.21.15.11    12.2.1.14       GTP <UDP>     241 50000 → 50000 Len=153
183… 4.359015   172.21.10.9     172.21.16.120   GTP <GTP>     252 T-PDU
183… 4.359987   172.21.15.11    12.2.1.14       GTP <UDP>     241 50000 → 50000 Len=153
183… 4.360024   172.21.10.9     172.21.16.120   GTP <GTP>     252 T-PDU
183… 4.360980   172.21.15.11    12.2.1.14       GTP <UDP>     241 50000 → 50000 Len=153
183… 4.361017   172.21.10.9     172.21.16.120   GTP <GTP>     252 T-PDU
Internet Protocol Version 4, Src: 172.21.10.9, Dst: 172.21.16.120
User Datagram Protocol, Src Port: 2152, Dst Port: 2152
GPRS Tunneling Protocol
  Flags: 0x34
  Message Type: T-PDU (0xff)
  Length: 200
  TEID: 0x521bbbc0 (1377549248)
  Next extension header type: NR RAN container (0x84)
  Extension header (NR RAN container)
    Extension Header Length: 3
    NR RAN Container
      NRUP
        0000 .... = PDU Type: DL User Data (0)
        .... 0... = Spare: False
        .... .0.. = DL Discard Blocks: Not Present
        .... ..0. = DL Flush: Not Present
        .... ...0 = Report Polling: Not Requested
        000. .... = Spare: 0
        ...0 .... = Request Out Of Seq Report: No
        .... 1... = Report Delivered: Yes
        .... .1.. = User Data Existence Flag: Yes
        .... ..0. = Assistance Info. Report Polling Flag: No
        .... ...0 = Retransmission Flag: No
        NR-U Sequence Number: 1865898
        DL report NR PDCP PDU SN: 30890
    Next extension header type: No more extension headers (0x00)
```

Figure 19. NR-User plane protocol GTP-U extension header for DL User Data

```
183… 4.358045   172.21.16.120   172.21.10.9     GTP            68 T-PDU
183… 4.358978   172.21.15.11    12.2.1.14       GTP <UDP>     241 50000 → 50000 Len=153
183… 4.359015   172.21.10.9     172.21.16.120   GTP <GTP>     252 T-PDU
183… 4.359987   172.21.15.11    12.2.1.14       GTP <UDP>     241 50000 → 50000 Len=153
183… 4.360024   172.21.10.9     172.21.16.120   GTP <GTP>     252 T-PDU
183… 4.360980   172.21.15.11    12.2.1.14       GTP <UDP>     241 50000 → 50000 Len=153
183… 4.361017   172.21.10.9     172.21.16.120   GTP <GTP>     252 T-PDU
Internet Protocol Version 4, Src: 172.21.16.120, Dst: 172.21.10.9
User Datagram Protocol, Src Port: 2152, Dst Port: 2152
GPRS Tunneling Protocol
  Flags: 0x34
  Message Type: T-PDU (0xff)
  Length: 16
  TEID: 0x80000343 (2147484483)
  Next extension header type: NR RAN container (0x84)
  Extension header (NR RAN container)
    Extension Header Length: 3
    NR RAN Container
      NRUP
        0001 .... = PDU Type: DL Data Delivery Status (1)
        .... 1... = Highest Transmitted NR PDCP SN Ind: Yes
        .... .0.. = Highest Delivered NR PDCP SN Ind: No
        .... ..0. = Final Frame Indication: Frame is not final
        .... ...0 = Lost Packet Report: No
        000. .... = Spare: 0
        ...0 .... = Delivered NR PDCP SN Range Ind: No
        .... 0... = Data Rate Ind: No
        .... .0.. = Highest Retransmitted NR PDCP SN Ind: No
        .... ..0. = Highest Delivered Retransmitted NR PDCP SN Ind: No
        .... ...0 = Cause Report: No
        Desired buffer size for the data radio bearer: 9999264
        Highest transmitted NR PDCP SN: 30890
    Next extension header type: No more extension headers (0x00)
```

Figure 20. NR-User plane protocol GTP-U extension header for DL Data Delivery Status Report.

2. Cumucore interoperability tests:

Network slicing functionality is an AF. The AF was integrated over N5 and N33 interfaces. Work was done internally in Cumucore.

3. Disaggregated RAN + Cumucore 5GC with Sennheiser application

The current target is to test the performance and compare it with performance of monolithic OAI setup. The tests are scheduled for July 2022 and will be reported in future deliverables.

4. Interoperability RED technologies SAS – Accelleran SAC

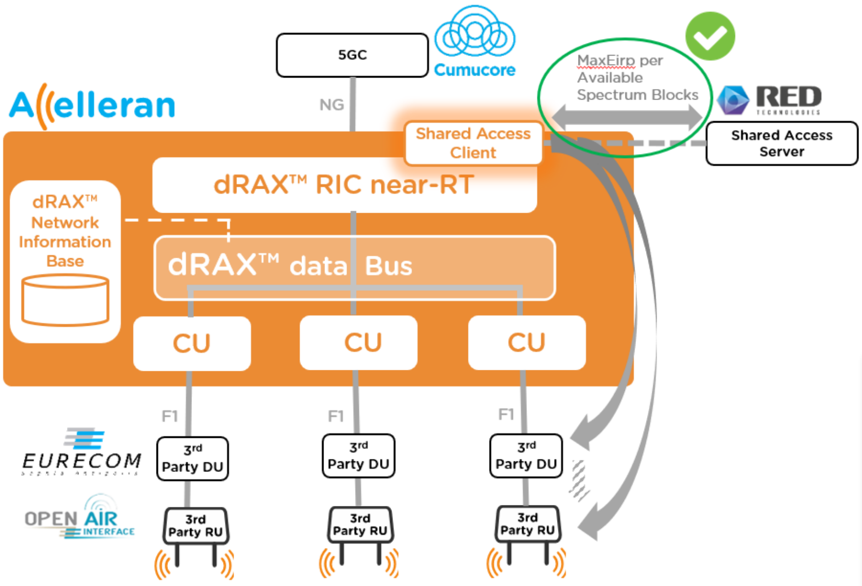


Figure 21. Scope of the Accelleran SAC and RED Technologies SAS interoperability tests

The interoperability of the protocol used between the Accelleran SAC and RED Technologies SAS as described in 4 was validated at the beginning of 2022. Accelleran cloud native Shared Access client was running in a local server setup in Accelleran premises communicating with RED Technologies Shared Access server running in the Cloud. The scope of the part validated is shown in Figure 21.

The following traces show some of the procedures involved in the dynamic spectrum acquisition during the test runs. The actual interoperability tests demonstrated how 100 MHz of 5G-NR spectrum in n78 could be allocated and relinquished, and what transmission power could be allowed, in geographical coordinates which for test purposes were simulated as being in Alaska. Registration procedure and API calls can be found in the Annex A.

5. Interoperability Accelleran SAC – OAI DU for spectrum configuration

The next step in the end-to-end Shared Access validation is the implementation of the appropriate interface in OAI to enable the configuration of the RF parameters of the DU/RU by the Accelleran SAC. The expected interface to be supported in OAI for this is based on Netconf. Once this is implemented in OAI and pre-validated against the Accelleran SAC, the total end to end behavior between RED Technologies Shared Access server, Accelleran Shared Access client and EURECOM OAI DU/RU can be proven fully for the dynamic spectrum access part of the disaggregated RAN setup.

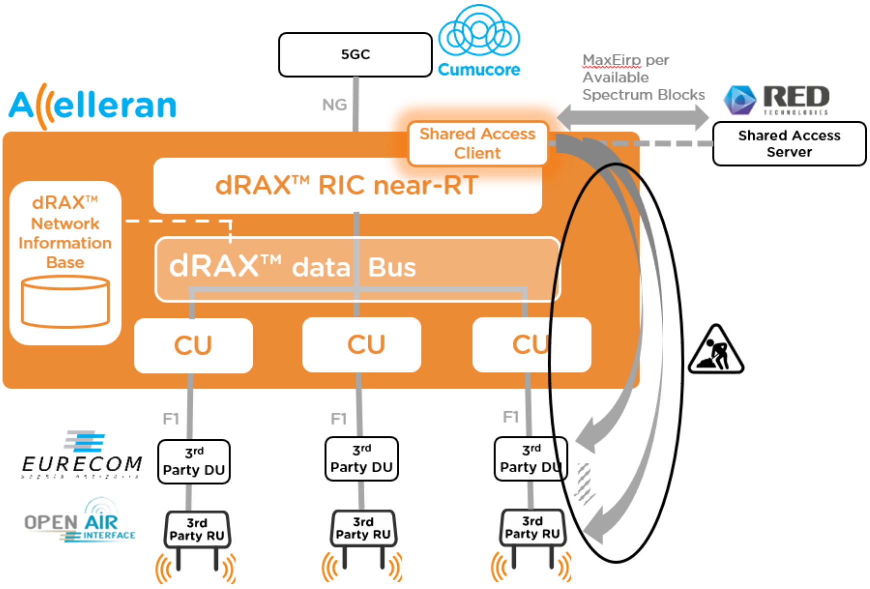


Figure 22. Scope of the Accelleran SAC and OAI DU/RU spectrum configuration tests

2.3.3 End-to-end solution

This use case has challenging requirements, especially transmission latency and packet error ratio, and many of the KPIs are intertwined and force complex trade-offs making it even more challenging to meet the full set of requirements within the 3GPP standard. In addition to finding the theoretical operation points within the standard, the implementation of 5G components capable of meeting targeted KPIs is equally challenging. In this work we focus on capturing the state-of-the-art of open-source or commercially available 5G component implementations with the goal of understanding practical challenges, trade-offs and to identify potential needs for further optimizations. Since the current testbed is stationary with radio channel characteristics that are not realistic for our use case and thus not allowing meaningful conclusions with respect to reliability, we focus only on the transmission latency of a single audio UE. The testbed mandates a limitation due to the forementioned fact that the UPF processing is currently not synchronized to GPS. For the time being, this excludes the latency optimization of the communication between audio device and UPF in downlink direction. Hence, we only present measurements and analysis for the optimized uplink direction. It is assumed that processing of the UPF can be synchronized. Therefore, we expect, that our results and conclusions also applicable for downlink direction in the future.

Latency analysis

Media capturing devices such as microphones uses media clocks to control sampling of analogue information for digital transport and processing. Playback devices such as IEMs use periodic media clocks to pace retransformation of media data back to analogue signals. In professional systems these media clocks are typically synchronized e.g., to avoid quality-reducing resampling. For network transport, multiple media samples are often bundled together. The creation of such packets is typically related to the media clocks in the sense that a fixed number of samples are bundled into one packet. A professional audio system that works with a 48 kHz media clock could for example constantly pack together 48 samples

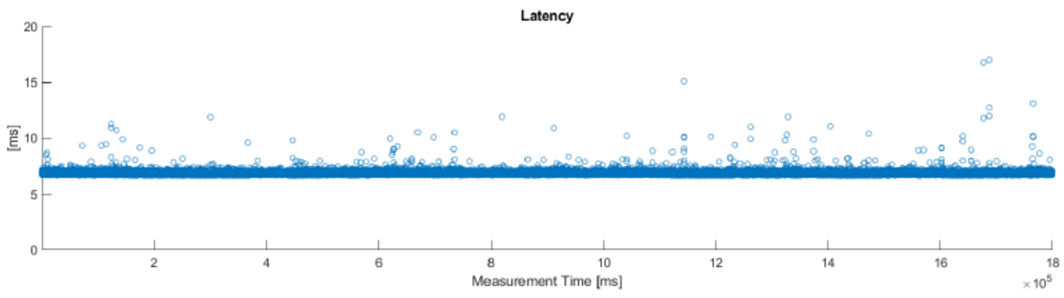


Figure 23. 5G end-to-end uplink latency, 5 ms 5G DL/UL periodicity, 5 ms audio packet periodicity

resulting in a packet ready for transmission every millisecond. As such, creation of media packets for transport follows a specific frequency / period and phase.

Digital wireless transmission systems, such as 5G, often work with a fixed synchronized timing grid to control and optimize communication between peers. In 5G this timing grid is dictated by the base-station to which UEs synchronize themselves. The time reference for this grid is typically GPS. Within this timing grid, participating devices have periodic opportunities to transmit or receive data, also following a specific frequency / period and phase.

Having the demanding requirements of professional live audio productions in mind, it stands to reason that understanding the relation between audio and 5G timing grid is of highest importance to subsequently parameterize and configure both system in an optimal way.

The initial 5G timing grid configuration was based on a repeating 10-slot frame. The ten slots were pre-scheduled in a *DDDDDDDXUU* pattern, where *D* represents an opportunity for a downlink transmission, *U* can be used for uplink transmissions, and *X* can be one or the other. With a 30 kHz SCS each slot has a length of 500 µs, resulting in a downlink / uplink periodicity of 5 ms.

1) Identical periodicity of audio packet creation and uplink transmission opportunity

For a first measurement we configured the packing of audio samples in the microphone function to the 5G downlink / uplink periodicity of 5 ms, resulting in IP-packets with 240 audio samples each.

Figure 23 shows the 5G end-to-end latency of every audio IP-packet sent from microphone to live audio processing for 30 minutes. Minimum observed latency is about 7.5 ms. According to (1) this results in a minimum transmission latency of about 12.5 ms. In general, the minimum latency is not relevant for a live media streaming application. Instead, the majority of packets are required to be within the latency budget. Here, the term majority has to be understood in relation to the required reliability as late packets are considered lost. Hence, in professional live audio productions, the transmission latency of at least 99.9999% of all packets is relevant. Real packet loss has to be taken into account. Still, reflecting on the theoretical smallest latency helps to understand the structural mechanisms to identify room for optimizations.

Figure 24 depicts the timing grids of the audio and the 5G system. For simplicity, all jitter and processing delays are assumed to be zero. In this theoretical example four audio samples are periodically combined to one packet, which is handed over to the

5G system, transmitted and received. The latency from sampling in the sender to playback in the receiver

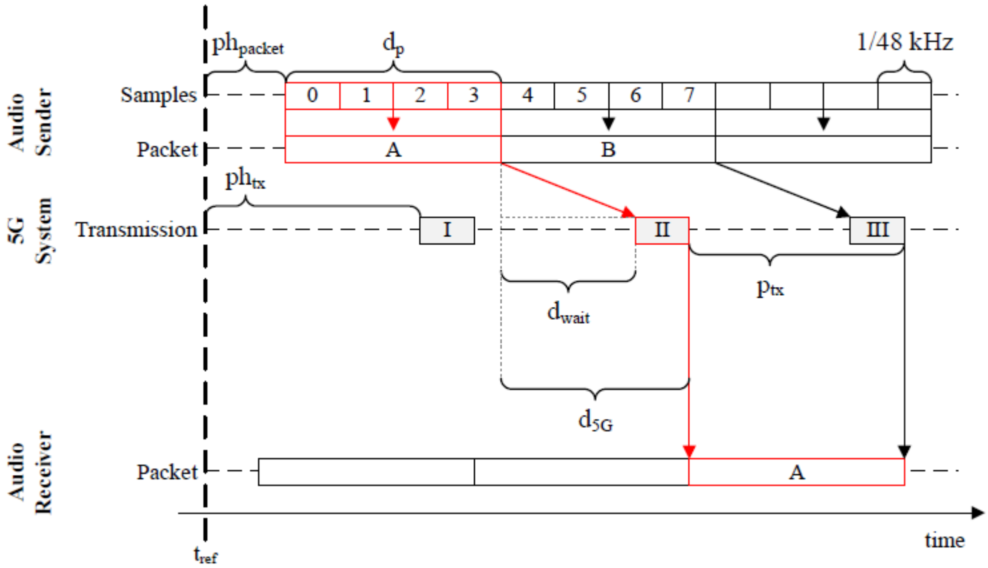


Figure 24. Timing grid with identical periodicity of audio packet creation and transmission opportunity

is calculated with

$$d_t = d_p + d_{5G}$$

where d_p is the audio packet periodicity and d_{5G} is the latency of 5G system. The 5G end-to-end latency d_{5G} contains a buffering time d_{wait} that each packet has to wait for the next transmission opportunity that depends on the phase difference between audio and 5G timing grid, and can range between 0 and the periodicity of transmission opportunities p_{tx}:

$$d_{wait} = ph_{tx} + ph_{packet}$$

In this theoretical consideration, the phase difference is constant over time if audio system and 5G system use the same time reference, and can be minimized by aligning the packet and transmission grid. In the real measurement shown in *Figure 23* the exact phase difference of both timing grids is unknown and significantly influenced by processing delays and jitter in the 5G system.

The effect of grid phase difference can be made visible when removing the time synchronization between both systems. This can be achieved by disconnecting the PTP server from GPS. Media clocks and 5G timing are then based on independent grids that drift past one another. Figure 25 illustrates this effect. The base-line latency is no longer a fixed horizontal line, but changes with the drifting clocks. The minimum latency here ranges from about 3 ms to about 8 ms. From this observation it can be concluded that d_{5G} in this setup could be optimized down to theoretical lower limit of 3 ms by aligning the timing grids. Still, the minimum transmission latency would be 8 ms, including the IP-packet periodicity.

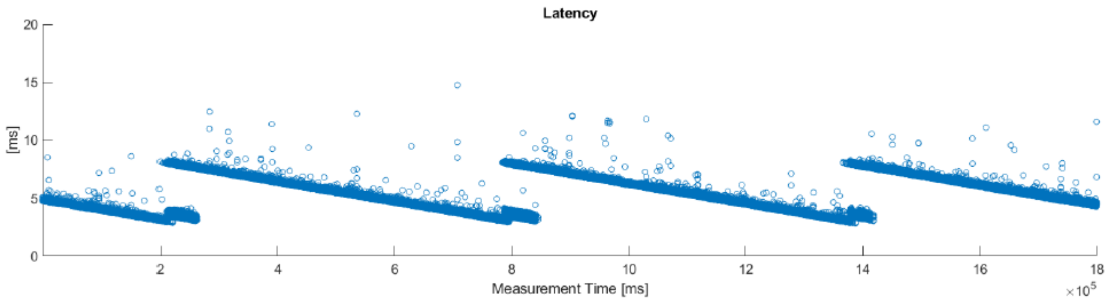


Figure 25. 5G end-to-end uplink latency, 5 ms 5G DL/UL periodicity, 5 ms audio packet periodicity, drifting timing grids.

2) Reduced audio packet periodicity

In a next step, we reduced the audio packet periodicity to 2.5 ms, half the 5G DL/UL periodicity of 5 ms. As a result, the audio sender generated twice as many IP-packets. 5G end-to-end latency measurement with this configuration is shown in *Figure 26*.

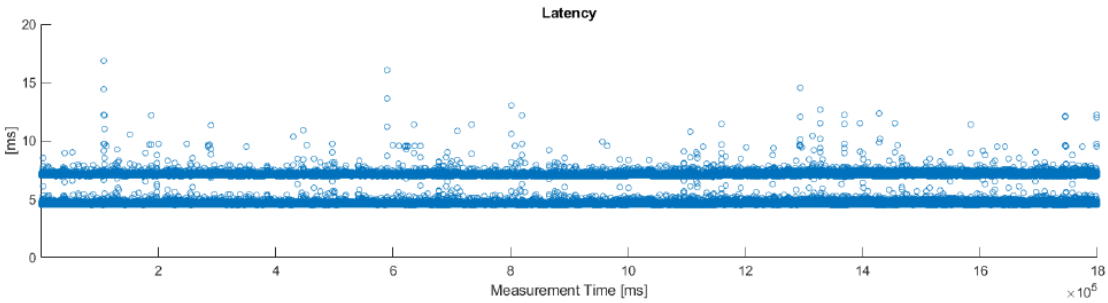


Figure 26. 5G end-to-end uplink latency, 5 ms 5G DL/UL periodicity, 2.5 ms audio packet periodicity

Here, measured latencies are distributed into two distinct groups, around 4.5 ms and 7.5 ms. To understand the behavior, it is again useful to examine the timing grids of the systems, which are shown in *Figure 27*. In this theoretical example, each two audio samples a packet is generated and handed over to the 5G system. Since the periodic constant in the 5G system has not changed, half the packets now have to wait for a significantly shorter time for a transmission opportunity due to the grids phase relation. Unfortunately, this is of no benefit for the application. To assure the correct order and pace of sample playback, the faster packets have to be buffered in the receiver now for the full length of a packet. Although, the transmission latency is now significantly reduced for half of the packets, the application latency does not benefit from this circumstance in any way. This illustrates why not the fastest packets are important in a media streaming application, but the slowest.

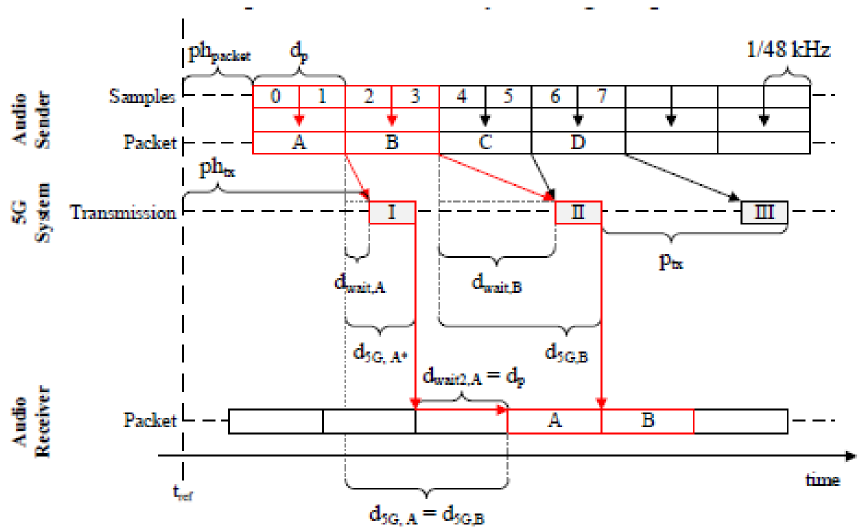


Figure 27. Timing grid with half audio packet creation periodicity

Based on this analysis it is evident that the internal 5G system DL/UL periodicity can play a major role in the latency of a live streaming application. Furthermore, it can be concluded that in order to achieve a transmission latency of 1 ms, as the use case requires, the 5G DL/UL periodicity has to be smaller than 1 ms.

B. Optimization of the testbed

On the road to a transmission latency of 1 ms, we reduced the 5G DL/UL periodicity in the testbed's implementation to 5 slots with a prescheduled DDXUU pattern of 2.5 ms length, and configured the audio packet creation periodicity to the same value. Figure 28 show the results of an exemplary measurement with this setup.

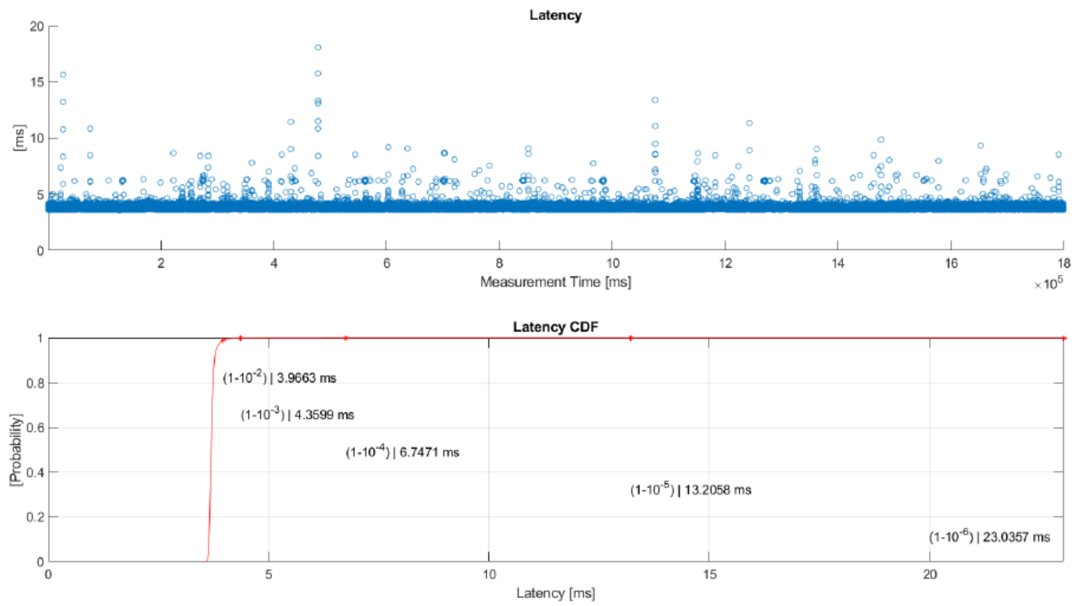


Figure 28, 5G end-to-end uplink latency and CDF, 2.5 ms 5G DL/UL periodicity, 2.5 ms audio packet periodicit

Until now our analysis omitted the latency jitter in the 5G system. Looking at the jitter it is mandatory for a realistic evaluation of the suitability of 5G for professional live audio productions. Useful for this analysis is considering the cumulative distribution function (CDF), see Figure 8. As explained before, not the fastest packets are of interest in this use case, but at least 99.9999% of all packets. Already a few late packets can shift the operation point significantly up. The CDF shows the respective marker at ~23 ms. With an audio packet periodicity of 2.5 ms we can calculate the transmission latency with to ~25.5 ms.

In the previous sections, we have not reported on DL latency measurements. In the current configuration there are still some unexplainable observations as depicted in *Figure 29* where we show DL latency statistics for the same DDXUU configuration. Two important aspects are to be noted. Firstly, despite network and application synchronization, the latency exhibits a drifting behavior as was the case for the UL in *Figure 25*. This suggests that some element on the end-to-end user-plane transmission chain is introducing a timing drift based on an asynchronous clock (e.g., CPU clock). Secondly, we note that although the minimal latency is 1.5ms, the typical latency is uniformly distributed between 4 and 9ms. This is different than earlier DL measurements on the monolithic gNodeB reference platform (i.e., without the CU/DU split). The minimal value is consistent with the limitations of the radio equipment which was configured with a 1.5ms preparation time for the TX signal. The reliability in terms of packet error rate is also an order of magnitude worse than the UL case which also remains unexplained at this point in time.

T13 Downlink

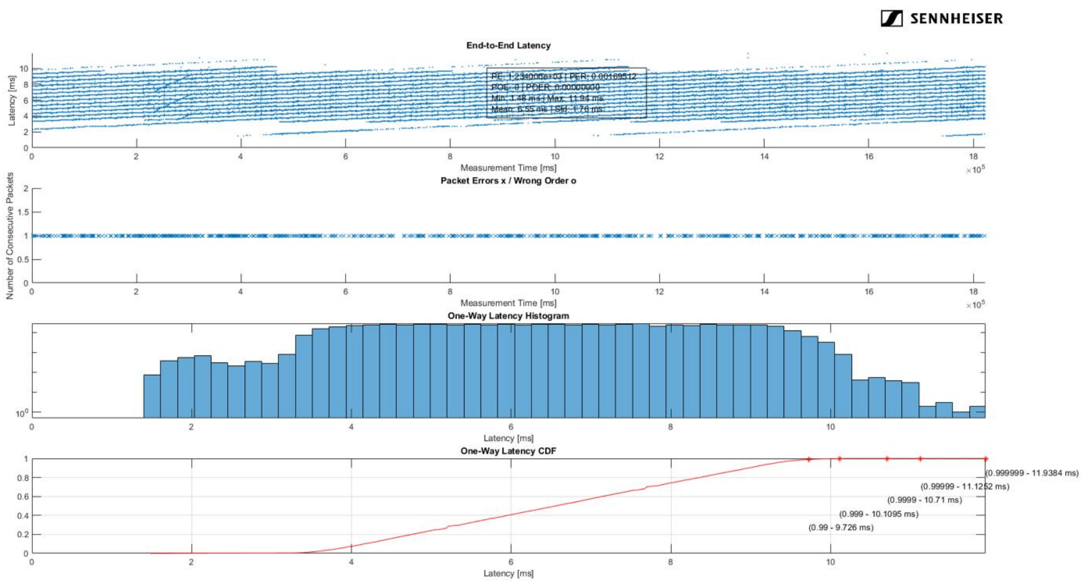


Figure 29. DL latency statistics, 2.5ms application packet period, DDXUU 2.5ms TDD configuration

2.4 Infrastructure update

2.4.1 Network configuration description

EURECOM configured its infrastructure for 5G-RECORDS using the following computing/switching components:

- Switching fabric
  - 3 x 3.6 Tbit/s EdgeCore Tomahawk-based switches (AS7312-54XS): one spine 2 ToR leaves
- Kubernetes controlled Nodes (NFVI currently RedHat Openshift 4.9)
  - Worker nodes: 8xDell R640 Xeon Gold 6154/6254 (288 x86-64 cores @ 3 GHz)
  - Simpler worker nodes for applications also available on cluster : quad-core x86
  - master nodes : 3x Dell R440 Xeon Silver (60 x86-64 cores @ 2.4 GHz
  - Single-node-cluster: 1x Dell AMD Epyq server (128 x86-64 cores @ 4 GHz)
- Jumphost on EURECOM's VM fabric interconnected to the CumulusOS switching fabric
- Bare-Metal nodes for development and radio nodes (e.g. gNodeB-DU)
- UE radio nodes with Quectel RM500Q and SIMCOM SIM8200 on mini-PCs

The overall UC1 network is shown in Figure 30.

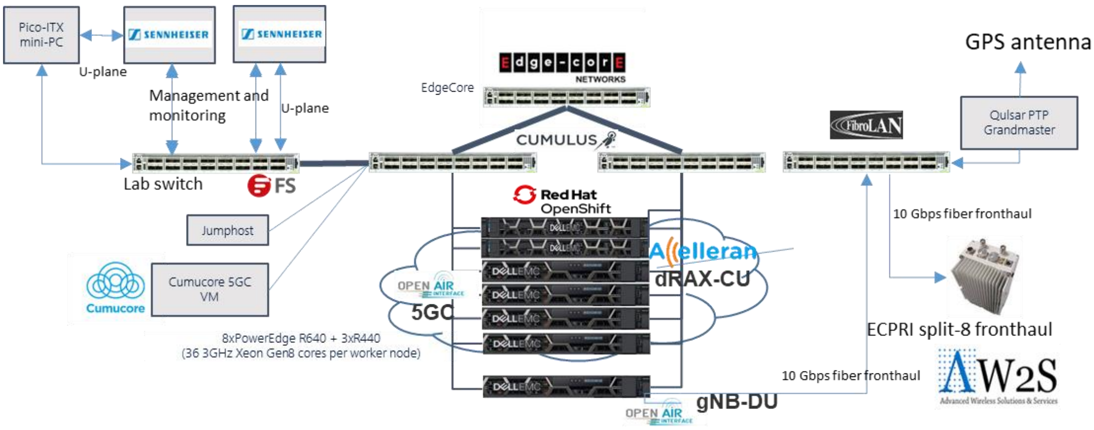


Figure 30, Network Configuration for 5G-RECORDS UC1 on EURECOM infrastructure

The radio unit used in UC1 are AW2S Jaguar 3.4-3.6 GHz (2x2 43 dBm, TDD band n78) connected to a Fibrolan Falcon-RX PTP switch to which the gNodeB-DU machines are also connected. The switch is synchronized by a Qulsar PTP grandmaster with an outdoor GPS antenna.

Accelleran dRAX-CU is deployed on EURECOM's OpenShift cluster along with the OAI 5G Core which is used interchangeably with the Cumucore 5G Core deployed on EURECOM's VM fabric. Currently the OAI gNodeB-DU is deployed alternately on two bare-metal nodes with Redhat Enterprise Linux 7 and 8 real-time configuration. Both RT nodes are connected via 10Gbps fiber to the Fibrolan fronthaul switch. Experiments are done both with 20 and 50 MHz cell channel bandwidths. The fronthaul link is ECPRI split-8 (time domain I/Q samples) and UDP transport. The Sennheiser Edge device (Local Audio Processor) is connected to the central switching fabric via a lab-switch with 2x10G connection to the main cluster fabric. The switch provides interconnections for both user-plane and management and monitoring. The latter is accessible by Sennheiser's application running on a public cloud. Similarly, the user-terminal device is also connected to the lab switch and directly connected via 1Gbps copper Ethernet to a mini-PC with Quectel and SIMCOM 5G IoT modules.

3 Multiple camera wireless studio

3.1.1 5G Modem and 5G network

One of the key integrations for an end-to-end communication is naturally the 5G connectivity between the user equipment and the network. As part of the integrated production scenario, two 5G modems from Fivecomm were sent to Aachen in October 2021. Integration of these two modems took place prior to the end-to-end tests. This integration was successfully completed and tested with ping and iPerf tools. The results of such work are provided in later section

The 5CMM modem was manually configured with the 5G private network in the lab setup in Aachen. The modem uses OpenWRT to attach to different slices in the network. Each slice uses a separate SIM card.

3.1.2 MG and MOCG

BISECT and BBC performed several integration tests during the 1st semester of 2022. These tests were performed over a VPN based on Wireguard, connecting the Camera Interface Unit running at BBC, and the MOCG and the MG running at BISECT. These integration tests eventually led to the successful integration between the different components, allowing the camera to register itself with the MOCG, and the MOCG to create the correct infrastructure to connect and process the stream coming out of the CIU into the MG and to the final destination.

Finally, in June, at the EBU Network Technology Seminar, BBC and BISECT demonstrated the integration of the MOCG with the MG, showing the discovery and processing of 3 simultaneous streams originated by 3 different CIU.

3.1.3 5CMM modem and Jetson Xavier

Fivecomm, in collaboration with Ericsson, worked on a portable solution to provide 5G connectivity to professional video cameras in Use Case 2. This is a development and integration work that has been done in parallel to the regular 5G modems described in Section 3.1.1 and other previous deliverables.

The portable solution is formed by a 5G modem developed by Fivecomm (the 5G module is included, without Raspberry Pi and Ethernet interface), which is connected via USB to an NVIDIA Jetson Xavier, provided by EBU, and an SDI card that is in turn connected to the Jetson and used to capture the video from the camera. In other words, the SDI card takes the video, the Jetson Xavier encodes the signal and the 5G modem sends it through the network. The following picture shows how these three components are interconnected with each other.

Note that the 5G modem is additionally connected to an external button, which is used to power on and off all components (the Jetson and SDI card take the power from the modem).

Figure 31. Interconnection of all components in the portable solution, without case

In order to make the solution portable and to be plugged into the professional camera, a 3D case was designed and printed. The case comes not only with an external button to power up the solution as explained, but also with external SMA connectors for mid-band 5G antennas, 3 LEDS for monitoring the status of the 5G modem, and 2 V-locks that are used to plug an external battery and the entire solution to the camera.

The following picture shows the 3D initial design from two different perspectives:

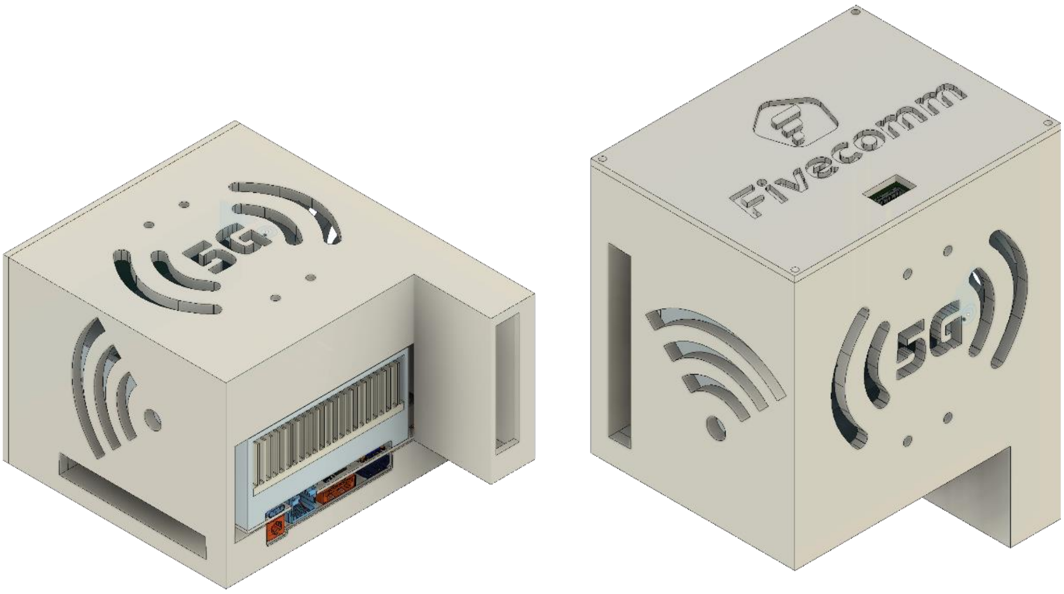


Figure 32. 3D initial design of the case for the portable solution.

Note that the design has been slightly modified and adapted to the needs of the use case. The portable solution, after printing the 3D case and integrating all components on it, looks as shown in the following picture.

Figure 33. Final prototype of the portable solution after assembling all components.

As shown in the picture, the current version of the case comes with all listed components, external antennas, external battery (to be easily replaced) connected through a V-lock, etc. This battery is used not only to power up the modem and the Jetson Xavier, but also the video camera where it is attached. In fact, there is a second v-lock in the back part of the solution that is used to be placed at the back part of the professional video cameras. Two cases were produced for this use case. The following picture shows how the two of them look when assembled and connected to the cameras.

Figure 34. Two portable solutions assembled and attached to the professional video cameras used in UC2.

3.1.4 MCR and MG

BISECT and EBU performed preliminary integration tests between the MG and GV AMPP. The streams originated from the MG were received by the MCR, albeit with some issues reported in their logs. BISECT and EBU are waiting for feedback from GV.

Further tests will be performed during the trials in Copenhagen, Denmark.

3.1.5 LiveU800 and the 5G network

The LU800 has successfully attached to the 5G network via different modems. At the first stage the device was attached via a 5G modem used in the 5G lab using ethernet connection. The device was also attached via the 5CMM modem using ethernet. At the final stage, the device was attached to the 5G network directly using the internal modem. The LU800 has a UI to configure the network settings such as the APN and the network id.

3.1.6 LU2000 and SMPTE 2110 network

With respect to the architecture described in D4.1 [2], there are a few updates. New equipment was added to execute the intercom tests and video quality tests. Figure 35 shows the new architecture of the SMPTE 2110 network deployed in the RAI's labs in Turin.

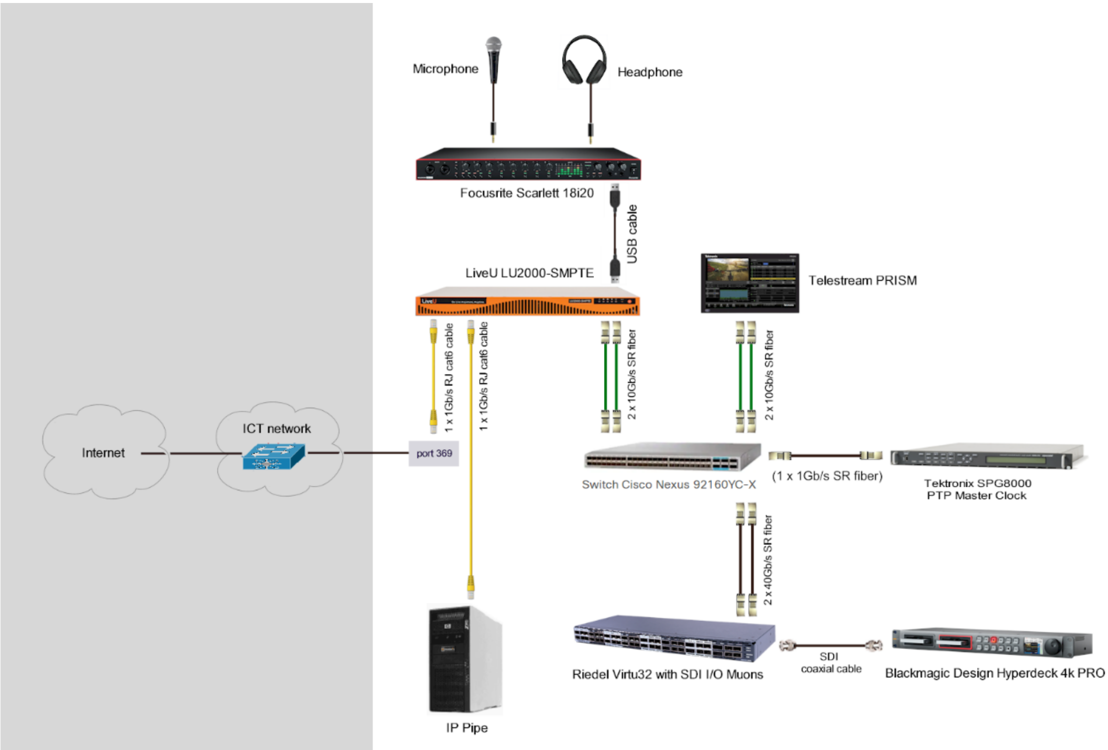


Figure 35. RAI testlab setup

To test the intercom functionality, a Focusrite Scarlett 18i20 audio interface was added and connected via USB to the LU2000-SMPTE server. A microphone and a headset were connected respectively to the analogue input and the output of the interface.

To perform video quality tests; an SDI recorder and an ST2110/SDI converter were added to the RAI's testbed and integrated into the architecture. We used a Blackmagic Studio 4K Pro as an SDI recorder and a Riedel MuonB10 as gateway ST2110/SDI.

The Riedel MuonB10 was connected directly to the Cisco switch. The switch receives the ST2110 output streams from the LU2000-SMPTE server and forwards them to all receiving devices, including the Riedel Muon. As soon as the IP stream is received by MuonB, it is converted to an SDI signal and sent to the SDI recorder, allowing extensive offline video quality analysis.

3.1.7 CY remote control and LU800

A Cyanview device that commands a Sony camera was connected in Aachen and later in TV2 Copenhagen to the LU800Pro over the RJ45 Ethernet port. The CY controller was in Rai lab in Turin and connected to the LU2000SMPTE over its RJ45 Ethernet. Both CY device were configured with IP addresses for the same subnet, so that although far away from one another and traffic passing over several IP networks, they can recognize and work with each other transparently. The commands and responses used the LiveU IP-PIPE between the LU2000SMPTE and the LU800Pro. The LU800Pro was connected to the Aachen 5G lab and later in TV2 - to a commercial TDC 5G network and used its embedded Sierra Wireless 5G modems and antennas.

The integration tests started in Rai Turin lab by configuring and setting the LiveU IP PIPE with laptops on both sides, configured to the right IP addresses, and testing that the communications worked over the local cellular network. Then the CY devices were added and configured, and traffic tested. Then the camera-side CY devices was shipped to Aachen and later carried to TV2 to finish the tests that COVID-restricted time in Aachen did not allow. The tests were completed with commanding the camera via the CY devices and the LU800Pro and 5G TDC commercial network and LU2000SMPTE in Rai. Latency from sending the command until seeing the effect back in Turin (which included the commands “translation” by CY devices and the camera reacting to them), was reasonable for this shading function, at ~100msec, any commands were missed/dropped. Shading/Iris by the camera was executed per the commands sent from Turin.

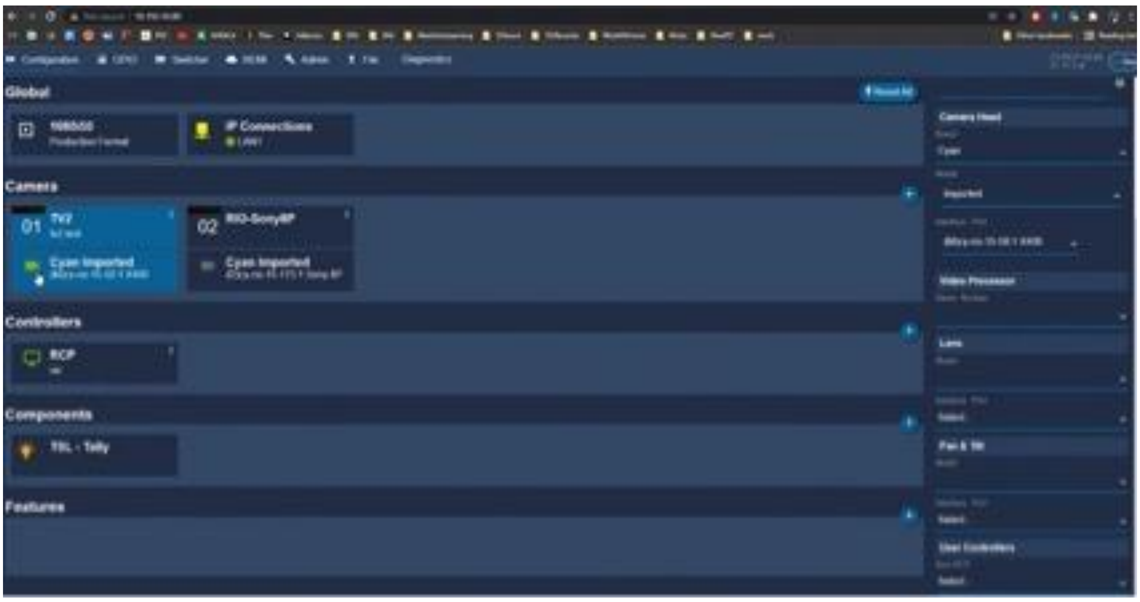


Figure 36. CY control when connected to remote camera via LU

3.1.8 End-to-end integration

To verify the Use Case 2 components in phase 3 lab session, we prepared two setup architectures shown in both Figure 37 and Figure 38.

Single device architecture:

It consists of a Jetson Xavier acting as an HEVC encoder connected to an SDI video source (Black magic media player) and the 5CMM modem via ethernet connection. The Media Gateway is attached to the 5G N6 interface as a MEC. The MG uses the PTP master clock used to synchronize the 5G core components to synchronize the clock. The synchronization is used for packet pacing in the ST-2210 network. The MG forwards the ST-2110 traffic to the PRISM to conform the ST-2110 traffic and to an SDI monitor via ST-2110 to the SDI converter to measure G2G latency.

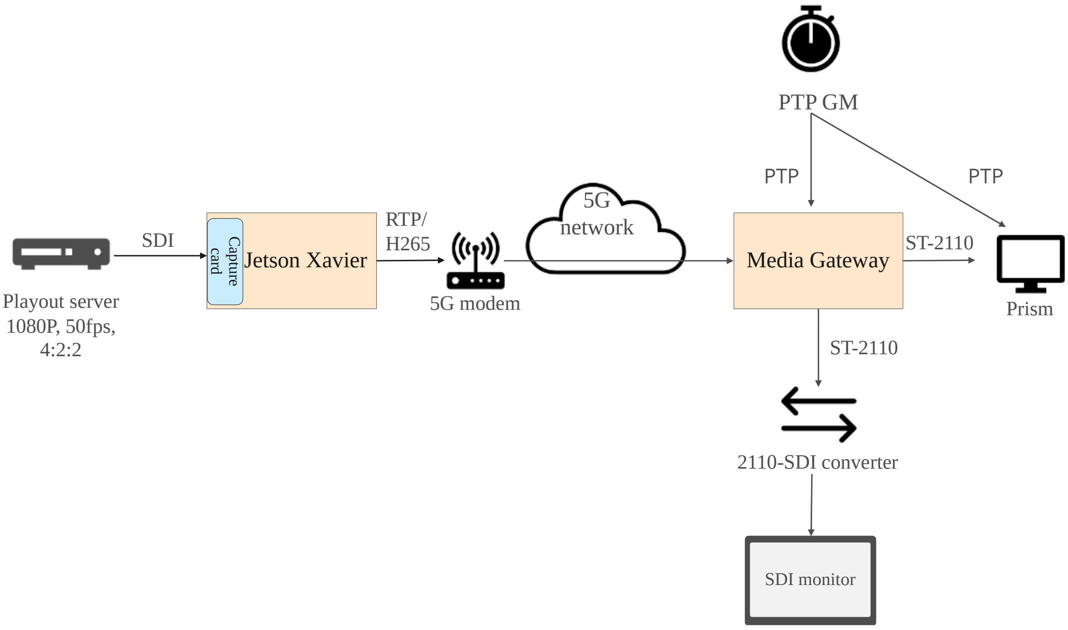


Figure 37. Single device architecture

Two devices architecture:

On the radio side, it adds to the single device architecture another Jetson nano encoder which connects to the network via the 5CMM modem. On the MEC side, the ST-2110 network is equipped with a video mixer, which receives the MG output, mixes it, and sends it to the MG. The MG converts the ST-2110 signal to HEVC and transmits it over the downlink to the UEs (i.e., Jetson nano and Xavier).

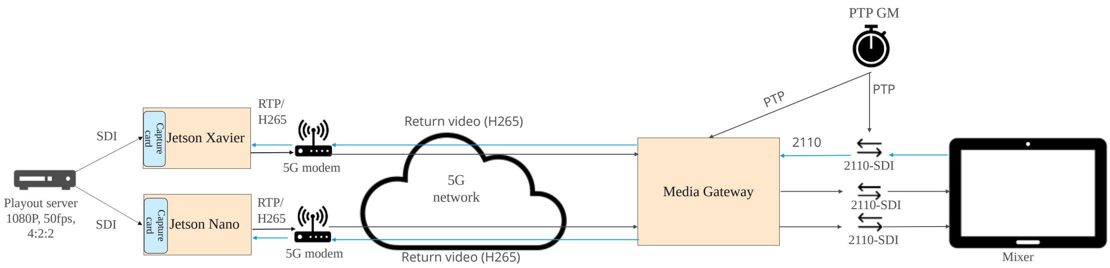


Figure 38. Two devices architecture

3.2 Measurement and monitoring tools

This subsection describes the tools used in the integration and testing of Use Case 2, as well as the KPIs employed to measure and monitor the performance of its components prior to their use in trials.

3.2.1 KPIs update

This section provides an update on the KPIs provided for phase-1 in D4.1 [2]. The use case consists of two main scenarios, where each scenario has different requirements and hence different KPIs. Scenario 1 describes the integration of wireless cameras within production, while scenario 2 describes outside remote contribution. The following subsections describe the selected KPIs per scenario.

Integrated production scenario

1. ***Uplink throughput:***

The system should support at least five cameras. To fulfil the video quality requirements, the main video stream must be at least 50 Mbps. Note that typically a studio setup will consist of multiple signals. This KPI refers to the video itself. Other signals may need lower values that will be added to the total Uplink (UL)/Downlink (DL) throughput that needs to be supported by the network. These signals are:

- Return video: 5-10 Mbps (DL).
- Teleprompter: 5-10 Mbps (DL).
- Tally: very low throughput (DL)
- Telemetric: low throughput (bi-directional).
- Intercom: medium (bi-directional)

2. ***E2E (glass-to-glass) latency:***

The system should support low latency profiles with an end-to-end latency in the region of 20-300 ms with ideal value below 40ms. The latency values apply to the programme video signal, but other signals may need similar values as well.

3. ***Packet error ratio:***

The system shall support a packet error rate of 10^{-8}. Packets that do not conform with the end-to-end latency are also considered an error. The packet error rate requirement is calculated considering 1500 Bytes packets, and 1 packet error per hour is $10^{-5}/(3*x)$, where x is the data rate in Mbps and then rounded.

4. ***Timing accuracy:***

The absolute difference between any synchronised clock in the network and the time master must be below 1 ms.

Remote production scenario

The remote production scenario with the LiveU equipment transmitting from Ericsson Aachen laboratory into RAI Turin laboratory is measuring slightly different KPIs due to the multiple public internet hops and different scenario attributes.

1. ***Uplink throughput:***

This will be measured using standard networking tools. The throughput for each camera should be greater than 15 Mbps. The contribution camera uses high compression schemes.

2. ***E2E (glass to glass) latency:***

The latency between the sensor capturing an image and the availability of the image in the production gallery should be less than 1000 ms. Due to the nature of the user story, the latency requirements are more relaxed than scenario 1.

3. ***SMPTE compliance:***

The video stream output at the production gallery should be SMPTE compliant and with dual video redundancy supported. SMPTE compliance will be measured using the video signal received by the LiveU video server and outputted by it into the RAI PRISM SMPTE testing equipment.

4. ***Video quality:***

The video received at the production gallery shall pass video quality tests. The exact benchmark video clips to be transmitted are TBD by the project broadcasters.

The partners will evaluate the transmission performance over the 5G and public internet hops using LiveU application-level parameters. This implies not only UL bandwidth, but also UL latency and UL loss rate with snapshots at time intervals. Additional functionality tests such as of Networked Media Open Specifications (NMOS) over the LiveU IP-Pipe (depending on availability of the NMOS nodes), remote intercom (from RAI laboratory back into the Aachen laboratory), etc. will also take place.

3.2.2 Tools update

The following professional content production tools are planned to be used in the context of Use Case 2.

1. ***Live IP Software Toolkit (EBU LIST)***

A suite of software tools that help to inspect, measure, and visualize the state of IP-based networks and the high-bitrate media traffic they carry. It is an open-source tool, currently tailored for SMPTE 2110 related measurements. Its application in this use case will be the measurement and compliance verification of the ST 2110 streams regenerated by the media gateway. This tool will be used in both considered scenarios, i.e., the integrated production and remote production scenarios.

Related KPIs: *UL throughput, packet error ratio.*

The following tools will be used for each of the considered scenarios only.

Integrated production scenario

1. *Glass-to-glass latency updated method*

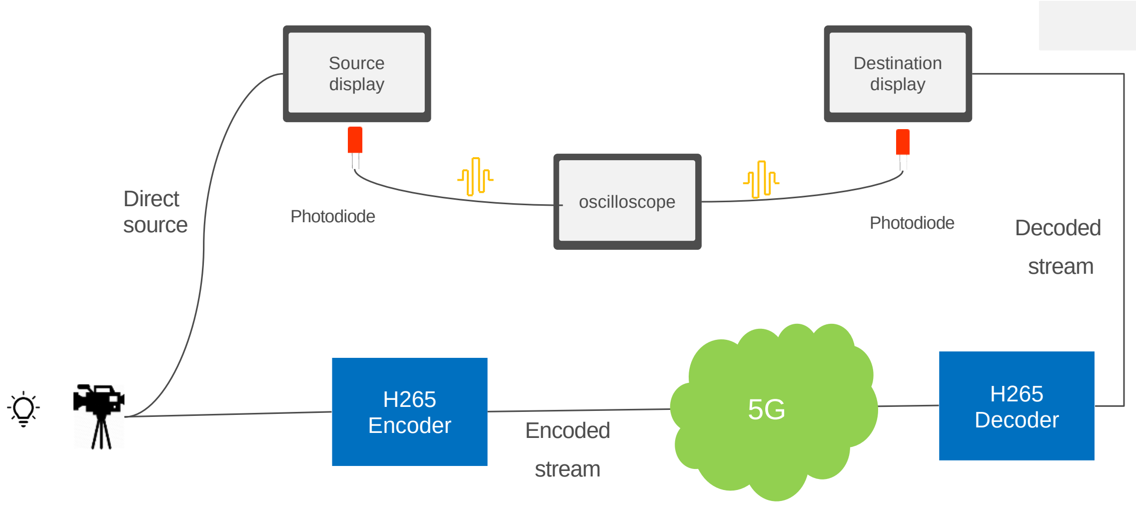


Figure 39. Architecture for measuring the G2G latency using the oscilloscope

The Glass-to-Glass latency measurement setup was created and installed by TV2 during phase 2 in Ericsson 5G test network in Aachen. The setup architecture is depicted in *Figure 39*. The setup consists of a media player with a dark video sequence, and a single white frame periodically inserted in the dark sequence. The media player is connected to the HEVC encoder and to an SDI display. The encoder decodes the stream and send it over 5G to the decoder. The decoder is connected to another SDI display. Both displays are mounted side-by-side. Each display has a photodiode glowed on top of the display. The photodiodes are connected to an oscilloscope. Once a white frame is rendered on the displays, an electric pulse is generated by the photodiode and sent to the oscilloscope. The oscilloscope displays the signals coming from both the direct source and the decoded stream. The oscilloscope operator freezes the oscilloscope capture and measure the delta between the peak of the electric signals. shows images of the setup and its evolution during the project timeline.

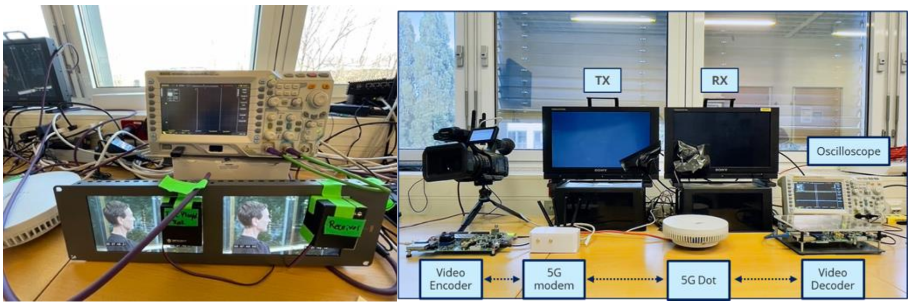


Figure 40. Left: updated setup during phase 3. Right: initial setup during phase 2

Related KPI: *E2E (glass-to-glass) latency*

2. *SCReAM Bandwidth measurement tool:*

SCReAM (Self-Clocked Rate Adaptation for Multimedia) is a congestion control algorithm devised mainly for video. Unlike many other congestion control algorithms that are rate-based, i.e., they estimate the network throughput and adjust the media bitrate accordingly, SCReAM is self-clocked which means that the algorithm does not send more data into a network than what exits the network.

To achieve this, SCReAM implements a feedback protocol over Real-Time Control Protocol (RTCP) that acknowledges received RTP packets. The feedback determines the congestion window, which determines how many RTP packets can be in flight, i.e., transmitted but not yet acknowledged. An RTP queue is maintained at the sender side to store the pending RTP packets. The RTP queue is usually empty but can temporarily become long when the link throughput decreases. The congestion window is frequently adjusted for minimal E2E delay while maintaining as high link utilisation as possible.

The network congestion control of SCReAM is similar to how the congestion control mechanism in Transmission Control Protocol (TCP) behaves; the main difference is that SCReAM does not retransmit lost packets. Similar to TCP, network congestion control is self-clocked. Therefore, packets are transmitted if feedback is received. This technique prevents the transmission link from becoming overloaded with data, which is good when the throughput decreases rapidly.

The SCReAM library provides a bandwidth test tool. it uses the same techniques used for congestion control during operation. It also allows the exposure of the actual estimation of the network bandwidth.

Related KPI: *available system UL throughput*

<u>Remote production scenario</u>

1. *SMPTE test equipment – Tektronix Prism:*

In the RAI Turin laboratory, the video output of the LiveU LU2000SMPTE server shall be connected to the Tektronix Prism test equipment to check for compliance. The Prism SMPTE tests screen for this component is shown in *Figure 41*.

Networking environment:

To support the tests under the RAI studio IT security policies, the LiveU LU2000SMPTE was connected and configured to work with three different sub-networks and addresses: (a) the sub-network connected to the public IP (via IT firewalls etc), through which the A/V packets from the remote LU800Pro were received and communication with it and with the cloud LU-Central management was done (b) subnet for the RAI studio PTP master clock (c) the RAI SMPTE sub-network to which the LU2000SMPTE video was outputted into the SMPTE test equipment. In addition, the LiveU intercom/audio server and the Cyanview IP control device were also connected and configured to work via the 3rd subnet above via the LU2000SMPTE.

Related KPIs: *SMPTE compliance*

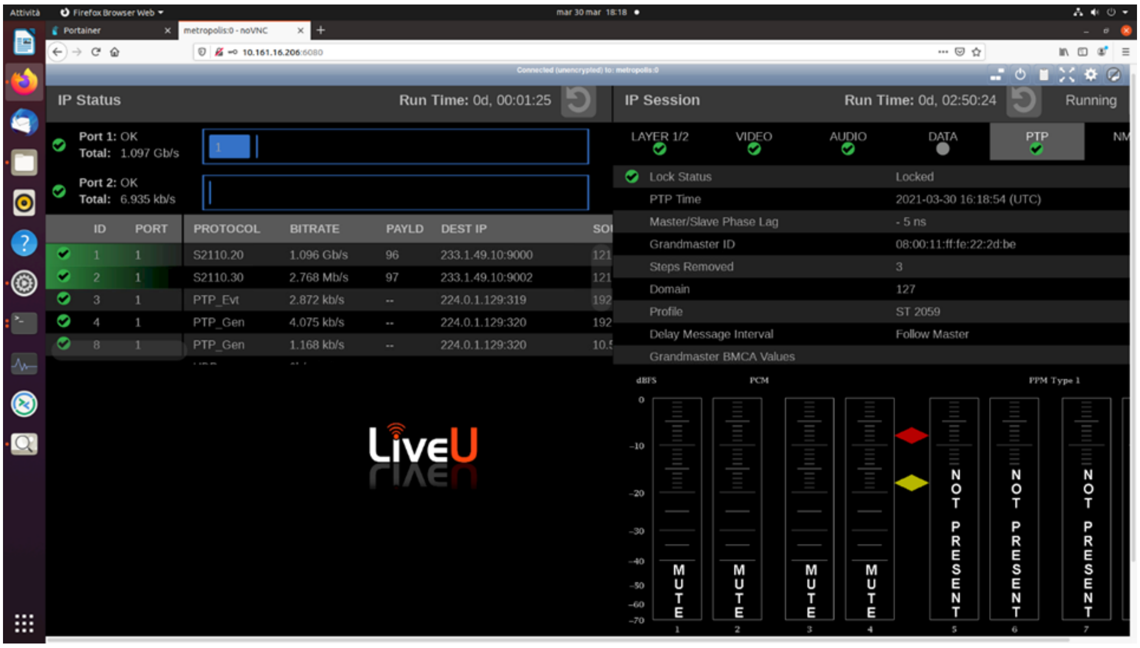


Figure 41. Prism SMPTE tests screen

2. LiveU LU800 and LU2000 SMPTE equipment:

As in the first phase, the LU800Pro embedded Sierra Wireless modem was not able to register with the Ericsson Aachen 5G SA lab network, it was shipped to Sierra Wireless labs in Paris to test it against a certified 5G SA lab with similar yet isolated configuration (single MCC/NMC). Tests were done, SW update was made, and it was able to connect in the Sierra Wireless lab. Then, at the Ericsson Aachen lab, after the network upgrade done there towards phase 3, the embedded Sierra Wireless 5G modem was able to register and get service, so tests using that embedded modem were done.

For measuring the application-level uplink bandwidth, latency, and packet loss rate, the LiveU LU800-LU2000SMPTE is used, exchanging information that enables it to calculate these parameters that are then logged in the application. The logging of these parameters is done per connected link (i.e., for each modem), at snapshots at 5 seconds intervals.

In cycles 2 & 3, instead of camera, LiveU provided A/V Blackmagic mini studio video player and Blackmagic SDI splitter 1:4, as well as A/V clips from RAI and LiveU (1080p). This setup was used for several reasons: (a) to allow repeatable, comparable testing of any test case by using the same video clip thus nullifying potential variations due to the dynamics of the video input that impacts the video encoding and bandwidth output; (b) to practically allow testing at any time rather than being dependent on expensive camera rentals and availability (c) some synchronization testing since the same feed is split into 4 identical and synchronized streams (more or less) that then feed the LU800Pro multi-cam for simultaneous encoding and transmission of the 4 streams. See *Figure 42*.

In addition, in order to congest the UL of the Aachen 5G lab network, a setup emulating user traffic was set up by Ericsson. It used Raspberry Pie and a Jetson NVIDIA device to send packets using the 5G cabled-in modem into the network at desired bandwidths.

Related KPIs: *application-level uplink bandwidth, latency, and packet loss rate*

Figure 42. LiveU LU800Pro 5G multi-cam fed by Blackmagic A/V player

3. ***Remote production test equipment:***

For the remote production capabilities, sets of devices were used as follows:

a. For the audio/intercom related tests, a LiveU IP audio server was connected to the LU2000SMPTE server at the RAI studio, and a headset connected to the LU800Pro on the test site.

b. For the remote control of camera over the LiveU IP PIPE, devices from Cyanview were connected to the LU2000SMPTE over the intranet and to the LU800Pro via its RJ45 Ethernet interface. These devices translate the remote operator (director/producer) commands to the commands relevant to the specific camera used on-site. The two Cyanview devices were configured with proper IP addresses so that although far away from one another and traffic passing over several IP networks, they can recognize and work with each other transparently.

4. ***Video quality test equipment:***

For testing the video quality under the various conditions in phase 3 (Mar 22), the video output from the LU2000SDI is recorded and then analysed offline against the known video clips fed into the LU800Pro encoder-transmitter.

Related KPIs: *Functional, latency (response time), video quality*

3.3 Tests

This subsection describes the tests performed to guarantee the proper integration of the components and the fulfilment of the expected KPIs.

3.3.1 Testing of individual components

Media gateway:

Tests that were performed in April 2022, prior to the tests in Aachen. All of them yielded successful results:

HEVC input

The ability to decode HEVC/RTP streams was tested using two sources: an encoder running on BISECT's own Jetson AGX Xavier; a Jetson Nano encoder from BBC, with a stream sent over the VPN.

ST 2110 input

The ability to receive an ST 2110 stream was tested using both a Matrox VERO signal generator and a generator based on NVIDIA Rivermax and a Connect-X 6 Dx card.

HEVC output

The HEVC output was tested using the same Jetson AGX Xavier that was used for the input test.

ST 2110 output

The ST 2110 output was tested using a Matrox VERO and a receiver based on NVIDIA Rivermax and a Connect-X 6 Dx card. The compliance with the standard was verified by capturing PCAP files and analysing them using EBU LIST.

NMOS IS-04

The basic NMOS IS-04 functionality was tested using a Sony nmos-cpp registry. The compliance was verified using the NMOS-TESTING, the official AMWA NMOS Testing Tool.

NMOS IS-05

The NMOS IS-05 functionality was tested using a Riedel NMOS Explorer and Sony nmos-js.

Resilience

The MG was successfully tested in all modes for long durations (> 24h) in order to test it for long-term resilience.

Media and orchestration control gateway

Tests between the BBC's "camera simulator" and the MOCG are still underway. We are able to get a camera to register with the MOCG and the MOCG allocates the necessary resources in the MG.

5G modem

This section explains how the default configuration of the Fivecomm 5G modem was tested in their office.

First, the antennas/RF cables were connected. In this case, for 5G SA configuration and n78/77 high bands (four SMA connectors). See Figure 43.

Secondly, we took off the lid and placed the SIM card in the reader, with MicroSim format. See Figure 43.

Figure 43. 5CMM modem

The 5G modem can be then powered on, by connecting the charger to the power connector. The LEDs turned on after approximately 30 seconds.

“Status” LED indicates that the 5G BROAD is powered and should be steady on.

“Connection” LED indicates the registration status, if it’s ON then the modem got registered into the network.

“Tx/Rx” LED should slowly blink as the 5G BROAD is searching for network in the beginning, after it gets registered it blinks at a lower rate, which means it’s idle.

Figure 44. 5CMM modem LEDs

Once the modem was ready, we accessed it using Web Management Interface (WMI). It was configured by connecting an Ethernet cable to a laptop. Once DHCP connection was activated, this configuration was possible. Access to WMI is possible from any browser, by introducing username and password. By default, the wwan0 interface is created and configured with an SA APN, as shown in the following figure. Also, NAT is enabled via the wwan0 interface. The wwan0 interface is assigned to the WAN zone within the firewall.

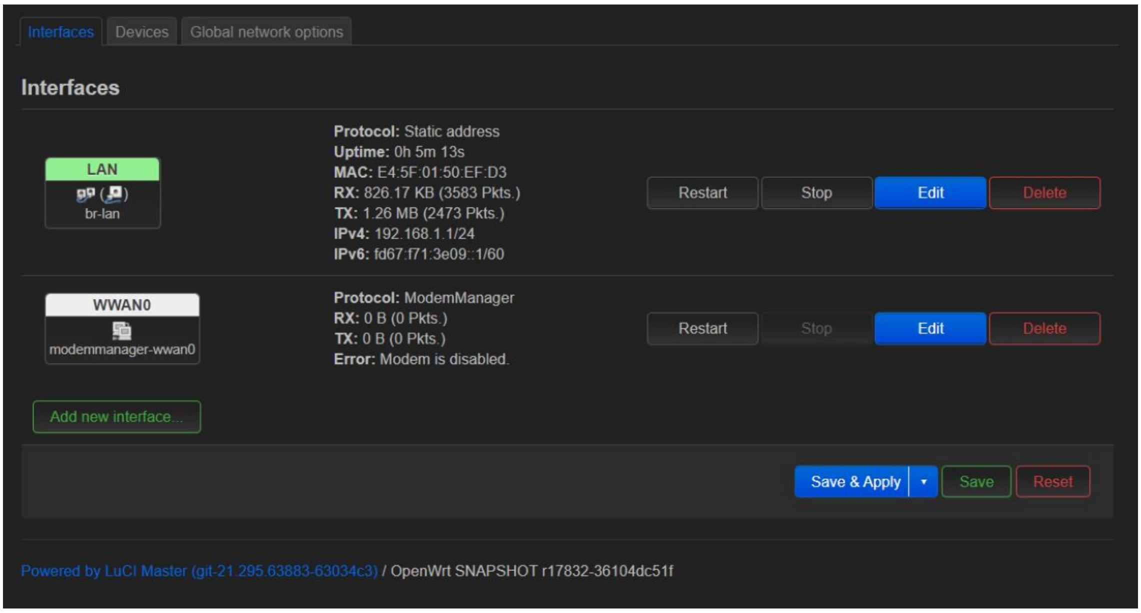


Figure 45. Modem configuration interface

MCR

Testing of the virtual MCR was performed over several test sessions with a number of endpoints: the Media Gateway located in Portugal at Bisect and 3rd-party SRT encoders and decoders located in Italy at RAI. MCR deployed in AWS public cloud was receiving SRT streams, it was able to switch between those and the test signal generated by MCR, and it was sending a PGM output also as an SRT stream back to the corresponding SRT endpoint.

Some other functionality was also checked, we confirmed that apart from being able to successfully receive and send video streams and being able to switch between those, we were also able to setup different routing scenarios, for example connecting a specific input to specific output directly bypassing the vision switcher. We confirmed that it can do video format conversion, changing the frame rate, resolution, etc.

As MCR is available both in the cloud and as a local instance, the latter also supports ST 2110 and SDI inputs and outputs. A comprehensive testing of the on-premise version of the MCR will be conducted at trials in Copenhagen.

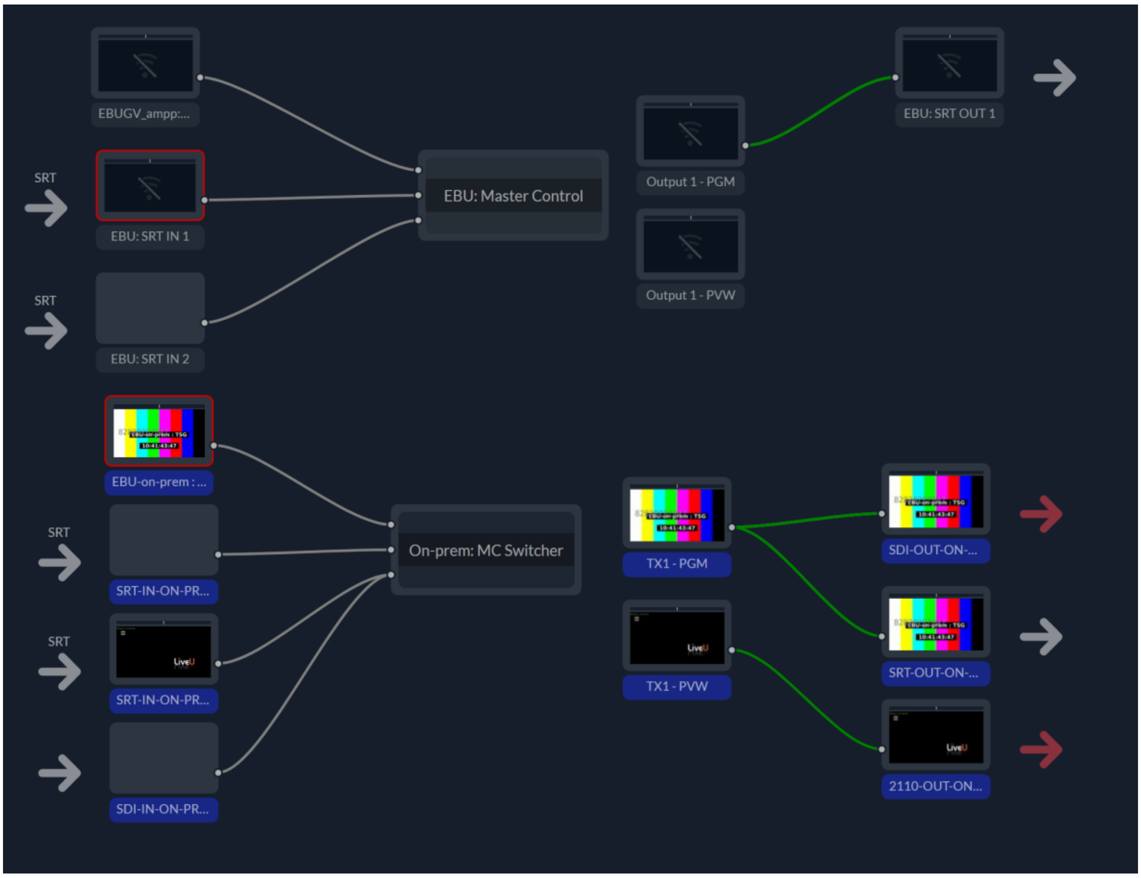


Figure 46. MCR System Dashboard (routing configuration)

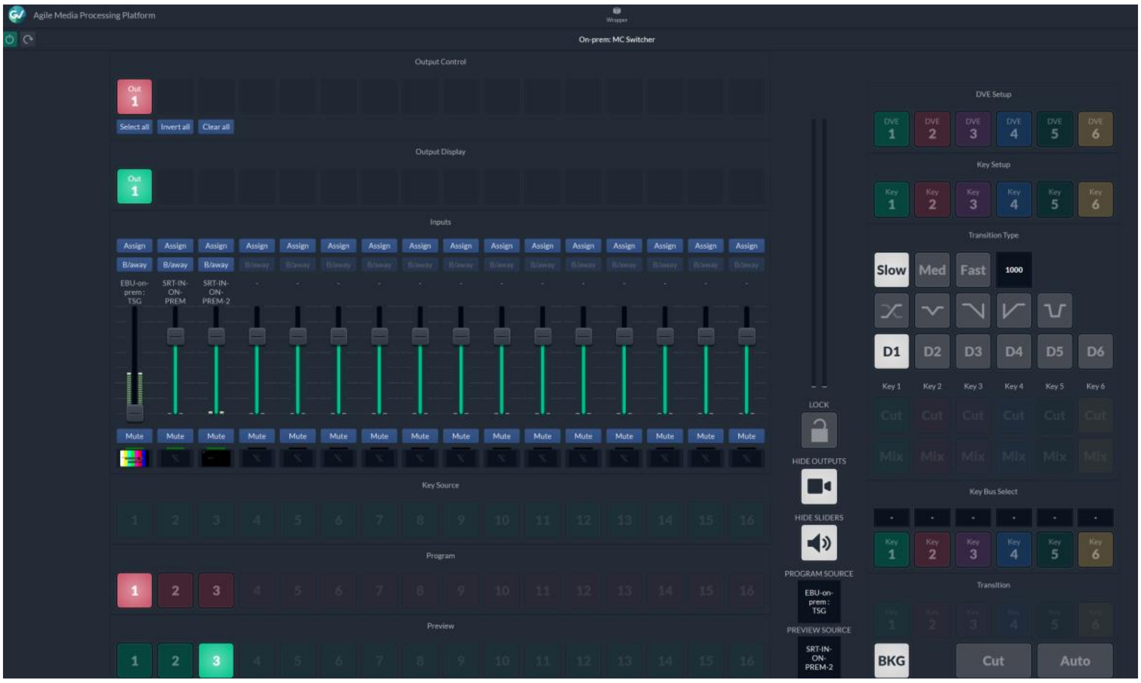


Figure 47. MCR – Switcher user interface

LU800 Pro

The LU800Pro with the 5G modems was validated in several stages for all relevant functionality: 5G-SA performance and functional over the 5G-SA (remote audio, IP PIPE for remote control, video quality end-to-end).

The LU800Pro was configured to connect with the Aachen 5G networks: first a NSA network and in later cycles – the SA and updated version of the network including with slices. Such configurations included setting the right private MNC+MNC and APN.

It was connected to the Ericsson lab network using embedded modems as well as external ones, all being “cabled” into the network due to lab policies of limiting the indoors over the air transmissions.

At the fist cycle, TV2 camera was feeding the LU800Pro. To discard of tis dependency, LiveU then shipped A/V equipment (Blackmagic video player and Blackmagic 1:8 video splitter) so that further tests could be done at will and in consistency with each other. Testing video clips were provided by RAI and LiveU. For additional functional tests, external equipment was connected such as the headset (using the audio jack) for audio testing and Cyanview camera control box (over the RJ45).

In the first cycles in Aachen, while all planned tests succeeded with the external modem/industrial router that Ericsson provided, still tests with the embedded Sierra Wireless failed as the modems were not allowed to register with the Aachen 5G SA lab network. A common effort for debugging this (LiveU, Ericsson, Sierra Wireless) revealed that there were two networks with the same MNC+MCC operating and received, which is an unrealistic scenario and might have “confused” the Sierra modem. However this is probably not the cause. LiveU then went to test the unit in Sierra Wireless labs in Paris, where it was discovered that a bug in the way the modem was “dialled” by the SW might have been the cause. Once fixed, and the network in Aachen also being upgraded to a new version, the problem was resolved and in cycle 3 the LU800Pro was validated with the internal Sierra Wireless modems too (including in bonding). Further than committed, the LU800Pro and Fivecomm modem were “inter-validated” as in some cycle 3 tests the LU800Pro used the externally connected Fivecomm modem.

Performance tests were done according to detailed test case prepared by LiveU, covering various aspects such as the following and their combinations: SA 5G, NSA 5G, single modem, dual modem bonding, under 0% - 90% UL congestion (at various steps), TDD UL:DL patterns DDSU, no slice, e-MBB/best effort slice, “guaranteed performance” UL-oriented slice, no bonding, two modems bonding of two modems on no slice, bonding of two different slices, bonding with a commercial network, single A/V feed (max cap transmission of ~25mbps) and 4 simultaneous feeds transmitted (max at ~60mbps).

Figure 48. LU800Pro four A/V feeds from a video player

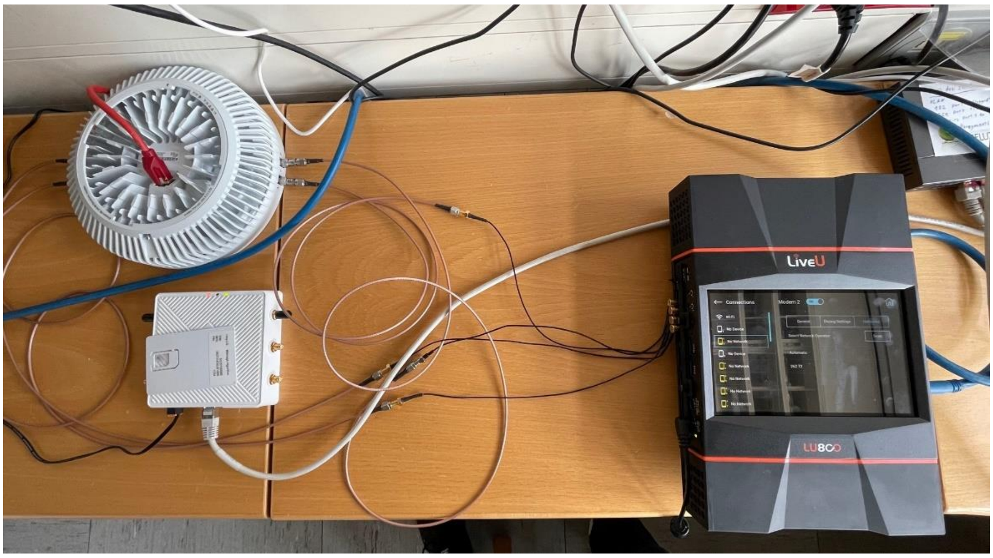


Figure 49 LU800Pro connected to Ericsson 5G lab network via external 5G modem

LU2000

The LU200SMPTE was validated in all cycles at Rai Turin lab for both SMPTE-2110 compliance, performance, additional functionality of remote control over this server and audio connectivity via the field, and in cycle 3 also for video quality.

The tests were conducted first separately from the LU800Pro in Aachen, using other LiveU remote transmitters. This allowed parallel progress in both sites with both components independently. Then in the 3 cycles, validation and full UC2 scenario 2 tests were also done from Aachen 5G lab to the Turin lab.

The tests used the same methodology of specific test cases by LiveU for the transmission and by Rai for the SMPTE compliance and video quality.

5G network validation

During the project, Ericsson has upgraded its 5G test network to support the features that can improve the media production process for both scenarios. Below is the testing of the traffic prioritization using network slicing.

Network slicing validation

To validate the operation of the network slicing, the following scenarios are measured using iPerf TCP connection:

Single client.

Two clients configured on the same network slice and transmitting stream at the same time.

One client is configured on the media slice (high priority), while the other client is using the e-MBB slice (low priority).

The command line for running the iPerf clients is as follows:

iPerf3 -c $serverIP -P 4 -t 600 -J | teel filelocation.json

The iPerf client uses 4 parallel TCP connections to reach the maximum bandwidth that the TCP congestion algorithm can estimate. Both clients are running iPerf3 on Linux using Cubic congestion algorithm. This setup ensure that no device has an edge over the other.

The iPerf servers are running at the edge connected to the N6 interface.

Single client:

This test demonstrates the available bandwidth for a single device using all the network resources. The test shows that a single device can reach an average of 97.45Mbps.

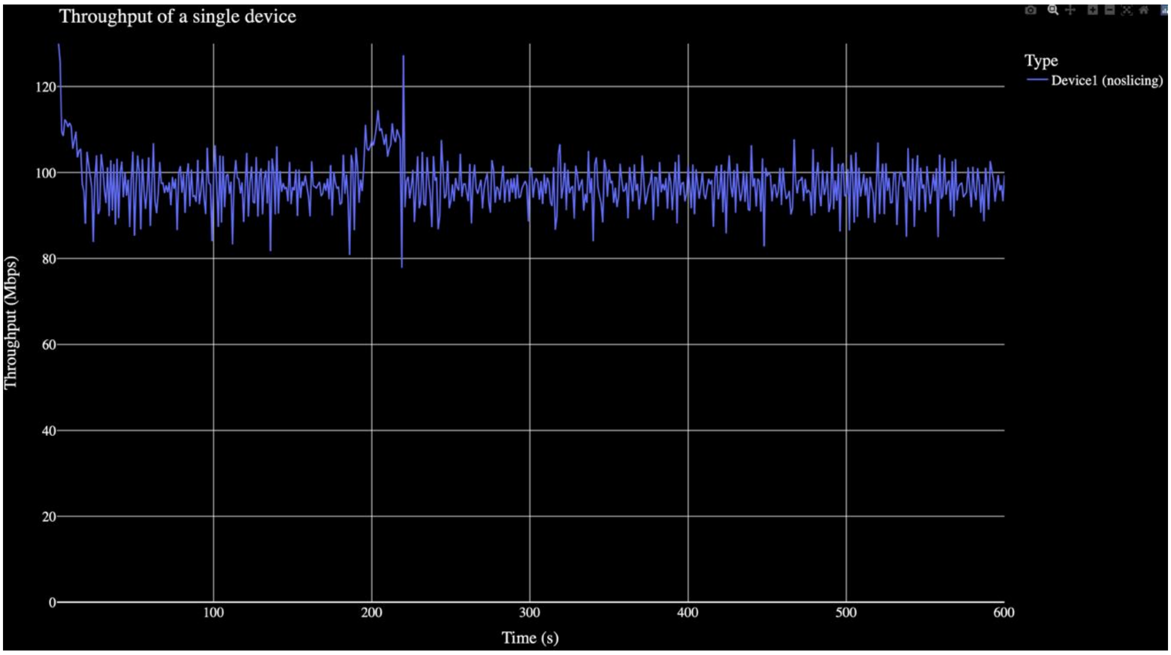


Figure 50. Single client throughput

1. Two clients configured on the same network slice:

This test demonstrates the devices performance without network slicing. Both devices have an equal priority for the network resources. The estimated average is 38Mbps, 53 Mbps for device 1 and device 2 respectively. Here, the network administrator has no possibility on preferring one device over the other and it is left for the device capability to compete over resources

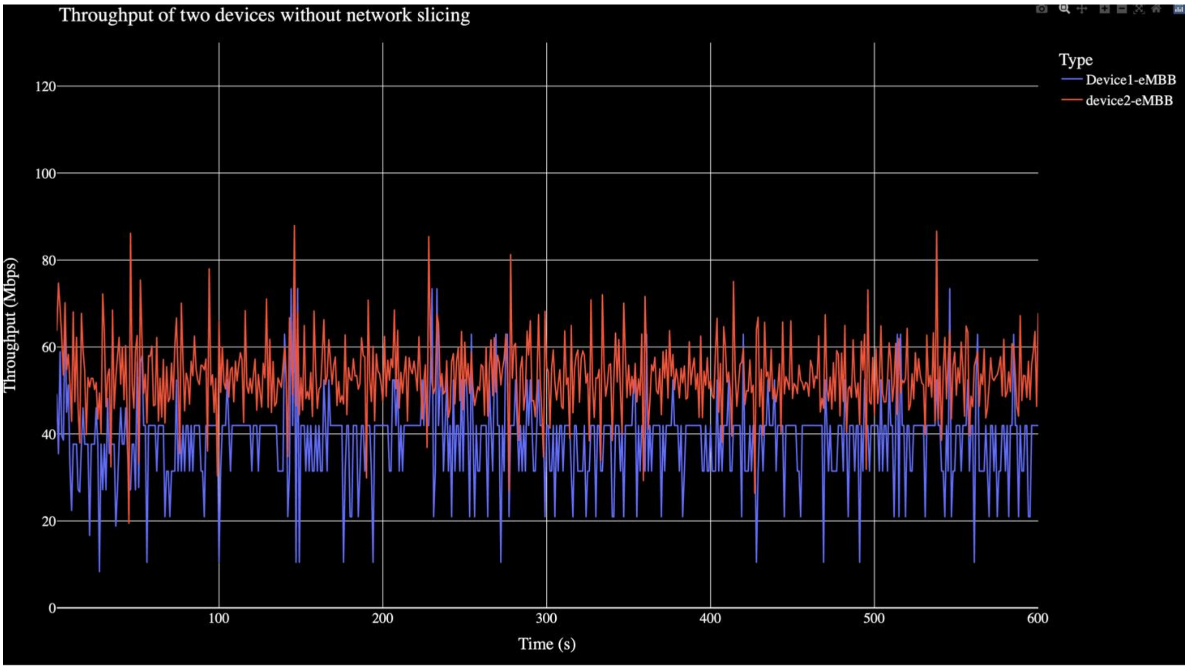


Figure 51. Two devices without network slicing

2. two clients with network slicing

This test is dedicated to demonstrating network slicing functionality. *Figure 52* shows two streams running at the same time, one with high priority slice and the other without, the low priority is turned off for a certain period, and the high priority consumes the whole bandwidth. The average throughput is 84.9 Mbps and 9.6 Mbps.

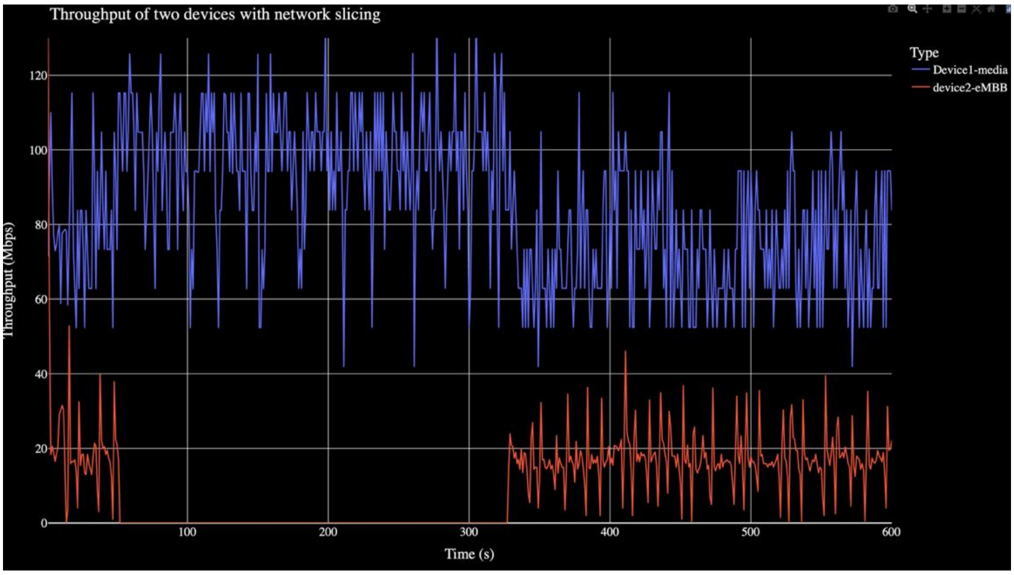


Figure 52. Network slicing with e-MBB slice device turned off for a period of time

Figure 53 shows two devices: device 1 connected to the media slice (high priority) with an average throughput of 70Mbps, while device 2 connected to the e-MBB slice with an average throughput of 15Mbps.

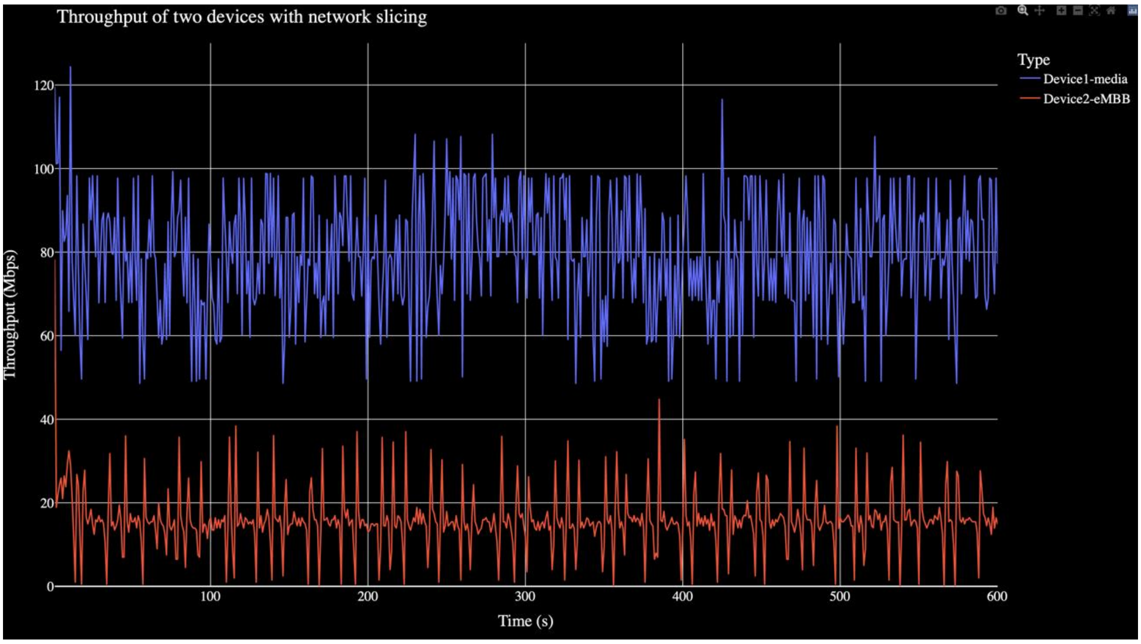


Figure 53. Two streams at different slices competing on resources

3.3.2 Interoperability tests

Integrated production scenario

May 2021

1. ***SCREAM throughput and packet loss analysis:***

Figure 54 and Figure 55 shows the throughput analysis and packet loss using the default configuration of SCREAM. The slow start can be seen at the beginning of the graph until the throughput achieves 100 Mbps, the bandwidth drops once packet losses are detected (the figure on the right).

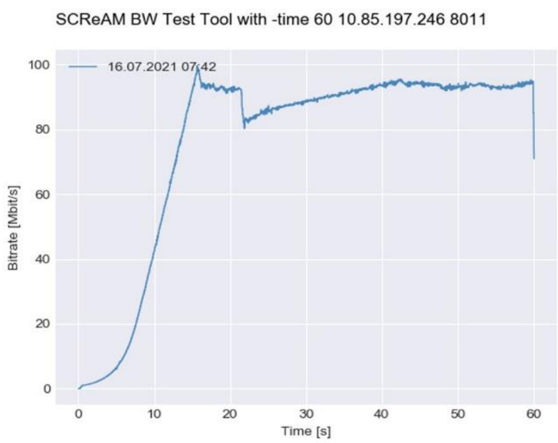


Figure 54. SCREAM bandwidth detection with default configuration

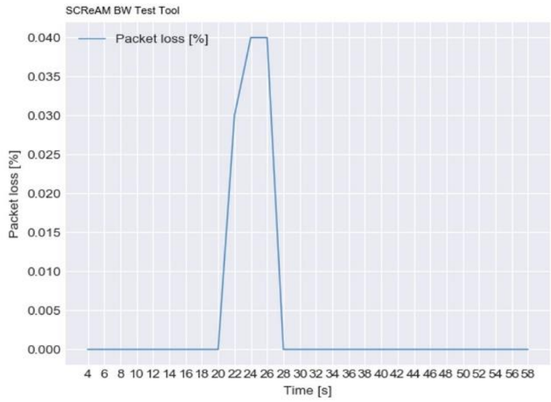


Figure 55. SCREAM bandwidth detection with default configuration

<u>October 2021</u>

Modem-network interoperability.

Once the modem was set up, it was integrated in the 5G network in Aachen. For that, we got into the PuTTY CLI to interact with the 5G modem as shown in Figure 56.

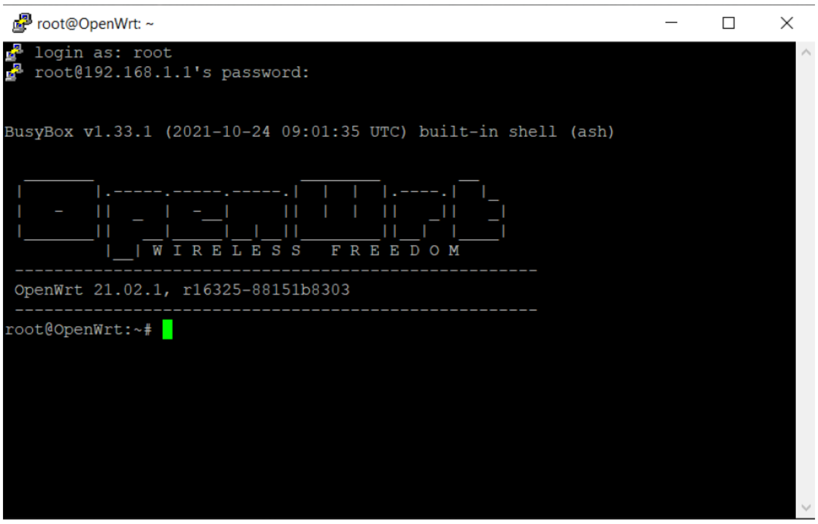


Figure 56. Modem interface

For 5G SA connection, we modified the connection profile with the right APN by using *qmicli* commands. Then, using WMI in parallel, the wwan0 interface needs to be configured. The parameters to configure are the APN, the SIM card PIN, the authentication type, and the IP type. Once the parameters were saved, the connection was up.

Once connectivity was set up, we performed the following measurements:

5G latency:

Goal: check if the modem latency meets requirements ~6-10 ms RTT

Requirement: the modem is attached to the network via the RF cable

How? Run the *ping* command from the modem to the edge of 5G network.

Result: ~10 ms (RTT) on average.

UL/DL throughput:

Goal: check if the modem uplink throughput meets the requirements.

Requirement: iPerf is installed on both RPi (client UE) and edge (Jeston nano)

How? Start iPerf server on the edge and start iPerf client (TCP) on the RPi (client UE).

Result: 82 Mbps (using 100 MHz BW).

```
- - - - - - - - - - - - - - - - - - - - - - - - -
[  6] 118.00-119.00 sec  2.61 MBytes  21.9 Mbits/sec    0    646 KBytes
[  8] 118.00-119.00 sec  4.10 MBytes  34.4 Mbits/sec    0    783 KBytes
[ 10] 118.00-119.00 sec  2.80 MBytes  23.5 Mbits/sec    0    434 KBytes
[ 12] 118.00-119.00 sec  1.37 MBytes  11.5 Mbits/sec    0    396 KBytes
[SUM] 118.00-119.00 sec  10.9 MBytes  91.2 Mbits/sec    0
- - - - - - - - - - - - - - - - - - - - - - - - -
[  6] 119.00-120.00 sec  2.61 MBytes  21.9 Mbits/sec    0    652 KBytes
[  8] 119.00-120.00 sec  3.36 MBytes  28.1 Mbits/sec    0    783 KBytes
[ 10] 119.00-120.00 sec   954 KBytes  7.82 Mbits/sec    0    444 KBytes
[ 12] 119.00-120.00 sec  2.05 MBytes  17.2 Mbits/sec    0    409 KBytes
[SUM] 119.00-120.00 sec  8.95 MBytes  75.1 Mbits/sec    0
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Retr
[  6]   0.00-120.00 sec   345 MBytes  24.1 Mbits/sec  150             sender
[  6]   0.00-120.23 sec   344 MBytes  24.0 Mbits/sec                  receiver
[  8]   0.00-120.00 sec   297 MBytes  20.8 Mbits/sec  122             sender
[  8]   0.00-120.23 sec   296 MBytes  20.7 Mbits/sec                  receiver
[ 10]   0.00-120.00 sec   294 MBytes  20.5 Mbits/sec  146             sender
[ 10]   0.00-120.23 sec   293 MBytes  20.4 Mbits/sec                  receiver
[ 12]   0.00-120.00 sec   244 MBytes  17.0 Mbits/sec  125             sender
[ 12]   0.00-120.23 sec   242 MBytes  16.9 Mbits/sec                  receiver
[SUM]   0.00-120.00 sec  1.15 GBytes  82.5 Mbits/sec  543             sender
[SUM]   0.00-120.23 sec  1.15 GBytes  82.0 Mbits/sec                  receiver

iperf Done.
```

```
Connecting to host 10.85.197.246, port 5201
[  6] local 192.168.1.50 port 40910 connected to 10.85.197.246 port 5201
[  8] local 192.168.1.50 port 40912 connected to 10.85.197.246 port 5201
[ 10] local 192.168.1.50 port 40914 connected to 10.85.197.246 port 5201
[ 12] local 192.168.1.50 port 40916 connected to 10.85.197.246 port 5201
[ ID] Interval           Transfer     Bitrate         Retr  Cwnd
[  6]   0.00-1.00   sec  2.76 MBytes  23.2 Mbits/sec    0    174 KBytes
[  8]   0.00-1.00   sec  2.56 MBytes  21.5 Mbits/sec    0    158 KBytes
[ 10]   0.00-1.00   sec  2.76 MBytes  23.2 Mbits/sec    0    167 KBytes
[ 12]   0.00-1.00   sec  2.52 MBytes  21.1 Mbits/sec    0    153 KBytes
[SUM]   0.00-1.00   sec  10.6 MBytes  89.0 Mbits/sec    0
- - - - - - - - - - - - - - - - - - - - - - - - -
[  6]   1.00-2.00   sec  2.86 MBytes  24.0 Mbits/sec    0    308 KBytes
[  8]   1.00-2.00   sec  2.61 MBytes  21.9 Mbits/sec    0    283 KBytes
[ 10]   1.00-2.00   sec  2.73 MBytes  22.9 Mbits/sec    0    291 KBytes
[ 12]   1.00-2.00   sec  2.61 MBytes  21.9 Mbits/sec    0    270 KBytes
[SUM]   1.00-2.00   sec  10.8 MBytes  90.7 Mbits/sec    0
- - - - - - - - - - - - - - - - - - - - - - - - -
[  6]   2.00-3.00   sec  2.92 MBytes  24.5 Mbits/sec    0    441 KBytes
[  8]   2.00-3.00   sec  2.55 MBytes  21.4 Mbits/sec    0    404 KBytes
[ 10]   2.00-3.00   sec  2.73 MBytes  22.9 Mbits/sec    0    420 KBytes
[ 12]   2.00-3.00   sec  2.61 MBytes  21.9 Mbits/sec    0    386 KBytes
[SUM]   2.00-3.00   sec  10.8 MBytes  90.7 Mbits/sec    0
- - - - - - - - - - - - - - - - - - - - - - - - -
```

Figure 57. Ping output screenshot

February 2022

PTP validation results:

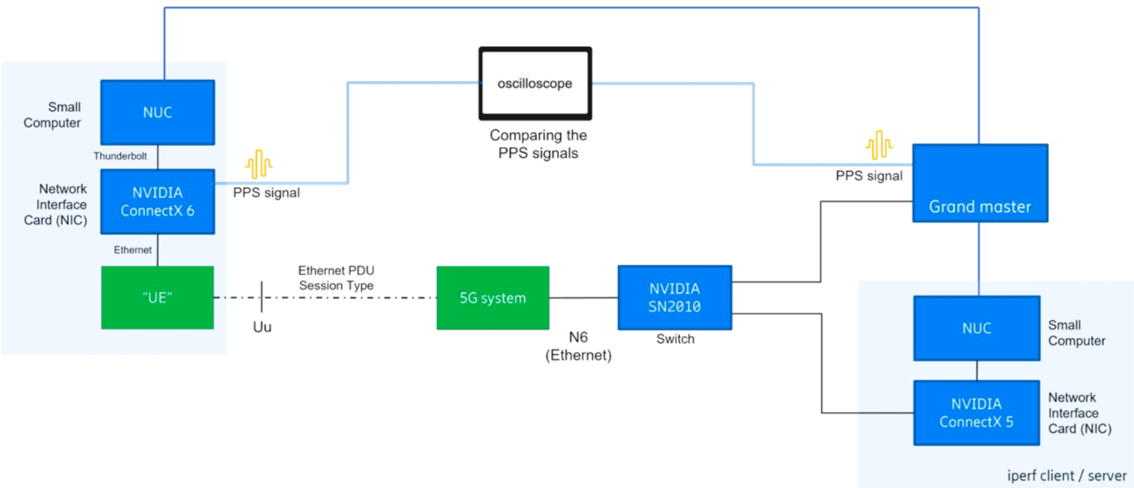


Figure 58. Architecture for PTP measurements

Figure 58 shows the setup used for PTP measurements, a NUC is connected to an NVIDIA ConnectX6 card with PTP support. The X6 connects the NUC to the 5G network via a special Rel.17 modem. The device is connected to the PTP Grandmaster via 5G. The 5G network supports the Rel. 17 time synchronization feature, more description for the network can be found in later section. The GM is connected to the 5G network via the N6 interface using an SN2010 switch. The PPS signal output from the ConnectX 6 and the GM are connected to the oscilloscope to measure the accurate offset between both devices. The measurements are collected both via the oscilloscope and the PTP4l client.

Figure 59 shows the measurement done without using the Rel. 17 time synchronization feature and without compensating for the known latency using the servo parameter in the PTP4l client. The average offset are as follows: 117 µs using the ptp4l log and 152 µs using the oscilloscope.

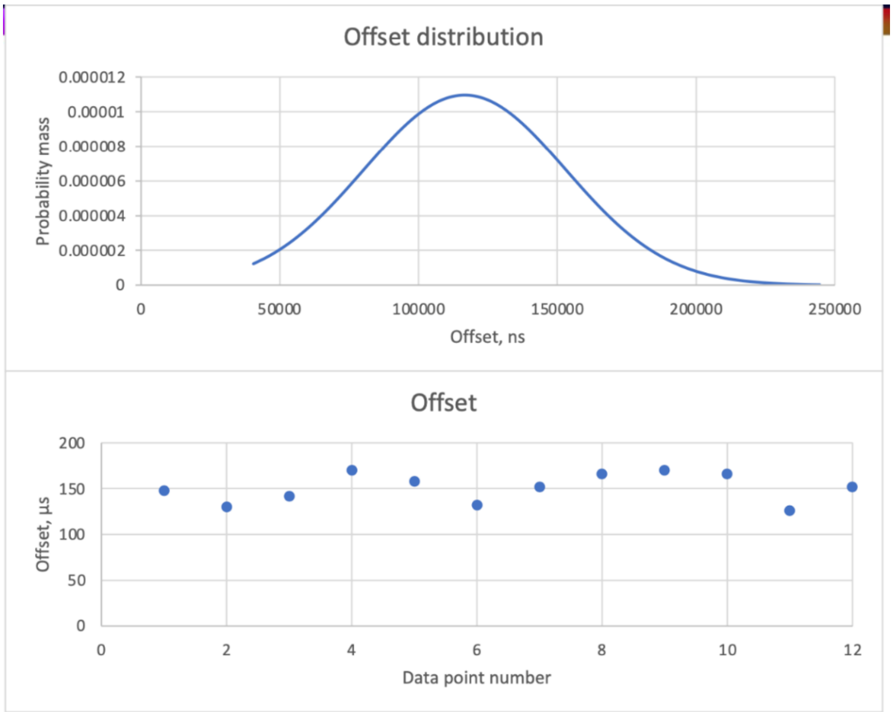


Figure 59. Measurement without timing assistance to PTP parameters tweaking

Figure 60 shows the improvement when the network inserts the residence time to the PTP packet, and the latency pre-estimation is inserted in the PTP client. The average offset are as follows: 3.5 µs from the PTP4l log and 4.006 µs from the oscilloscope.

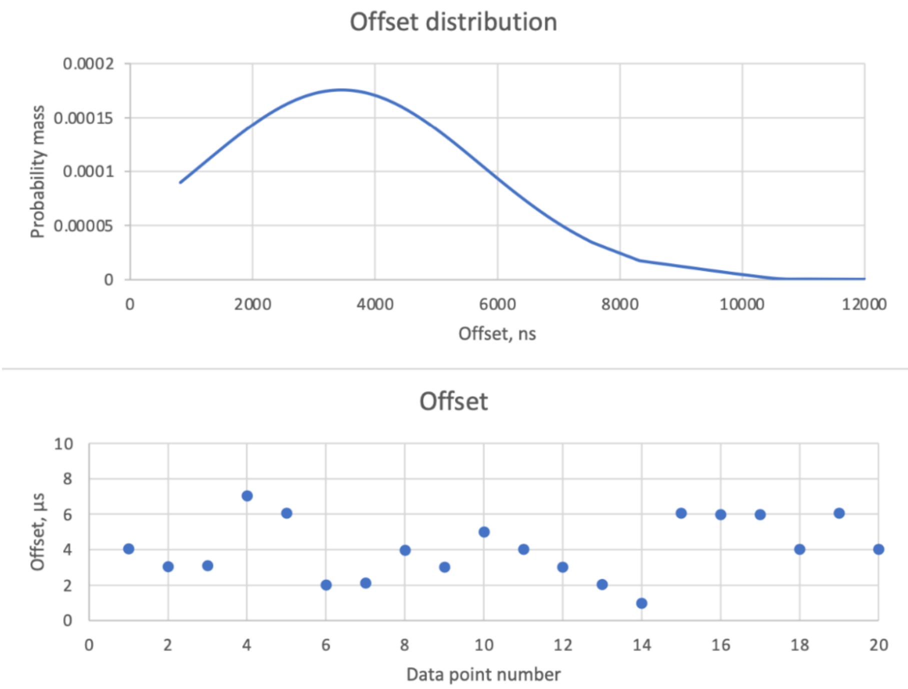


Figure 60. Measurement with timing assistance and PTP client tweaking

Figure 61 shows the timing offset when only the network assistance is used: the PTP4L log has 3.6 µs, while the oscilloscope has an average of 4.756 µs.

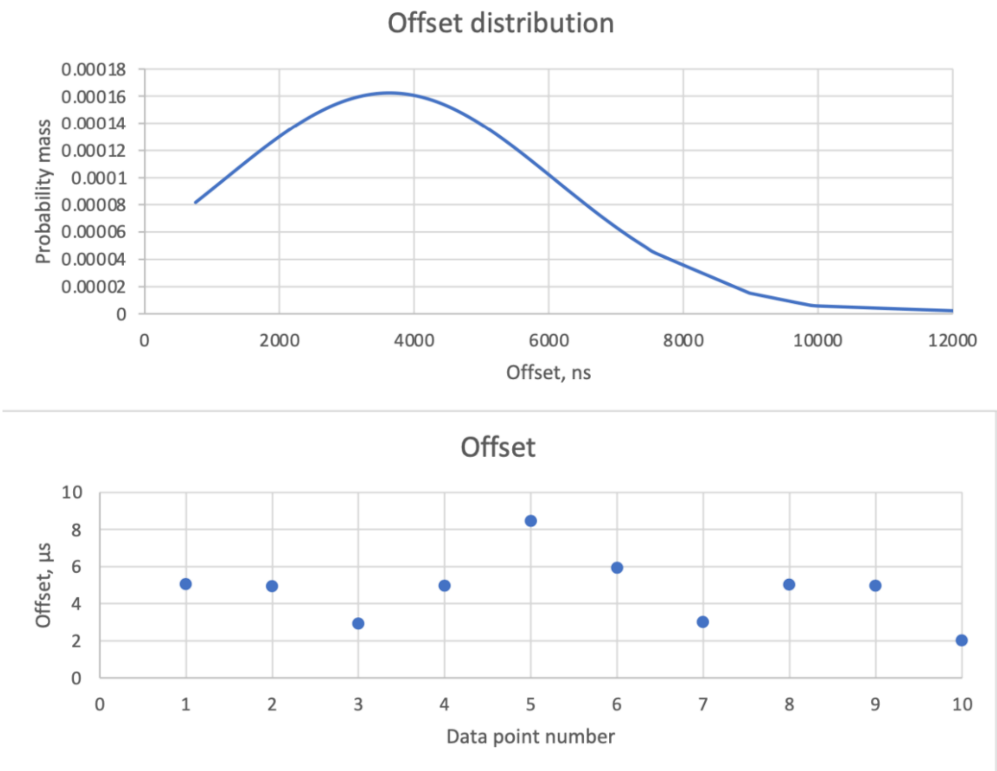


Figure 61. Measurement with network assistance but without PTP client tweaking

April 2022

ST 2110 output

The output was tested using a Tele-stream PRISM and with an AJA ST 2110 to SDI converter. Several PCAP files were captured and successfully validated with EBU LIST.

HEVC to ST 2110 latency

The latency introduced by the Media Gateway alone was not measured. We measured the glass-to-glass latency of encoding an SDI stream, sending it over the 5G network, decoding it and converting it to ST 2110 in the MG, and displaying it. The result was between 10 and 12 frames, that is 200 to 240 ms.

ST 2110 to HEVC latency

As above, we tested the glass-to-glass latency. The result was between 6 and 8 frames that is 120 to 160 ms.

Simultaneous streams

We successfully tested, on the same MG, the simultaneous processing of 2 streams from HEVC to ST 2110, in parallel with 1 stream from ST 2110 to HEVC.

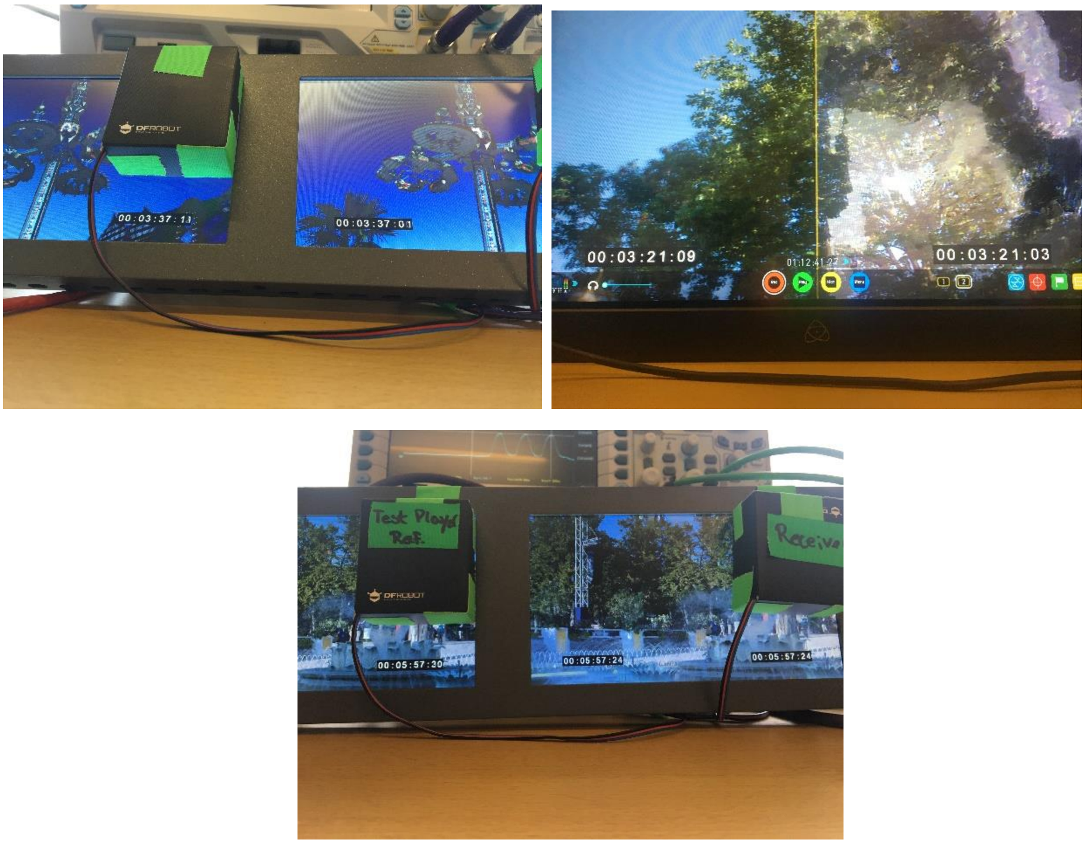


Figure 62. Multiple stream via the MG

Integrated production scenario

These tests, performed in Mar 2021, were reported in D4.1 (3.4.1, 3.4.2) [2]

October 2021

1. ***Connectivity tests***

- Goal
    - Ensure the LiveU components (LU800Pro, LU2000SMPTE, LU IP audio server) can properly communicate with each other via the various IT networks and subnetworks of both Aachen 5G lab and RAI studio.
- Requirements:
    - LU800Pro connected to a LU2000 (anywhere)
    - LU2000SMPTE connected to a LU encoder-transmitter (anywhere)
    - LU2000SMPTE connected to RAI PTP master clock over subnet 2
    - LU2000SMPTE connected to RAI SMPTE test equipment over subnet 3
    - LU2000SMPTE connected to LiveU IP audio server over subnet 1
    - Cyan view camera-side control device connected to Cyan view control device via the LiveU IP PIPE over public internet and 5G networks
- Steps (multiple tests here)
    - In several separated tests the various IP IT configurations were done in the LU800Pro, LU2000SMPTE, Rai lab components, Cyan view devices and Rai IT firewalls, and tested.
    - The tests were done in parts, from RAI to/from LiveU cloud and LiveU lab, from Ericsson 5G lab to/from LiveU cloud and LiveU lab, Cyan view boxes in RAI studio via another LiveU encoder-transmitter and local 5G networks to same RAI studio Cyan view control box etc.

  - This methodology allowed a step by step progress, without dependencies on staff being at the same time in both Aachen and RAI Turin, with reduced dependencies on COVID-imposed access limitations and absences and without interdependencies between the two sited different networks and IT policies.
  - It further allowed the easy moving of the LU800Pro and Cyan view equipment from Aachen lab to TV2 studio to complete the October tests of remote production functionalities that were not completed during the limited time in Aachen and immediate execution from there to RAI studio.
- Success/fail
  - Connectivity of all components was configured and established
- Results:
  - All tests passed
  - Movement of relevant configured on-site equipment from Rai lab to Aachen lab to TV2 studio was done easily and smoothly, with immediate resumption of the functional testing from TV2 to Rai

2. ***Transmission under load performance tests:***

- Goal
  - Test the ability of LRT algorithm, single modem/no bonding, to compete with background traffic
- Requirements:
  - LU800Pro connected to a single external 5G CPE, which is connected directly into the lab 5G (no RF)
  - Single and multiple video feeds into the LU800 (camera or video player, LiveU video clips)
  - Background UL traffic emulator is connected to another modem
- Steps (multiple tests here)
  - Benchmark: quick “ideal conditions” to see all is ok, inter-site connectivity works, end-to-end ping and PC-PC UDP/TCP traffic checks over the LiveU IP-PIPE …
  - LU800 uses 1, 2, 3, 4 SDI inputs to transmit single feed @30mbps and up to 4 @60 Mbps total
  - LU800 is tuned to low video latency (600msec) and higher (1 sec)
  - Background traffic emulator uses iPerf to consume different levels of the lab 5G UL capacity
  - Performance is calculated at LU application level (UL BW, latency, loss rate)
- Success / fail
  - Adaptive UL transmission is maintained under the various network congestion test cases.
  - Packet loss is reduced by reducing the overall video bitrate transmitted / High packet loss is detected (without bonding)
- **Result**
  - 9 tests done; Passed in all configurations

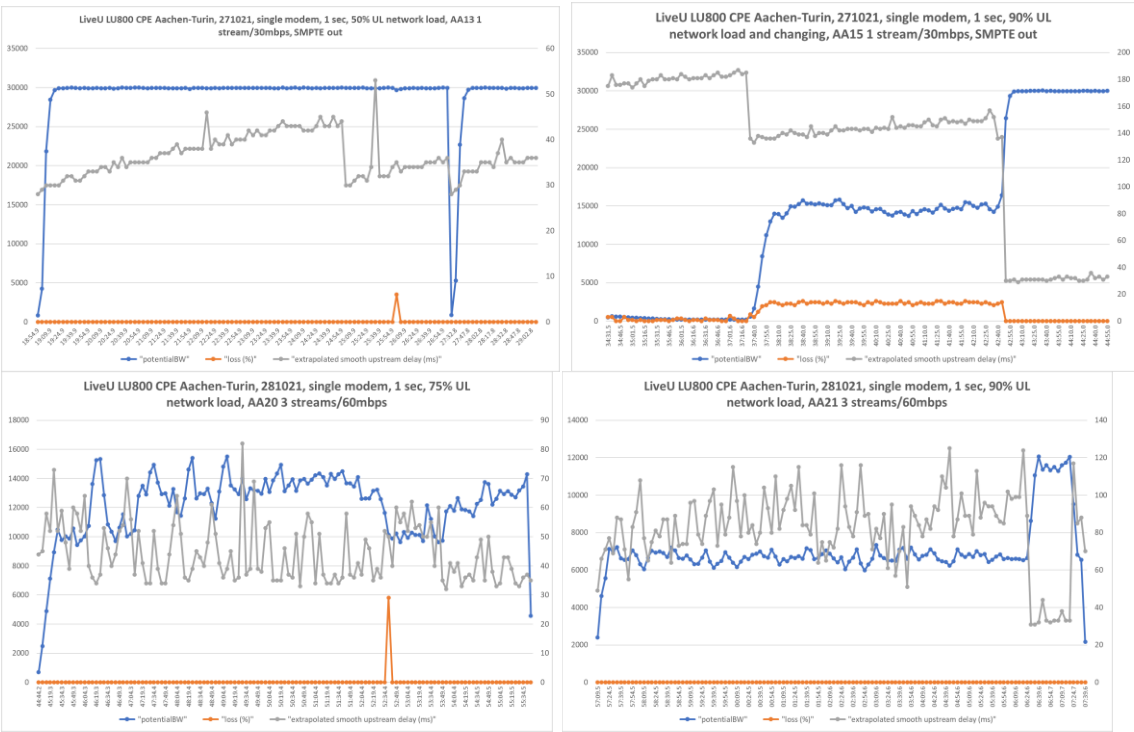


Figure 63. Throughput, packet loss and delay under different load

- UL latency increases and available UL is decreased with more network loading (50%, 75%, 90%)
- LU800 video encoding and transmission adapts to available BW – both decreasing and increasing
- All 3 streams are still encoded and transmitted even at high network load, BW is split internally between them

3. *LU2000-SMPTE (receiver-decoder) compliance*

- Goal
    - Continue Cycle1 testing the compliance of the LiveU LU2000SMPTE with the SMPTE2110 standard
- Requirements:
    - LU800 transmitting as before, single stream
    - LU2000SMPTE is connected to RAI Tektronix Prism testing tool incl. video redundancy, to RAI PTP master clock and to the public internet (to receive the video from Aachen)
- Steps (multiple tests here)
    - Configure and connect all IP devices
    - LU800 uses 1 input, transmitting up to 30 Mbps
    - SMPTE compliance is measured by RAI in Torin Tektronix Prism Performance
- Success / fail
    - Compliance with SMPTE2110 / major non-compliance
- Results
    - Passed, few minor non-compliance; to be explored further

SMPTE 2110 compliancy of LU2000 server output stream

Referring to LU2000-SMPTE server, the compliancy of the video output with respect to the ST2110 standard family has been evaluated at RAI labs. A subset of tests taken from the official JT-NM's test list [3] was selected and evaluated. Almost all of the tests have been passed by LU2000-SMPTE, with few exceptions. The table below reports the updated results of this analysis, with respect to D4.1 [2]. Some of these were done in Cycle 2, some repeated also in Cycle 3 (Mar 22 below) for benchmarking and some were new in Cycle 3.

Table 2. ST2110 compliance test results

Standard	**Test description**	**Result**
2110-10	TX provides SDP: y/n?	Yes
2110-10	SDP validated via SDPoker and/or manually: y/n?	No, SDPoker states that an attribute is missing ('ts-refclk')
2110-20	stream present: y/n?	Yes
2110-20	multicast address correct: y/n?	Yes
2110-20	video format is correct: y/n?	Yes
2110-20	decoded by reference RX: y/n?	Yes
2110-20	no visible errors: y/n?	Yes
2110-20	no errors reported by prism: y/n?	Yes
2110-20	sender N and/or NL and/or W: y/n?	Yes, Narrow Gapped
2110-20	Cmax compliant: y/n?	Yes
2110-20	VRXfull compliant: y/n?	Yes
2110-30	stream present: y/n?	Yes
2110-30	multicast address correct: y/n?	Yes
2110-30	DSCP marking according to AES67: y/n?	No: media stream marked with DSCP Default value (0); PTP packet marked with DSCP 0
2110-30	stream audible: y/n?	Yes
2022-7	video stream redundancy working: y/n?	Yes

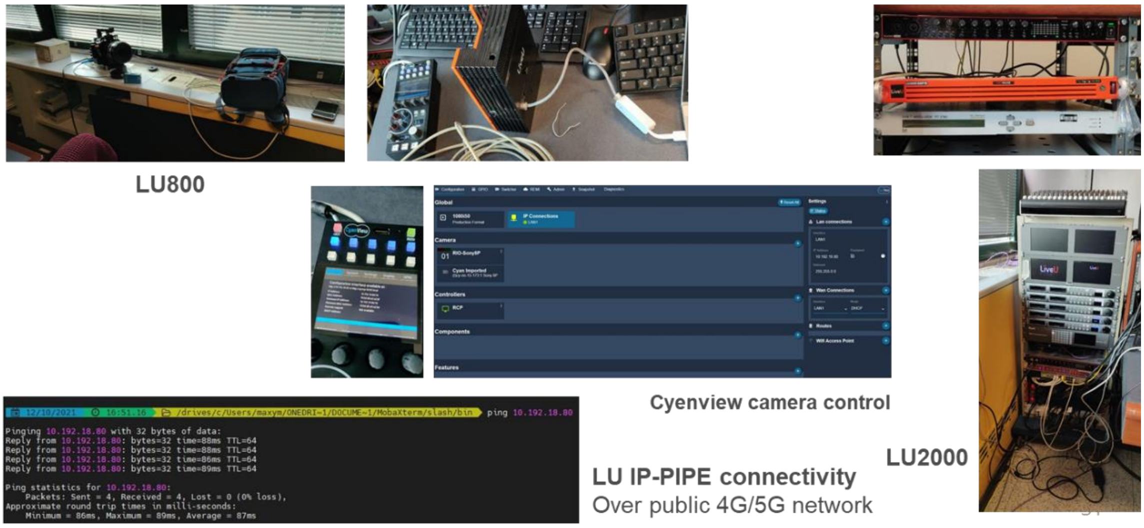


Figure 64. Lab setup and tools

March 2022

1. LU800Pro Sierra Wireless embedded modems tests
- Goal:
    - To ensure that the Sierra Wireless EM9190 modem embedded inside the LiveU LU800Pro is working in a certified 5G SA network, since in phase 1 and 2 it failed to register with the Ericsson 5G SA network, due to various potential causes
- Requirements
    - LU800Pro, Sierra Wireless 5G SA lab, LiveU LU2000-cloud, support teams, configurations,
- Steps:
    - The same LU800Pro was tested in Sierra Wireless 5G SA lab in Paris, with LiveU remote support.
- Success/fail
    - Registering/not registering in Sierra Wireless labs, transmitting/receiving to/from there to/from the public network
- Result:
    - Success: The LU800Pro got registered by the network and after a LU800Pro SW change also got full service.
    - Shipped back to Aachen, and after the Aachen lab versions upgrade, the lab network registered the Sierra Wireless and gave it full service.

2. Fivecomm modem tests
   Succeeded – performance was similar to both the external 5G router and the embedded Sierra Wireless modems

3. Benchmark tests
    - Goal:
        - To ensure the LU800Pro works in the updated Aachen 5G SA lab similarly to previous phases
        - To ensure performance of the LU800Pro with each of the 3 modems and chose the right ones for the more intense performance tests
    - Requirements:
        - Test in Aachen lab environment
    - Steps:

   - Several test cases were devised for these, e.g. transmit with each of the modems, test connectivity between Aachen and Turin labs
- Success/fail
   - Sierra Wireless embedded modem, Fivecomm modem and industrial router perform similarly for the LU800Pro UL transmission for a reasonable duration
- Results
   - Initial results (real time looking at performance over the LU800Pro and LU-Central monitors) indicate all modems performed similarly

4. Performance tests under various conditions and their combinations:
   a. Single and 4 A/V feeds, best effort slice, “guaranteed performance UL-oriented slice, UL congestion of 0%, 50% and 90%, single modem transmission and bonding (two same slices, two different slices, a slice with the commercial network)
   b. Succeeded in all tests.
   c. Some unexpected results were such that the network increased its latency even on the “guaranteed performance” UL-oriented slice, even when the e-MBB slice was loaded, and similar.
   d. The results will be presented and discussed in D5.3 as they are end-to-end full flow.

			UL Media slice				eMBB slice			
			Modem 1		Modem 2		Modem 1		Modem 2	
Test ID			user	type	user	type	user	type	user	type
Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9	Column10	Column11
T1-T3	**Benchmark, modems**	multi stream, ~65Mbps max, 0.8/1 sec					LU800	**All** of: 1. Sierra 2. 5Com 3. Router		
T4		multi stream, ~65Mbps max, 0.8/1 sec	LU800	**One** of: 1. Sierra 2. 5Com 3. Router						
T7	**Benchmark bonding**	Bonding eMBB slice multi stream, ~65Mbps max, 0.8/1 sec					LU800	Sierra, or 5Com or Router	LU800	Sierra, or 5Com or Router
T36-T37	**Congestion w single feed**	congestion on UL media slice; **no bonding with eMBB;** single stream, ~30Mbps max, 0.6 sec	LU800	5Com or Router			Congestor @50%, 90%	Sierra, or 5Com or Router		
T38	**Benchmark**	**no congestion,** eMBB; single stream, ~30Mbps max, 0.6 sec	congestor @0%							
T39-T40	**Congestion w single feed**	congestion on UL media slice; **no bonding with eMBB;** single stream, ~30Mbps max, 0.6 sec	Congestor @50%, 90%	5Com or Router			LU800	Sierra, or 5Com or Router		

Figure 65. Examples of LiveU LU800Pro performance test cases

3.3.3 End-to-End solution

Integrated production scenario

October 2021

4. ***Glass to glass latency measurements:***

Glass to Glass latency is measured using an Oscilloscope connected to photodiodes mounted on the source and reception.

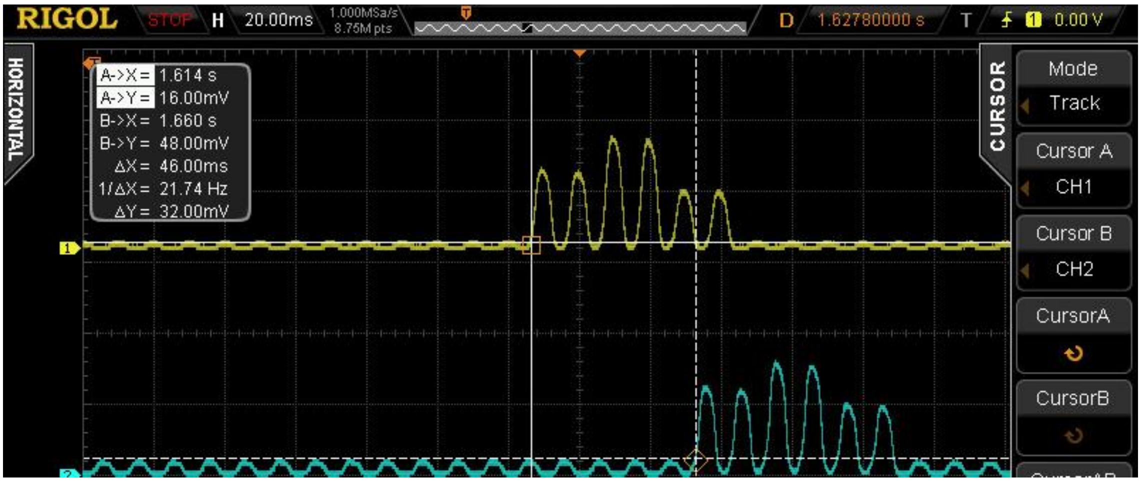


Figure 66. 10Mbps @ 50fps, Latency= 46ms

Figure 67. 10Mbps @ 50fps, Latency= 237ms, De-jitter buffer = 200 ms

<u>April 2022</u>

G2G latency measurements are collected for various scenarios. The 5G network used network slicing to demonstrate traffic prioritization. It should be possible to show dynamic QoS assignment in the future.

The following table summarizes the G2G measurements conducted using the setup described in the deliverable.

Table 3. G2G measurement summary

Test description	Encoder	bitrate	Latency
G2G over ethernet	Xavier	50 Mbps	183 ms
Return video over ethernet	Media Gateway	10 Mbps	122 ms
G2G latency using single stream	Xavier board	50 Mbps	231 ms
G2G latency using single stream	Xavier board	20 Mbps	211 ms
Return video 5G	Media Gateway	10 Mbps	134 ms
Using 2 streams without QoS to the MG	Xavier board	50 Mbps	225 ms
	Jetson nano	20 Mbps	324 ms
Stream from two encoders sent to two decoders	Xavier →MG	50 Mbps	217 ms
	Nano→MG	50 Mbps	223 ms

Remote production scenario

Video quality test

<u>March 2022</u>

Expert viewers graded each test with a mark to evaluate how different network conditions or configurations impact on the transmitted stream, a video quality test session was organized during the month of April 2022 in the RAI laboratories in Turin.

The video material used for the assessment tests was recorded during one of the project test sessions held in Aachen.

In that circumstance, two different network slices were configured on the Ericsson's 5G network in Aachen: the "Media slice" (high priority) and the "e-MBB slice" (best effort)

Two devices were connected to the network in Aachen: a LU800 encoder, connected to a lab small cell through a modem, and a network load generator, connected to the same small cell through another different modem.

At RX side, a single radio unit was used. Both modems were competing for an available bandwidth of 100 Mbps in the same cells.

While LU800 encoder was placed within the Ericsson's 5G network in Aachen, the IP stream carrying its video output was sent through the Internet to RAI's labs in Torino, where it was recorded for later analysis.

The recorded clips, captured under different network load scenarios, once cut and reorganized, were shown to see from 1 to 5. Here below the grade scale used, according to ITU-R BT.500

ITU-R quality and impairment scales

Five-grade scale			
Quality		**Impairment**	
5	Excellent	5	Imperceptible
4	Good	4	Perceptible, but not annoying
3	Fair	3	Slightly annoying
2	Poor	2	Annoying
1	Bad	1	Very annoying

Figure 68. ITU-R BT.500 grade scale

Seven tests have been planned and accomplished:

- the percentage of network load (50%, 90%)
- the mapping of LiveU encoder and the congesting device to different slices

They are resumed in the following table. T38 is the benchmark test; it was executed without slicing and without network load.

Table 4. List of tests

Test ID	Total available bandwidth	Network load	Slice for LU800 encoder	Slice for network congesting device
T34	100 Mbps	50%	Media	Media
T35	100 Mbps	90%	Media	Media
T36	100 Mbps	50%	Media	e-MBB
T37	100 Mbps	90%	Media	e-MBB
T38	100 Mbps	0% (no background load)	---	---
T39	100 Mbps	50%	e-MBB	Media
T40	100 Mbps	90%	e-MBB	Media

Figure 69 shows the average results of video quality tests. Some observations can be gathered:

- In general, results seem coherent with expectations. Similar scores have been assigned to similar network load.

- 50% of load seems to be too little to make noticeable impact to the video quality
- Some quality degradation was noted during T35 and T40. That might be ascribable to the worse network condition / configuration set during these two tests.

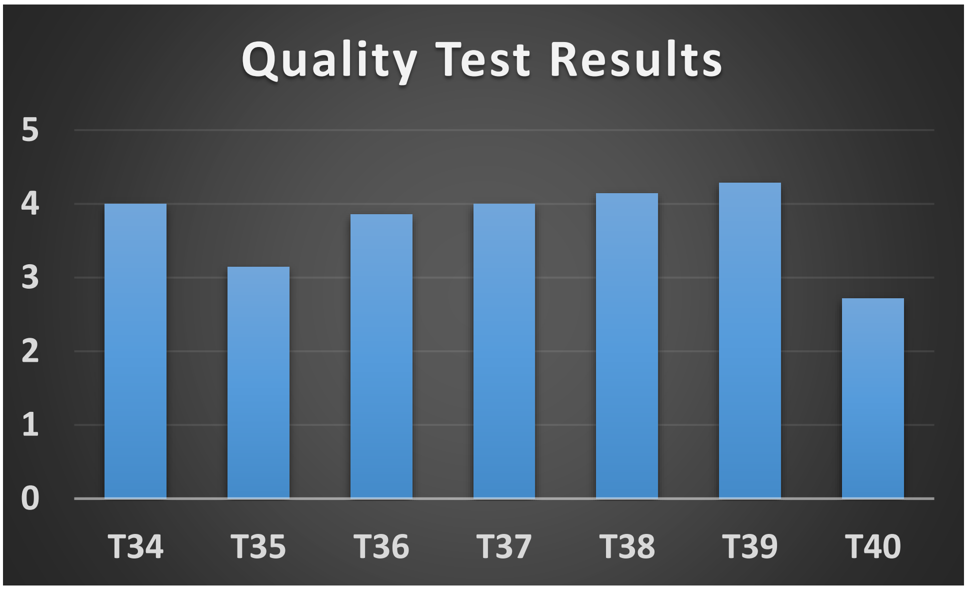


Figure 69. Quality tests results

Lab result summary from LiveU:

This is an initial highlight of the integrated solution. Further discussion will be provided in WP5 deliverable.

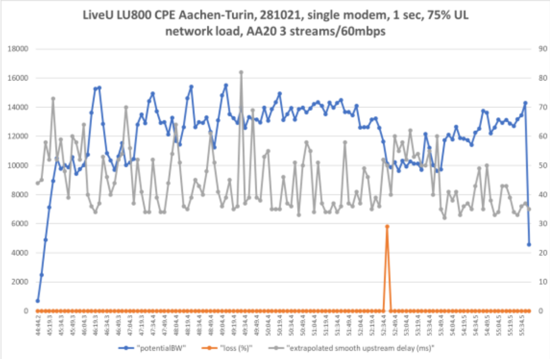
The end-to-end tests in this phase were focused on video transmission performance over the 5G SA network including slices and bonding and transmitted video quality.

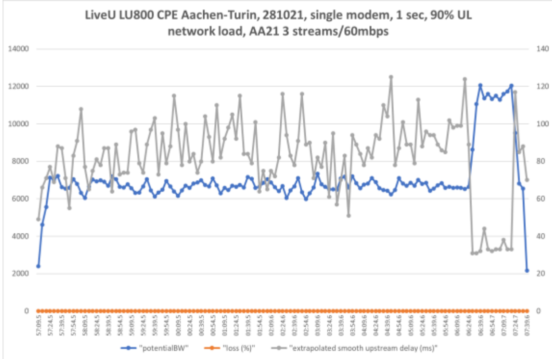
- The A/V transmission tests were performed in the Aachen 5G SA indoor lab by using a modem cabled into the lab RF. Performance over several modems were tested, including LU800 embedded modem, an external industrial router, and Fivecomm new 5G modem. Multiple scenarios were tested, with a single video feed and 4 feeds into the LU800Pro. UL transmission while congesting the UL in this lab network was also tested, at several congestion levels: 0%, 50% and 90% (correlating approximately to similar numerical values in Mbps). Transmission over the lab 5GSA NPN without slices as well as over specially configured UL slice, e-MBB/default slice, with and without congestion applied in each such slice were also tested. Bonding of two modems was also tested, including of 5G UL-oriented slice with the e-MBB slice as well as of the lab 5G with commercial and 4G network. In all these scenario variations, the end-to-end performance (A/V-in to remote A/V-out) was measured by the LiveU A/V encoding-transmitting application and recorded in its log files. These were then analysed for its application-level estimation of the end-to-end UL bandwidth, UL latency and UL loss rate.

Additional transmitted A/V output compliance to SMPTE standards were done end-to-end under some of the above various conditions. The performed tests were an essential subset of test from JT-NM Tested Catalog, with particular attention to: ST 2110-10 Tests, ST 2110-20, ST 2110-30 and SMPTE ST 2022-7 redundancy.

This is an initial highlight of the integrated solution. Further discussion will be provided in WP5 deliverable.

9 test cases with multiple sessions were done; Passed in all configurations





- UL latency increases and available UL is decreased with more network loading (50%, 75%, 90%)
- LU800Pro HEVC video encoding and adaptive transmission adapts to available BW – both decreasing and increasing
- All 3 streams are still encoded and transmitted even at high network load, BW is split internally between them

3.4 Infrastructure update

3.4.1 5G URLLC network description 5G Rel. 16 with Rel. 17 features:

Ericsson developed the Ultra-reliable low-latency communication (URLLC) test network to focus on 3GPP Release 16 radio functions for time-critical communication. The network includes features primarily from Release 16 but also from Release 17.

The testbed operates within Frequency Range 2, i.e., at 28GHz (mmWave) and with a 200MHz bandwidth. It is configured with a 1:1 TDD pattern, which means the scheduler can split radio resources equally between the uplink and the downlink. The subcarrier spacing is set to 120KHz, resulting in a time slot duration of 0.125ms. This configuration will result in low latency because the UE gets a slot for transmission every short period of time. The testbed network can provide a consistent RTT of ~2ms.

For PTP support, the URLLC testbed acts as an end-to-end transparent clock. This PTP clock was added in Release 17 to support time synchronization for media production use-cases as defined by SMPTE ST 2059-2:2015.

3.4.2 Rel 15 Network configuration description

To improve the network stability, Ericsson has continued the upgrade of the software releases of the Rel.15 test network. The network operates on band n78 (midband) with 100 MHz bandwidth, which was assigned by the regulators for industrial usage. The following features are added to the network to achieve the targeted KPIs:

Network slicing:

The network is configured with 2 slices: a best-effort slice with QCI-9 which is used for e-MBB traffic and a media slice with QCI-6 and higher absolute priority. The slice edges are separated for added security. The network slicing is used to demonstrate the functionality of PNI-NPN. The result and the demonstration of network slicing is discussed as part of the remote production scenario section and the network configuration.

Dynamic Quality of service (QoS)

Support of dynamic quality of service requires an upgrade for the 5GC components: PCF, SMF and NEF. The target is to implement an AF within the MOCG to dynamically change the QoS per camera stream. Ericsson is working on upgrading the current lab network to support the functionality.

TDD slot configuration:

To provide higher uplink throughput, Ericsson has reconfigured the 5G lab network to use a TDD pattern DDSU with special slot configuration (11:3:0) instead of the default DDDSU with special slot configuration (10:2:2). Table 5 summarizes the improvement in the uplink capacity with the DDSU pattern compared to DDDSU.

Table 5. TDD pattern throughput improvements

TDD pattern	Layer	DL(Mbps)	UL(Mbps)
DDSU	MAC	1461	145
	App	1432	142
		256QAM	256QAM
DDDSU	MAC	1601	116
	APP	1568	114
		256 QAM	256 QAM

4 Live immersive media production

4.1 Updates on integration of 5G components

4.1.1 FVV live and 5G/MEC integration

May-July 2021

Integration of the first phase of the FVV system with the 5G network and the MEC is done in Nokia Lab in Madrid.

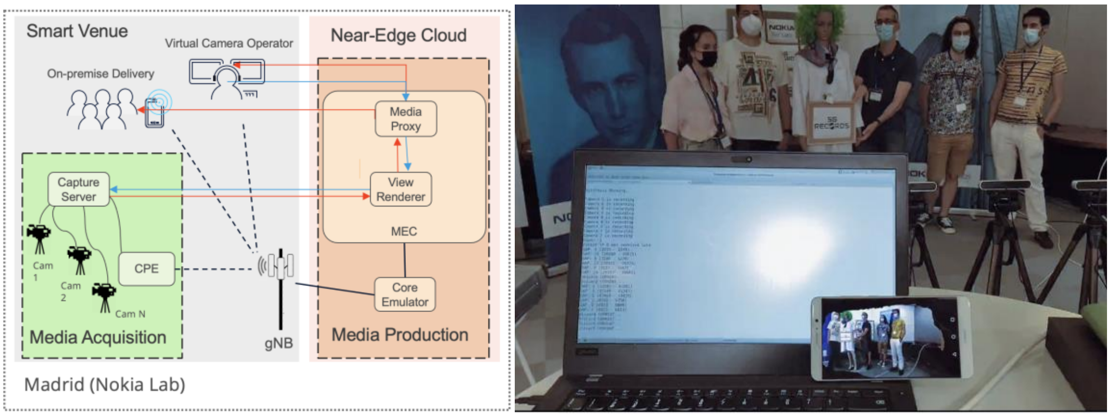
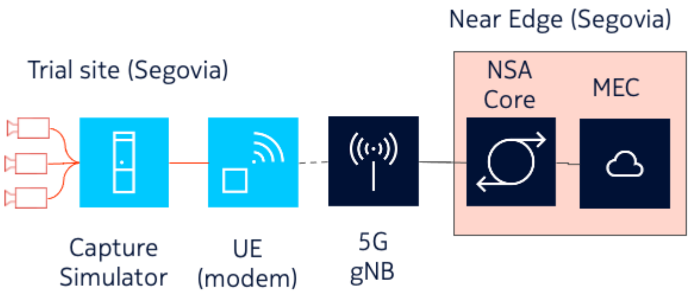


Figure 70. Integration execution process

- Integrated elements
    - 3x Capture servers (Camera simulator & real cameras)
    - 1x Askey modem
    - RAN + Core + MEC
    - Online render on docker (MEC)
- Test conditions
    - Different scene complexity (simple - complex)
    - Resolution: 720
    - 30 – 15 fps
    - Virtual camera auto-movement on-off, long-short path
- Measures
    - Average packets losses (tcpdump)
    - Average bitrate
    - Rendered virtual view saved to file and inspected
- Issues addressed
    - MPI connectivity
    - RTP reordering
    - Traffic shaping

October 2021

Integration in Segovia with FVV emulator.



AVERAGE BITRATE AND PACKET LOSSES @30FPS.

	3 RGB+D @30fps		5 RGB+D @30fps	
	Mbps	% packet loss	Mbps	% packet loss
720p simple	33.8	0	54.2	0
720p medium	46.9	0	79.4	0
720p complex	135.7	0.001	212.6	2.5
1080p simple	165.7	0	-	-
1080p complex	220+	32	-	-

AVERAGE BITRATE AND PACKET LOSSES @15FPS.

	3 RGB+D @15fps		5 RGB+D @15fps	
	Mbps	% packet loss	Mbps	% packet loss
720p simple	-	-	24.7	0.002
720p medium	-	-	42.2	0
720p complex	-	-	120	0
1080p simple	55.6	0	90.1	0
1080p complex	180.2	0	220+	25

Figure 71. Measurement summary

March 2022

Integration of phase 2 developments.

- Integrated elements
    - 3x Capture server (Camera simulator)
    - 1x Askey modem + 2x emulated RAN access
    - RAN + Core + MEC
    - New lab configuration supporting portable setup
        - New core configuration to support 5QIs/QCIs
        - Updated networking to support all VNFs in the same MEC platform
        - Internet connectivity through TID FTTH access
    - Online render on docker (MEC)
    - Slice selector
    - 1x New production console
- Test conditions: same as phase 1 (functional parity with new architecture)
    - Different scene complexity (simple - complex)
    - Resolution: 720
    - 30 – 15 fps
    - Virtual camera auto-movement on-off, long-short path
- Measures
    - Average packets losses (tcpdump)
    - Average bitrate
    - Rendered virtual view saved to file and inspected
- Results
    - Same qualitative results as previous phase (i.e. phase 2 setup works correctly)

April 2022

Final integration including cameras.

- Integrated elements
    - 3x Capture server, 9x cameras
    - 1x Askey modem + 2x emulated RAN access
    - RAN + Core + MEC

        - New lab configuration supporting portable setup
            - New core configuration to support 5QIs/QCIs
            - Updated networking to support all VNFs in the same MEC platform
            - Internet connectivity through TID FTTH access
        - 2x online render on docker in parallel (MEC)
        - Slice selector
        - 2x New production console
        - 2x Video player
- Test conditions:
    - Different scene complexity (simple - complex)
    - Resolution: 720, 1080
    - 30 – 15 fps
    - Virtual camera auto-movement on-off-manual, long-short path
- Measures:
    - Sanity checks (logs of RTP packet losses)
    - Functional: 2 rendered views in parallel
        - Same captured streams (distributed from stream selector)
        - Two parallel renderer VNFs
        - Two parallel production consoles
        - Two parallel local users
- Results
    - The whole FVV production pipeline is fully integrated with the 5G+MEC environment for the final setup

4.1.2 5G/MEC and Edge Cloud integration (slices)

May-June 2021

Connectivity between Segovia and Peñuelas.

Integration is done by connecting Peñuelas Media Delivery with TID SDN.

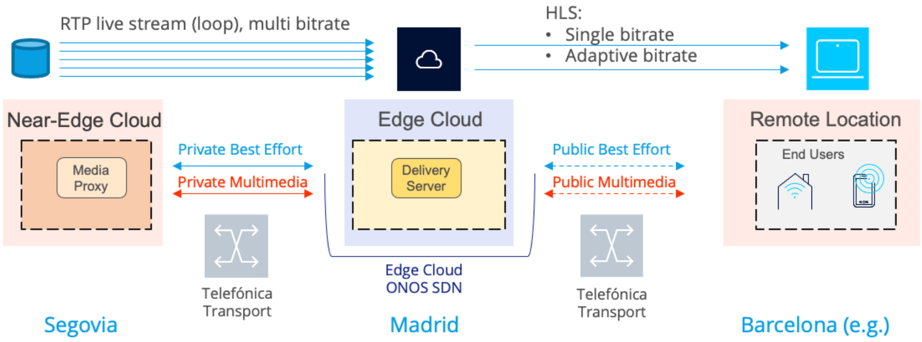


Figure 72. E2E architecture between Segoiva and Madrid

- Integration between Segovia and Madrid
- 2 slices e2e
    - Multimedia gold
    - Best effort
- Rendered view sent in loop from disk
- Test two slices at transport and access levels
- Transport
    - Send rendered video to delivery server
    - All possible qualities

- Delivery
  - Send HLS from Delivery Server to remote end users
  - A/B testing different slices
- Functional validation and tests available at Grafana dashboard

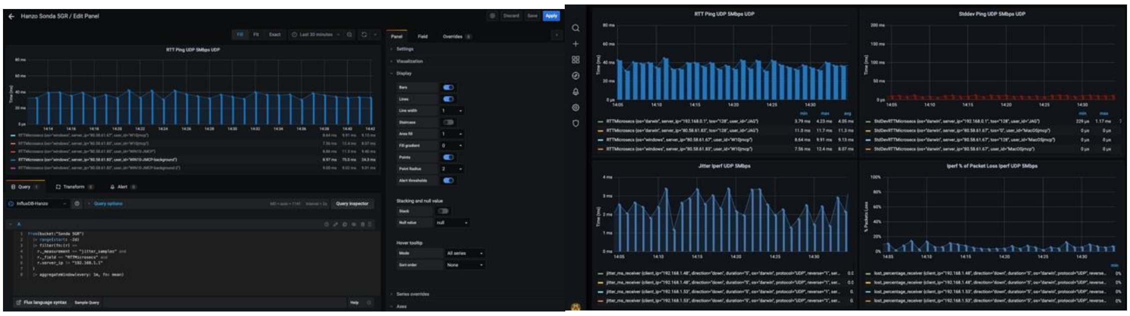


Figure 73. Grafana dashboard

February 2022

Test connectivity Peñuelas-Segovia.

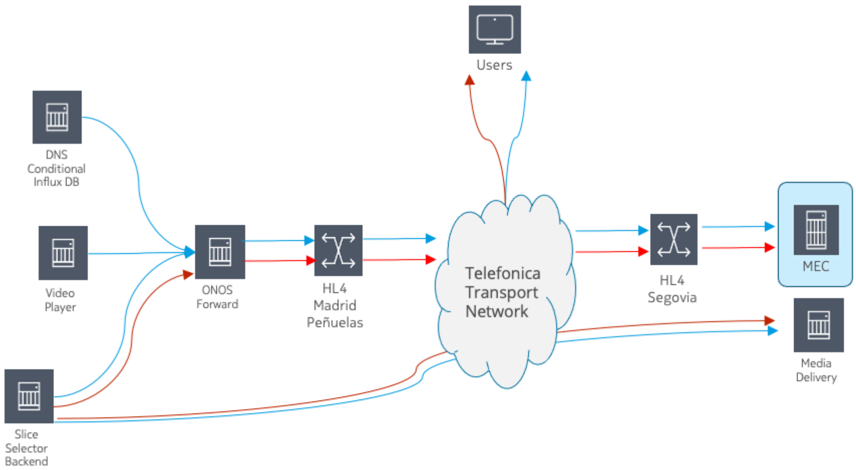


Figure 74. Overall architecture for integration tests

- Integration between Segovia and Madrid
- 2 slices e2e
  - Multimedia gold
  - Best effort
- Test media delivery from Segovia MEC
  - Handled by Slice Selector Backend in Madrid Peñuelas
  - This tests simultaneously the production and delivery network sections (e2e slice)
  - Send HLS from Delivery Server to remote end users
  - A/B testing different slices

Additionally, validate FTTH access in Madrid

April 2022

Integration of TID 5GR Test client into Nokia Lab.

5GR Test Client is built on docker with following software:

- Behave 1.2.6

- influxDB Client 1.23.0
- IPerf 0.1.11
- Pandas 1.3.4
- Request 2.26.0
- Selenium 4.1.0
- Webdriver manager 3.5.2

Docker installed in Nokia Lab in a laptop connected to an UE in the mmWave RAN:

- Different QCIs (6, 9) are identified as different users in the system
- DNS handle both users to differentiate them in the system
- From transport perspective, both users can access either multimedia gold and best effort slice. Therefore, all possible combinations of transport and RAN slices are tested.
- Additional noise is introduced (using iPerf) between Nokia MEC and another test user in best effort priority (QCI 9).

The result of the integration is that:

- The whole test setup is working as expected
- The QoS/slicing solution is integrated and ready for the final validation

May 2022

Integration of TID automatic QoS slice change into Peñuelas Video Delivery Infrastructure:

- Development of slice change based in RTT threshold.
- Execution of 5GR Test client to test automatic slice change.
- Insert QoS change into Influx DB with timestamp
- Correlate all measurements and events in an Influx DB dashboard for comprehensive view
- The result of the integration is that: whole test setup is working as expected
- The QoS/slicing dynamic solution is integrated and ready for the final validation

4.1.3 End to End integration

November 2021

Phase 1 validation (Segovia)

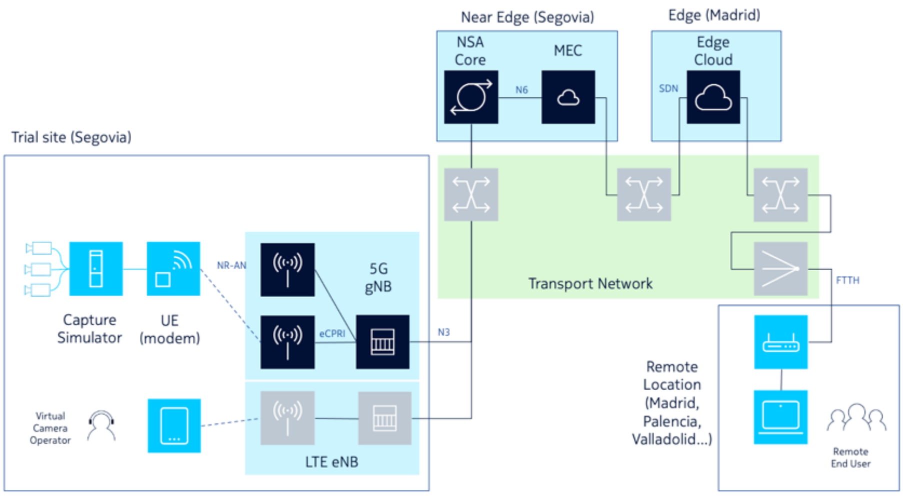


Figure 75. E2E use case architecture

Phase 1 addressed the validation of the "5G Theater" scenario described in D2.1 [1], which is the usage of a public network to produce immersive content. The integration was done in the pilot field deployment installed by Nokia, within Telefónica network, in Segovia, Spain. Four different sites were integrated:

- **Trial site,** located in Segovia (Spain). It is an indoor space with a stage for the Free Viewpoint Video setup. The location includes a 5G gNodeB with two mmWave antennas, as well as LTE eNodeB. The integration included installing camera simulators and 5G modems connected to the 5G network.
- **Near edge**, also located in Segovia (in a Telefónica data center). It contains the distributed NSA core with a UPF providing IP access to the applications over the N6 reference point. The near edge also contains the Multiaccess Edge Computing platform (MEC) with the production VNFs (media renderer).
- The **edge**, located in Madrid (Spain). It contains the delivery software-defined network (SDN), including the slice manager and conditional DNS, as well as the Media Delivery VNF and a monitoring VNF.
- Several **remote locations** in Spain (Barcelona, Madrid, Valladolid…) connected via FTTH with end users which will access the content in real time.

The results of this integration and validation phase were fully reported in deliverable D5.2.

May 2022

Phase 2 validation (Madrid).

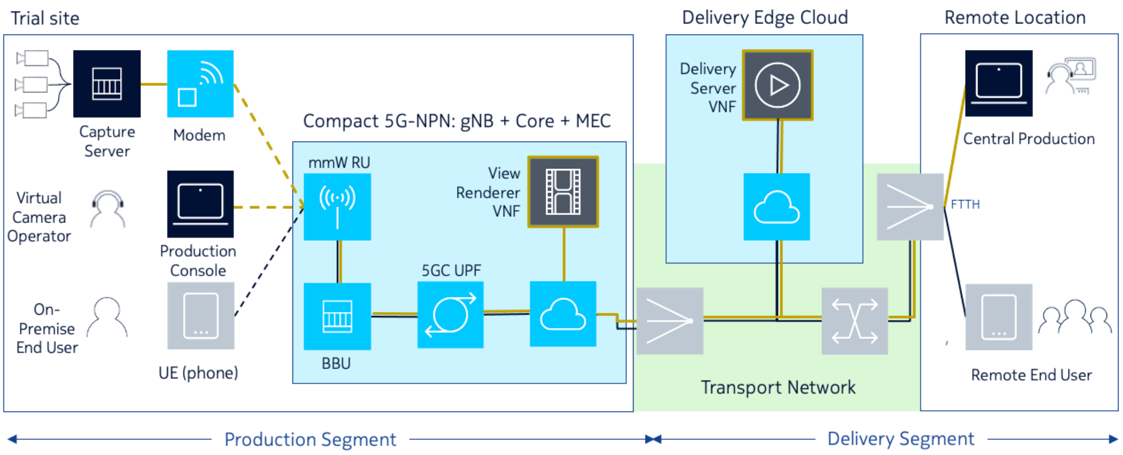


Figure 76. Final integration phase

This was the final integration phase of the project, to ensure that all elements in phase 2 were totally interoperable. It was done in Nokia premises, and it included the following setup:

- Deployment of 9 FVV cameras with 3 capture servers.
- Integration with one 5G modem for the uplink (one capture server), plus two other emulated uplink connections.
- Integration with two production consoles via 5G (one with a 5G modem, the other one emulated).
- Running the 5G Core and MEC infrastructure in the compact NPN setup.
- Running all VNFs in the MEC: stream selector, 2 media renderers in parallel, media proxy and media delivery.
- Connectivity with delivery edge cloud through a FTTH access.

See section 4.3.3 for a description of the end-to-end validation scenario.

Figure 77. Testing location

4.2 Measurement and monitoring tools

This subsection describes the tools employed for testing and validation activities of use case 3. It also provides an update on the KPIs employed to measure and monitor the performance of the 5G and media components prior to their use in trials.

4.2.1 KPIs update

As done in use cases 1 and 2, this section provides an update on the KPIs defined in D4.1 [2] the final stage of integration and testing. The following KPIs have been selected for this phase:

1. E2E (motion-to-photon) latency:

Motion-to-photon latency is the time needed in the system for a specific user movement to be reflected on a display screen. The system should support low latency profiles with an end-to-end latency in the region of 170 ms. This E2E latency refers to the virtual camera control loop: between the cameras, the view renderer, and the virtual camera operator (production console).

2. Uplink bitrate:

The system should support nine to twelve cameras that generate bitrates between 50 and 100 Mb/s uplink per camera. Note that this setup will consist of multiple cameras. This KPI can be split in three different areas:

a) Each camera should produce a bitrate of 100 Mbps or lower. The target bitrate would be ~ 50 Mbps.
b) Each Capture UE should at least support 150 Mbps (the uplink from three cameras). The target uplink throughput would be 300 Mbps.

c) The system should support several Capture UEs simultaneously. In the first release, only 3 to 5 cameras will be streaming simultaneously (o a total of 9 cameras in the deployment), but the target would be supporting up to 12 cameras simultaneously streaming over the UL.

3. Round-trip time (RTT) from UE to MEC:

Defined as the time it takes for a packet to go from the sending endpoint (UE) to the receiving endpoint (MEC) and back, and vice versa. It is required to support a low motion-to-photon latency on the camera control loop. It should be less than 40 ms.

4. Virtual View rendering frame rate:

Defined as the achieved frame rate in the View Renderer. In the first release, 15 frames per second (FPS) will be considered the reference operational point, but the target would be supporting 30 FPS.

5. Remote user throughput:

Remote premium users should support TCP/UDP throughputs as defined in D4.1 [2]. Note that multiple users can be receiving service simultaneously.

6. Remote user load time and pause (rebuffering) count:

Remote users should satisfy the KPIs described in D4.1 [2]. Note that several users may be receiving service simultaneously.

4.2.2 Tools update

1. Motion-to-photon measurement tool:

The Motion-to-photon delay measurement is carried out using a custom software tool developed specifically for this purpose. This methodology is based on the detection of two specific visual signals that indicate the starting and ending instants of the delay under measurement. These signals are:

1. Abrupt image translation along the vertical axis when a virtual camera movement command is detected on the virtual camera control.
2. When the viewpoint is updated, and the new virtual view is sent to the production console, an abrupt viewpoint change in the direction indicated by the virtual camera movement is generated once it is received.

As both instants are tagged with highly visible effects, it is possible to easily isolate them on a recorded video of the production console using an external high frame rate camera (slow motion mode). If we know the number of frames span between both events and the framerate of the recorded external video, we can compute the time difference between both events. This procedure can be repeated several times so the average motion to photon delay can be computed.

Related KPI: *motion-to-photon latency.*

2. FikoRE 5G Network Emulator:

FikoRE is Nokia open source 5G Radio Access Network (RAN) emulator, carefully designed for application-level experimentation and prototyping. Its modularity and straightforward implementation allow multidisciplinary user to rapidly use or even modify it to test their own applications. Contrarily to other simulators/emulators, the goal of FikoRE is not mainly to understand and test the network, but study how the network and its different possible configurations behave for specific applications, use-cases and verticals.

In 5G-RECORDS, FikoRE has been used to emulate network configurations which are not available with the existing systems. This way, it is possible to evaluate the performance of different parts of the system under the next generation of mmWave chipsets and gNBs.

FikoRE is available at https://github.com/nokia/5g-network-emulator

Related KPI: *motion-to-photon latency, uplink bitrate*

4.3 Tests

Measure and monitoring in this Use Case will be done at four different layers:

1. ***Testing of individual components***. Functional testing and individual validation of each of the components. These tests will be reported in section 4.3.1.
2. ***Interoperability tests / KPI measurement***. The KPIs will be measured in their respective systems, both in isolation and in the integrated test-bed. It will be based on standard performance tools, such as *iPerf*, *ping*, *Wireshark*, as well as specifically developed tools and logs. These tests will be reported in section 4.3.2.
3. ***End-to-end tests / Monitoring under operation***. Global network-wise tests will be done, involving several systems simultaneously. Real-time monitoring of relevant KPIs will be added to key measurement points in the system. Performance logs will be sent to a monitoring VNF (influx DB + Grafana collector). This will allow fine tuning and field trial monitoring. These tests will be reported in section 4.3.3
4. ***System validation / End-to-end QoE***. Subjective tests will be performed to map existing KPIs to higher-level Quality-of-Experience indicators (video KPIs). These tests will be reported in deliverable D5.3.

4.3.1 Testing of individual components

There are 4 components in Use Case 3: Free-Viewpoint Video Immersive Media Production over 5G Networks, two of them cover production and delivery functionality: FVV and Media Delivery. Their individual tests will be described here. Two other components involve infrastructure (5G/MEC and Edge/SDN), which will be further described in section 4.4.

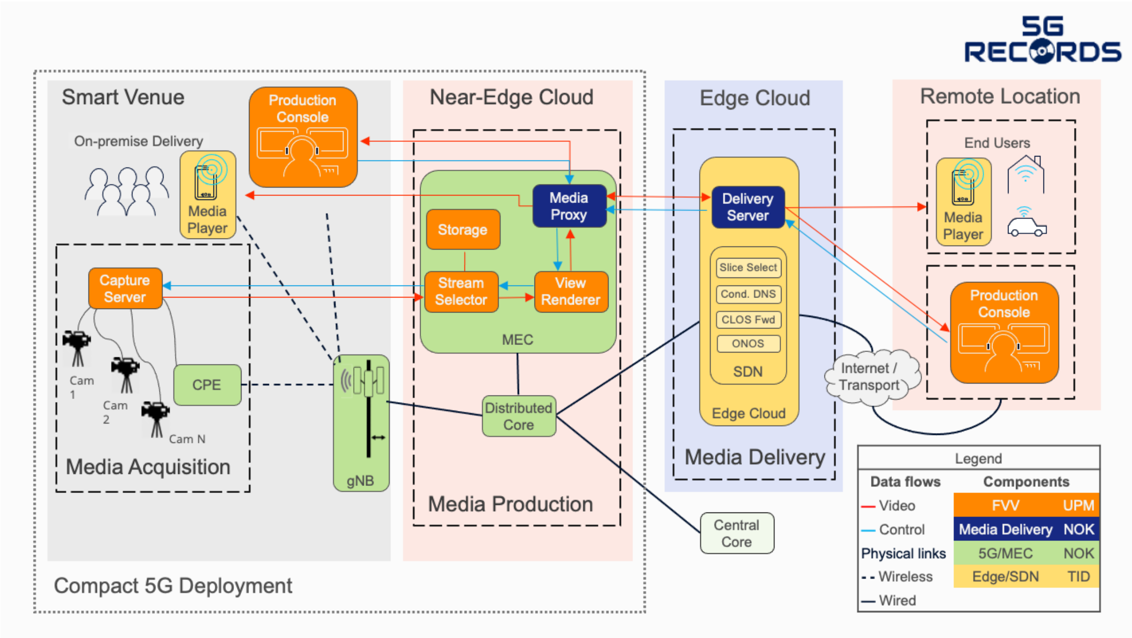


Figure 78. E2E component distribution

1. ***Free Viewpoint Video (FVV):***

The complete FVV chain has been evaluated, as an individual component, both on the laboratory and on a complete field deployment. The following modules have been developed and tested:

- Capture Servers
- FVV-Replay + Camera simulator
- Stream Selector
- View Renderer
- Production Console

For the laboratory tests, every component has been tested working in real-time and including all the new developments described in document D3.2.

Capture Servers

Three Capture Servers have been tested each one managing three cameras. The following video configurations have been tested:

- 1080@30fps
- 1080@15fps
- 720@30
- 720@15
- The three Capture Servers are able to generate 9 RGB+D streams and transmit them to the Stream Selector encapsulated over RTP. The following functionalities have been tested:
- Video acquisition (Colour and depth).
- Post-processing.
- Real time GPU-based video encoding.
  - Colour: 5-15 Mbps depending on the desired quality.
  - Depth: Variable bitrate due to lossless encoding.
- RTP video transmission over wired ethernet link.
- Traffic smooth algorithm to avoid high peak bitrate bursts.
- Configurable PDU size to avoid IP layer fragmentation.

- Monophonic audio capture and encoding.
- RTP audio transmission over wired ethernet link.

FVV-Replay and Camera Simulator

The FVV-Replay and Camera Simulator modules have been designed to replace the Capture Servers without performing any changes to the pipeline, so the rest of the modules are not able to differentiate if the received RTP traffic are delivered from the actual Capture Servers or from the Camera Simulator. This module has been tested using different pre-recorded sequences and transmitting them to through the complete FVV pipeline. The recorded sequences resolutions and framerates are:

- 1080@30 fps.
- 1080@15 fps.
- 720@30
- 720@15fps

All the Capture Servers functionalities have been included on the camera simulator, except those related to the actual cameras management and the video encoding process. The following functionalities have been tested successfully:

- Reading and parsing pre-recorded and encoded video files from hard drive.
- Video encapsulation over RTP and transmission over a wired ethernet link.
- Traffic smooth algorithm to avoid high peak bitrate bursts.
- Configurable PDU size to avoid IP layer fragmentation.

Stream Selector

The Stream Selector manages the RTP video streams by dynamically sending a sub-set of the RGB+D streams requested by each View Renderer instance. This module has been successfully tested for both 1080 and 720 resolutions at 30 and 15 fps, managing the 9 RGB+D streams and dynamically delivering them to two View Renderer Instances working in parallel. These tests have been performed using both the actual Capture Servers and the Camera Simulator as video stream sources.

View Renderer

The View Renderer module has been tested on both the regular version and the virtualized (based on docker containers) working in real-time. The incoming testing RTP streams sources are both the actual Capture Servers and the Camera Simulator. The following functionalities have been tested successfully:

- Receive RGB+D streams from the Stream Selector.
- Received packets re-ordering algorithm.
- GPU-based video streams decoding.
- GPU-based virtual view computation.
- Resulting virtual view GPU-based encoding.
- Encoded resulting virtual view RTP transmission to the Production Console.
- Control data UDP-based communication with the Stream Selector for dynamic camera switching.
- Management of UDP-based virtual camera movement messages received from the Production Console.
- RTP audio stream retransmission to the Production Console.

Production Console

Each Production Console is associated with a specific View Renderer instance. The Production Console receives the resulting synthesized video stream and shows it to the camera operator. Also, when the system is working live, the captured audio stream is received and synchronized with the video. The following functionalities have been successfully tested:

- Receive the RTP streams incoming from the View Renderer
- Receive and synchronize the monophonic RTP audio stream (only while working on live mode)
- Send virtual camera position control messages to the View Renderer

Production focused scenario

In addition to the laboratory tests, a field deployment has been performed so the complete FVV pipeline could be tested on a production-type environment. The tests consist of the recording of several scenes of a theatre group performing their show on stage. All the FVV modules were involved on this deployment. FVV system was deployed and carefully calibrated according to the stage conditions. The RGB+D data was acquired, transmitted, synthesized, and shown on the Production Console in real-time, working at 1080 resolution and 30 fps. Additionally, to the live operation, all the RGB+D streams were saved to file to test the FVV-Replay module storage capabilities. Also, the resulting recorded sequences will be used for the QoE assessment of the system and also to perform bitrate and packet losses measurements over the 5G network.

2. ***Media delivery software:***

- Integrated and modified media delivery server, with the following modules
  - RTP/UDP video flow management. The following functionalities have been tested:
    - Replication of RTP/UDP traffic across the network (i.e. level 4 packet redirector).
    - Tunneling of RTP over ZeroMQ/TCP for content protection. Only suitable for transport / trunk mode (too much overhead to be used in uplink).
    - Logging of RTP statistics: packet loss rate, packet rate, bit rate, etc.
    - Looping RTP streams from disk (single and multiple qualities).
  - Segmentation and generation of HLS streams. The following functionalities have been tested:
    - HLS segmentation of live streams. Single-quality and multiple-quality.
    - HLS segmentation of offline streams. Single-quality and multiple-quality.
    - Real-time trans-packaging to MPEG-DASH.
  - Video Transcoding, based on gstreamer pipelines. The following functionalities have been tested:
    - CPU transcoding (too expensive to work on real time), live and offline.
    - GPU-based transcoding, live and offline.
- Deployed in project cloud infrastructure.

4.3.2 Interoperability tests

We provide here an update of results already shown in D4.1 [2], now in the integrated scenario of phase 2. The main changes compared to phase 1 (reported in D4.1) are:

- A new version of the FVV software, together with new test streams, captured in a more production-type environment.
- The use of a compact 5G-NPN including mmW gNB, 5G NSA Core, and MEC in the same physical location (see section 4.4 for more detail on the updated infrastructure).
- Besides doing tests in the actual deployment, relevant KPIs have been measured using different configurations that mimic the capacities of the next generation of hardware (emulated RAN and different GPUs).

1. ***E2E (motion-to-photon) latency***

The measurements have been carried gRenderer. The simulated 5G link was configured to emulate a more advanced 5G link than the actual.

Table 6 shows results for the M2P measurements on both the actual and the simulated 5G network.

Table 6. Motion-2-Photon measurement results over actual and simulated 5G network

Test conditions	Average M2P (ms)	Std (ms)
Actual 5G link	210.19	20.37
Simulated basic configuration 5G link	221	62
Simulated advanced configuration 5G link	145	34

2. ***Camera bitrate and uplink***

Every camera contributes with two streams: one carries texture information and the other one transports depth data. The texture streams are set to a fixed bitrate, whereas the depth streams are encoded using lossless compression to avoid quality drops that could significantly impair the result of the synthesis. Thus, the bitrate of the latter can vary heavily depending on the specific captured scenario and so it is worth controlling. Therefore, to measure quantitatively the overall bitrate from each camera, a set of scenarios will be set up. Each scenario is the result of the combination of different parameter values: picture resolution, framerate, and scene complexity.

For the camera bitrate and packet losses measurement a set of different sequences have been used, i.e. a sub-et of the sequences recorded at the theatre with different complexities and bit-rates. The tests have been performed at Nokia's laboratory. Three Camera Simulator instances have been used to simulate the three Capture Servers, two of them transmitting through a wired link and one through a 5G link to a Stream Selector and View Renderer instances deployed on Nokia's MEC using docker containers. Each one of the Camera Simulator instances manage 3 RGB+D streams working at 1080 resolution and 30 fps. Packet losses and received bitrate have been measured on the View Renderer. Table 7 shows results for the bitrate and packet losses measurements of different sequences running over the 5G link.

Table 7. Bitrate tests over the 5G network for a set of 3 RGB+D streams

Sequnece complexity	Transmission bitrate over 5G link(Mbps)	Reception bitrate over 5G link(Mbps)	Packet losses (%)
Simple	44.67	44.66	0.004
Medium	94.98	94.84	0.15
Complex	112.40	112.22	0.16
Super-complex	216.91	201.4	7.15

3. Uplink throughput

IPerf3 has been used to test uplink (and downlink) throughput in the RAN or, more specifically, between the capture server and the view renderer locations. Different combinations of carrier aggregation and uplink patterns have been used.

The following graphic shows traffic measurements at network link level (at the core interfaces) for a combination of 9 tests. It includes 3 network configurations: the reference one 8CC DL / 2CC UL, and two ones with less carriers: 2CC DL / 2CC UL and 1CC DL / 1CC UL. Note that each carrier is configured in TDD 4DL:1UL and 100 MHz of bandwidth. For each of the network configurations, three tests have been done: TCP Downlink (limited to about 400 Mbps), TCP Uplink (10 parallel threads) and UDP uplink (configured to saturate the network).

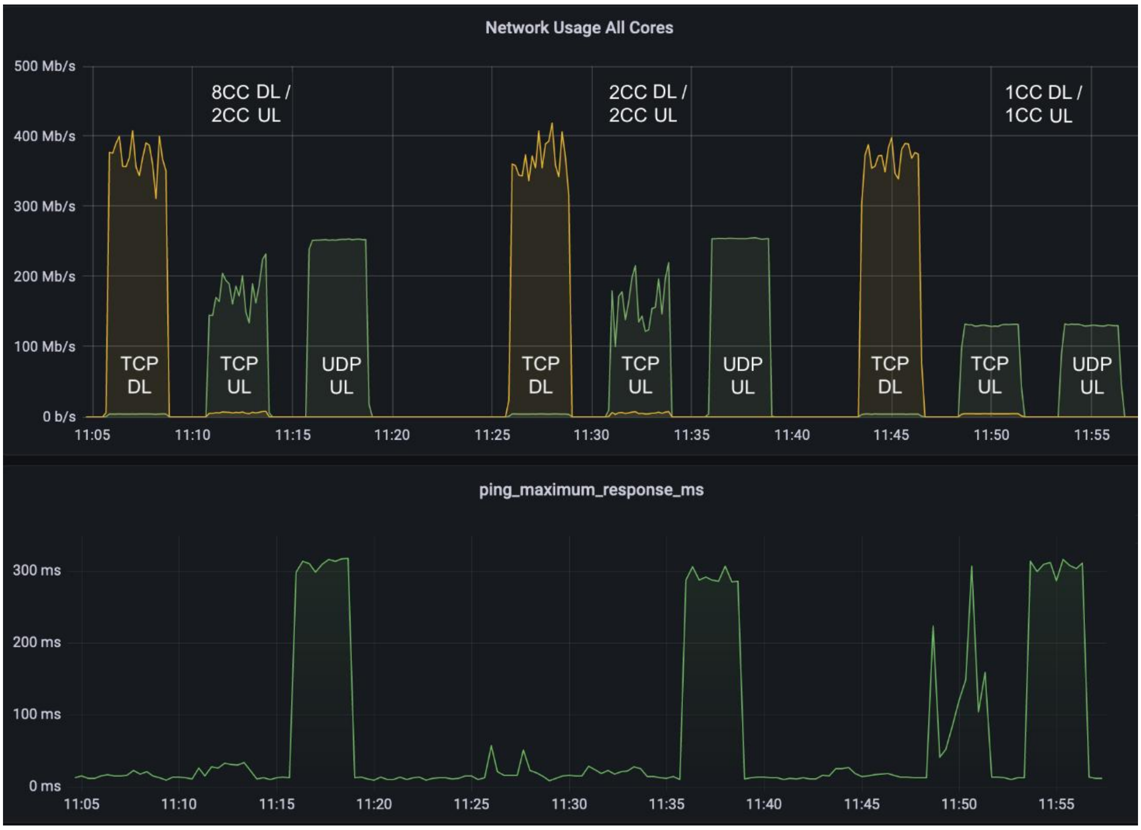


Figure 79. Throughput measurements and RTT

The bottom side of the graphic shows the RTT of a parallel ping test (see next item). Note that the TCP Downlink tests have only been included to measure RTT under load, since they are not actually stressing downlink capacity (which is about 1 Gpbs per carrier in current configuration).

We can summarize downlink tests in the table below:

Table 8. UL/DL throughput results

Configuration	Test	Mean Rate	Peak Rate	Saturated
8DL / 2UL	TCP UL	184 Mb/s	232 Mb/s	No
8DL / 2UL	UDP UL	253 Mb/s	253 Mb/s	Yes
2DL / 2UL	TCP UL	166 Mb/s	220 Mb/s	No
2DL / 2UL	UDP UL	254 Mb/s	254 Mb/s	Yes
1DL / 1UL	TCP UL	132 Mb/s	130 Mb/s	Yes
1DL / 1UL	UDP UL	132 Mb/s	130 Mb/s	Yes

With current network configuration, it is safe to work at a target UL bit rate of around 170 Mbps. The maximum achievable UL capacity is around 250 Mbps with two aggregated DL carriers (130 Mbps on a single carrier). However, operating close to this physical limit is done at the cost of saturating the network, which has a sever impact on RTT, as seen below.

4. Round-trip time (RTT) from UE to MEC

ICMP ping has been used to measure RTT between the UE and the MEC. It has been run in parallel with the iPerf3 test. As shown in the previous figure, there is a clear dependency of the RTT on the saturation of the network. Therefore, we have taken measurements in three different saturation points:

- **Idle**: no background traffic
- **Loaded**: background traffic without network saturation (TCP DL tests, most TCP UL tests, as seen before).
- **Saturated**: background traffic saturating the network.

The results are shown in the following table. Worst case scenarios have been selected for each of the network conditions.

Table 9. RTT under different network conditions

Network Condition	Min RTT	Mean RTT	Max RTT
Idle	8.0 ms	12.9 ms	16.9 ms
Loaded	12.5 ms	26.5 ms	57.2 ms
Saturated	286 ms	292 ms	307 ms

It can be seen that a round-trip-time lower than 40 ms (UE to MEC) is achieved even in loaded cases (even though there might be peeks which temporarily exceed it). If the network is saturated, however, latency increases up to around 300 ms.

5. Virtual view rendering frame rate

The output of the view renderer (video stream of the synthesized result) and the system performance results (time measurements) are stored on a logging file that allows after execution analysis. The rendered GPU performance is measured for each rendered frame by the View Renderer. For GPU performance testing purpose, different

GPUs (NVIDIA T4000 and RTX 3090) performance has been evaluated using different complexities sequences working at 1080@30 fps and a View Renderer instance.

Table 10. Average GPU rendering time per frame for different NVIDIA GPUs and sequences

Sequnece complexity & GPU	Average rendereing time (ms)	Std (ms)
Simple T4000	12.55	1.75
Complex T4000	48.83	2.75
Simple RTX3090	3.8	0.33
Complex RTX3090	8.3	0.6

6. Remote user network measures

The following KPIs have been measured:

- **KPI Throughput End User**: **(bitrate)**: is the number of packets (bps) that are processed, in this case in the device of the end user.
- **KPI Jitter End User**: is the variation in the latency of the packets flow between the delivery server and the end user device.
- **KPI Latency End User**:**(RTT)**: is the duration in milliseconds (ms) that takes for a network request to go from the delivery server to the end user probe and back again to the starting point.

The following table shows the measurements obtained for these KPIs testing with 5GRtest tool against Peñuelas environment in Best Effort quality:

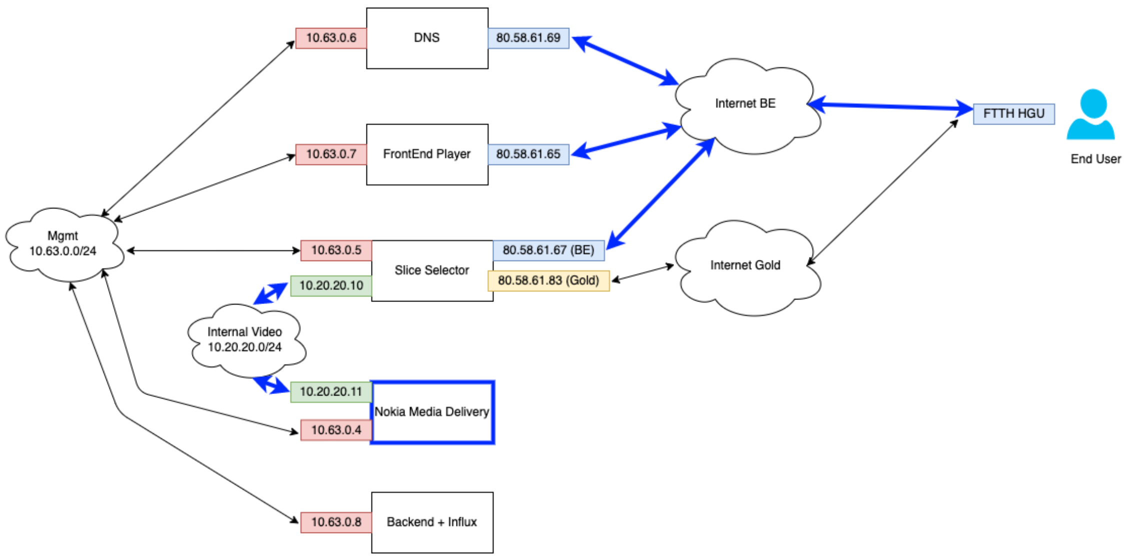


Table 11. Peñuelas Results – BestEffort Slice

Selected Quality	Noise MBytes/s	RTT	JITTER	Bitrate
auto	None	12,34528424	6,02853871	1500000
auto	250M	15,2827143	10,43860662	1500000
auto	500M	15,34239138	12,5435526	1500000
auto	800M	40,87160058	25,5868788	1500000
540p	None	12,05697459	8,644507437	1500000
540p	250M	24,69860116	16,99811283	1500000
540p	500M	24,77927079	16,75313275	1500000
540p	800M	53,59031992	24,32020413	1500000
720p	None	12,83126722	8,182036074	3000000
720p	250M	14,3796547	13,09664473	3000000
720p	500M	72,20718687	29,04851321	3000000
720p	800M	24,58564477	17,6617554	3000000
1440p	None	14,77117407	12,124323	12000000
1440p	250M	63,40040418	38,86369995	12000000
1440p	500M	71,85581782	32,45738389	12000000
1440p	800M	23,90267032	17,36344998	12000000
2160p	None	17,33682872	13,43190506	24000000
2160p	250M	45,95252391	27,73245174	24000000
2160p	500M	18,13256663	14,80570466	24000000
2160p	800M	84,84747749	41,91138468	24000000

As expected, in average, RTT and JITTER increases when introducing noise traffic with iPerf.

The following table shows the measurements obtained for the KPIs testing with 5GRtest tool against Peñuelas environment in Gold quality:

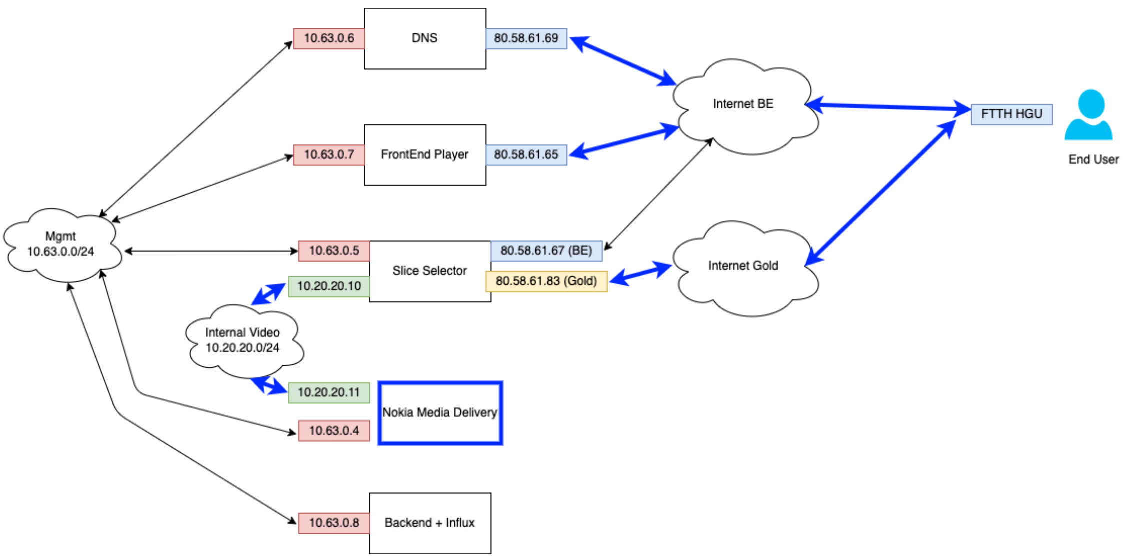


Table 12. Peñuelas Results – Gold Slice

Selected Quality	Noise MBytes/s	RTT	JITTER	bitrate
auto	None	12,48429849	7,70898891	1500000
auto	250M	13,19036271	10,36099287	1500000
auto	500M	48,40616948	25,98507733	1500000
auto	800M	29,924845	18,40023347	1500000
540p	None	12,37702084	5,969108309	1500000
540p	250M	18,4005813	13,84763348	1500000
540p	500M	51,33180786	29,01383722	1500000
540p	800M	19,69120405	15,98393221	1500000
720p	None	12,37393088	9,744526197	3000000
720p	250M	33,25729874	19,43260689	3000000
720p	500M	38,4785303	23,14386105	3000000
720p	800M	58,60388467	29,69780872	3000000
1440p	None	16,52679668	13,63934211	12000000
1440p	250M	16,30593503	11,38900243	12000000
1440p	500M	17,7059616	12,24772222	12000000
1440p	800M	72,56230441	33,88831364	12000000
2160p	None	23,6867194	20,30883826	24000000
2160p	250M	37,2972294	24,34546012	24000000
2160p	500M	30,409923	19,77419466	24000000
2160p	800M	28,31598617	21,60074128	24000000

As expected, in average, RTT and JITTER are lower than in Best Effort mode.

The following table shows the measurements obtained for the KPIs testing with 5GRtest tool against Segovia environment in Best Effort quality:

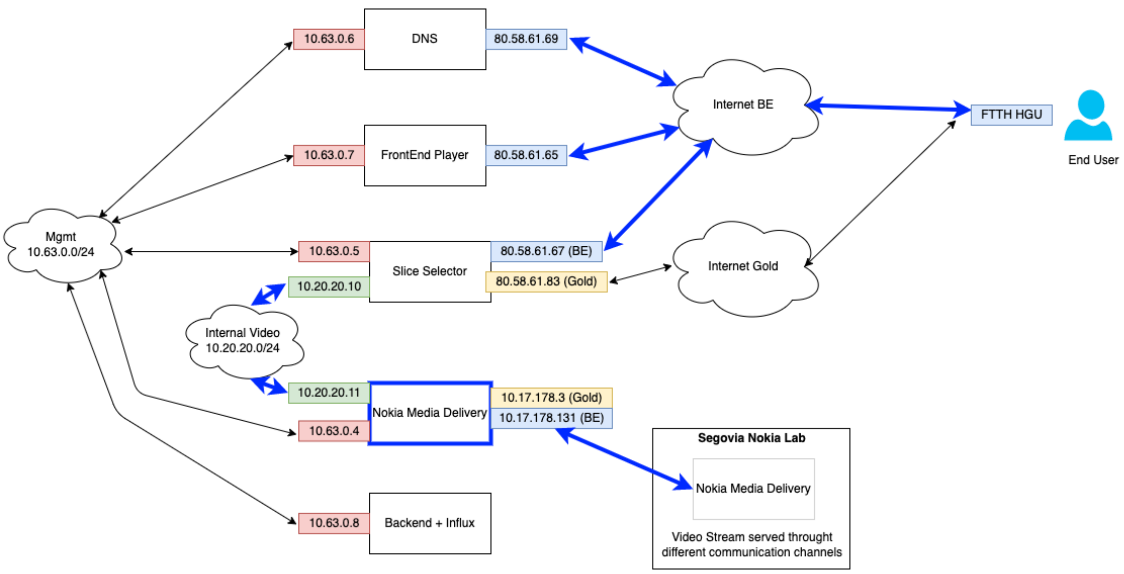


Table 13. Segovia Results – Best Effort Slice

Selected Quality	Noise MBytes/s	RTT	JITTER	Bitrate
auto	None	12,4405612	10,1291566	1500000
auto	250M	64,33247959	38,64501502	1500000
auto	500M	42,99057099	22,65848192	1500000
auto	800M	37,08831124	20,49242622	1500000
540p	None	13,77118494	8,420762072	1500000
540p	250M	54,82438535	29,82807206	1500000
540p	500M	59,52614749	21,92277223	1500000
540p	800M	98,41448991	42,65623479	1500000
720p	None	19,99130941	9,802169041	3000000
720p	250M	73,09937459	38,9831084	3000000
720p	500M	61,738642	34,40018978	3000000
720p	800M	141,2619954	81,85816897	3000000
1440p	None	28,25176405	19,61853294	12000000
1440p	250M	98,8375706	40,25691846	12000000
1440p	500M	73,93347216	41,26226451	12000000
1440p	800M	83,1361478	45,13424014	12000000
2160p	None	38,82725775	23,47998484	24000000
2160p	250M	84,4817869	42,73672007	24000000
2160p	500M	96,104187	45,1518928	24000000
2160p	800M	165,1998008	93,15009871	24000000

The following table shows the measurements obtained for the KPIs testing with 5GRtest tool against Segovia environment in Gold quality:

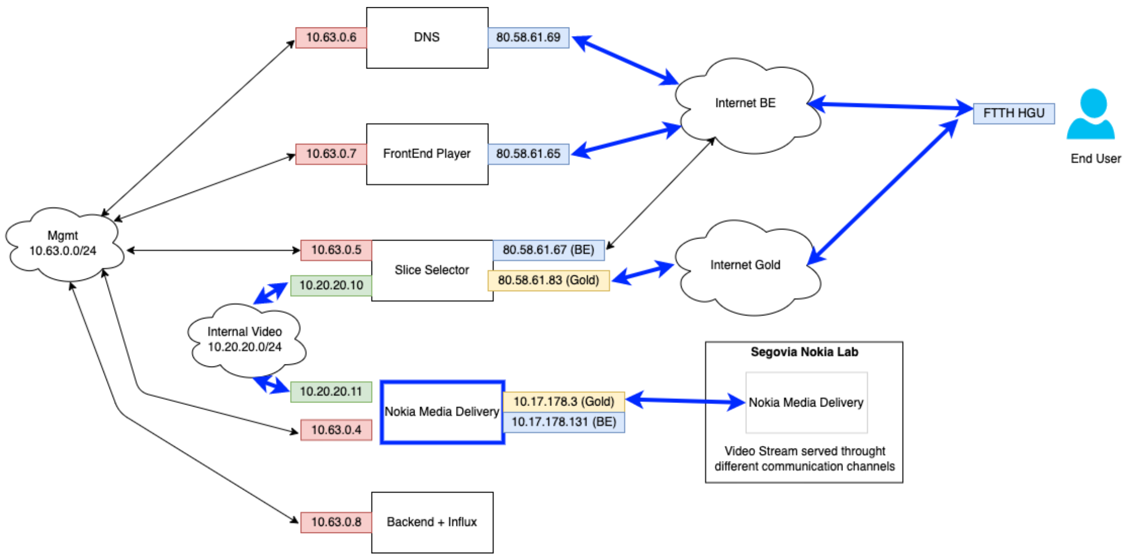


Table 14. Segovia Results – Gold Slice

Selected Quality	Noise MBytes/s	RTT	JITTER	Bitrate
auto	None	11,91989453	7,905187096	1500000
auto	250M	77,17906619	51,323764	1500000
auto	500M	61,87931165	36,04197382	1500000
auto	800M	38,56716701	15,9813509	1500000
540p	None	11,9625487	8,39935107	1500000
540p	250M	71,19993187	34,66100455	1500000
540p	500M	60,2032376	30,21296032	1500000
540p	800M	67,13176553	30,73198578	1500000
720p	None	13,10097529	8,261996432	3000000
720p	250M	89,3761367	43,11708234	3000000
720p	500M	72,13215349	44,05822829	3000000
720p	800M	54,3051397	28,15558542	3000000
1440p	None	20,59381254	9,309204538	12000000
1440p	250M	92,00721452	38,80764189	12000000
1440p	500M	74,89884104	34,44304495	12000000
1440p	800M	89,57304943	39,35621007	12000000
2160p	None	26,45110253	16,82590199	24000000
2160p	250M	102,0050173	47,42135166	24000000
2160p	500M	81,19591667	53,25833149	24000000
2160p	800M	66,6014041	39,028367	24000000

Results measuring against Segovia environment behave similar than Peñuelas, with higer values coming from the added network segment between Peñuelas and Segovia.

7. Remote user video measures

KPIs from player perspective are:

- **KPI InitialLoadTime**: number of milliseconds that elapse from when the video request is made until its playback begins, or the first frame is received.
- **KPI Buffer Count**: number of times of Buffer events triggered.
- **KPI Buffer Duration**: number of second that buffering has occurred

The following table shows the measurements obtained for these KPIs testing with 5GRtest tool against Peñuelas environment in Best Effort quality:

Table 15. Peñuelas Results - BestEffort Slice

Selected Quality	Noise MBytes/s	initialLoadTime (s)	bufferDuration (s)	bufferCount
auto	None	0,387	0	0
auto	250M	0,843	0	0
auto	500M	0,608	0	0
auto	800M	0,545	0	0

540p	None	0,601	0	0
540p	250M	0,397	0	0
540p	500M	0,695	0	0
540p	800M	0,36	0	0
720p	None	1,019	0	0
720p	250M	0,784	0	0
720p	500M	0,777	0	0
720p	800M	0,71	8,364	12
1440p	None	0,894	0	0
1440p	250M	2,056	0	0
1440p	500M	0,717	27,288	12
1440p	800M	3,777	0	0
2160p	None	2,13	262,584	175
2160p	250M	3,041	298,464	112
2160p	500M	0,693	168,667	107
2160p	800M	5,88041667	190,29	94

The following table shows the measurements obtained for the KPIs testing with 5GR test tool against Peñuelas environment in Gold quality:

Table 16. Peñuelas Results - Gold Slice

Selected Quality	Noise MBytes/s	initialLoadTime (s)	bufferDuration (s)	bufferCount
auto	None	0,413	0	0
auto	250M	0,356	0	0
auto	500M	0,321	0	0
auto	800M	0,381	0	0
540p	None	0,438	0	0
540p	250M	0,615	0	0
540p	500M	0,514	0	0
540p	800M	0,368	0	0
720p	None	0,72	0	0
720p	250M	0,68	0	0
720p	500M	0,742	0	0
720p	800M	0,891	0	0
1440p	None	1,623	0	0
1440p	250M	0,937	0	0
1440p	500M	1,742	0	0
1440p	800M	1,704	31,152	33
2160p	None	1,672	299,72	154
2160p	250M	2,826	242,301	44
2160p	500M	3,441	236,528	36
2160p	800M	2,826	267,808	142

InitialLoadTime increases with higher resolutions and when noise is introduced, as expected. Buffering happens only in heavy traffic conditions. Gold slice gets lower values than Best Effort slice.

The following table shows the measurements obtained for these KPIs testing with 5GRtest tool against Segovia environment in best effort quality:

Table 17. Segovia Results - BestEffort Slice

Selected Quality	Noise MBytes/s	initialLoadTime (s)	bufferDuration (s)	bufferCount
auto	None	0,64	0	0
auto	250M	1,98	0	0
auto	500M	0,982	0	0
auto	800M	1,489	0	0
540p	None	1,062	0	0
540p	250M	1,173	0	0
540p	500M	0,638	0	0
540p	800M	0,723	0	0
720p	None	0,835	0	0
720p	250M	0,842	24,132	12
720p	500M	2,507	18,798	15
720p	800M	6,313846154	0	0
1440p	None	2,579	0	0
1440p	250M	4,96283333	24,032	8
1440p	500M	5,62375	0	0
1440p	800M	4,521	37,068	19
2160p	None	2,056	133,364	153
2160p	250M	9,07775	91,457	80
2160p	500M	6,15266667	151,905	92
2160p	800M	15,24323077	95,295	35

InitialLoadTime increases with higher resolutions and when noise is introduced, as expected. Buffering happens only in heavy traffic conditions.

The following table shows the measurements obtained for these KPIs testing with 5GRtest tool against Segovia environment in Gold quality:

Table 18. Segovia Results - Gold Slice

Selected Quality	Noise MBytes/s	initialLoadTime (s)	bufferDuration (s)	bufferCount
auto	None	0,543	0	0
auto	250M	1,772	0	0
auto	500M	1,518	0	0
auto	800M	1,208	0	0
540p	None	1,417	0	0

540p	250M	0,83	0	0
540p	500M	0,933	0	0
540p	800M	0,699	0	0
720p	None	0,727	0	0
720p	250M	1,506	8,217	11
720p	500M	2,719	49,843	18
720p	800M	1,718	0	0
1440p	None	3,38	0	0
1440p	250M	4,191	0	0
1440p	500M	2,234	0	0
1440p	800M	2,523	0	0
2160p	None	1,981	69,117	80
2160p	250M	3,523	285,659	77
2160p	500M	3,255	122,723	23
2160p	800M	3,786	195,839	94

Again, InitialLoadTime increases with higher resolutions and when noise is introduced, as expected. Buffering happens only in heavy traffic conditions. Gold slice gets lower values than Best Effort slice, in some cases, with big difference.

4.3.3 End-to-End solution

The end-to-end solution has been tested in two different integration scenarios: i) Media capture and production, and ii) Media delivery. Besides, several application and infrastructure components include a real-time monitoring component, which is used to measure the relevant KPIs during the system operation.

1. ***Media capture and production tests: real-time production***

Media capture and production tests include the functionality of the use case from the captured scene in the cameras to the generation of the virtual view, including the real-time selection of the view by the remote operator. Functional tests have been done in the NPN environment to prepare the final trial and validation (to be reported in D5.3).

As described in section 4.1.3, all the systems were integrated and the whole end-to-end chain was validated. Three scenarios were validated: live production, live capture, and offline production.

Live production involved the following functionality:

- Real-time capture of a live scene with 9 FVV stereoscopic cameras connected to 3 capture servers.
- Uplink transmission of 3 capture servers through the 5G mmWave network to the MEC.
- Replication and distribution of streams within MEC from the stream selector to 2 different view renderers.
- Generation of 2 virtual views in parallel.
- Control of the 2 virtual views by 2 production consoles located in the 5G network.
- Delivery of the virtual views to the Media Proxy and Media Delivery systems.

- Generation of two HLS live streams in the Media Delivery, one for each rendered view.
- Simultaneous streaming of the two rendered views to two Media Players, located in the 5G network.

Live capture involved the following functionality:

- Real-time capture of a live scene with 9 FVV stereoscopic cameras connected to 3 capture servers.
- Uplink transmission of 3 capture servers through the 5G mmWave network to the MEC.
- Storage of the 9 RGB+D streams in the storage VNF.

Offline production involved the following functionality:

- RTP streaming of the 9 captured streams from the storage VNF to the stream selector VNF.
- Replication and distribution of streams within MEC from the stream selector to 2 different view renderers.
- Generation of 2 virtual views in parallel.
- Control of the 2 virtual views by 2 production consoles located in the 5G network.

2. Media Delivery tests: automatic slice change

Media delivery tests include the functionality of the use case from the output of the media renderer to the end client. In this second phase, a new feature was added and validated within the media delivery segment: automatic slice change.

Purple: RTT Blue: JITTER

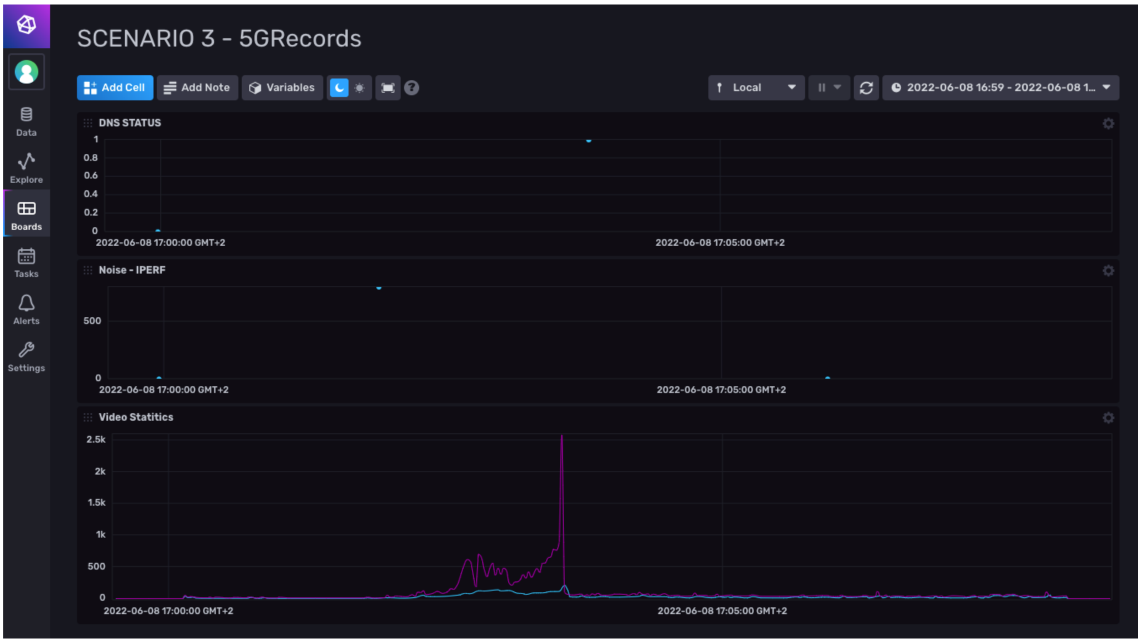


Figure 80. Video Stream BestEffort

This test is divided in 4 stages:

- Stage 1: Video stream is loaded from an IP with BestEffort QoS and without noise conditions. Values registered on this stage are the reference to compare with values on next stages.

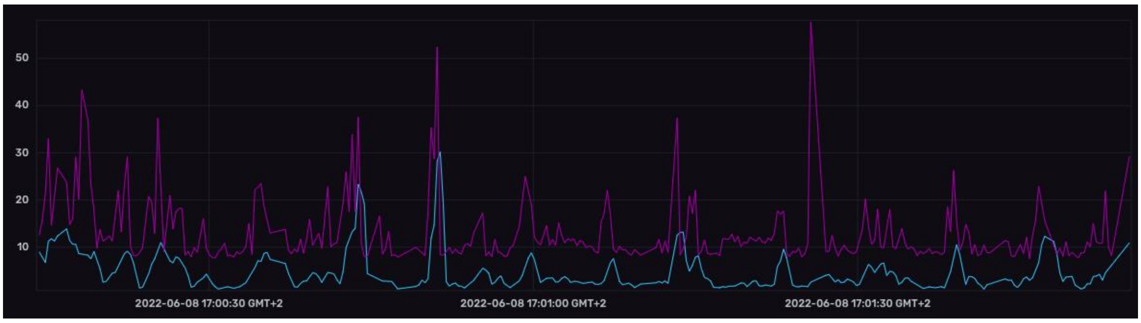


Figure 81. Video stream best effort

- Stage 2: Using IPerf, traffic is introduced into the communication channel to force congestion. As we can see, Jitter and above all the RTT increases its values.

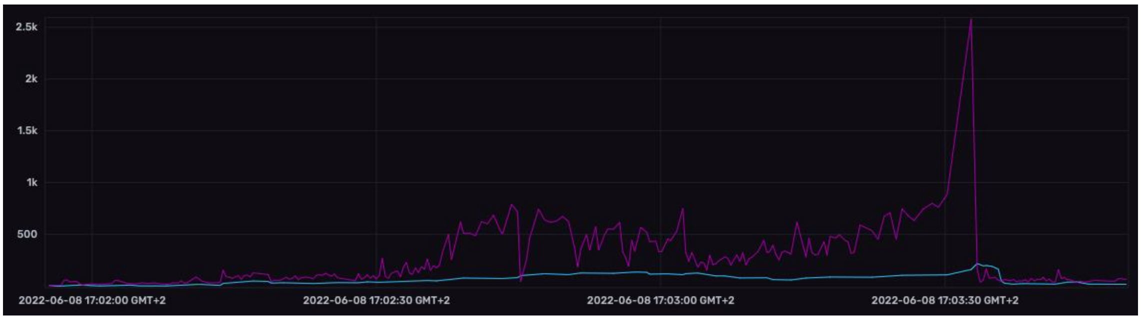


Figure 82. Video Stream BestEffort + Noise IPerf

- Stage 3: Still using IPerf, the slice is switched to another IP with GOLD QoS. In this stage the average values keep constant and much lower than in previous stage.

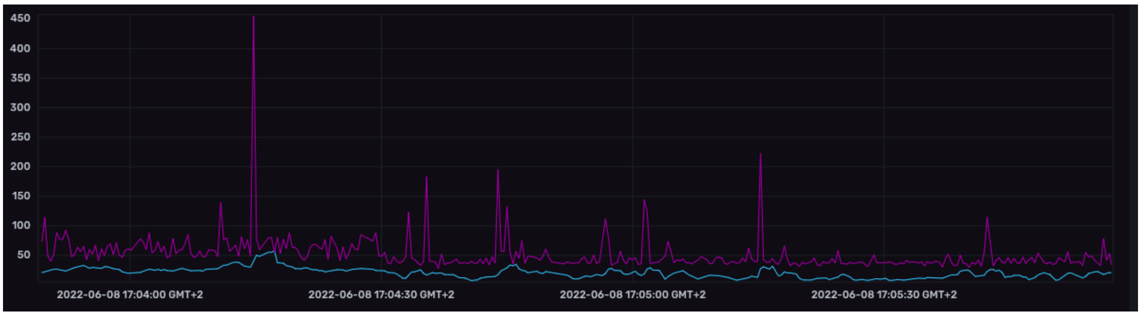


Figure 83. Video Stream Gold + Noise IPerf

- Stage 4: Without additional traffic (IPerf stopped), video stream continues loading from an IP with GOLD QoS. Without noise, values return to the same magnitude as in stage 1. In normal conditions, Gold and BestEffor slice are similar.

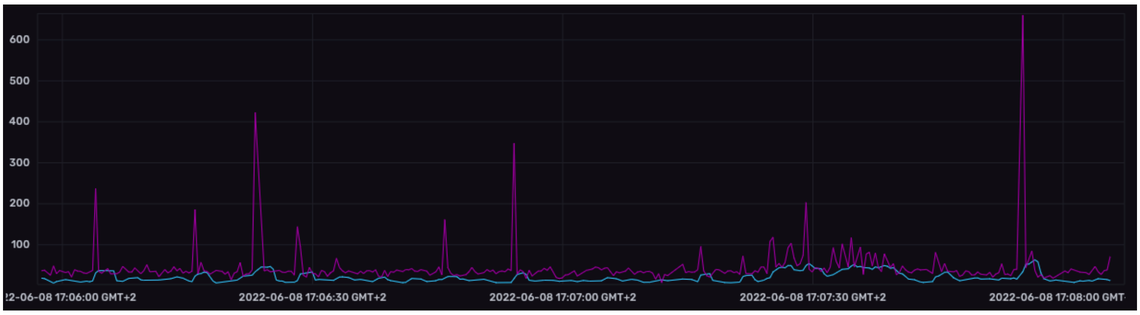


Figure 84. Video Stream Gold

3. Real-time application monitoring: Grafana

Both the infrastructure elements (network, computing, storage…) as well as the applications can report real-time measures to a monitoring server based on Telegraf, InfluxDB and Grafana stack. Two different servers are used to monitor the two segments of the system: production and delivery.

Production segment monitoring

The following measurements are used in the production segment:

Table 19. Measurements in the production segment

Measurement	Location	Periodicity	KPIs
fvv.cameras	View Renderer	500 ms	bytes, packets, lost packets
fvv.render	View Renderer	<50 ms	decoding time, render time
polyp	Media Proxy	10 s	Bit rate, loss rate, jitter, bytes, packets, lost packets

The following figure shows a dashboard with the production segment monitoring.

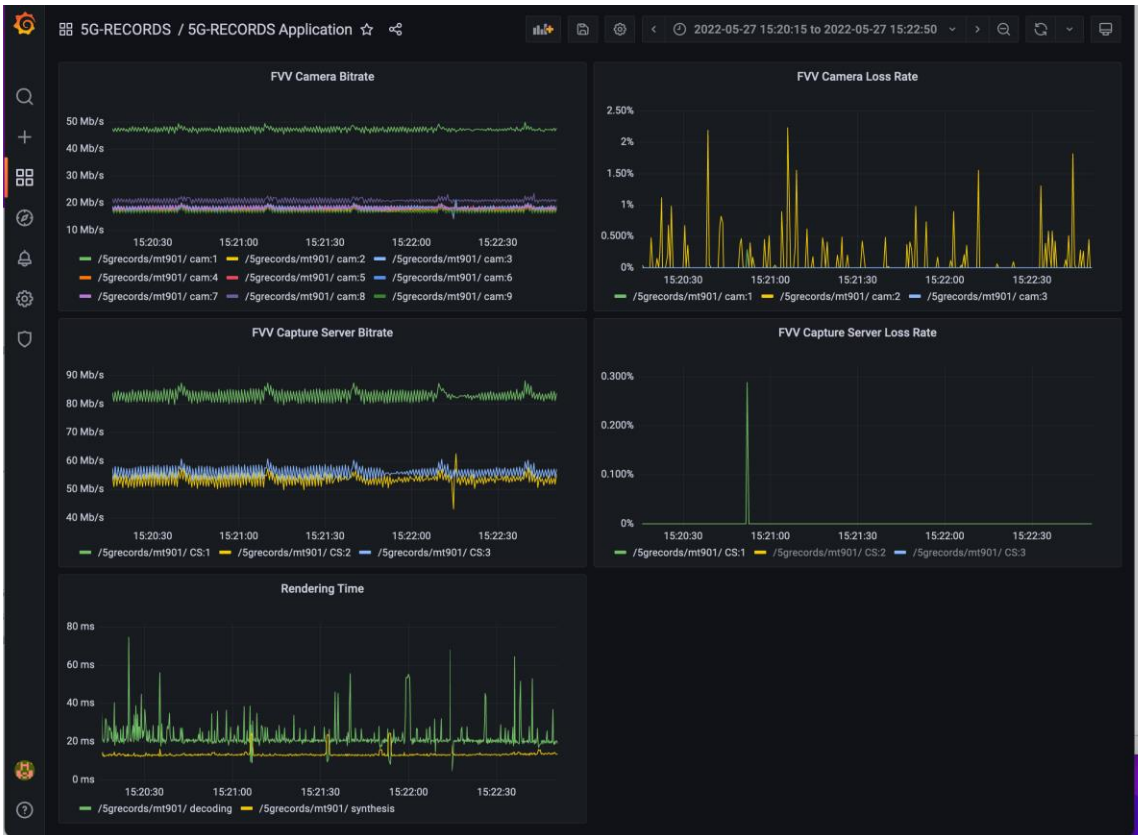


Figure 79. Grafana dashboard

Besides, standard system monitoring is performed in the infrastructure, both at MEC level and within all the VMs (5G core and VNFs):

- CPU usage (user/system/idle/…)
- Disk usage and Disk I/O (iops, writes, reads, bytes read and written…)
- Network, per interface (bytes sent, received, packets dropped, …)
- Memory
- …

The status of the radio cells is also monitored (both 4G and 5G).

<u>Delivery segment monitoring</u>

These are the metrics that can be logged from the web player against the media server

- RTT: is the amount of time it takes for a packet to be sent plus the amount of time it takes for acknowledgement of that signal having been received.
- JITTER: is the variation in latency as measured in the variability over time of the end-to-end delay across a network.
- pauseCount: Total number of Pause events triggered
- seekCount: Total number of Seek events triggered
- bufferCount: Total number of Buffer events triggered
- totalDuration: Total duration provided by the file
- watchedDuration: Total number of seconds watched, this excluses seconds a user has seeked past.
- bufferDuration: Total seconds that buffering has occured
- initialLoadTime: Seconds it took for the initial frame to appear

These are some examples of graphs during the execution of a test:

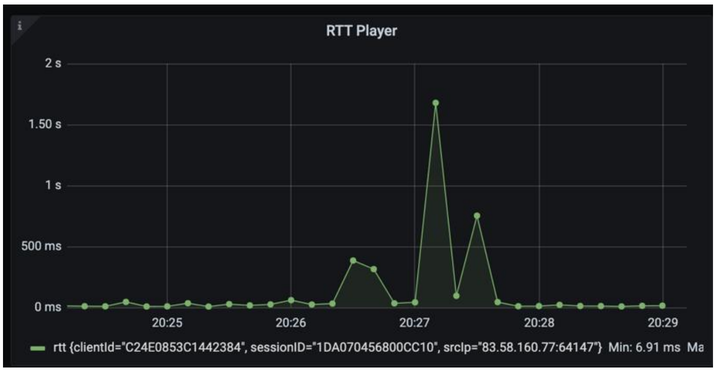


Figure 80. RTT evolution during a test

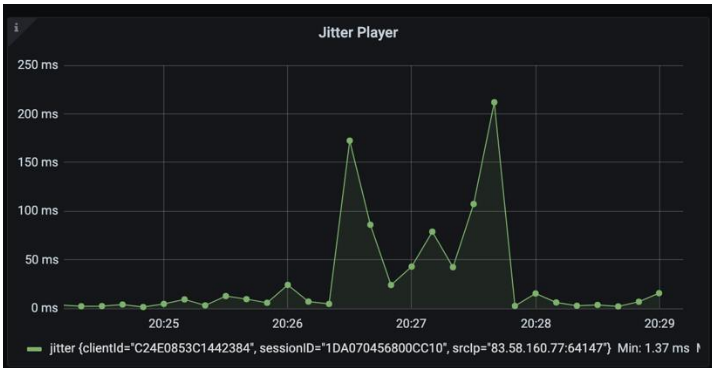


Figure 81. JITTER evolution during a test

Figure 82. Grafana's 5GRecords Player Dasboard

4.4 Infrastructure update

4.4.1 5G Radio Access, Core, and MEC

The network setup in Nokia has been updated to be able to support the new functionality, including:

- Compact 5G deployment with a NPN
- Simultaneous rendering of multiple views
- End-to-end slicing with QoS support in the RAN

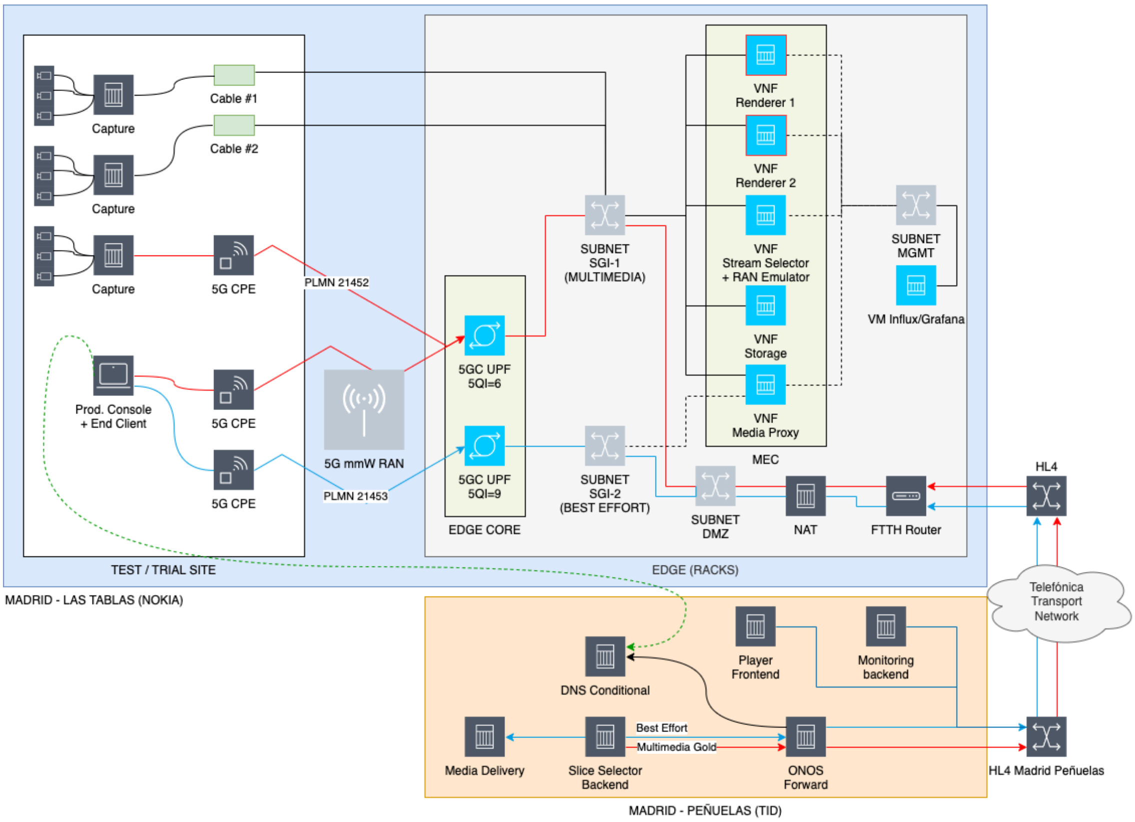


Figure 83. 5G Radio Access, core and MEC arquitecture

Due to the unavailability of mmWave equipment (particularly UEs) supporting 5G SA, the network has been configured using NSA.

A flexible configuration has been used to be able to support all the test cases.

The setup includes:

5G mmW gNB (Nokia AirScale). 5G uses FR2 band (n257), with 8 x 100 MHz CC in TDD configuration. LTE band is used for signaling (NSA). The radio is configured in MOCN mode for maximum flexibility. Two PLMNs have been created (21452, 21453).

5G CPEs for the Capture Servers, Production Console and End Clients. ISIM cards have been programmed to support the lab PLMNs.

Edge Core. A Nokia CNS supported low-footprint LTE/5G core has been installed on top of a Nokia AirFrame edge computing platform. Two core instances have been configured to support both PLMNs. Each core is configured using different QoS values (5QI/QCI): 6 and 9, for multimedia priority and best effort respectively.

MEC. Nokia AirFrame OpenEdge platform is used to support the different VNFs required in the project:

- Renderer. This VNF has full access to GPU (nVidia Tesla T4) to support the View Rendering functions.
- Stream Selector. This VNF implements the stream selector functionality. It also includes FikoRE RAN Emulator to be able to test several network configurations.
- Storage. It includes the capture server emulators used to support off-line FVV rendering
- Media Proxy. It runs the Media Proxy functions to send the uplink traffic to the Media Renderer in Madrid Peñuelas edge.

FTTH Access. Nokia Lab infrastructure is connected to Telefónica Transport network using a residential FTTH access. An intermediate (DMZ) network is used to isolate the traffic from the core/MEC networks. This network also provides internet access to the MEC VNFs and UEs.

Nokia 5G+MEC compact deployment is thus connected to the Edge Cloud location in Madrid-Peñuelas (Telefónica I+D laboratory).

4.4.2 Edge Cloud and SDN

There are minor changes on the architecture. Mainly E2E SDN still being the same and is defined based on these building blocks:

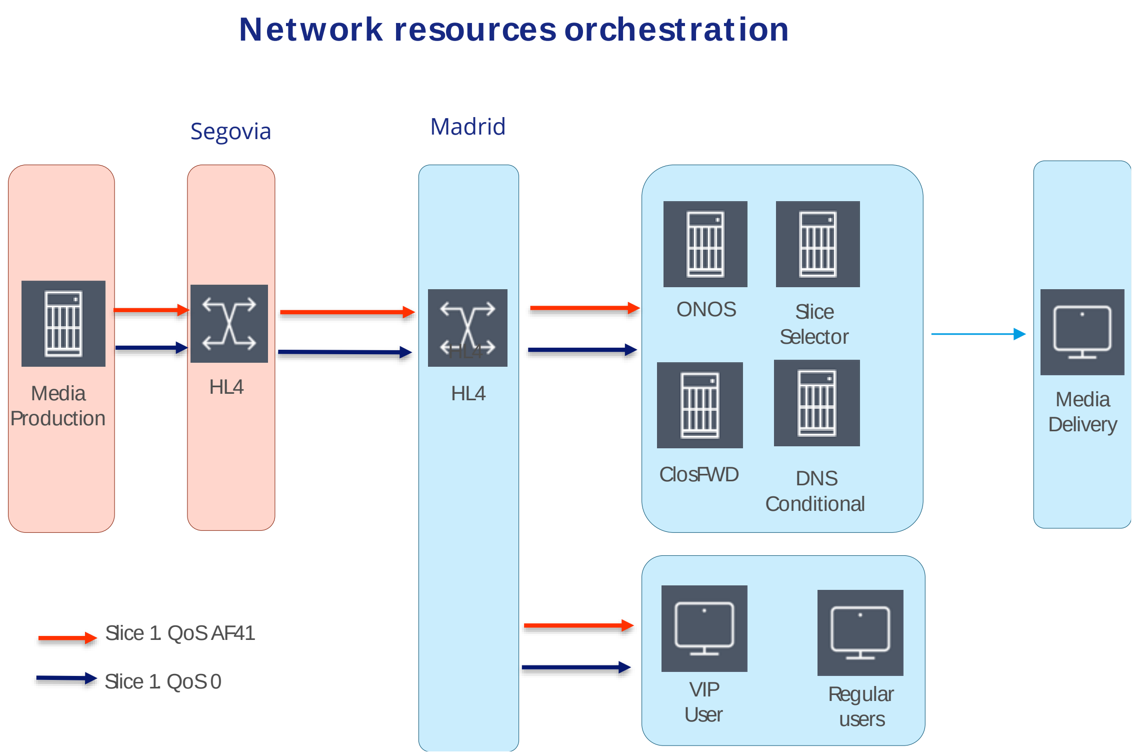


Figure 85. Network resources orchestration

- **ONOS**: used as the SDN controller, in charge of managing the switch fabric, as described in section “Network connectivity subsystem”.

- **ClosFwd**: application of the ONOS environment is responsible for managing the CLOS fabric of Edge Cloud switching.
- **Slice Selector**: Software component based on NGINX servers acting as reverse proxy with capability to redirect request to the correct slice based on the IP accessed and the URL. Combining server instances listening on different public interfaces and different VHOST to segment the traffic along the correct slice. It is connected to slices gold and best effort internal and external, and to the internal video delivery.
- **DNS Conditional**: implemented using opensource software bind and several views configuration in order to response correctly. That means that responses for VIP users will be different that for regular users.

There is a change on how the slice selector route the traffic between Segovia or Peñuelas Media delivery base on the URL that the end user uses to play de video stream. In previous version there was a mix between iptables rules + static routes + static ports. The current implementation is based on two NGINX (one for bestEffort and other for Gold), configured as reverse proxy with several virtual host to route traffic to different media servers based on the URL.

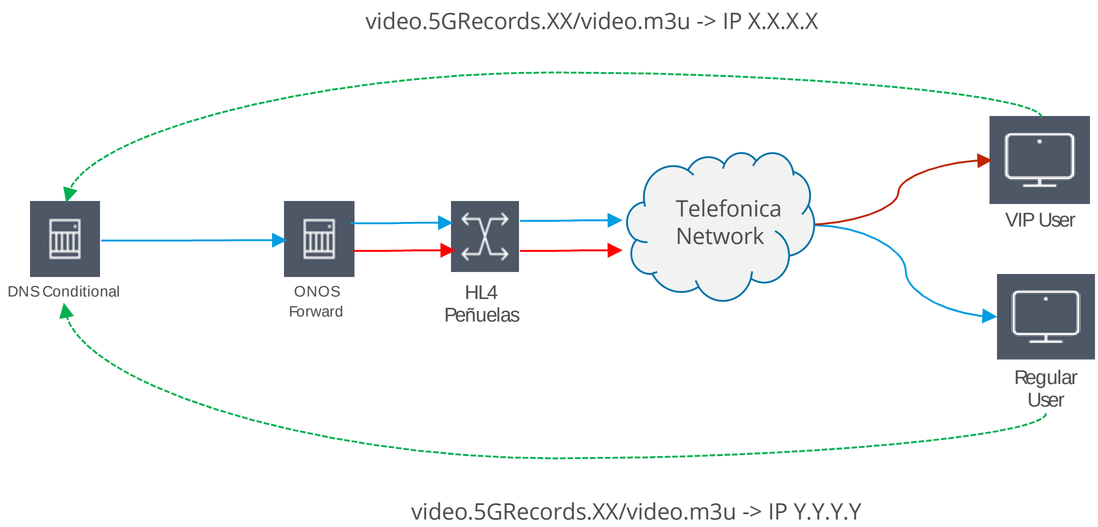


Figure 85. DNS conditional

5 Conclusion

This document described the final phase of integration and testing for the media components in the 5G infrastructures. The document builds on the first phase of integration plan described in D4.1 [2]. The document described for each use case the integration steps for several relevant components. To verify the functionality and the compliance of individual components, the document has also described the testing procedures for each component separately. As a final step for verifying the components integration, the document describes the E2E solution consisting of all the discussed components per use case.

The document has dedicated a section to discuss the updates of the tools and the KPIs described in D4.1 [2]. It also described the procedures and the phases of testing different components, and the evolution of the use cases along the project duration. This evolution is highlighted in multiple testing sessions organized by each use case to integrate the developed components and verify the KPIs. The document has discussed the result and the analysis of all each phase including the End-to-End solution evaluation.

5.1 Live audio production

Use case 1 has provided a detailed description of the integration of the 5G components. The CU and the core network GUI used for configuring the core was described in detail along with screenshots for the integration process. The CU and the OAI DU was successfully integrated over several stages in the Accelleran lab. The MIC and 5G UE was successfully integrated. After correctly configuring the device, the connection between different ANT devices is tested using Ping. The local audio processing and timing server are also integrated into the core network. The devices were connected directly to the core as a MEC. A detailed description of the network slice manager was provided along with the supported features and interfaces. The shared access client and shared access server for the configuration of the spectrum are tested. The use case has conducted several integration sessions and a single testing session using the EURECOM infrastructure. EURECOM has included the following features in its infrastructure

- Radio interface configurations (5ms and 2.5ms TDD configurations, URLLC MAC-layer scheduling)
- Time synchronization of radio, mobile-edge application and end-user application
- 3GPP compliant gNB-DU functionality (F1 interface)
- Integration of a test UE with the Sennheiser application framework
- OpenShift Cluster modifications to host Accelleran dRAX
- VM Provisioning on network to host Cumucore 5GC
- Network configuration to support remote access to Sennheiser devices their application measurement and monitoring tool

5.2 Multiple camera wireless studio

Use case 2 has provided a detailed description of the integration of the 5G components in the infrastructure. The 5G modem and the 5G network were successfully integrated and tested. The 5G modem attached to both slices and by testing its performance it was in line with the expected values. The MG and the MOCG was successfully tested outside the 5G lab. The focus is on the interaction between both components and the interoperability of the designed interfaces. 5CMM is working with Ericsson on providing a compact portable solution that can be used in field trials. 5CMM has provided detailed description for the process of building the setup.

For the remote production scenario, the LU800 was integrated successfully within the 5G network. After multiple upgrades for the LU800, it attached successfully to the network. The LU2000 and the SMPTE2110 network was upgraded to support the intercom test and the video quality tests. The 5CMM modem was also used as a backup modem with the LU800.

The End-to-End integration has tested the Jetson nano and Xavier as an encoder connected to the 5CMM modem, while the MG was connected to the UPF as a MEC and to the SMPTE2110 network. The use case tested the whole E2E solution and measured G2G latency using a specialized test setup using the oscilloscope. The use case has also tested time synchronization feature from release 17 using a special URLLC test bed from Ericsson.

The remote contribution scenario has run an evaluation of the video quality under different conditions and loads. They also tested the usage of network slicing and modem bonding.

Ericsson has upgraded its infrastructure to support the following features: a new test bed for time synchronization, network slicing, QoS, MEC and DDSU TDD pattern.

5.3 Live immersive media production

Use case 3 has run the integration process on different phases. During the first phase the integration between FVV live system and the 5G network took place, using a public 5G pilot deployment in Segovia. The second phase has started in March 2022 using camera simulators, both mmWave and emulated RAN access, 5G Core and MEC. The new configuration has also supported the portable setup. The final stage took place in April 2022 were 3 capture servers and 9 cameras were used. The functional test using 2 rendered views in parallel was done to verify the integration process. During May 2022 the integration with the delivery network and the transport network slicing was executed. The integration of the automatic QoS slice changes was tested. To verify the successful integration, the average packet losses, average bitrate and rendered virtual view was evaluated. The End-to-End integration was executed over different phases described in the document. The end-to-end solution has been tested in two different integration scenarios: i) Media capture and production, and ii) Media delivery.

Nokia has upgraded its infrastructure to support the following functionality: Compact 5G deployment, simultaneous rendering of multiple views and End-to-End slicing with QoS support in the RAN.

A Annex A

Registration procedure

Jan 27 13:20:42.582 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:127|sendHttpRequest|URL: https://81.255.146.119:443/v1.2/registration

Jan 27 13:20:42.582 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:147|sendHttpRequest|successfully sent: {"registrationRequest": [{"userId": "ACC-TEST-USERID", "fccId": "ACC-TEST-FCCID", "cbsdSerialNumber": "0002", "cbsdCategory": "A", "airInterface": {"radioTechnology": "NR"}, "installationParam": {"latitude": 61.170400000000001, "longitude": -150.01669999999999, "height": 0.0, "heightType": "AMSL", "indoorDeployment": false, "antennaAzimuth": 0, "antennaDowntilt": 0, "antennaGain": 6, "antennaBeamwidth": 360}, "measCapability": []}]}

Jan 27 13:20:42.868 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasStateTop.cpp:114|transition|content = {"registrationResponse":[{"cbsdId":"ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b","response":{"responseCode":0,"responseMessage":"SUCCESS"}}]}(0x7f47ac0986d4)

Spectrum Inquiry

Jan 27 13:20:42.868 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:127|sendHttpRequest|URL: https://81.255.146.119:443/v1.2/spectrumInquiry

Jan 27 13:20:42.868 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:147|sendHttpRequest|successfully sent: {"spectrumInquiryRequest": [{"cbsdId": "ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b", "inquiredSpectrum": [{"lowFrequency": 3550000000, "highFrequency": 3700000000}]}]}

Jan 27 13:20:42.953 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasStateTop.cpp:114|transition|content = {"spectrumInquiryResponse":[{"cbsdId":"ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b","availableChannel":[{"frequencyRange":{"lowFrequency":3550000000,"highFrequency":3560000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3560000000,"highFrequency":3570000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3570000000,"highFrequency":3580000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3580000000,"highFrequency":3590000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3590000000,"highFrequency":3600000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3600000000,"highFrequency":3610000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3610000000,"highFrequency":3620000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3620000000,"highFrequency":3630000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3630000000,"highFrequency":3640000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3640000000,"highFrequency":3650000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3650000000,"highFrequency":3660000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3660000000,"highFrequency":3670000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3670000000,"highFrequency":3680000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3680000000,"highFrequency":3690000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"},{"frequencyRange":{"lowFrequency":3690000000,"highFrequency":3700000000},"channelType":"GAA","ruleApplied":"FCC_PART_96"}],"response":{"responseCode":0,"responseMessage":"SUCCESS"}}]}

Grant Procedure

Jan 27 13:20:43.095 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:127|sendHttpRequest|URL: https://81.255.146.119:443/v1.2/grant

Jan 27 13:20:43.095 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:147|sendHttpRequest|successfully sent: {"grantRequest": [{"cbsdId": "ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b", "operationParam": {"maxEirp": 12.0, "operationFrequencyRange": {"lowFrequency": 3550000000, "highFrequency": 3650000000}}}]}

Jan 27 13:20:43.217 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasStateTop.cpp:114|transition|content = {"grantResponse":[{"cbsdId":"ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b","grantId":"cf37c153-a910-451a-8b95-dc7ec0875388","grantExpireTime":"2022-02-08T02:07:24Z","heartbeatInterval":10,"channelType":"GAA","response":{"responseCode":0,"responseMessage": "SUCCESS"}}]}

Heartbeat Procedure

Jan 27 13:20:43.220 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:127|sendHttpRequest|URL: https://81.255.146.119:443/v1.2/heartbeat

Jan 27 13:20:43.220 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:147|sendHttpRequest|successfully sent: {"heartbeatRequest": [{"cbsdId": "ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b", "grantId": "cf37c153-a910-451a-8b95-dc7ec0875388", "operationState": "GRANTED"}]}

Jan 27 13:20:43.296 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasStateTop.cpp:114|transition|content = {"heartbeatResponse":[{"cbsdId":"ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b","grantId":"cf37c153-a910-451a-8b95-dc7ec0875388","response":{"responseCode":0,"responseMessage":"SUCCESS"},"grantExpireTime":"2022-02-08T02:07:24Z","transmitExpireTime":"2022-01-27T12:24:44Z"}]}

Jan 27 13:20:52.299 wout-XPS user.info |0:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:127|sendHttpRequest|URL: https://81.255.146.119:443/v1.2/heartbeat

Jan 27 13:20:52.300 wout-XPS user.info |0:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:147|sendHttpRequest|successfully sent: {"heartbeatRequest": [{"cbsdId": "ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b", "grantId": "cf37c153-a910-451a-8b95-dc7ec0875388", "operationState": "AUTHORIZED"}]}

Jan 27 13:20:52.359 wout-XPS user.info |0:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasStateTop.cpp:114|transition|content = {"heartbeatResponse":[{"cbsdId":"ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b","grantId":"cf37c153-a910-451a-8b95-dc7ec0875388","response":{"responseCode":0,"responseMessage":"SUCCESS"},"grantExpireTime":"2022-02-08T02:07:24Z","transmitExpireTime":"2022-01-27T12:24:53Z"}]}

………. Heartbeats are repeated every 9 seconds from this moment on ………..

Grant Termination Procedure (Shared Access server triggered)

………. Heartbeats are repeated every 9 seconds until SAS Server triggers a grant termination with the "last" Hearbeat Response ………..

Jan 27 13:57:55.300 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:127|sendHttpRequest|URL: https://81.255.146.119:443/v1.2/heartbeat

Jan 27 13:57:55.300 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:147|sendHttpRequest|successfully sent: {"heartbeatRequest": [{"cbsdId": "ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b", "grantId": "cf37c153-a910-451a-8b95-dc7ec0875388", "operationState": "AUTHORIZED"}]}

Jan 27 13:57:55.411 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasStateTop.cpp:114|transition|content = {"heartbeatResponse":[{"cbsdId":"ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b","grantId":"cf37c153-a910-451a-8b95-dc7ec0875388","operationParam":{"maxEirp":-5.0,"operationFrequencyRange":{"lowFrequency":3550000000,"highFrequency":3650000000}},"response":{"responseCode":500,"responseMessage":"TERMINATED_GRANT"},"grantExpireTime":"2022-02-08T02:07:24Z","transmitExpireTime":"2022-01-27T13:01:56Z"}]}

Relinquishment and Deregistration Procedures

Jan 27 13:57:55.411 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:127|sendHttpRequest|URL: https://81.255.146.119:443/v1.2/relinquishment

Jan 27 13:57:55.411 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:147|sendHttpRequest|successfully sent: {"relinquishmentRequest": [{"cbsdId": "ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b", "grantId": "cf37c153-a910-451a-8b95-dc7ec0875388"}]}

Jan 27 13:57:55.555 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasStateTop.cpp:114|transition|content = {"relinquishmentResponse":[{"cbsdId":"ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b","grantId":"cf37c153-a910-451a-8b95-dc7ec0875388","response":{"responseCode":0,"responseMessage":"SUCCESS"}}]}(0x7f47ac093474)

Jan 27 13:57:55.555 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:127|sendHttpRequest|URL: https://81.255.146.119:443/v1.2/deregistration

Jan 27 13:57:55.555 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasFsm.cpp:147|sendHttpRequest|successfully sent: {"deregistrationRequest": [{"cbsdId": "ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b"}]}

Jan 27 13:57:55.640 wout-XPS user.info |4:2982815488|APPL_SAS | |-|application/spectrumAccessSystem/sas/module/sasStateTop.cpp:114|transition|content = {"deregistrationResponse":[{"cbsdId":"ACC-TEST-FCCID/c5e8754637504e5ebf868efc915ae09cb8ba1c3b","response":{"responseCode":0,"responseMessage":"SUCCESS"}}]}(0x7f47ac0a4454)

References

[1] R. Ortiz y E. Sanchez, «"Uses cases, requirements and KPIs", Deliverable D2.1, 5G-RECORDS project,» 2021.

[2] P. Perez, M. Fuentes y M. Skarp, «Integration of 5G components (phase 1),” Deliverable D4.1 v1.0, 5G-PPP 5G-RECORDS project,» July 2020.

[3] 3GPP, «29.514 - 5G System; Policy Authorization Service; Stage 3».