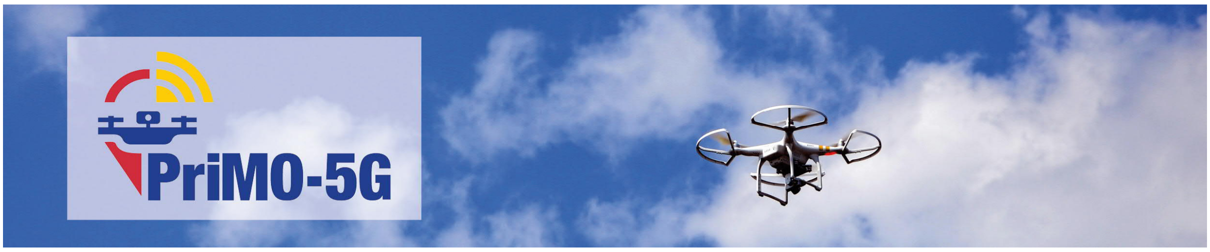

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D5.3 - FINAL REPORT – END-TO-END IMMERSIVE DEMONSTRATIONS

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Executive Summary

The PriMO-5G project aims to demonstrate an end-to-end 5G system providing immersive video services for moving objects. This is achieved by both local and cross-continental testbeds that integrate radio access and core networks developed by different project partners to showcase end-to-end operations of envisaged use cases, particularly those related to firefighting. The experimentation activities planned in PriMO-5G project has occurred in multiple phases, namely: initial component and early (sub)system demonstrations. This is then followed by demonstration of systems based on integrated components from different partners, and finally intercontinental demonstrations based on end-to-end systems deployed between Europe and Korea.

This deliverable D5.3 *Final report – end-to-end immersive demonstrations* presents the summary of the final results from the system integration and demo activities in the PriMO-5G project and spans the period M24 (June 2020) until the end of the project M36 (June 2021). The goal of these experimentation activities was to test and demonstrate key 5G developments in radio, edge and core networks in the context of PriMO-5G firefighting use cases. To that end, particular interest was to experimentally investigate 5G enhancements to provide immersive services (augmented, virtual or mixed reality, high definition video etc.) to firefighters with the support of unmanned aerial vehicles (UAVs) and robots.

A major effort in the project has been to develop demonstrations of large-scale system integration activities with multiple partners within Europe and Korea. These were referred to as intracontinental system integration targeting the interconnection of PriMO-5G testbeds between two European countries or between multiple partners in Korea. Furthermore, intercontinental demos interconnecting PriMO-5G testbeds between Europe and Korea were considered. In all cases, the end-to-end system demo scenarios have been specified and mapped to PriMO-5G firefighting scenarios (forest/rural and urban scenarios) and their respective use cases . The deliverable presents the details on the demo background, integration steps and an evaluation report with the results underpinned by key performance indicators (KPIs) relevant for the firefighting use cases. Many of the demos were also presented as pre-recorded videos at various events.

In addition to the system demos, some partners still had some stand-alone experimental activities taking place during the final year, that have served to provide further validation of key PriMO-5G technologies. Three such component demos are showcased in this deliverable with descriptions of the demo background, developments of the demo and the final results.

Finally, the PriMO-5G project noted that the concepts and solutions developed and experimentally validated within the project have potential impact not just in other public safety scenarios but could also be exploited for scenarios and use cases in other vertical segments. To that end, project analysed the applicability of demonstrated PriMO-5G concepts and solutions to other vertical segments. Moreover, the project created an additional end-to-end system demo leveraging the intercontinental setup to demonstrate the remote control a factory robot in an industrial facility in Korea with the robot operator in Europe.

In summary, the system integration and demonstration activities developed over the life span of the project have been notable in highlighting the potential of 5G for supporting demanding and critical operations. These activities have contributed to the development of technological innovations, as well as created new collaborations among the partners. The main achievements described herein have also been documented in several articles and demo videos showcased in various events as showcased in the project's website[1].

[1] https://primo-5g.eu/

List of Acronyms

Acronym	Definition
3GPP	Third Generation Partnership Project
5G	Fifth-Generation Mobile Network
5GC	5G Core Network
5G-NR	5G New Radio
AALTO	Aalto University
AGV	Automated Guided Vehicle
AF	Application Function
AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
AMF	Access and Mobility Management Function
ARFCN	Absolute Radio Frequency Channel Number
AUSF	Authentication Server Function
BM-SC	Broadcast Multicast Service Centre
BS	Base Station
CIoT	Cellular IoT
CMC	Cumucore
CRPI	Common Public Radio Interface
CSCF	Call Session Control Function
DL	Downlink
E2E	End to End
eNB	Evolved Node B
EPC	Evolved Packet Core
FRx	Frequency Range x (where x is 1 or 2)
FUNET	Finnish University and Research Network
GCS	Ground Control Station
gNB	Next Generation Node B
GRE	Generic Routing Encapsulation
GTP-U	GPRS Tunnelling Protocol User Plane

Acronym	Definition
GW	Gateway
HSS	Home Subscriber Service
IAP	IP Announcement Point
IoT	Internet of Things
IP	Internet Protocol
KAIST	Korean Advanced Institute of Science and Technology
KCL	Kings College London
KOREN	Korea Advanced Research Network
KPI	Key Performance Indicator
KU	Korean University
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control Layer
MBMS	Multimedia Broadcast/Multimedia Service
MCPTT	Mission Critical PTT
MEC	Multi-access Edge Computing
MIMO	Multiple-Input Multiple-Output
MME	Mobility Management Entity
MPLS	Multiprotocol Label Switching
NB IoT	Narrowband IoT
NI	National Instruments
NIB	Network-In-a-Box
NREN	National Research and Education Network
NRF	Network Repository Function
NSSF	Network Slice Selection Function
Nxxx	Corresponding service interface of the 5G network function, e.g., Nausf, Nnsf, Nnrf, Npcf, Nsmf, Nudm
ONAP	Open Network Automation Platform
OSM	Open Source MANO
PAL	Physical Abstraction Layer
PBCH	Physical Broadcast Channel

Acronym	Definition
PCF	Policy Control Function
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PHY	Physical Layer
PMCH	Physical Multicast Channel
PRACH	Physical Random Access Channel
PTT	Push-To-Talk
PxCCH	Physical Control Channel, x=uplink(u)/downlink(d)
PxSCH	Physical Shared Channel, x=uplink(u)/downlink(d)
QCI	QoS Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
QSFP	Quad Small Form-Factor Pluggable Transceiver
RAN	Radio Access Network
RLC	Radio Link Control
RRC	Radio Resource Control
RTP	Real Time Protocol
SCEF	Service Capability Exposure Function
SDN	Software Defined Networking
SFP	Small Form-factor Pluggable Transceiver
SMF	Session Management Function
SRT	Secure Reliable Transport
SSB	Synchronization Signal Block
TEIN	The Trans-Eurasia Information Network,
TRP	Transmission Reception Point
UAV	Unmanned Aerial Vehicle
UDM	Unified Data Management
UDN	Ultra Dense Network
UE	User Equipment
UL	Uplink

Acronym	Definition
UPF	User Plane Function
URLLC	Ultra-Reliable Low Latency Communications
V2X	Vehicle-to-Everything Communications
vEPC	Virtual Evolved Packet Core
VLAN	Virtual Local Area Network
VM	Virtual Machine
VNF	Virtual Network Function
VoLTE	Voice Over LTE
VR	Virtual Reality
WP	Work Package
YU	Yonsei University

1 Introduction

1.1 Scope of the document

The EU-KR PriMO-5G project involves partners from several countries from Europe and several partners from South Korea, who together are addressing objectives of the 'EUK-02-2018:5G' call in the area "a) Focus on mmWave and super broadband services". Specifically, the PriMO-5G project aims to demonstrate an end-to-end 5G system providing immersive video services for moving objects. This is achieved by both local and cross-continental testbeds that integrate radio access and core networks developed by different project partners to showcase end-to-end operations of envisaged use cases, particularly those related to firefighting.

The experimentation activities planned in PriMO-5G project will occur in multiple phases. In the initial phase, the focus is on testing and demonstrating the key enabling radio, edge and core network components and applications. The objective is to identify and demonstrate the capabilities of these sub-systems. The component demonstrations are essentially building on the existing commercial equipment, demonstration platforms and testbeds that the have been contributed by different European and Korean project partners. To that end, the component testing and demonstration activities provide insights on the capabilities of these components from the perspective of the end-to-end operations of the PriMO-5G use cases. Moreover, these activities enable the consortium members to identify and/or enhance the components needed for the subsequent system integration phase. The system integration phase is envisioned to occur over selected partner sites on Europe and Korea. Finally, in the third phase the testbeds on the European and Korean sides will be interconnected to demonstrate global applicability and feasibility of end-to-end operations of PriMO-5G use cases.

The first phase, described above, was documented in the deliverable D5.1 Demonstration Plan [PRIMO-D51] in June 2019. The second phase of WP5 efforts was reported in D5.2 Intermediate Report - Component Demonstrations and Integration Plan [PRIMO-D51]. It contained (i) documentation of the results of component demonstration, (ii) described the demonstration activities resulting from the integration of continental demonstrations spanning multiple European partners or Korean partners together with initial results, and (iii) presented a plan for an intercontinental system integration activity between Korean and European partners.

At present, the project is approaching the end and this final deliverable of WP5 contains the main results from the various demonstration activities. More specifically, we document the results from the system integration activities and demonstrations related to the continental demos, as well as the intercontinental PriMO-5G system integration activities. Additionally, results from a few stand-alone demonstration activities are provided.

1.2 Structure of the document

The remainder of Section 1 outlines the linkages to other project outcomes and provides a high-level overview of the implemented PriMO-5G system demos. Thereafter, Section 2 documents the results from the continental integration activities between multiple European and Korean partners. Section 3 presents the results of the intercontinental PriMO-5G system integration activities. The outcomes of a few standalone component are given in Section 4. Section 5 provides an overview of possible other verticals, where PriMO-5G technology can be exploited, together with an example. Conclusions are provided in Section 6.

1.3 Relationship to other project outcomes

The overall work structure of PriMO-5G project is illustrated in Figure 1. In this work structure, WP1 specifies the PriMO-5G firefighting use cases that inspired research and technology developments in WP2, WP3, and WP4. Thereafter, WP5 builds on outcomes of WP1-WP4 to develop component, local and cross-continental testbeds to demonstrate end-to-end operations of 5G system for PriMO-5G WP1 use cases.

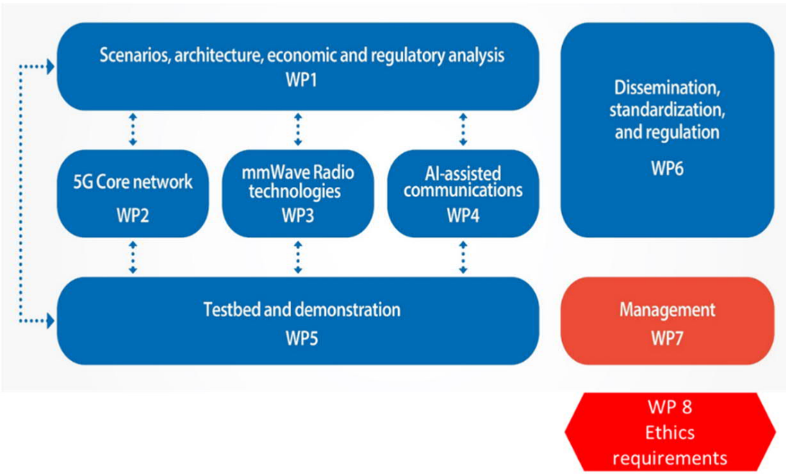


Figure 1 PriMO-5G work structure.

A particularly strong link is with WP1, whereby, this deliverable presents a plan for end-to-end system demonstrations derived from PriMO-5G firefighting scenarios and use cases described in *D1.1 PriMO-5G Use Case Scenarios* [PRIMO-D11]. These include two scenarios, namely:

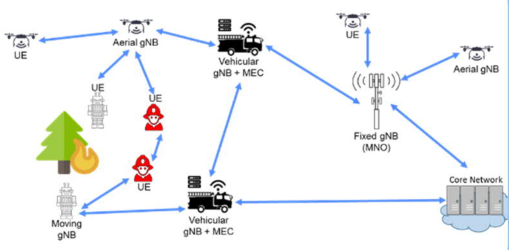
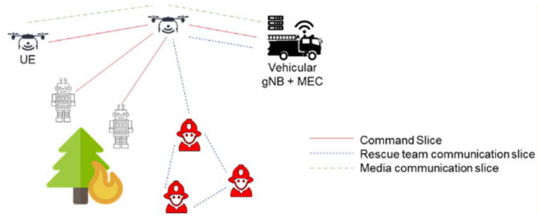
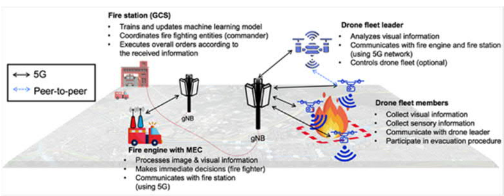
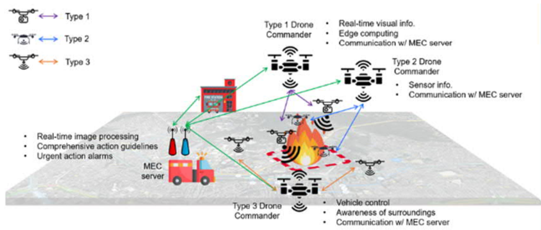
- Scenario A: Forest firefighting (in rural areas) with robots and unmanned aerial vehicles (UAVs)[2]
- Scenario B: Smart firefighting with UAVs in urban area

Each of these scenarios having two associated use cases, each addressing some specific operational requirements, which result in technical challenges and associated solutions or innovations proposed by the project.

Table 1 provides a summary description of the use cases that are considered in the PriMO-5G system and intercontinental demonstrators.

[2] The terms UAV and drone may be used interchangeably in this report

Table 1 PriMO-5G scenarios and use cases

Scenarios	Use cases	
Scenario A: Forest firefighting with robots and UAVs	*Use case A1. Placement of communication and computing for forest firefighting* 	*Use case A2. Network slice management for forest firefighting* 
Scenario B: Smart firefighting with UAVs in urban area	*Use case B1. UAV-assisted preparatory measures for smart urban firefighting* 	*Use Case B2. Differentiated UAV fleet management for smart urban firefighting* 

1.4 High-level overview of PriMO-5G system demos

The end-to-end system demonstration activities in PriMO-5G are organized into four local or intracontinental demos (Demos 1-4) and two intercontinental demos (Demos 5/6) as illustrated in the overall demos picture of Figure 2. Each of these demos involves multiple partners from either Europe or Korea, or both. The involved partners are indicated in the name of each demonstration, except for the intercontinental demo which includes CMC, YU and AALTO. The coverage of these demos addresses PriMO-5G use cases in both rural/forest and urban firefighting scenarios recalled in Section 1.3. The exact mapping the system demos to different use cases and further details of the local/intracontinental and intercontinental demos is provided in Section 2 and Section 3, respectively.

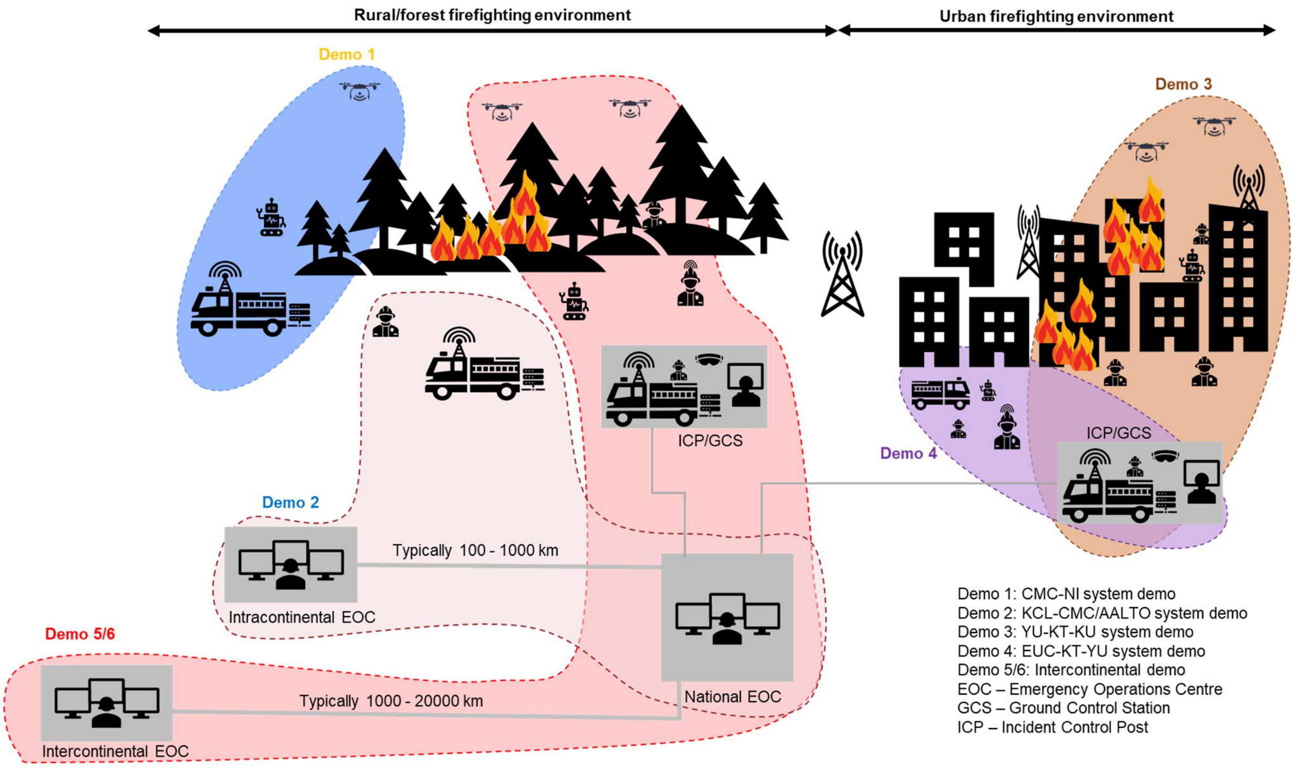


Figure 2 Overview of PriMO-5G end-to-end system demos

2 Local and Intracontinental System Integration Results

2.1 Overview

In this section, we provide the final results from the intracontinental system integration activities and demonstrations involving multiple partners in Europe or Korea. There are four demonstrations, with two involving European partners and two involving Korean partners, and they are listed below:

- Demo 1: CMC-NI system integration and demonstrations (Section 2.2)
- Demo 2: KCL-CMC system integration and demonstrations (Section 2.3)
- Demo 3: YU-KT-KU system integration and demonstrations (section 2.4)
- Demo 4: EUC-KT-YU system integration and demonstrations (Section 2.5)

The involved partners are indicated in the name of each demonstration. For each demonstration, in the following sections, we provide background information with a short description of the system, an integration report with information about the test set up and environment and the evaluation report containing documentation of the results.

Each demonstration, as listed above, is related to one or more use cases listed below:

- A1: Placement of communication and computing for forest firefighting
- A2: Network slice management for forest firefighting
- B1: UAV-assisted preparatory measures for smart urban firefighting
- B2: Differentiated UAV fleet management for smart urban firefighting

The use cases details are summarized in Section 1.3 and described in more detail in D1.1 [PRIMO-D11]. The summary of how each demonstration maps to the use cases is given in Table 2

Table 2 Mapping of intracontinental demonstrations to PriMO-5G use cases

Demo/Use case	A1	A2	B1	B2
Demo 1	X			
Demo 2			X	
Demo 3			X	X
Demo 4			X	

2.2 CMC-NI System Integration and Demos

This section summarizes the demo and integration activities from the intracontinental demo with partners CMC and NI.

2.2.1 Background of the Demo

The objective of the overall integration and demo efforts of CMC and NI is to showcase the integration of the CMC 5G core towards the mmWave capable 5G gNB from NI. The following components are part of this demonstration:

- CMC 5G Core
- NI 5G NR gNB stack with mmWave physical abstraction layer (PAL)
- NI 5G NR UE stack with mmWave PAL
- NI 5G NR gNB MAC-Stub with 26 GHz mmWave 8x8 antenna array
- NI 5G NR UE MAC-Stub with 26 GHz mmWave 2x8 antenna array

These components have been used to integrate and showcase the PriMO-5G objectives in two different setups:

- *5G NR mmWave Transceiver*: It shows the integration of the 26 GHz mmWave active antenna arrays to NI 5G NR gNB and UE. A real-time antenna array control is implemented, which is used by 5G NR protocol stack, represented by MAC-Stubs of gNB and UE, for beam steering.

- 5G Core and gNB/UE Setup: It shows the integration of the CMC 5G core with the NI 5G NR gNB. In this test, the CMC 5G core is running in NI premises with NI gNB, which is running locally in Germany. The objective is to test the interoperability between a 5G core and NI mmWave gNB with PAL setup.

2.2.2 Integration report

The integrated systems of the two demo setups are shown in Figure 3. It shows a visualization of the complete 5G NR End-to-End mmWave demonstrator, which has been split up into two sub-demos:

- Sub-Demo A: 5G NR mmWave Beam Management Demonstrator
- Sub-Demo B: 5G Core and gNB/UE integration

The sub-demos are described in the following subsections.

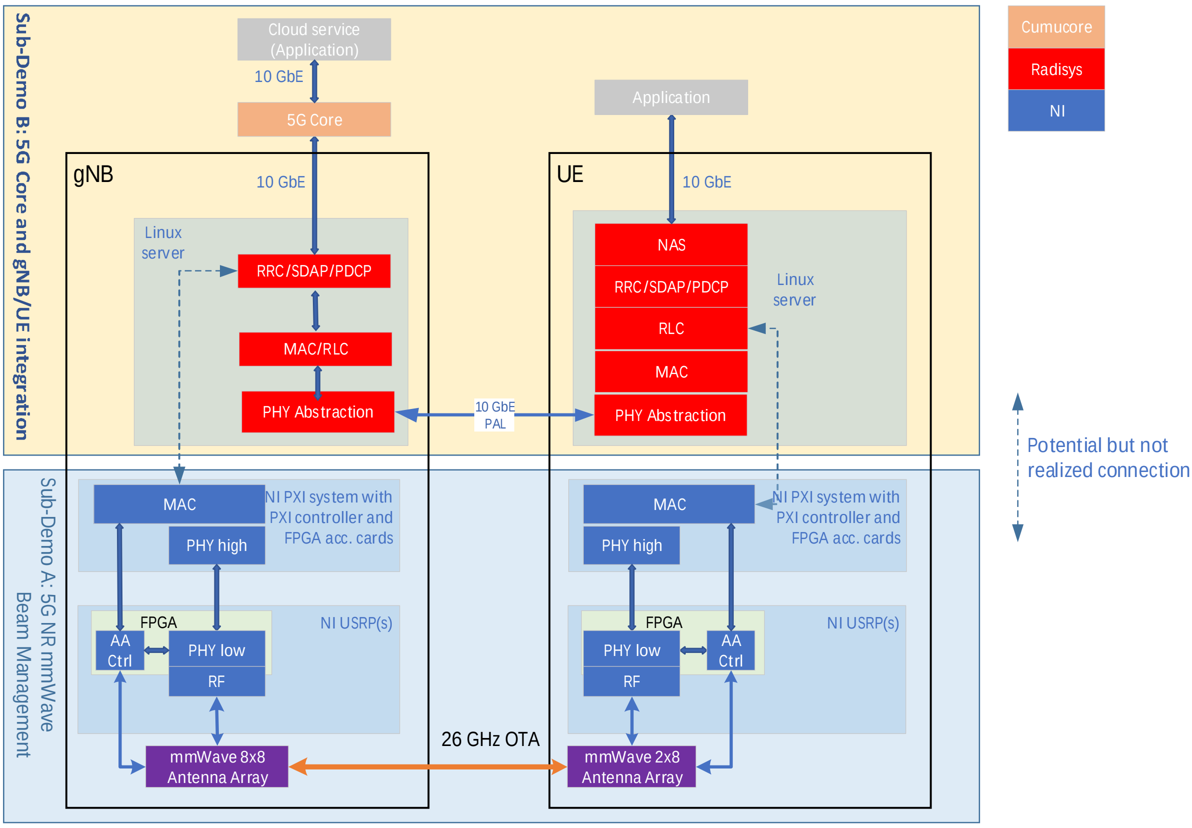


Figure 3 NI's two sub-demos and their potential connection to each other

Sub-Demo A - 5G NR mmWave Beam Management Demonstrator

This sub-demo is a result of the activities in Work Package 3. The goal of this integration effort is the inclusion of the mmWave active antenna arrays on both gNB and UE sides. This is depicted as the attachment of the 8x8 active antenna array on the gNB side as well as the 2x8 active antenna array on the UE side. The components of NI mmWave transceiver system used in PriMO-5G is described extensively in Section 2 of deliverable D3.2 of PriMO-5G [PRIMO-D32]. The novel mmWave transceiver design is presented in Section 3.2.2 of Deliverable D3.3 [PRIMO-D33]. For beam steering in 5G NR, a real-time antenna array control with hard switching rate based on 3GPP specifications is required as described in Section 3.2.1 of Deliverable D3.3 [PRIMO-D33]. The designed Real-Time Antenna-Array-Agnostic Control is integrated into the MAC-Stub and PHY of gNB and UE as it is shown in Figure 3, which is described in detail in Section 3.2.3 of Deliverable D3.3 [PRIMO-D33].

In Sub-demo A, the layers up to the MAC layer on gNB and UE are covered as it is shown in Figure 3[3]; since these are the layers where control functionality for the beam management had to be integrated into the system. The MAC-Stub beam management extensions and procedure are presented in Sections 3.3.5.2 and 3.2.6 of Deliverable D3.3 of PriMO-5G [PRIMO-D33]. As the demonstration of this setup includes an over-the-air transmission in the mmWave band, we plan to use parts of the spectrum in the 5G NR band n258. Besides that, the demonstration of this setup will also incorporate mild mobility according to the use case mentioned in Section 2.2.3. Due to the overall weight of the setup, an attachment to a drone is not possible so a modeling of mobility in the demo setup needs to be achieved by mobile carts at ground level or similar.

Sub-Demo B - 5G Core and gNB/UE Integration

This sub-demo is a result of the activities in Work Package 2. It consists of the CMC 5G Core network and a gNB and UE Simulator designed for mmWave frequencies in stand-alone mode. The interoperability of these components is demonstrated using the full NI 5G gNB and UE stack but without the mmWave PHY layer and active antenna arrays. Instead, a physical abstraction layer (PAL) is used. Figure 4 shows the setup. The PriMO-5G Final Core Interoperability Report D2.5 [PRIMO-D25] gives more details about the integration activities in Section 4.2. The PAL setup helps to still work with a complete 5G NR stack for integration but have a setup at hand that does not involve over-the-air transmission and therefore does not rely on RF licenses to be used. The 5G core by CMC could then be directly attached to the system. Various possibilities for MEC setups were investigated that were subject to a final demonstration according to the use cases considered. The partitioning of components to different server hardware has been investigated, which should be sufficient for the requirements of

[3] Additional description of the vertical 5G NR UE stack integration is also available in project's YouTube channel via this link https://www.youtube.com/watch?v=txwsQrXu9_Q

the final demonstration setup.

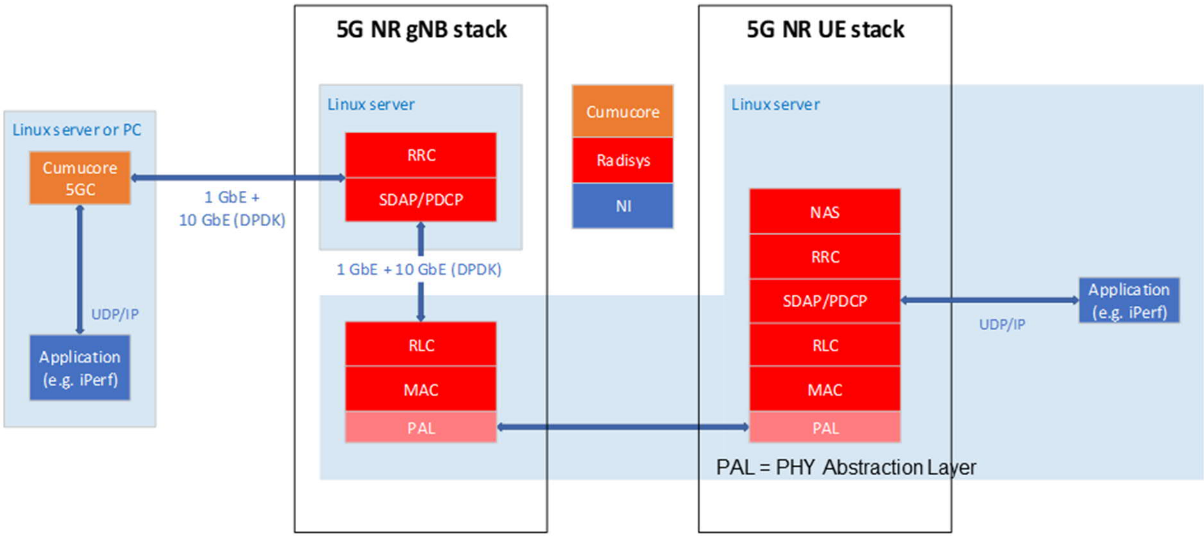


Figure 4 Integration and demo setup for 5G Core integration with 5G mmWave gNB and UE

2.2.3 Demo scenarios and evaluation report

Sub-Demo A - 5G NR mmWave Beam Management Demonstrator

The NI 5G mmWave transceiver system setup is used to showcase a forest fire fighting scenario as in Scenario A from D1.1 [PRIMO-D11]. An incident commander in the fire truck is connected to a stationary access drone that acts as an aggregation point for uplink video streaming of surrounding video capturing drones. These video capturing drones are observing the forest fire scene and produce a video stream in the uplink towards the aggregating stationary access drone. This drone collects the different video streams and forwards the information to the incident commander for further processing. As the aggregation of video streams will require a high bandwidth, the 5G mmWave links properties of high bandwidth are favorable for these requirements. The demonstration will focus on showcasing the mmWave link and beam steering functionality while the link from the stationary access drone to the video capturing drone will be abstracted with video application.

Figure 5 shows the expected PriMO-5G mmWave Beam Management Demonstrator. Since the equipment used by NI is too big and too heavy for being installed on a drone, we use a land-based robot which is connected to the gNB side of the Beam Management Demonstrator via LAN. However, just like the drones from the PriMO-5G firefighting scenario this robot can be controlled remotely: A Linux PC equipped with a game controller is connected to the UE via LAN and sends the robot control packets via UDP in the uplink direction. The UE system is installed on a movable cart which – with the limitations of the power cord and network cable length – demonstrates the ability of the Beam Management to handle mobility. The robot is equipped with a camera which provides a UDP video data stream in the downlink direction which is displayed on the robot control PC again. While one user controls the robot and gets the feedback from the camera, another user moves the UE cart. The application remains stable. With this, Beam Management, and low latency together with high data rate are demonstrated.

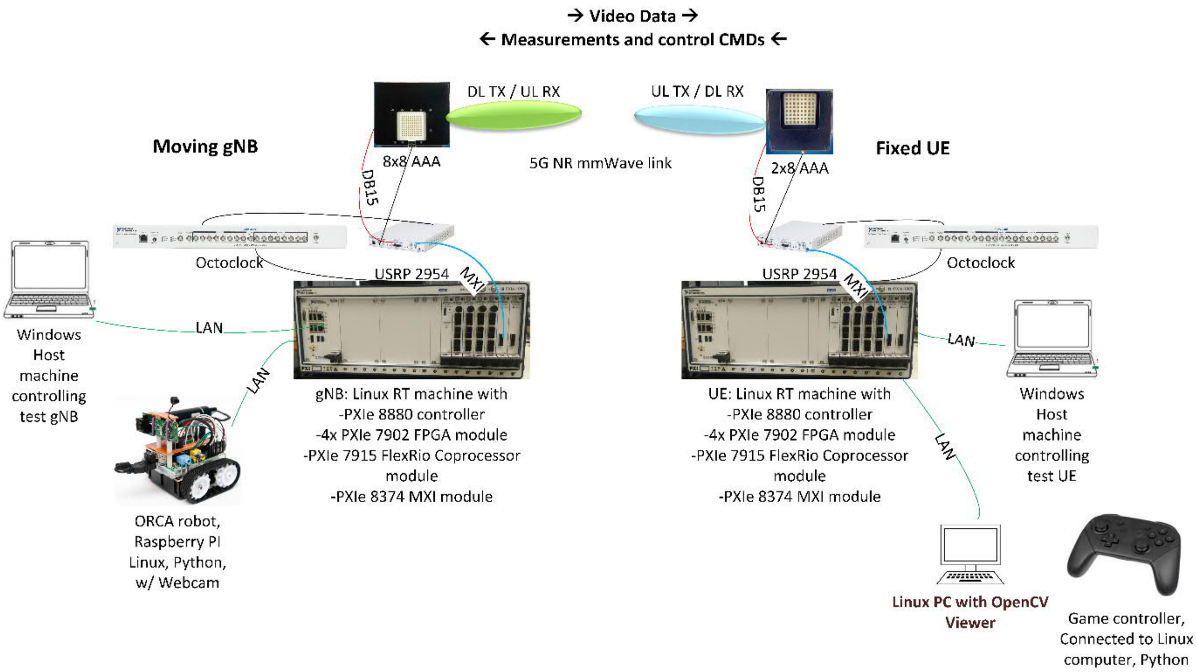


Figure 5 PriMO-5G mmWave Beam Management Demonstrator.

Continued developments of the demo

Since the last reporting period concluding with D5.2 [PRIMO-D52], considerable amount of progress has been made: The real-time antenna-array-agnostic control is implemented and integrated to gNB and UE, all the necessary mmWave components have been characterized, the integration of the mmWave components into the PHY subsystems on gNB and UE has been done, the required PHY and MAC-Stub extensions have been implemented towards 5G NR FR2 and beam management. The DL and UL data transmission has been enabled. The required beam management on gNB and UE is implemented. It includes initial beam establishment, beam adjustment based on UE and gNB beam schedulers, and beam failure recovery procedures.

Evaluation report

The gNB and UE are running in a lab environment as it is shown in Figure 6. The gNB mmWave antenna array has a fixed location while the UE mmWave antenna array is installed on top of a telescope movement unit.

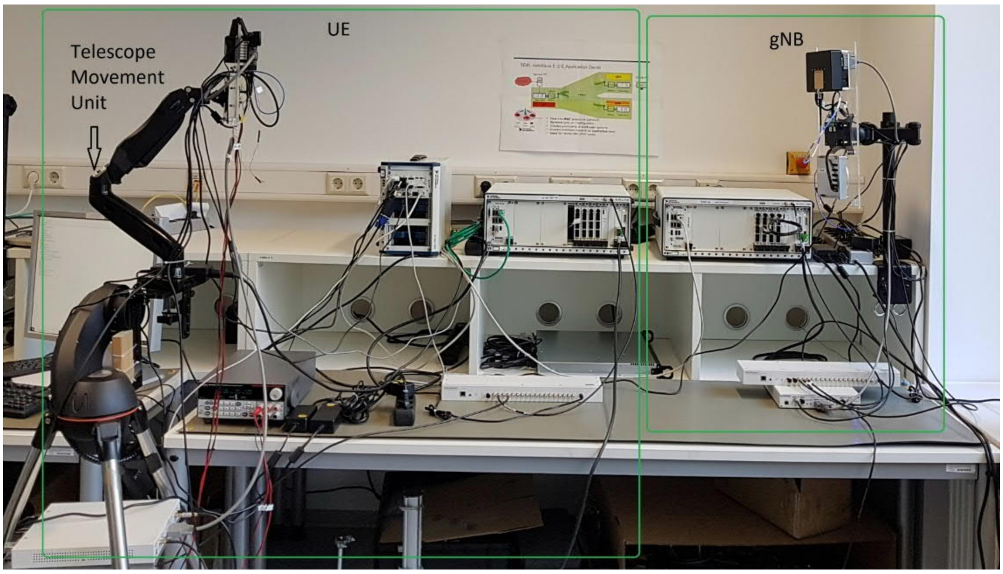


Figure 6 Physical setup of gNB and UE in the demo.

The system has been parametrized as in Table 3. The 5G NR 3GPP Rel-15 compliant waveform has a subcarrier spacing = 120 kHz, 64QAM as modulation scheme and the usage of PTRS is not enabled. The used modulation and coding scheme is number 25 based on Table 5.1.3.1-1 of TS 38.214 [3GPP-TS38214]. The TDD slot type [DDDDDDDSUU] is used and all DL slots in the second half of the frame are occupied with Data using MCS number 25, the expected PHY throughput is 124.6 Mbit/s.

Table 3 System Parameters

Parameter	Value
IF frequency	3,34938 GHz
RF frequency	28,03296 GHz
SSB center ARFCN	2079163
DL and UL pointA ARFCN	2078923
component carrier bandwidth	100 MHz
choice for *ssb-PositionsInBurst*	Long (64 SSBs)
PRACH configuration index	10
ssb-perRACH-Occasion	1

dmrs-TypeA-Position	2
number of layers	1
physical resource blocks (PRB)	66
number of scheduled OFDM symbols per slot	11 (1…11)

During the initial beam establishment, the UE goes through all DL RX beams, and after every beam update, it scans the RX frame to identify the SSB with the highest SS-RSRP. Each SSB is transmitted by a different beam ID from the gNB. At this stage, the UE finds the proper gNB DL TX beam, represented by SSB-index, and UE DL RX beam. For more details, see Section 3.2.6 of mmWave Beam Management Prototyping in deliverable D3.3 [PRIMO-D33]. Figure 7 shows a snapshot from the UE beam management status tab. It shows the DL RX and UL TX beam direction, since beam reciprocity is existing, DL RX and UL TX beam ID, SSB index preferred on UE, SSB measurements, and beam management stage. In addition, it shows the UE Beam Tracker State, which can be in “Connected”, “Probing”, or “Degraded” mode. In this test, the DL RX beam ID number 28 (Azimuth angle = 12° and Elevation angle = 0°) is the proper one; the SS-RSRP is -44.7 dBm. The SSB index is 40. The UE should report the PRACH on odd frames on a specific slot number and OFDM symbol start index based on the preferred SSB index. The PRACH occasion is used then on the gNB to identify the SSB index preferred on the UE side. The beam ID of this SSB index is used on the gNB for data transmission and reception.

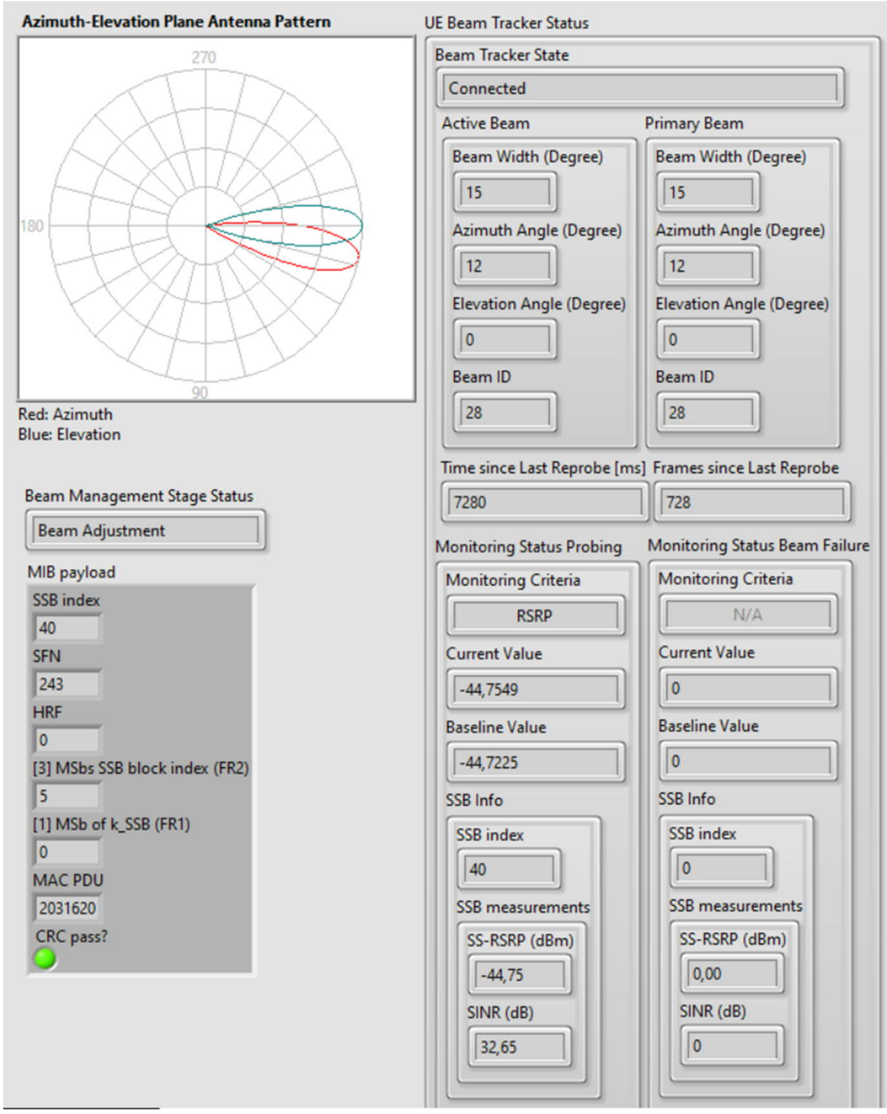


Figure 7 Snapshot from Beam management status tab on UE MAC-Stub (DL RX and UL TX beam direction, related beam ID, SSB index, SSB measurements, and beam management stage)

The PRACH reception on gNB terminal is shown in Figure 8, where the slot number, OFDM start symbol index, and the number of timing advance are presented.

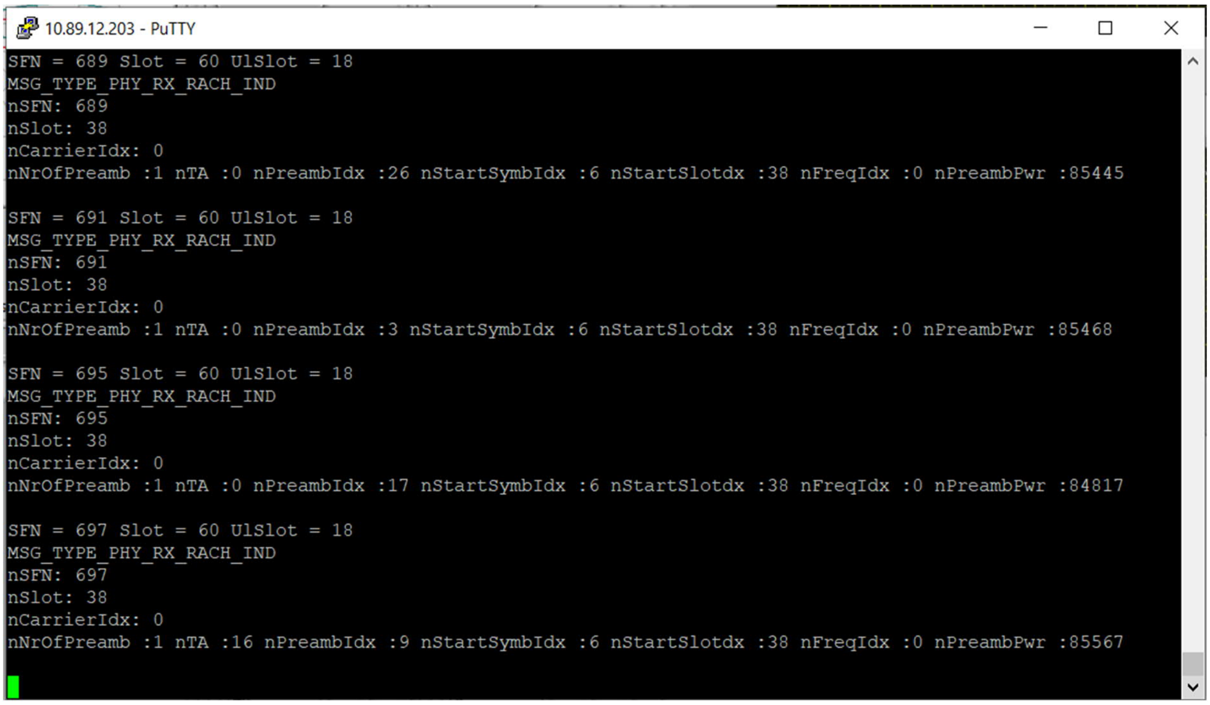


Figure 8 gNB Terminal showing the PRACH reception.

Figure 9 shows a snapshot from the gNB beam management status. It shows the DL TX and UL RX beam direction, since beam reciprocity is existing, DL TX and UL RX beam ID, SSB index preferred on UE side, and beam management stage. In more detail, it shows the measurement report transmitted from UE to gNB. The measurement report has been configured to report the best four SSBs measured on UE side. The best four SSBs in this test are SSB1 (index = 40, RSRP= -47 dBm), SSB2 (index = 49, RSRP= -52 dBm), SSB3 (index = 36, RSRP= -56 dBm), SSB4 (index = 57, RSRP= -58 dBm). The gNB terminal shows the reception of measurement report from UE as it is presented in Figure 10. The SSB index that is used for data and control channel transmission is number 40; where this SSB is transmitted on gNB Beam ID of 61 (Azimuth angle -12 and Elevation angle 0).

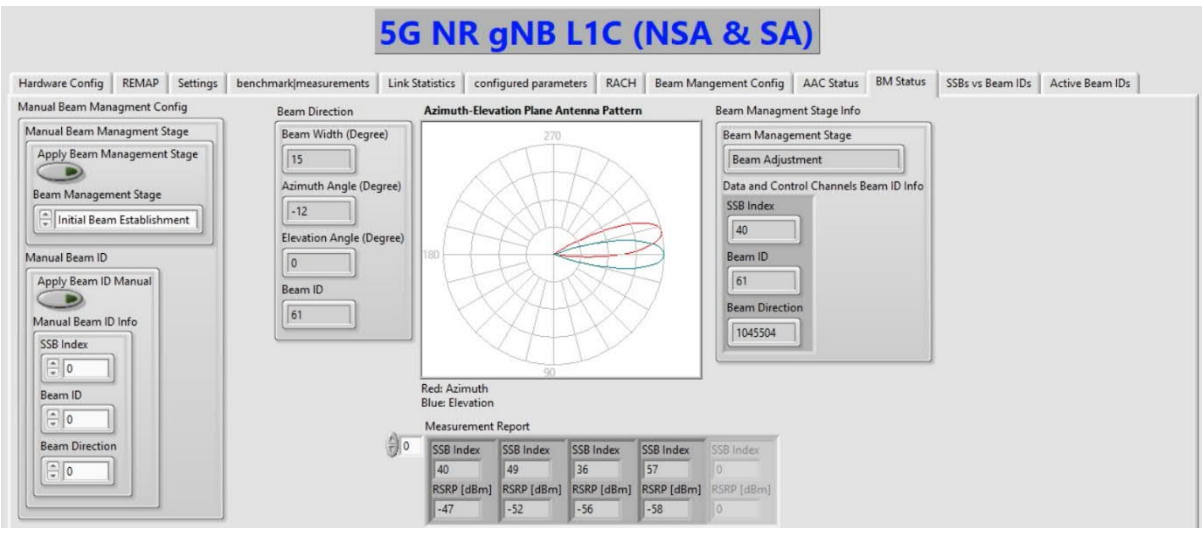


Figure 9 Snapshot from Beam management status tab on gNB MAC-Stub (DL TX and UL RX beam direction, related beam ID, SSB index preferred on UE side, and beam management stage)

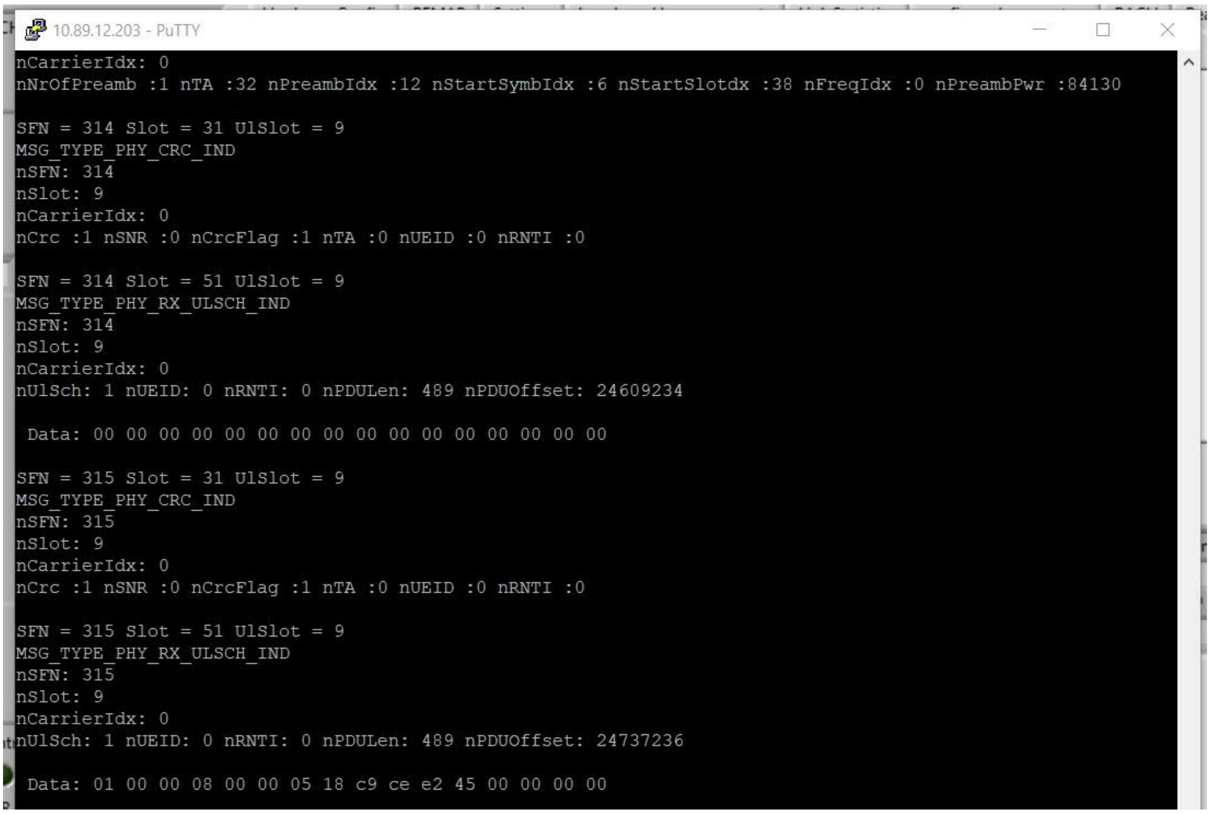


Figure 10 Snapshot from gNB terminal showing the reception of measurement report.

Figure 11 shows the UE GUI, which shows that the 5G NR Test UE reaches a PDSCH throughput of 124.6 Mbit/s. A measured averaged EVM of approximately -26 dB would allow the usage of 64QAM as modulation scheme while spectrum emission mask is kept.

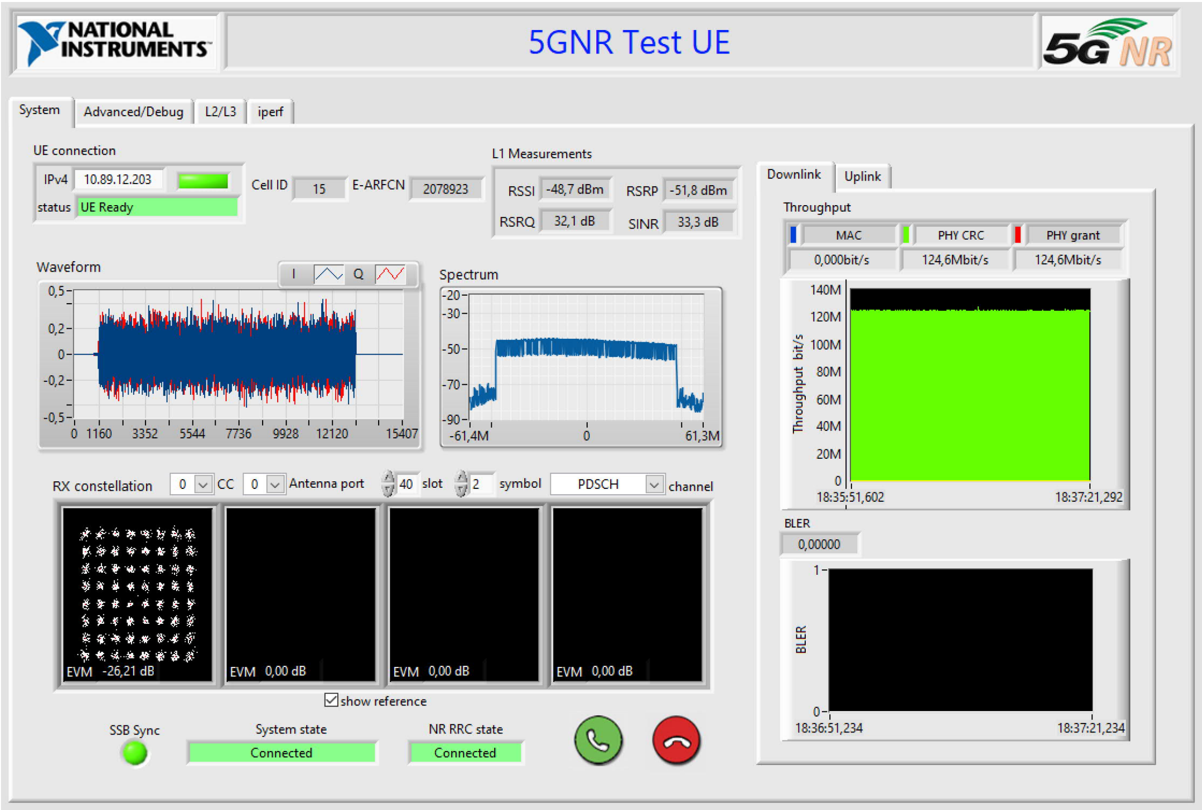


Figure 11 5G NR Test UE reaching PDSCH throughput of 124.6 Mbit/s

Sub-Demo B - 5G Core and gNB/UE Integration

In sub-demo B we can show the successful connection between the CMC 5G core network and the third-party gNB. The default setup is based on three Supermicro servers as shown in Figure 12. They are all connected via 10 Gbps ethernet links.

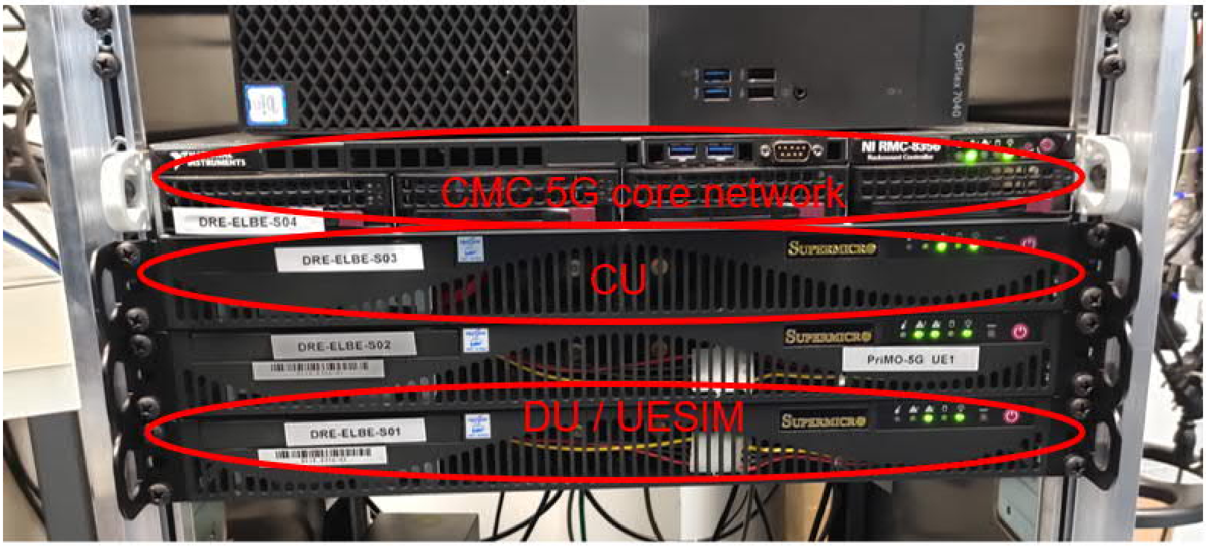


Figure 12 Default setup for core and gNB integration

As a baseline for the CMC core network integration, we used the reference system of the third-party vendor Radisys consisting of their gNB and – for demonstration purposes – a simplified core network and a UE Simulator. These components have been set up and tested with respect to their performance. After this was done, the simplified core network was replaced with the CMC 5G Core network[4].

To enable this connection, several adaptions both in the core network and in the UESimulator had to be done. This was necessary mainly because the UESimulator provided by the third-party vendor of the gNB is supposed to be a not fully standard-compliant demonstrator tool for their gNB together with their simplified core network.

As a result, we can achieve the same values for the data rate and for the latency. The bottleneck of this setup in terms of data rate might be the performance of the DU machine as this machine has some heavy load (see Table 4). Tests with more performant machines could not yet be executed.

To test multiple scenarios for the distribution of components, virtual machines with only 1 Gbps connections were added to the setup as needed. In that way, a greater distance or less performant connections to network components were simulated.

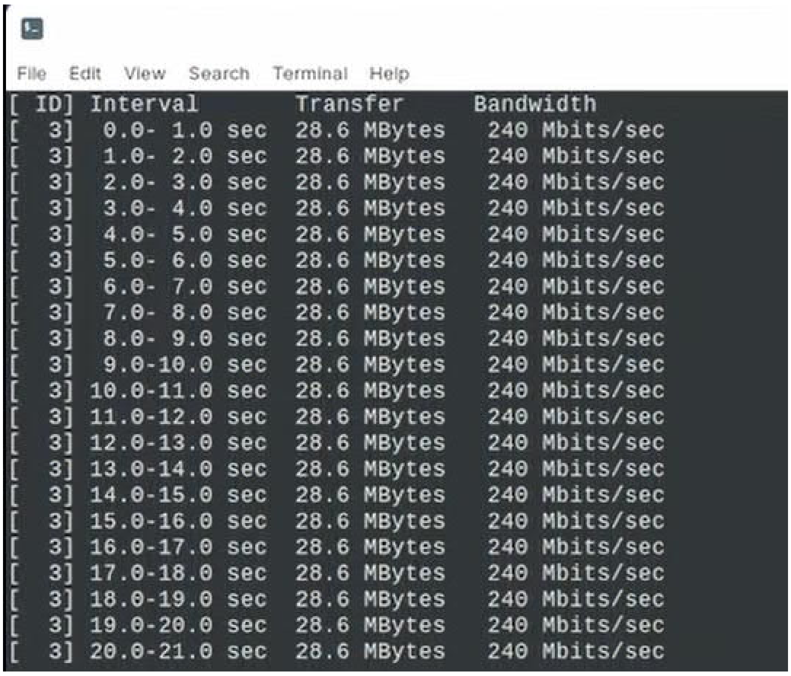
For the demo, however, we focus on the default setup as the differences in terms of data rate and latency between a local core network and a distant core network are negligible if at least the UPF has a good connection as can be seen in Table 4. The firefighting scenario in PriMO-5G is based on such a local UPF at the incident commander truck.

Table 4 Measurements with CMC 5G Core and Radisys gNB + UE Simulator performed by NI

Scenario	Measurement	Packet length Bytes	Data rate DL/UL Mbps	Jitter DL/UL µs	CPU load Core/CU/DU+UESIM
Local UPF RTT: 5.361ms	Max Throughput	1400	1220/240	11/75	0.00/1.30/4.00
	10Mbps DL+UL	1400	10/10	89/874	0.00/0.00/3.10
	Max Throughput, individual UL/DL	100	152/56	2/61	0.00/2.80/11.50 DL 0.00/0.60/3.5 UL
Distant Core (300ms delay), w/ local UPF RTT: 5.322ms	Max Throughput	1400	1220/240	6/78	0.00/1.00/4.20
	10Mbps DL+UL	1400	10/10	89/889	0.00/0.00/0.40
	Max Throughput	100	153/56.6	2/102	0.00/2.80/8.30 DL 0.00/0.40/2.90 UL

With this, the demo presents transfer rates in the command line tool iperf as shown in Figure 13 and data can be streamed from the UE towards the core network.

[4] Additional details of the IP data transmission over 5G NR gNB and UE PAL setup is available on the project's YouTube channel via this link https://www.youtube.com/watch?v=o2_LKuVsFEE



```
File   Edit   View   Search   Terminal   Help
[ ID] Interval       Transfer     Bandwidth
[  3]  0.0- 1.0 sec  28.6 MBytes   240 Mbits/sec
[  3]  1.0- 2.0 sec  28.6 MBytes   240 Mbits/sec
[  3]  2.0- 3.0 sec  28.6 MBytes   240 Mbits/sec
[  3]  3.0- 4.0 sec  28.6 MBytes   240 Mbits/sec
[  3]  4.0- 5.0 sec  28.6 MBytes   240 Mbits/sec
[  3]  5.0- 6.0 sec  28.6 MBytes   240 Mbits/sec
[  3]  6.0- 7.0 sec  28.6 MBytes   240 Mbits/sec
[  3]  7.0- 8.0 sec  28.6 MBytes   240 Mbits/sec
[  3]  8.0- 9.0 sec  28.6 MBytes   240 Mbits/sec
[  3]  9.0-10.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 10.0-11.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 11.0-12.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 12.0-13.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 13.0-14.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 14.0-15.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 15.0-16.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 16.0-17.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 17.0-18.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 18.0-19.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 19.0-20.0 sec  28.6 MBytes   240 Mbits/sec
[  3] 20.0-21.0 sec  28.6 MBytes   240 Mbits/sec
```

Figure 13 iperf output in the uplink of the integrated system

2.3 KCL-CMC System Integration and Demos

In this test CMC 5G core is running in KCL in the UK, and gNB running at Aalto University in Finland, see Figure 14. The objective is to test an architecture where network functions are deployed in different locations.

Figure 14 shows the setup for testing whereby KCL and Aalto are connected using a remote connectivity through Virtual Private Network (VPN). The setup consists of CMC 5G with NSA and SA functionalities running on a Linux PC at KCL, which is connected to the Aalto gNB manufactured by Nokia and 5G UE.

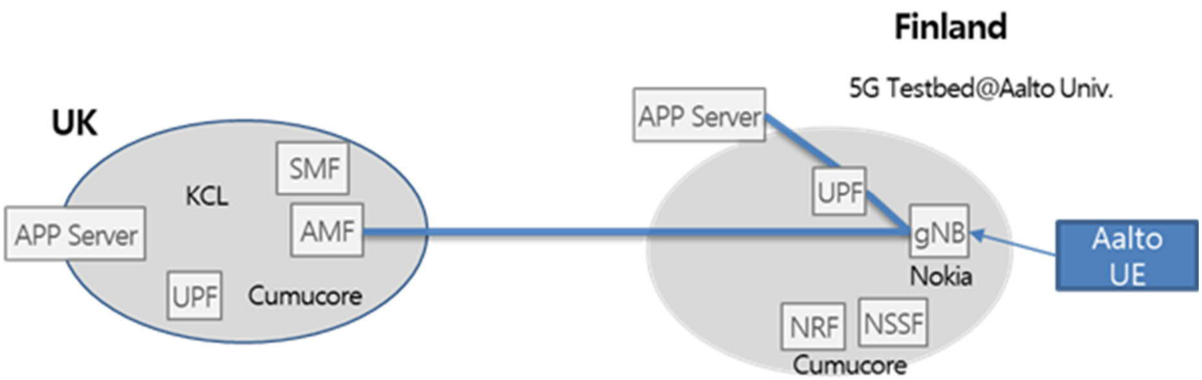


Figure 14 Intracontinental test setup CMC 5GC in KCL- gNB in Aalto University

The deployment scenario consists of gNB that is located in Aalto University communicates with the CMC core network components, such as, Access and Mobility Management Function (AMF), Session

Management Function (SMF) and User Plane Function (UPF), at remote site through the intracontinental connection between the UK and Finland. Another deployment included in the experiments consist of having the gNB that will contact the default AMF which is located in KCL as part of the mobile operator but then, the default AMF will allocate a suitable UPF that is located close to the gNB. In this second scenario, the UPF is located in close proximity to the gNB in the data center of Aalto University to deliver lower latency.

2.3.1 Background of the Demo

The two demos described are planned with similar functionality but changing the location of network components. This first demo will show feasibility of remotely controlling a moving object across a remote network. The second demo intends to demonstrate the scenario where mobile operator deploys local network functions in the area of the emergency situation to handle connectivity on-site where low latency is required.

In previous deliverable D5.2 [PRIMO-D52] only first deployment was tested. In this deliverable, the second scenario is demonstrated, whereby the user plane is handled using local instance of the UPF in Aalto data center. This is due to proximity of the event to the gNB in Aalto premises. The KPI to be measured would be user plane latency and available bandwidth.

This demo is related to PriMO-5G scenario B1 in D1.1 [PRIMO-D11] aiming to show feasibility of UAVs in a fire scene through 5G wireless communication technology. Smart firefighting with UAVs in urban area where the mobile operator has coverage. In this situation, it is critical that the firefighters obtain the appropriate information to deal effectively with fire situation. The signaling is handled in the mobile operator cloud to provide reliable communications. However, for user plane, where UAVs need to share the status of the fire spreading among firefighters through live video streaming, the reliability and low latency are required. For this reason, user plane is handled locally where firefighting is taking place. The local deployment of user plane allows to achieve low latency.

2.3.2 Integration report

The integration of 5G core in KCL server was performed and the configuration of the intercontinental link between KCL and Aalto campus was performed successfully after spending several weeks with the configuration. The integration was additionally delayed due to COVID which prohibited the physical access to premises In KCL and Aalto data center. The integration was completed during March 2021 and following test cases were possible to run with people being able to access the campus to perform field testing. The CMC 5GC was running in KCL and Aalto gNB running in Finland and two test cases were demonstrated.

1- gNB installed in Aalto University campus and is connected to the CMC core with all the network functions i.e AMF, SMF and UPF running in server at KCL. The connection between gNB and 5GC was performed through intercontinental link established over OpenVPN secure connection.

2- gNB installed in Aalto University is connected to the CMC core with the network functions i.e. AMF and SMF are running in server at KCL but UPF selected for handling the user plane is running in Aalto data centre close to the gNB.

2.3.3 Demo scenarios and evaluation report

The demo for both scenarios was successfully performed and performance measurements were taken for both cases. The user plane when all the network functions were running at KCL had longer delay of about 50-60ms while the user plane when using the user plane function (UPF) running at Aalto data center was 4-8ms. Figure 15 below shows the traffic and device connected to 5GC running in KCL and the performance when connecting to the local UPF.

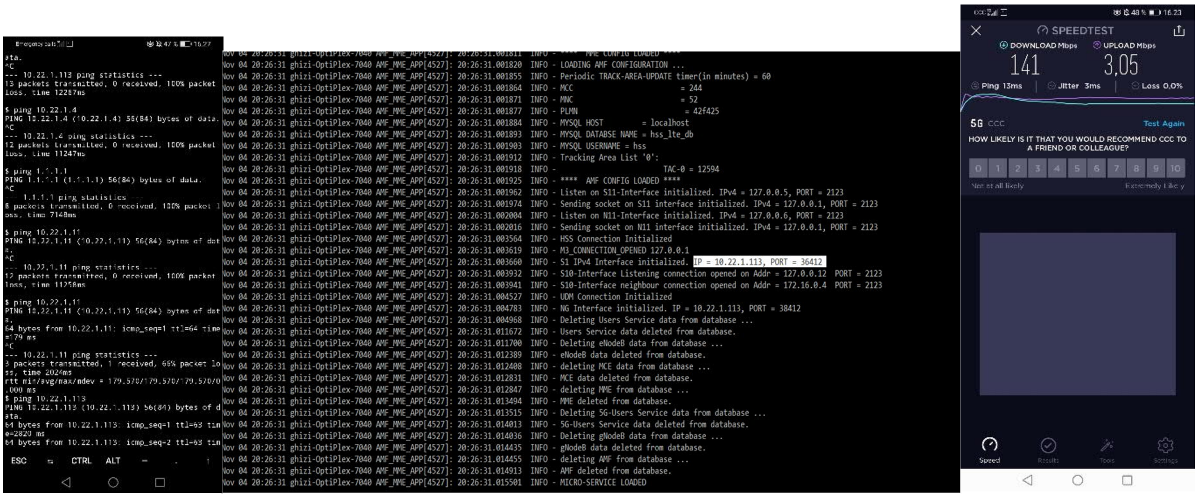


Figure 15 Traffic and performance from test setup CMC 5GC in KCL- gNB and UPF in Aalto University

2.4 YU-KT-KU System Integration and Demos

This section describes the integration activities and results on the aerial video streaming demonstration developed by YU, KT and KU. The demos in this section show results that continues from the developments of D5.1 [PRIMO-D51] and D5.2 [PRIMO-D52]. To stream high quality videos from UAVs in real time, YU's communication-computation pipeline optimization, KU's vehicular edge computing and super resolution, and KT's technologies regarding commercial 5G are jointly utilized.

2.4.1 Background of the Demo

The images from the UAV are provided beforehand to train the object detection and depth-controllable super resolution algorithm. Then, the trained models are implemented in the MEC and the GCS, and the real-time videos are transported to them through the pipeline using gstreamer [GSTR]. In short, the functions run on the onboard computer on the UAV, GCS, and MEC's computing servers are all wrapped up by gstreamer, thus providing a fully functional video and processing pipeline.

The simulation using vehicle-based MEC station and UAV are as follows. The UAV, which has a mounted camera, streams low-resolution image/video to the near vehicle-based MEC station and the MEC station performs Super-Resolution deep learning to restore the low-resolution source. The vehicle-based MEC station has limited computing and storage & power resource compared to the GCS. Using only the high-performance SR model in MEC station may affect the overall system inefficiency. For these reasons, an adaptive controllable SR model is needed.

2.4.2 Integration report

Immersive video streaming: The video captured from the UAV's camera is stitched in real-time to produce and encode the raw videos into a single 4K video; then it is captured in the onboard computer through the HDMI 2.0 cable. The captured video is transported and streamed along three routes. The first route is the route from the camera to the onboard camera, processing the video immediately on the UAV, for immediate usage. The second route is from the camera to the 5G device, then from the 5G device to the MEC or GCS through 5G. In the MEC and GCS, the videos are applied to the object detection and depth-controllable super-resolution algorithm explained in the description; and they are also viewable as a VR video using an HMD. The visual information pipeline explained above is implemented as shown in Figure 16.

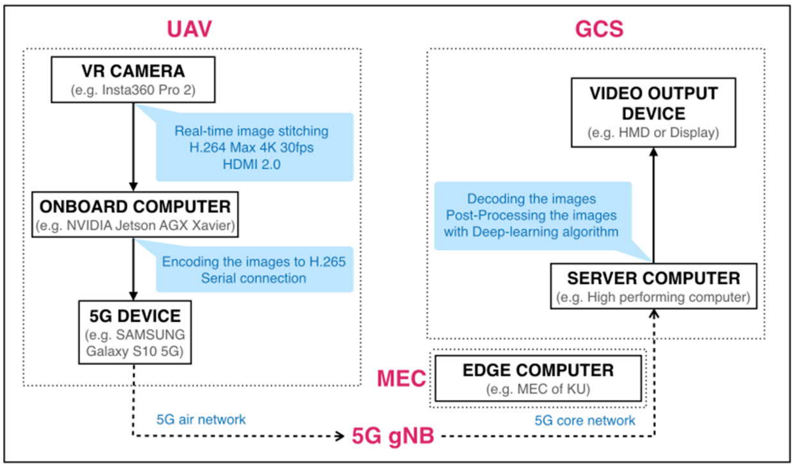


Figure 16 Pipeline of visual information from UAV to GCS and MEC

When the visual information pipeline is composed, various network protocols can be used according to network environments and the users' latency requirements. The most commonly used protocol is Secure Reliable Transport (SRT) [SRT], which outperforms the other protocols in terms of latency performance. SRT supports low latency and high-quality video streaming by utilizing packet loss recovery through advanced low latency retransmission techniques and detecting the network performance between endpoints (packet loss, latency, jitter). On the other hand, when the latency requirement is not tight but the quality of the video should be the first requirement, we can use TCP-based network protocols that guarantee the perfect delivery of the video.

Real-time object detection: For real-time object detection, there are two intriguing points for investigation, thus requiring real-time system optimization. Seen from a distance, this problem is the epitome for two well-known tradeoffs: computation vs. communication and exploration vs. exploitation. Firstly, computation and communication tradeoff is evident from the heterogeneous computing power and latency of each computing entity, including but not limited to the UAV itself, other UAVs within the fleet, mobile edge computers, and the GCS. This tradeoff is well demonstrated in Figure 17. One on pipeline, the video is processed and classified within the UAV, then transported to the server with the classification results; and on the other pipeline, the encoded video is streamed to the server then processed and classified with the server computer within the GCS.

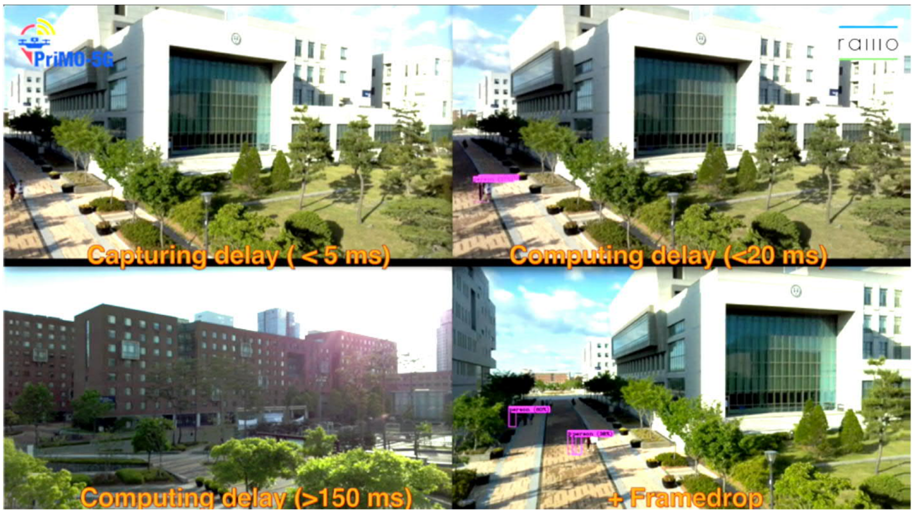


Figure 17 Computation and communication tradeoff arises from the heterogeneity of computation and communication specification of the servers: results from the 5G UAV platform located in YU International Campus, Incheon (left) and results from the GCS located

Depth-controlling super-resolution streaming: We model the buffer status of the server as a queuing system after receiving images/videos from the UAV, and define the trade-off relation between the server's buffer backlog (delay) and SR performance as an Lyapunov optimization equation. Overall architecture of the proposed super-resolution network is shown in Figure 18. The depth-controllable super-resolution algorithm maintains stability, which is essential in real-time computing systems. As you can see in Figure 19, the trade-off between speed and performance over depth is defined, and this model could control the depth depending on the number of images in a buffer. If there are a lot of images in a buffer, then the super-resolution algorithm should process them as soon as possible even though certain amount of performance is sacrificed to avoid overflow. Thus, a small number of hidden layers are used in our proposed depth-controllable super-resolution algorithm. On the other hand, if there are rare images in a buffer, the super-resolution algorithm can maximize its performance without the consideration of processing time. In this case, the entire hidden layers are used in our proposed depth-controllable super-resolution algorithm.

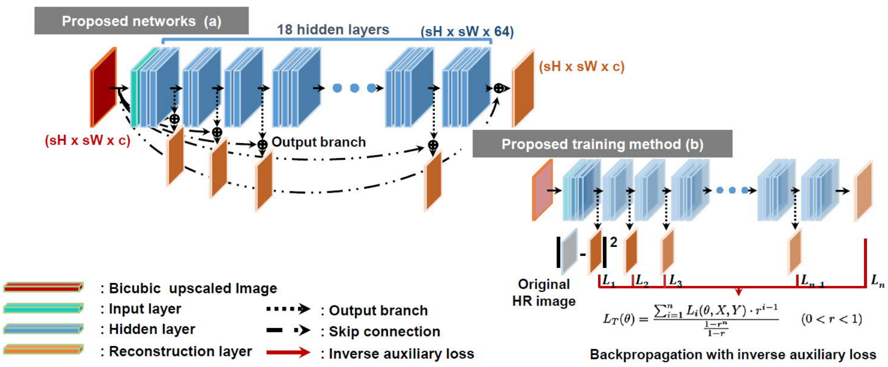
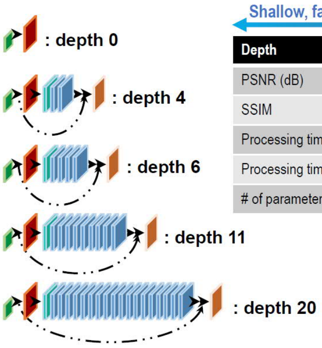


Figure 18 Overall architecture of the proposed SR network



Shallow, faster, lower performance — Deeper, slower, higher performance

Depth	0	4	6	8	11	14	17	20
PSNR (dB)	30.4	32.56	33.01	33.229	33.379	33.435	33.495	33.523
SSIM	0.8682	0.91	0.916	0.918	0.92	0.92	0.921	0.922
Processing time (CPU)	0.002	0.321	0.5468	0.7725	0.994	1.317	1.622	1.96
Processing time (GPU)	0.001	0.01	0.012	0.0152	0.0189	0.0224	0.0262	0.0305
# of parameters	0	75K	148K	222K	333K	444K	555K	665K

(processing time have measured on butterfly, 512 x 768)

Figure 19 Trade-off between speed and performance over depth

KU conducts vehicle-based testing within Korea University to apply the proposed depth-adaptive super-resolution algorithm verified using real-time streaming image/video and server to the actual vehicle-based MEC station and UAV communication environment.

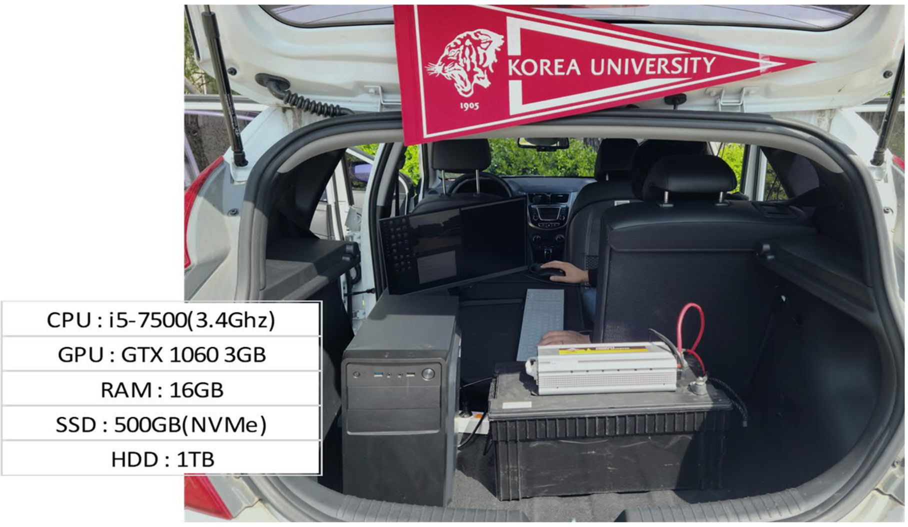


Figure 20 Vehicle-based MEC station setting

In a situation where there is a hazard such as a fire or an earthquake, UAVs can be dispatched instead of risking human capital. In isolated regions, the UAV cannot inspect the hazardous zone and simultaneously transfer the collected data to its corresponding infrastructures such as fire departments merely due to its distance and energy inefficiency. Therefore, we have devised an environment where the UAV can send this data to a nearby vehicle, where the data processing stage in the vehicle acts as an auxiliary edge server. The vehicle is equipped to process the data received from the UAV with the depth-adaptive super-resolution algorithm.

It has been confirmed that this algorithm performs seamlessly with a computer that runs on an i5-7500 (3.4GHz) CPU, GTX 1060 3GB GPU, 16GB RAM, and an SSD of 500GB (NVMe) with a 1TB HDD. Our vehicle-based MEC station setting is presented in Figure 20.

Intuitively, as the vehicle is free to travel adaptively to wherever the UAV advances, there are no longer any restrictions in terms of energy efficiency or latency that comes with most GCS-to-UAV connections. Thus, this is the critical step to the YU-KT-KU system integration.

2.4.3 Demo scenarios and evaluation report

In YU international campus, aerial performance of the UAV-5G platform was evaluated. The testing locations are illustrated in Figure 21. The result was presented along with multi-armed drone upper confidence sampling (MADUS) algorithm at Mobicom 2020 [SKK+20].

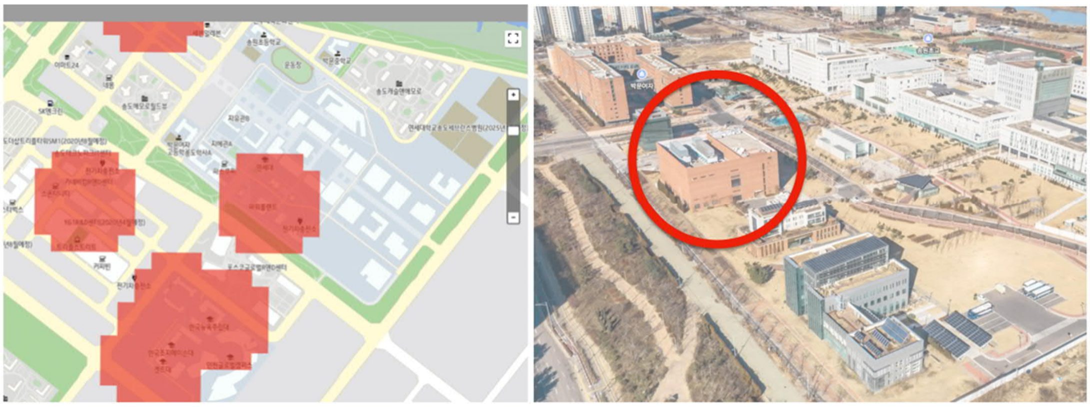


Figure 21 The location of KT 5G gNB (RU-antenna) in YU international campus from KT 5G coverage map.

Figure 22 summarizes the performance evaluation of UAV-5G platform, and its algorithm counterpart. When using only a deep-layer model, the performance of SR is always high but the server may suffer a big delay in waiting for the computing requests in the queue. This leads to serious delay issue to the whole system that puts focus on real-time communication and computation. Compared to the deep-layer model, when utilizing a shallow layer, the real-time data from the UAV can be processed immediately with poor SR results. The evaluation result shown in Figure 23 that the proposed depth-adaptive super-resolution algorithm can maintain the computing server's backlog to a stable status by controlling the SR algorithm's performance quality based on the dynamic queue state.

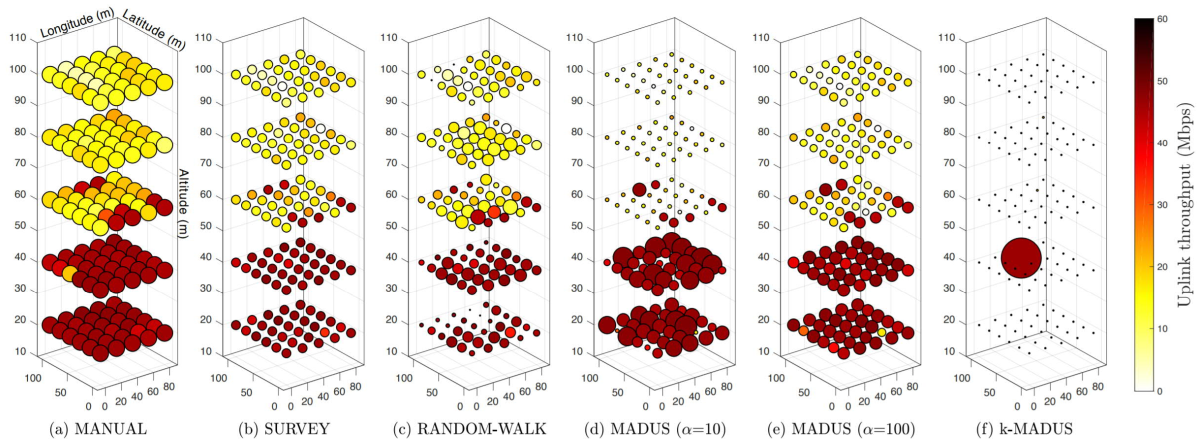


Figure 22 Aerial 5G performance sampled in YU international campus. MADUS samples the performance stably, allowing a stable high quality aerial streaming mission on UAV.

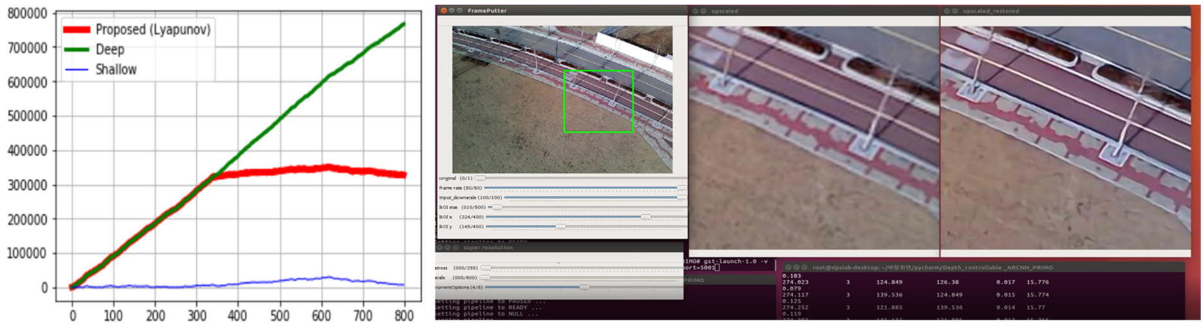


Figure 23 Depth Adaptive Deep Super Resolution Network test result

2.5 EUC-KT-YU System Integration and Demos

This demo will demonstrate the streaming of live video from UAV (emulator) to mobile devices. through LTE access network and 5G backhaul. EUC Network-In-a-Box (NIB) used for LTE access network in this demo includes LTE eNB and EPC. 5G NR network is composed of 5G NR UE and 5G NR network components such as MeNB, SgNB and EPC.

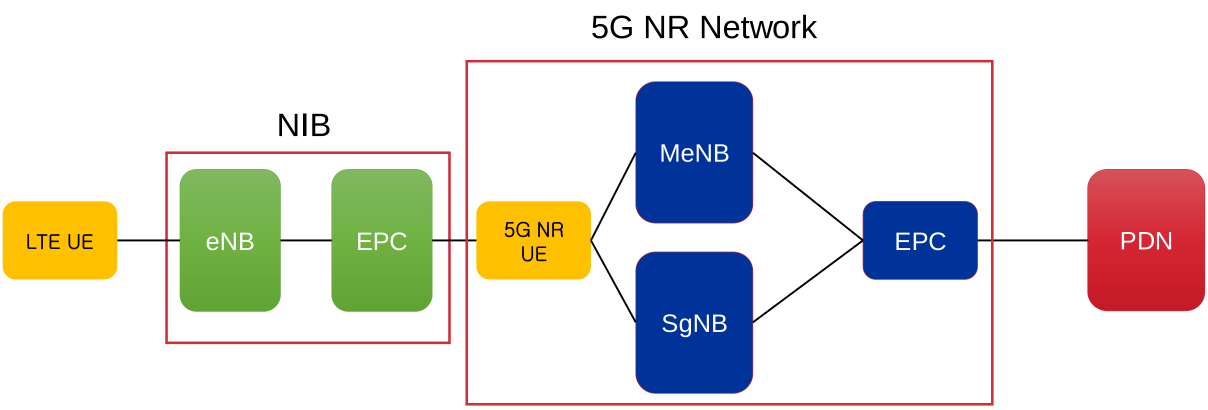


Figure 24 Testing setup in EUC-KT-YU demo.

Figure 24 shows the setup for testing. 5G NR network can be used as a backhaul between LTE eNB and EPC, or between EPC and PDN (Packet Data Network). In case of Portable NIB, since eNB and Local EPC is co-located, it is more feasible to locate the wireless network between EPC and PDN as shown in Figure 24.

2.5.1 Background of the Demo

The objective of this integration and demo is to show that the emergency communication service is feasible through portable LTE NIB and 5G NR backhaul to demonstrate PriMO-5G scenario B1 in D1.1 [PRIMO-D51] aiming to show feasibility of UAVs in a fire scene through 4G/5G wireless communication technology.

For this, originally two demo scenarios are planned:

- Locate eNB in EUC portable NIB, and then eNB communicate with the core network components at remote site through 5G backhaul

- Locate eNB and core network components in EUC portable NIB, and then communicate with PTT server (or any other application server at PDN) at remote site

But only the second scenario was tested because, as already explained, the wireless network between EPC and PDN might be more usual in case of Portable NIB.

The following components are part of this demonstration:

- KT PS-LTE UE
- EUC NIB composed of LTE eNB and EPC
- 5G NR UE supporting LTE band 4 and 5G NR n257 (mmWave)
- EUC MeNB supporting Rel.15 EN-DC
- ETRI/EUC mmWave SgNB (coworking with ETRI)
- ETRI/EUC EPC supporting Rel.15 5G NR NSA (coworking with ETRI)

2.5.2 Integration report

For the demo, PGW of NIB is connected with application server through 5G NR network, that is 5G NR UE provides internet access for PGW of NIB through tethering. 5G access network is composed of LTE band 4 MeNB and 5G NR band 257 SgNB. For user traffic, 5G NR UE is connected with 5G network through 5G deployment option 3x (SN Terminated MCG/SCG/Split bearer). Figure 25 illustrates the setup.

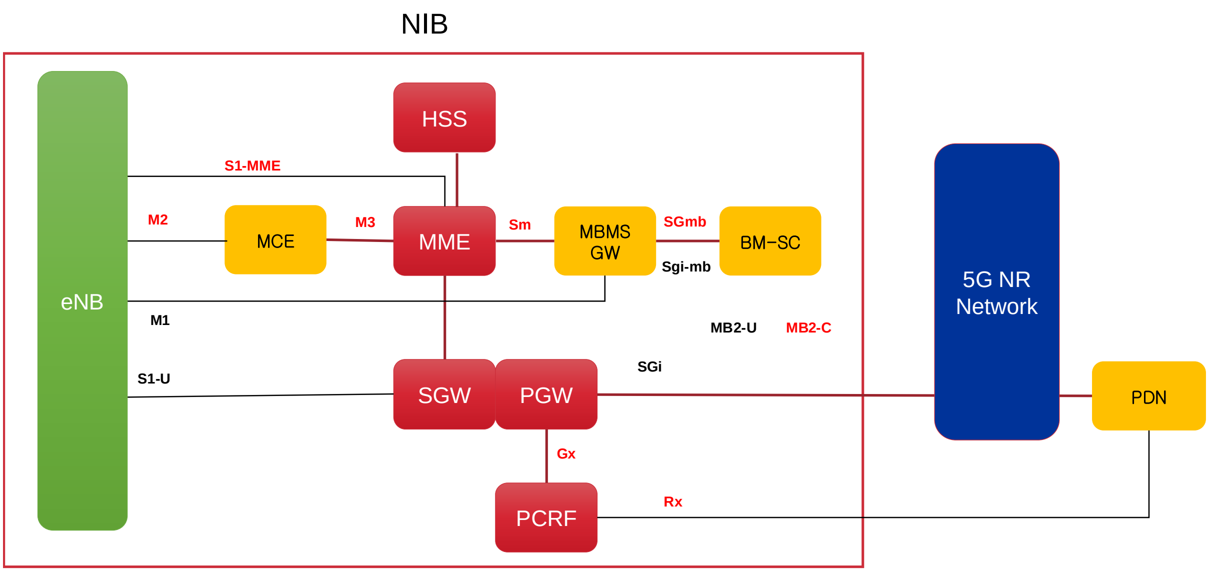


Figure 25 Integration for EUC-KT-YU demo

Figure 26 shows action demo setup – it was done in indoor environment due to regulatory issue.

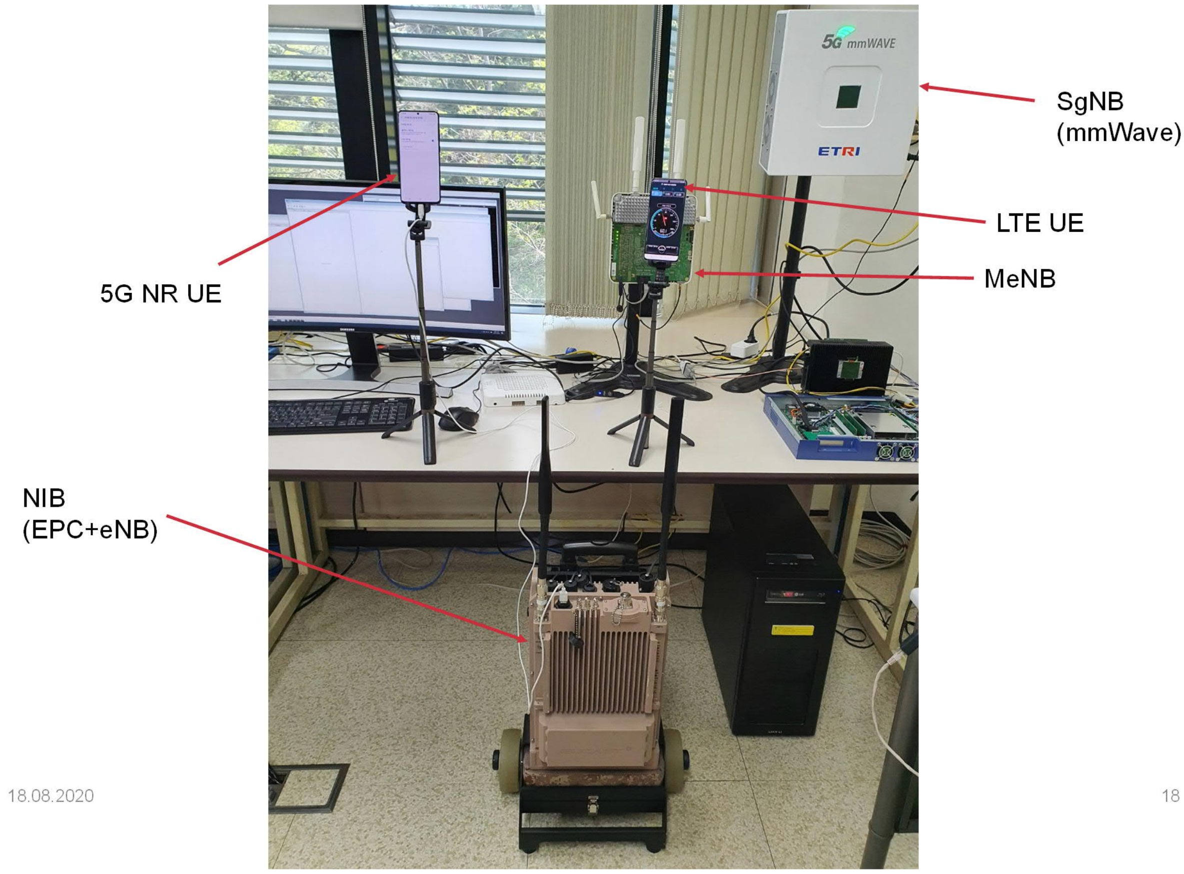


Figure 26: Test setup in EUC-KT-YU demo

2.5.3 Demo scenarios and evaluation report

Our original demo scenario was to show eMBMS based MCPTT of LTE using 5G backhaul, and as a pre-test we confirmed that it is working in LTE network using collocated BM-SC, MCE, MBMS-GW and MCPTT server in NIB. This is demonstrated in Figure 27.

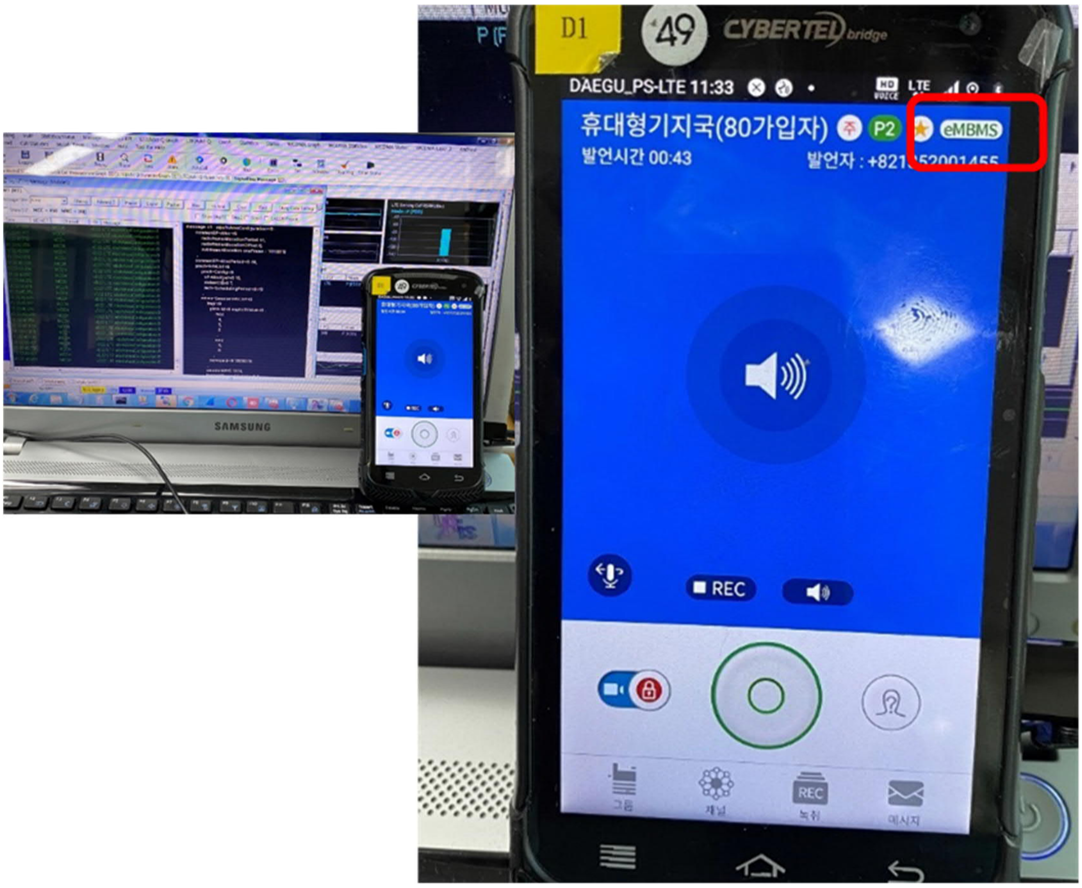


Figure 27 eMBMS based MCPTT

Next step was to locate MCPTT server in remote site, and to connect it with NIB using 5G network. But it could not be done because remote MCPTT server was not ready, the demo scenario was replaced with video streaming – since there's no difference in the viewpoint of remote application access and data streaming between MCPTT and video streaming.

The demo for the streaming of live video from UAV (emulator) to mobile devices through LTE access network and 5G backhaul was successfully performed. Since mmWave provides sufficient bandwidth, the video streaming was successfully received without interruption or blur, and our test result showed the same. But when we measured the uplink and downlink data rate using the setup in Figure 26, it turned out to be much less than expected max data rate - when we measure the capacity of mmWave backhaul itself with 100MHz bandwidth, it shows around 500Mbps in downlink and 50Mbps in uplink, see Figure 28. To improve the data rate in this scenario, in-depth investigation will be conducted, e.g. the interface between LTE eNB and 5G NR UE.

Figure 28 Measured 5G NR backhaul data rate

3 Intercontinental PriMO-5G System Integration Results

This section gives an overview of the PriMO-5G intercontinental demo. The demo describes activities, where European and Korean partners have jointly contributed.

3.1 Background and motivation

Large-scale fire disasters increasingly common (e.g. due to global warming, extended settlements etc.) and typically require firefighting resources (e.g. firefighters, equipment etc.) which exceed resources that could be mobilized locally. In this case, international assistance is essential through deployment of firefighting resources from other supporting countries. For instance, in D5.2 [PRIMO-D52] an example was highlighted of major wildfire event in Australia engulfing a land area of 50,000 square kilometers ended requiring assistance from disaster first responders from five countries as well as local volunteers.

To that end, the incident planning and management processes (e.g. situational analysis, incident assessment, action planning etc.) may be implemented by the collaborating groups at different levels of tier of command. At the disaster scene, temporary Incident Command Posts (ICPs) are setup to identify local objectives and possible courses of action, assign tasks and manage resources under immediate command of the ICP. The ICPs are supported by one or more Emergency Operations Centre (EOC) that operate in fixed locations away from the disaster area. An EOC provides strategic command and facilitates coordination of resources across different ICPs of the same or different emergency agencies. This necessitates interagency coordination and collaboration to have a common operational picture and guarantee an overall rapid, efficient and safe responses to the event [KS17].

The illustration of Figure 29 provides high-level example of organization of a multinational disaster response operation with involvement ICPs and EOCs from both affected and assisting countries. In this operational context, 5G flexible architectures and supported immersive, computing and caching services have potential to provide significant added value in terms of enhancements in:

- *Communications and coordination* through information sharing among the different agencies, avoiding duplication of effort, minimizing risk and promote successful outcomes.
- Achieving *shared situational awareness* across based on common understanding on the circumstances and immediate consequences of the emergency, as well as, the available capabilities and response priorities.
- Supporting *joint decision making* across all tiers of command including local and international participants.
- Deriving a *common operating picture* from assessment and fusion of information from multiple sources, and shared between tiers of command of collaborating agencies to support joint decision-making”

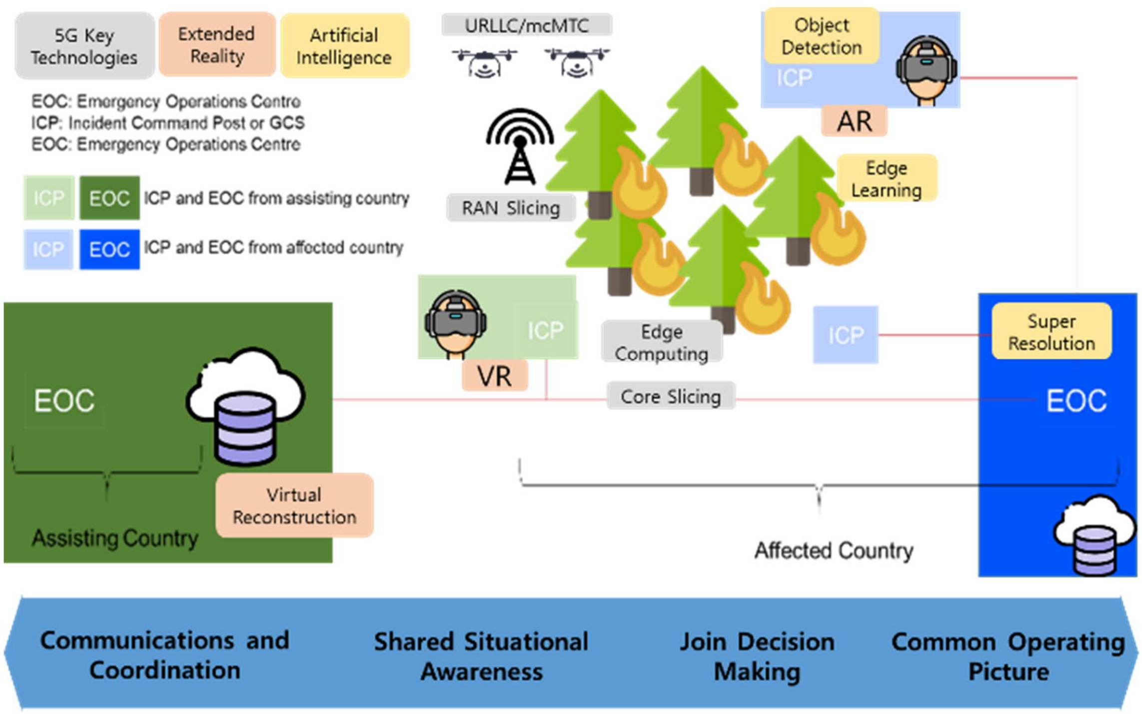


Figure 29 Example of organization of disaster first response involving resources from two countries

3.2 Overview of the intercontinental demos

The PriMO-5G system integration targets interconnection of PriMO-5G testbeds between Europe and Korea and thereafter demonstration of end-to-end immersive video services for firefighting use cases via the federated 5G network. Preliminary work for intercontinental system integration involved setup a direct high-capacity connection between the testbed at AALTO 5G test network in Espoo, Finland, and the YU – KT 5G Open network in Seoul, South Korea. This cross-continental connection, see Figure 31, utilizes national research and education networks (NRENs) to meet the QoS and security requirements needed in cross-continental testbed experimentation[5].

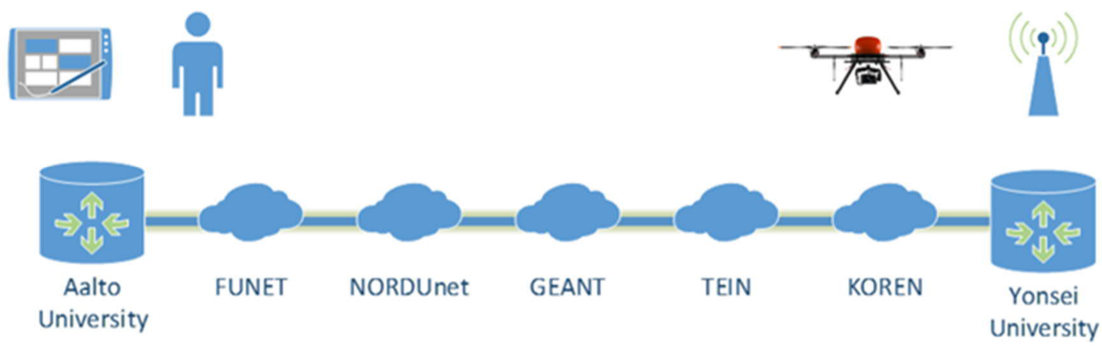


Figure 30 Intercontinental connection setup between Aalto University and Yonsei University (Note: FUNET – Finnish University and Research Network, TEIN - The Trans-Eurasia Information Network,

[5] Additional details may be viewed in the collated demo showcase video available at project's YouTube channel via this link https://www.youtube.com/watch?v=3tS6uuVmj3E

KOREN - Korea Advanced Research Network)

The intercontinental system integration and demo activities bring together partners associated with each 5G testbed, that is, AALTO and CMC from Finland and YU, KT, KAIST and EUC from the Korean side. In terms of the linkages to WP1 use cases, the intercontinental demo links to more than one following use cases as noted in Table 5.

- A1: Placement of communication and computing for forest firefighting
- A2: Network slice management for forest firefighting
- B1: UAV-assisted preparatory measures for smart urban firefighting
- B2: Differentiated UAV fleet management for smart urban firefighting

The use cases details are summarised in Section 1.30 and described in more detail in D1.1 [PRIMO-D11].

Table 5 Mapping of intercontinental demonstrations to PriMO-5G use cases

Demo/Use case	A1	A2	B1	B2
Intercontinental D1	X	X		
Intercontinental D2	X	X		

3.3 Integration report

The intercontinental system demos aim at demonstrating the flexibility of 5G Service Based Architecture (SBA) that allow having different network slices where network functions can be running in different interconnected 5G networks (in this case the 5G testbeds in Finland and Korea). Public safety missions would require flexible architectures that can be constructed in a way that is most fitting to achieve a success in its own criteria, such as, maximum public protection, fast recovery, and so on. Accordingly, an end-to-end network slice should be constructed and allocated to meet the requirements of a specific mission. To that end, in PriMO-5G intercontinental firefighting scenarios, a slice could be allocated to route traffic from UAV to a local MEC platform for processing video collected by the UAVs during firefighting event in an affected country. Furthermore, an intercontinental slice between 5G networks in assisting and affected countries, would allow for support staff at EOC of assisting country to have richer and current situation picture through immersive video transported over the slice.

Two intercontinental demo scenarios are planned with similar functionality but changing the network components. The first demo scenario will test the SBA using Network Repository Function (NRF) and Network Slice Selection Function (NSSF) for AMF re-registration from remote AMF in Korea to local AMF in Finland after discovering it includes MEC functionality as shown in Figure 31. In this demo scenario, it assumed that Finland is the affected country and Korea is the assisting country.

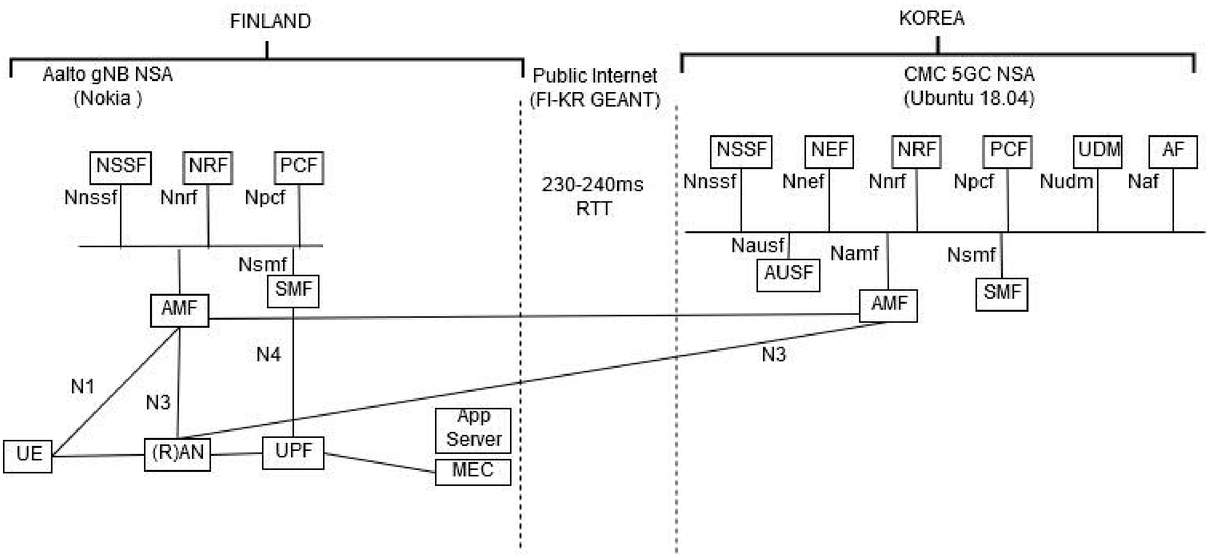


Figure 31 Intercontinental test setup with 5GC in KR and gNB in FI SA mode with SBA functionality.

This second intercontinental demo is similar to the first one, but the main difference being that it will test the 5G core interoperability with YU or KT after changing some of the components either gNB or 5GC from KT and the SBA that uses NRF and NSSF to locate optimal AMF with UPF including MEC functionality as shown in Figure 32. This setup now assumes that Korea is the affected country and Finland is the assisting country.

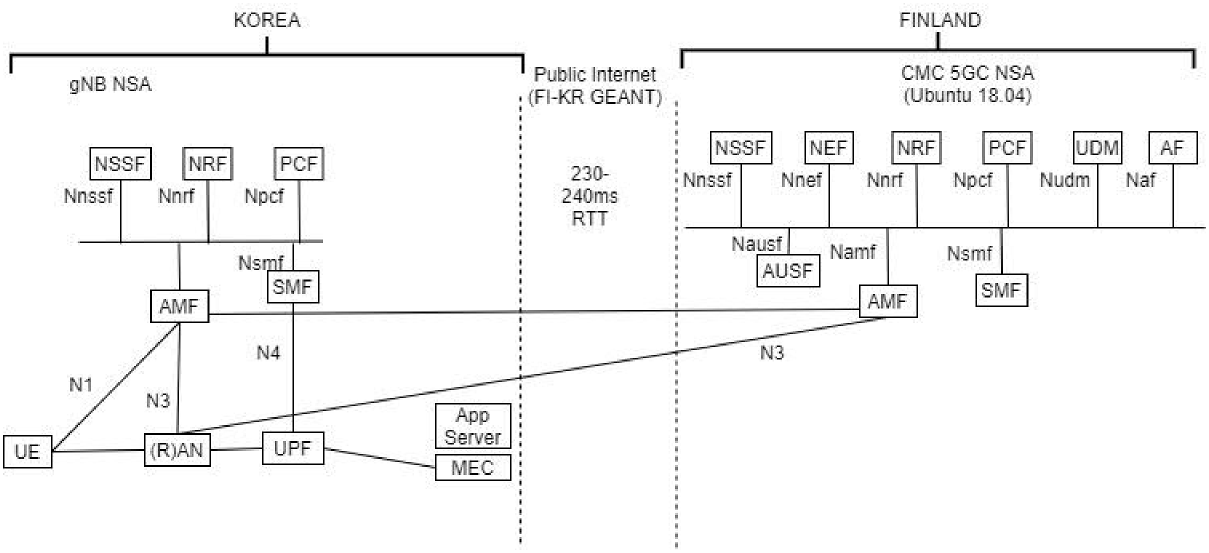


Figure 32 Intercontinental test setup with 5GC in FI and gNB in KR SA mode with SBA functionality

In both intercontinental demos, since the gNB and UE still do not support the possibility of requesting network slices, the UE (that is, 5G connected UAV) will select different APN to request from the network different slice. Thus, UE will use default APN with name e.g. Internet, and will have allocated default network functions with the associated delay. The UE will use a second APN with name e.g. FastInternet, and the default network function will search for local instances of network functions in the current location of the UE with MEC support to provide reliable and low latency communications on the site of the assumed emergency area.

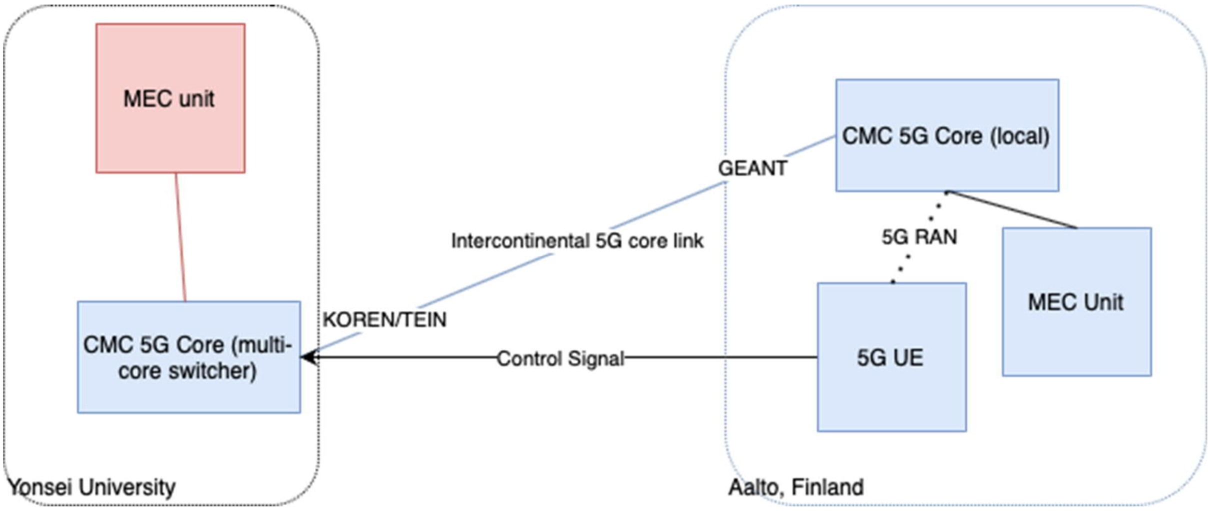


Figure 33 The final intercontinental E2E network topology.

The final intercontinental system is integrated as shown in Figure 33. The core components of YU-KU-KT and mobile edge computing are integrated into the intercontinental 5G system connecting CMC (Finland) and YU (Korea).

The UE in Finland is connected to a gNB that has multi-APN configuration. Multi-APN configuration runs on the premise that both Korea and Finland's core has the functionalities that support basic operations required by the UE while each core has its distinct functions that differentiate it from the other.

3.4 Demo scenarios and evaluation report

Demo scenario for an intercontinental firefighting incident consists of 3 parts as shown in Figure 34. There are drone camera sites (AALTO), 5G core and MEC (AALTO), and international switching server (YU). And the connection between Korea and Finland which is made by core switching.

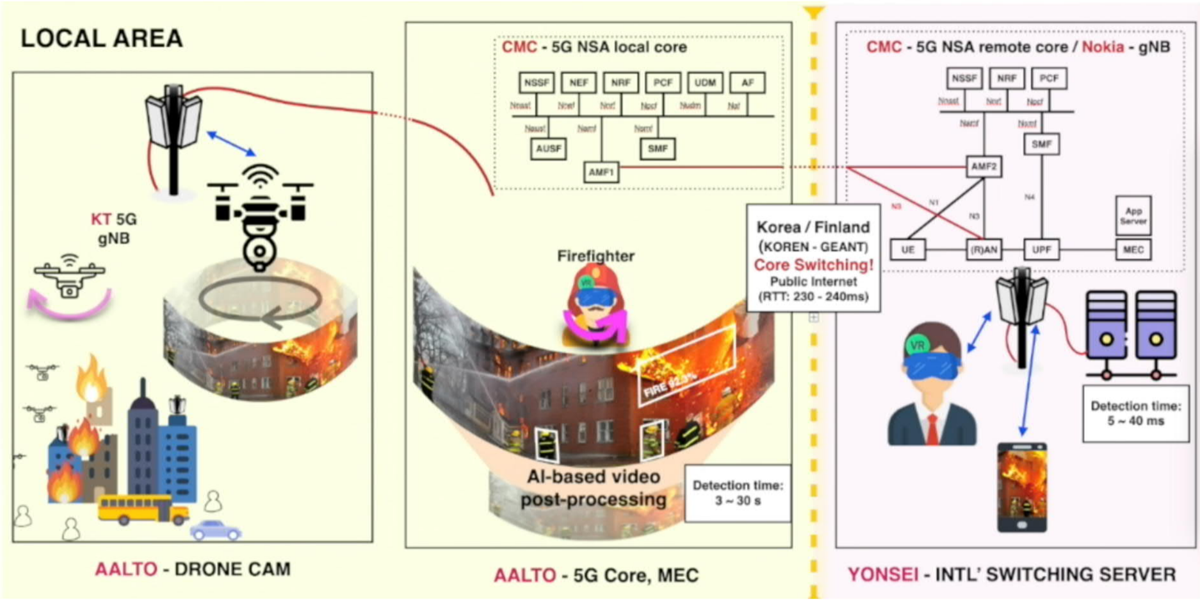


Figure 34 Demo scenario for an intercontinental firefighting incident.

5G core switching: The novel concept of 5G core switching was demonstrated in the intercontinental testbed. By configuring the multi-APN system in a gNB, the UE in Finland has access to the distinctive functionalities in both Finland and Korea. We tested the system with multi object image detection. Finland has a CPU based object detection function and Korea has a GPU based object detection function at its core. The UE in Finland, e.g. 5G device on a drone, sends its object detection request, e.g. detecting people at a fire incident, to the local gNB. The primary core connected to the gNB responds to the request, but takes a long time to process, due to the image specification and its hardware limitation. After observing that the local gNB is not capable, the UE requests the switched core in Korea, receiving the detection result after 270 ms, including 30 ms computation delay and 240 ms round trip communication delay. Figure 35 shows the core switching based MEC task offloading program that is running at CMC and YU: A UE in CMC is connected to a 5G core in Finland and a core in YU in a multi-APN fashion, and it offloads the task to the Korean core after trying out and failing to get a result from its local core.

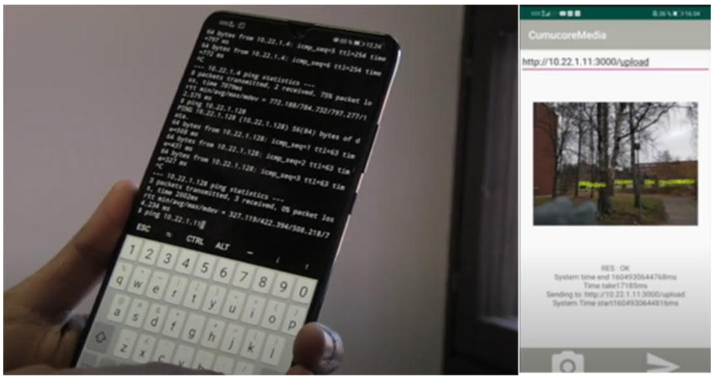


Figure 35 YU-CMC core switcher based MEC task offloading program

4 Other Component Demo Results

4.1 Overview

During the initial phase of the PriMO-5G project, European and Korean partners developed mostly independent or standalone demos that we described in more detail in deliverable D5.1 [PRIMO-D51]. In particular, the Europe partners developed demos showcasing the various components they are developing with plan future integration into system demos. On the other hand, some of the early demos by Korean partners already constituted integration of various system components. The integration of component demos into local site, intracontinental and intercontinental system demos was outlined initially in deliverable D5.2 [PRIMO-D52], as well as, being revisited again in Section 2 and Section 3 of this deliverable report. While some of the component demos were not integrated into system demos, their development continued due to their significance in providing experimental validation of the technical developments coming from WP3 and WP4. The continued developments and evaluation outcomes of these maintained component demos is presented in the remainder of this Section.

4.2 Cell-free UDN Demo by AALTO

4.2.1 Short Description

Ultra-dense network (UDN) is characterized by dense base station network. Some visions propose to create with BS at each lamppost. In such dense network even modest user speed creates huge number of handovers. One way to release the network from the burden of traditional handover signaling is to use cell free network. One component of a cell free network is tracking and predicting user location.

In this demo we show how multiple antenna base station track user location. The measurement system corresponds to dense network with large antenna arrays at the sites. This demo is aiming to show the experimental setup of cell free network environment. The UE in this demo, is flying UE and ground UE. The user position is computed from signals received by two antenna systems. In the demo we identify how an antenna system is suited for active user location tracking.

4.2.2 Continued Developments of the Demo

Measurement setup

This demo models a set up with two BS sites. The used algorithm is illustrated in Figure 36. A BS site has 16 element antennae arranged as 4x4 matrix. The BS measures a signal from UE at each antennae element. We use MUSIC algorithm to compute measured signal azimuth and elevation. Azimuth and elevation from both sites are combined in a central node for user location estimation. The user location is computed by minimizing difference between measured angles and computed angles from estimated user location. The location computation is defined as nonlinear minimization problem and solved by `optimproblem` optimization function provided by Matlab programming language.

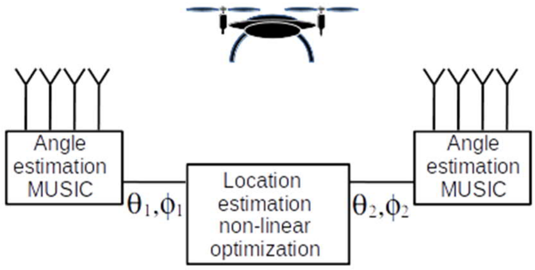
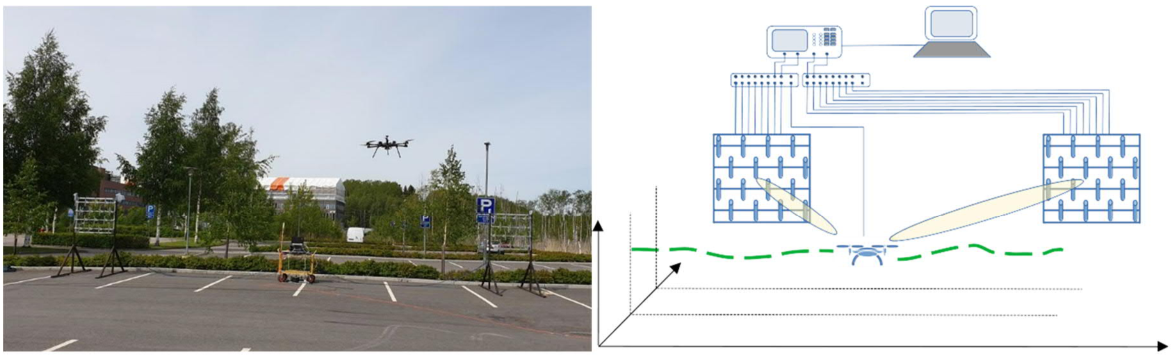


Figure 36 Location estimation with two BS using MUSIC algorithm at BS and non-linear location estimation at a central node.

The demo system is constructed from two 16 element antenna arrays corresponding to two BS sites, (see Figure 37a). The ground UE is a pole with antenna and flying UE is a drone with mounted antenna below the drone. All antenna elements and UE are connected for vector network analyzer (VNA). The signal at each antennae element is measured in synchronous manner by commanding VNA from a controlling computer (see Figure 37b).



a) b)

Figure 37 Measurement setup a) the actual measurement set up with antennae flying drone and VNA, b) schematic of the measurement setup in a).

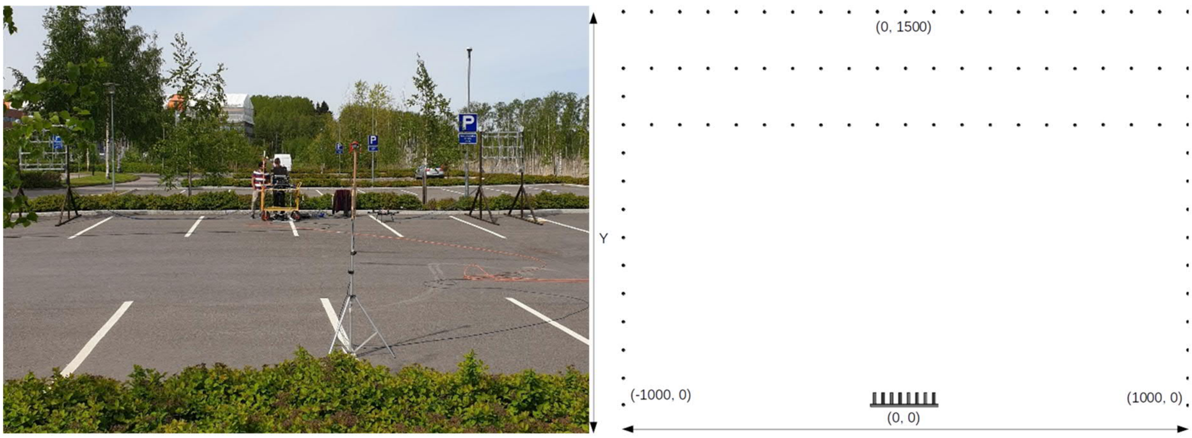
System testing and calibration

Measurement instrument is a 4 port R&S ZNB 8 vector network analyzer (VNA) which is expanded to 48 ports by the use of two R&S ZN-Z84 switch matrix units (see Figure 38a). As the instrument only has four transmitters and receivers, measurements from a maximum of three array antenna elements is possible simultaneously. However, the use of single frequency mode and quick switching action of RF semiconductor switches enables measurements from all elements within approximately 65 ms duration.

a) b)

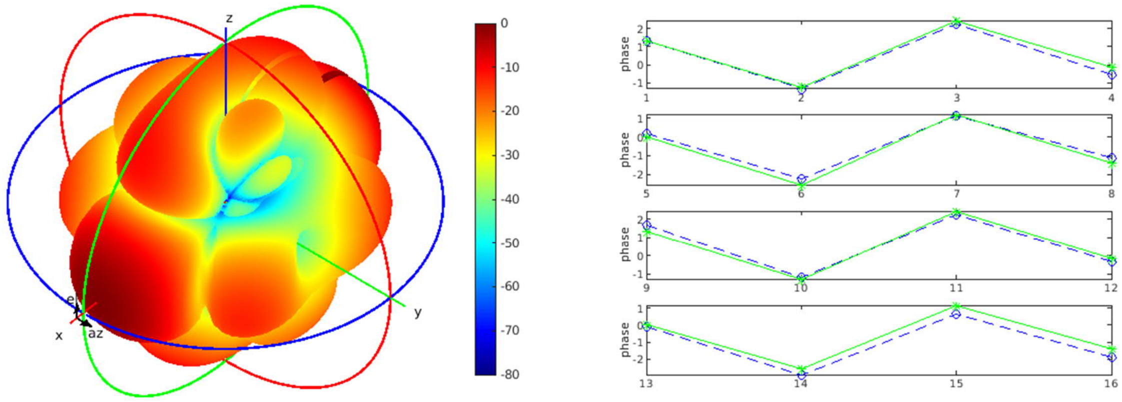
Figure 38 a) 4 port R&S ZNB and two R&S ZN-Z84 switch matrix units, b) 4x4 antenna cable connected to VNA switch unit.

Multiple antenna performance requires good antenna elements phase alignment. In practical system exact location and orientation of antenna elements introduce errors that can numerically be compensated. Measurement system is calibrated with standard VNA calibration procedure using a R&S ZV-Z51 calibration unit such that the calibrated reference planes are at the end of the antenna feed cables. We evaluated the quality of the antenna system by a test measurement. A fixed antenna pole with test transmission antenna was positioned at known location in front of the 4x4 measurement antenna (see Figure 39a). The calibration data was collected from a grid (see Figure 39b). At each transmitter location we recorded complex received signal in each antenna element (16 measurements). From those values we computed the received signal phase and compared it with the phase of the ideal signal arriving from a given direction. The computed antennae array gain is depicted in Figure 40a. The measured and ideal phases were found to be close enough to be suitable for the localization measurements without any numerical phase correction (see Figure 40b).



a) b)

Figure 39 Antenna calibration measurements a) measurement system, b) grid of measurement points used for calibration.

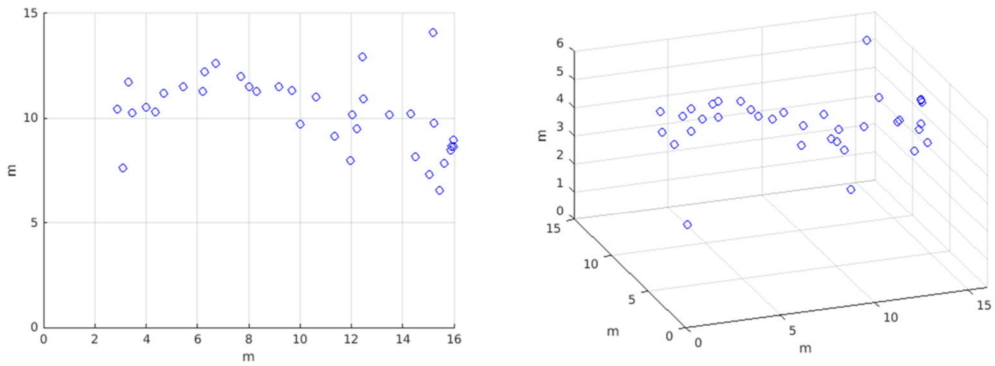


a) b)

Figure 40 a) ideal antennae array gain b) ideal antenna phase (blue dashed line) and measured phase (green line) at each 16 antenna elements at location (x=1000, y=700 see Figure 4.b above). Each subplot corresponds to one antennae elements row. Elements are numbered from upper left corner 1 to lower right corner 16.

4.2.3 Evaluation Report

Evaluation is done for drone flying in front of the antennas. In the demonstrated setup the drone flied perpendicularly to the antenna arrays in straight line, y = 10.4 m, and about 3.5 m height. The 3D plot of the measured/estimated locations is shown in Figure 41b. In Figure 41a, the same measurement is shown in the xy plane. During the measurement the drone was hovering in the wind. Impact of the wind is visible as drone not following straight line but moving further and closer around the planned flying trajectory. Evaluation results indicate that in cell less system the location estimation must integrate wind impact into drone location estimate.



a) b)

Figure 41 Estimated drone location a) top view, b) 3D view. Drone is flying along the line y = 10.4 m at height ~3.5 m

As seen in Figure 40.a antenna gain has zero in some directions. During the measurements it was observed that if drone direction falls into antenna zero even in one of BS the location estimation precision is reduced drastically.

4.3 Haptic Communications by YU

4.3.1 Short Description

This demonstration was performed to test a proof of concept of haptic communications. In firefighting scenarios, remote-controlled robots are used to help put out fires and rescue people. The haptic communications enable the control center to control UEs' haptic equipment remotely with low latency and high reliability.

This demonstration implemented a VR/haptic teleoperation system over wireless networks in Figure 42[6]. The user equips a VR HMD and manipulates a six degree-of-freedom (DoF) robot arm. These are the interfaces for providing visual feedback and generating haptic-motion data, respectively. In order to collect the visual information of the surroundings on the teleoperator side, we used a 360-degree camera, thus providing the operator side a full range of vision. The captured video data was encoded by the embedded computing device and packetized at the host PC to be sent over the wireless link. Moreover, the haptic-motion data, consisting of the three-dimensional position of the tips of the robot arms, is exchanged over the wireless link bi-directionally to provide haptic feedback to the operator.

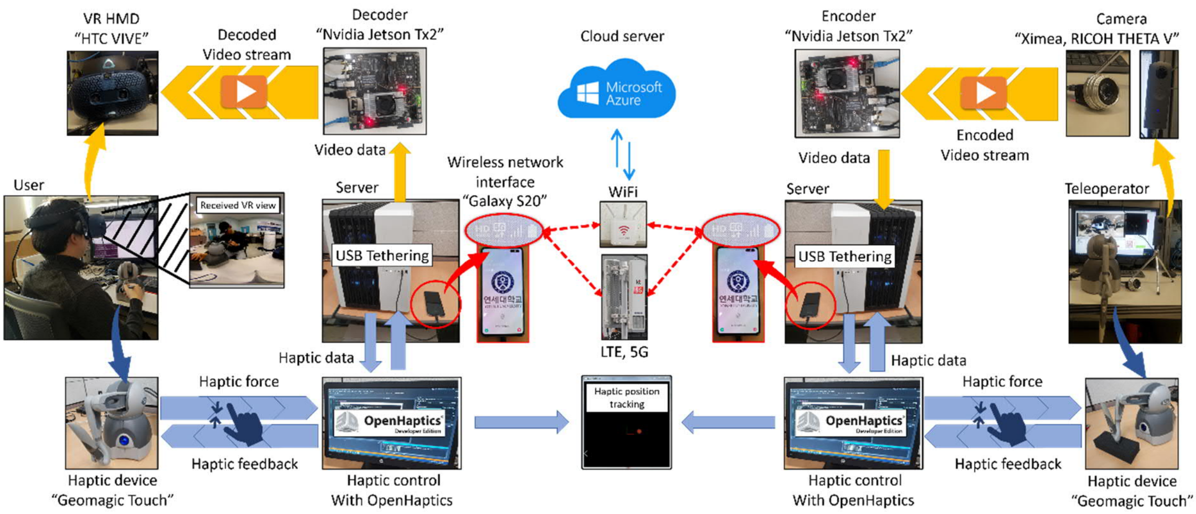


Figure 42 The diagram of the haptic communication system with VR over wireless networks.

The server PCs performed the local control, handled computational tasks, and exchanged packets with the network interface. To reproduce the motion, the teleoperator site calculated the difference between the received coordinate data and the teleoperator coordinate data, then generated and applied a force vector proportional to it. Among these processes, we applied simple linear prediction and perception-based compression algorithms to reduce the system latency in Figure 43. The wireless communication system was implemented using Wi-Fi, LTE, and 5G with commercial products to compare performances of the current wireless networks regarding system latency. The networks exchange the packets through

[6] Additional details may be viewed in the collated demo showcase video available at project's YouTube channel via this link https://www.youtube.com/watch?v=3tS6uuVmj3E

the cloud server relaying both the OP and the TOP side.

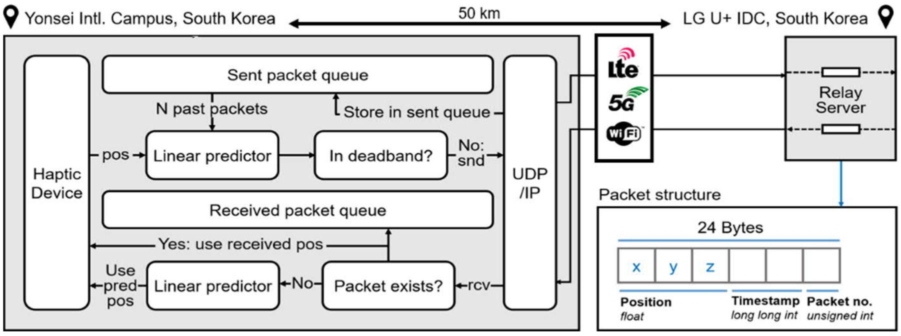


Figure 43 The block diagram of haptic control process and packet structure.

4.3.2 Continued Developments of the Demo

The following lists the progress of this demo since the last report D5.2 [PRIMO-D52]:

- Integration of the visual interface (VR HMD) and encoding/decoding embedded processors to haptic communication systems.
- Applying the haptic processing algorithms to reduce the system latency.
- Different wireless network interfaces are applied to compare the system latency performances.
- Installation of a cloud server deals with bi-directionally exchanged visual and haptic data.

4.3.3 Evaluation Report

Figure 44 shows the result of applying the haptic data processing algorithms. With a simple hold-last-sample algorithm, the haptic data rate drops to 74% even with 0% deadband since the haptic packets are sent only when the movement is detected. Deadband is a region that represents the limitations of human perception. Deadband can be exploited to reduce the data rate of haptic samples by haptic force stimulus. After applying linear prediction using 5 and 10 past values, the rates are even more reduced to 54% and 53%, respectively, thanks to perfectly predicted values. But due to noisy sensor data and fluctuating position values, in some cases, prediction error increases compared to the hold-last-sample method. These result in higher data rates for the linear prediction method at 25% or more deadband. The data rates on higher deadbands tend to increase with larger predictor queue size since the prediction slope changes more slowly as the number of past values used increases.

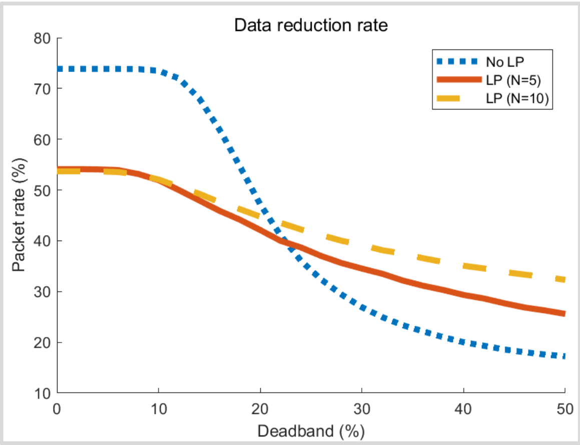
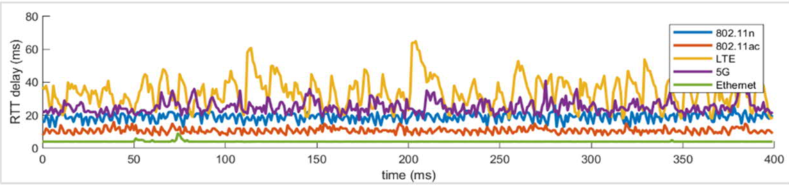


Figure 44 The data reduction rate of haptic data.

Both sites on an LTE or 5G network are connected to the relay server to exchange their packets bidirectionally. With this network setup, the round-trip delay (RTT) can be measured precisely. After the user site sends the packet to the relay server with its timestamp, the operator site records that value in its packet and executes retransmission. As the user site gets the message from other sites, the difference between two timestamps can be measured as the RTT delay. The table of Figure 45 shows the average delay with various network links. Ethernet latency results, 4~ms on average, contain pure delay from packet routing and physical distance to relay server, record lowest delay and jitter, providing a baseline for comparison. Comparing two Wi-Fi standards, 802.11ac beat its predecessor by halved average delay and jitter thanks to its higher frequency range and more advanced technologies such as multiple-input multiple-output (MIMO). 5G shows lower delay and jitter than LTE by adopting higher base frequency and improved channel efficiency, but it is still worse than two Wi-Fi technologies. Outdoor base station's farther distance compared to indoor Wi-Fi router can be one good reason explaining those results.



RTT (ms)	AVG	JITTER	STDEV
802.11n	20.75	2.83	8.00
802.11ac	11.79	1.71	12.40
LTE-A	33.56	4.89	8.69
5G FR1	25.33	2.84	7.44
Ethernet	3.99	0.04	0.15

Figure 45 The end-to-end latency performances of different wireless network interfaces.

4.4 Real-time Object Detection with Distributed Compute Nodes by KCL

4.4.1 Short Description

This demonstration concerns the deployment of a novel platform for real-time object classifications using distributed compute nodes with machine learning capabilities for performing inference on video streams provided by UAVs equipped with camera sensors. The video streams are composed of packetized video frames which are transmitted to a server. The server's role is to distribute the video frames to compute nodes that perform the object detection task to each frame they receive and return back to the server the object detection results. Then, the server needs to synchronize the results with the video stream previously sent by the relevant UAV.

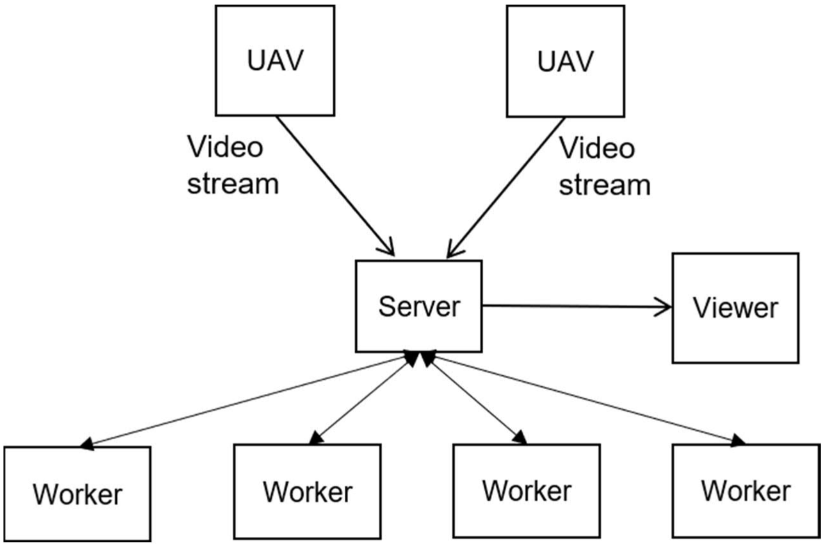


Figure 46 System Architecture

In more detail the entities that compose the system architecture (as shown in Figure 46) are:

- **UAV**: The UAV is a video source device responsible for generating a data stream composed of video frames. The UAV will stream the video frames to the edge server.
- **Edge Server**: The edge server is responsible for receiving and distributing data from and to other entities. In particular, the server receives the video frame stream from the UAVs and distributes the frames to the workers. The server is also responsible for receiving the results from the workers, synchronise them with the video stream frames and make them available for viewing by a human user.
- **Worker**: Each worker entity is responsible for performing inference for object detection to each frame it receives from the edge server. The worker then transmits the results back to the server.

4.4.2 Continued Developments of the Demo

Since the last report, this demo was designed, deployed and evaluated regarding the impact that worker availability has to the latency of the results being displayed to the viewer.

4.4.3 Evaluation Report

The evaluation of the system is focusing on measuring the latency of object tracking the results to be presented to the viewer with respect to the availability of the workers. Regarding the evaluation of this demo, the availability of the workers is the amount of time they are able to receive video frames distributed by the server and is calculated as the worker uptime duration over the total duration of the video.

The system was deployed on three PCs connected to the same network, each one using an NVIDIA GeForce GTX 1080 Ti 11G. The system components deployed were the edge server, one video source (i.e., the UAV) and 9 workers performing inference using Single Shot Detector Model (SSD) model with Mobilenet v1 configuration for MSCOCO Dataset. All system components communicate with each other using TCP.

The tradeoff between using a centralized and a distributed approach for processing a video stream from single source can be seen by the fact that the average latency value for a system where one worker is deployed on the edge server using all available resources is 172ms. The latency performance of the distributed system was evaluated using a video from the LaSOT data set [LaSOT] called “bear-12”. As seen in Figure 47, the results show increase in latency from 2 seconds to 26.8 seconds as the availability drops from 100% to 2%.

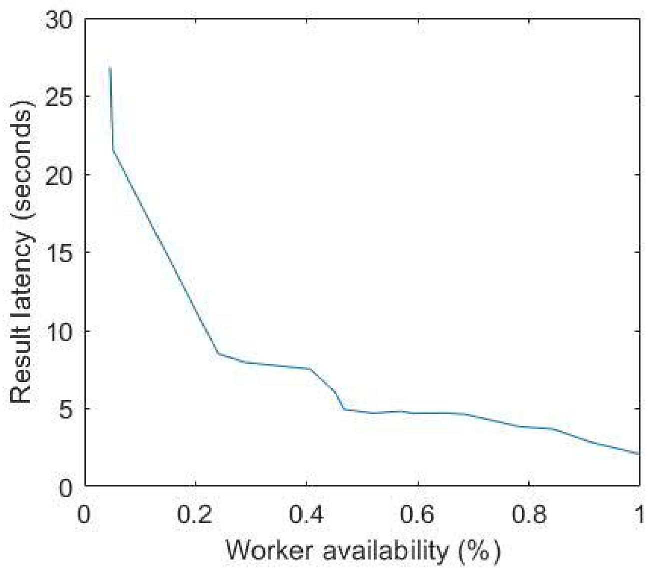


Figure 47 Result latency vs Worker availability

5 Exploitation of PriMO-5G Demos in Other Vertical Use Cases

In this section, we identify possible vertical use cases for the ProMO-5G technology. Additionally, one example application scenario is described that emerged from the work carried out by YU in the project.

5.1 Overview

The introduction of 5G (and beyond 5G) technologies has targeted significantly broader and deeper impact on different vertical industries compared to observed impacts from preceding generations of mobile wireless technologies. To that end, 5G technology solutions are developed from the beginning to address a diverse range of use cases and business models for verticals with disparate requirements [5GA]. In the case of PriMO-5G, the project has focused on enhancing these impacts of 5G in public safety verticals, and specifically on firefighting scenarios through investigation of immersive video services for moving objects, radio access enhancements for aerial scenarios, AI-enabled communications and computing trade-offs, cross-continental 5G systems and so on (demonstrated in preceding chapters). However, these concepts and solutions developed and experimented within the PriMO-5G project have potential impact not just in other public safety scenarios, but also scenarios and use cases in other vertical segments.

In this chapter we review the applicability of demonstrated PriMO-5G concepts and solutions to other vertical segments. To that end, we leverage the clustering utilised of vertical industries as proposed in the 5G-PPP vertical cartography[7]. Table 6 below summarizes potential application of PriMO-5G solutions to each of the vertical clusters. It is emphasized that the list of potential applications per vertical is not exhaustive.

Table 6 Potential applicability of PriMO-5G experimented concepts and solutions to different vertical clusters (verticals icons borrowed from Global5G.org project)

Vertical Cluster (Category)	Potential applicability of PriMO-5G solutions
1. Automotive 	• *Connected cars – vehicle-to-everything (V2X)*: Seamless handovers with cell free architectures are also useful for V2X connectivity, whereby, vehicle may have frequent handovers when connected to roadside small cells with short intersite distances. • *On the move services*: Immersive video services in moving objects is useful in vehicular environments for both assisted or automated driving, as well as, in-vehicle infotainment services.
2. Industry 	• *Factory and process automation*: Immersive video services when using drones and automated guided vehicles (AGVs) on factory floors. Cross-continental 5G networks may enhance remote operations in smart factories (experiment on this is conducted in PriMO-5G as noted next in Section 5.2). • *Farming technologies*: PriMO-5G use of drones for sensing and immersive video services also useful for smart farming for managing of farm and livestock assets, as well as, capturing of high-resolution images for planning of farming operations (e.g. irrigation, harvesting, fertilization etc.).

[7] https://global5g.org/cartography

Vertical Cluster (Category)	Potential applicability of PriMO-5G solutions
3. Media and Entertainment	• *Content creation, aggregation, distribution and consumptions*: PriMO-5G use of drones for immersive video in firefighting also useful for non-critical entertainment services, with drones used for aerial content creation, which can be aggregated on the edge, distributed and consumed in more immersive formats.
4. Health	• *Smart health*: 5G-enhanced cross-continental connectivity with potential use in low-latency remote health services (e.g. remote surgery).
5. Public Safety	• *Rapid disaster response*: While the focus of PriMO-5G has been on solutions for response to fires (urban or wildfires), it is equally applicable to response for other natural or man-made disaster (e.g. floods, earthquakes etc.). • *Public event management*: The monitoring of public events with real-time immersive video captured from drones to allow event managers to rapidly react to emerging safety or security concerns.
6. Energy	• *Monitoring and control*: Use of drones and immersive video services useful for monitoring of power assets (e.g. power lines, substations, solar farms, wind turbines etc.), which may in turn support optimization of voltage profiles and power flows, forecasting of power generation and consumption, and so on.
7. Smart Cities	• *People mobility*: Leverage aerial immersive video from drones to enhance city management operations, such as, multimodal people or goods mobility, crowd or incident management, route planning. • *Tourism*: Aerial immersive video of city tourist sites and 5G cross-continental networks can enable virtual tourism with tourists consuming the immersive video in real time regardless of location thus overcoming travel barriers e.g. due to pandemics.
8. Transport and Logistics	• *On the move services*: Immersive video services in moving objects can be useful to both passengers and operators of rail/maritime/aviation transport (e.g. monitoring of people or goods transported).

5.2 5G-connected Robot Demo by YU

5.2.1 Background

5G enabled UAVs and the E2E system comprising it are translatable to an industrial scenario. The UAV is translated to a machine in a factory, trying to execute commands requested by either a human commander, or an intelligent computing node.

5.2.2 Integration Report

The deployment from the UAV 5G platform has been extended to Yonsei Robotics Testbed as shown in Figure 48. The Yonsei Robotics Testbed consists of different nodes: 5G core, mobile edge computer, and mobile object picker robot. 5G core is the core linked to Finland, as in the multi-DNN configuration of the CMC-YU core switching testbed; mobile edge computer is a computer linked to the 5G core that is capable of advanced processing like GPU acceleration and streaming; and the mobile object picker robot is a multi-joint robot that has a vision sensor and engine.

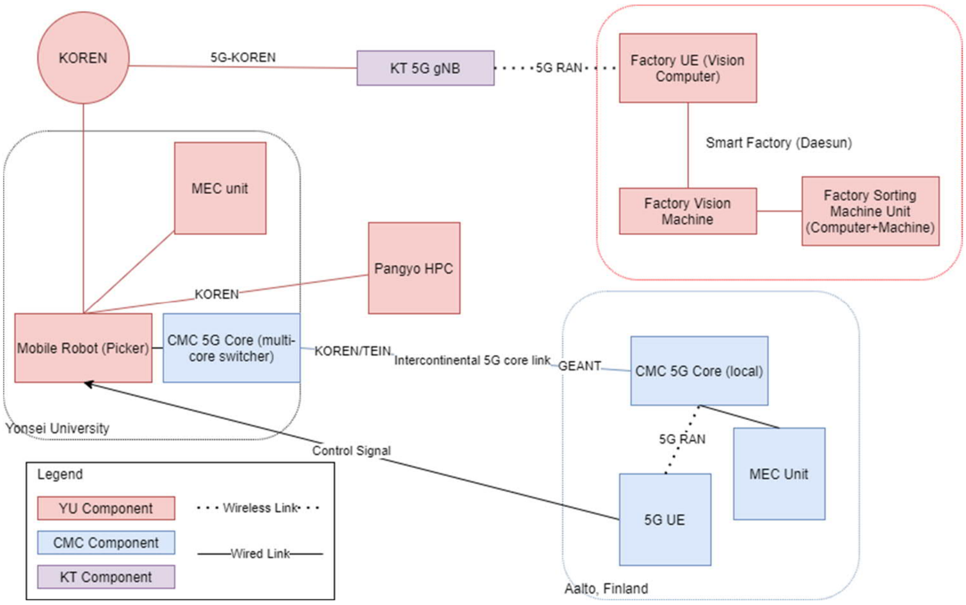


Figure 48 E2E network topology of Yonsei University-Aalto University-Daesun intercontinental smart factory testbed.

As shown in Figure 49, a vision sensor decides the arrival time of the boxes in a bottle factory. The boxes are then detected to count the number of appropriate or faulty bottles.

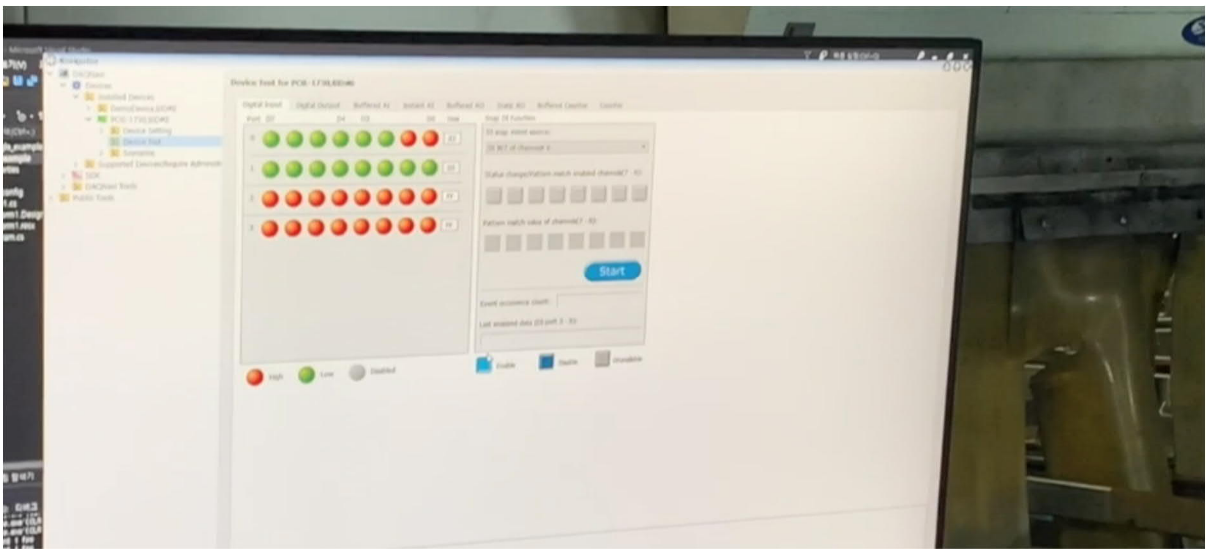


Figure 49 Sensor compartment decides the arrival time of the boxes at a bottle factory. The boxes are then detected to count the number of appropriate or faulty bottles.

5G cores in Korea and Finland are connected via KOREN, TEIN, and GEANT, which is identical to the topology explained in previous sections. Using the linked cores, Finland controls the robot in Korea remotely. The control signal exploits the optimal routing provided by the closed L2VPN network configuration of the intercontinental testbed. In addition to responding to the control signal from Finland, the mobile robot offloads its processing task, i.e. real-time multi-object detection, to the MEC or HPC, then returns Finland the result[8].

5.2.3 Evaluation report

Finally, as an exploitation of the PriMO-5G network architecture, the deployment is further extended to the Yonsei industrial testbed, which consists of a smart factory linked to the Yonsei Robotics Testbed.

As depicted in Figure 50, software was developed to receive detection results from an intelligent computing node, and respond to the signal by moving the robot's arm to the right position, picking the detected (faulty) bottles, and transferring the bottle to a new location, i.e. a to-be-filled box.

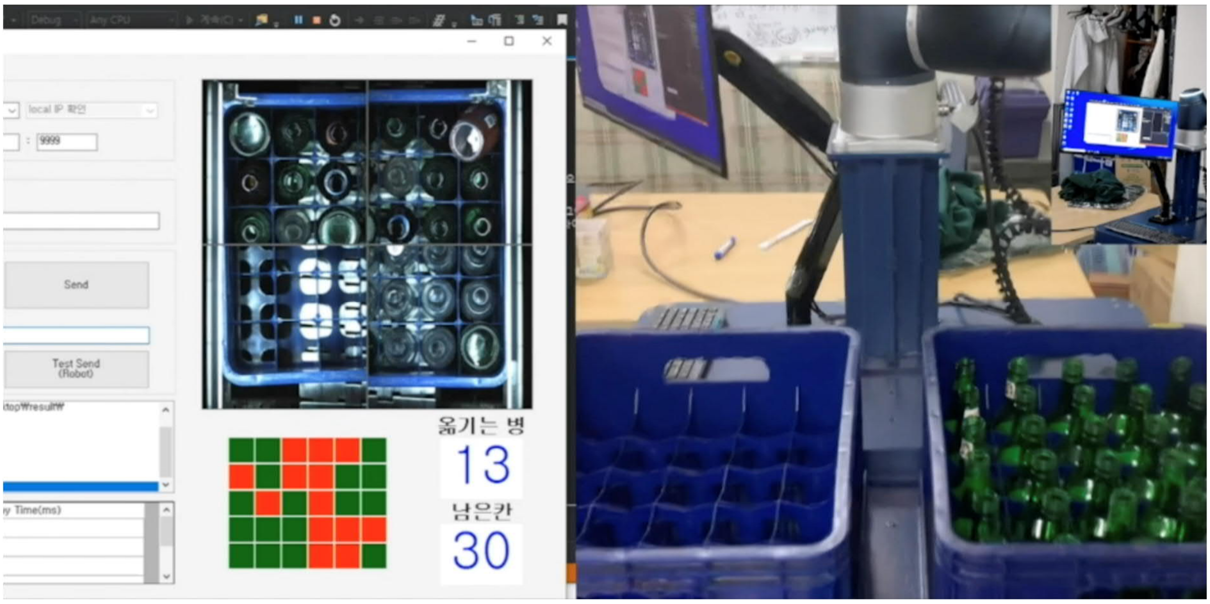


Figure 50 Developed software screenshot image (left), and the robot's arm transferring the bottles (right).

We conducted a latency measurement of our proposed testbed. The industrial site has a latency requirement of less than 500ms to conduct its bottle classification task based on the moving speed of boxes on the conveyor belt in the factory. The result, see Table 7, showed that our proposed testbed can meet the requirement of the bottle factory requested under the assumption that the robot would have deployed in the actual industrial site.

[8] Additional details may be viewed in the collated demo showcase video available at project's YouTube channel via this link https://www.youtube.com/watch?v=3tS6uuVmj3E

Table 7 Latency measurement based on the industrial site’s latency KPI

Industrial Site (bottle factory)	Yonsei Robot	Latency	The Industrial Site’s latency KPI
Image acquisition			500ms per 1 box
Bottle Classification		400ms (avearge)	
	Data request	30ms (average)	
Data trasnfer (indexs / image)		indexes : under 5ms	
		Image : 2000ms	
	Robot Actuation		

Low latency remote control of industrial robot: For factories located abroad, private and low latency communication must be enabled to ensure a secure and fast remote control of the factory equipment, e.g. industrial picking robot. We test this scenario by using the private tunnel between CMC and YU, letting CMC control an industrial robot in YU. In the test, CMC wakes up and commands the robot to move a bottle from a box to another box, in low latency, i.e. 120 ms, considering the long distance. Figure 51 shows a real-time demo of CMC controlling the industrial robot in YU.

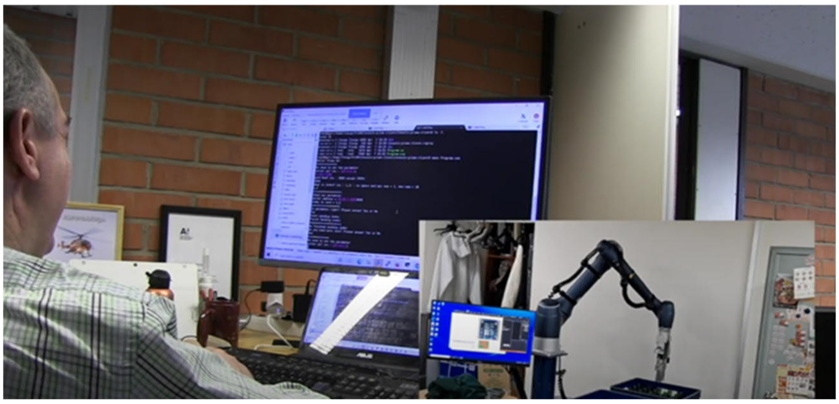


Figure 51 CMC is controlling YU’s industrial robot in low latency using the intercontinental interoperable network.

6 Conclusions

This deliverable D5.3 *Final report – end-to-end immersive demonstrations* presents the summary of the final results from the system integration and demo activities in the PriMO-5G project and spans the period M24 (June 2020) until the end of the project M36 (June 2021). The goal of these experimentation activities was to test and demonstrate key 5G developments in radio, edge and core networks in the context of PriMO-5G firefighting use cases according to the plan of D5.1 [PRIMO-D51].

A major effort in the project has been to develop demonstrations of large-scale system integration activities with multiple partners within Europe and Korea. These were referred to as intracontinental system integration targeting the interconnection of PriMO-5G testbeds between two European countries or between multiple partners in Korea. In all cases, the end-to-end system demo scenarios have been specified and mapped to PriMO-5G firefighting scenarios and use cases of deliverable D1.1 [PRIMO-D51]. Altogether four such system integration and demo activities were presented with details on the demo background, integration steps and an evaluation report with the results on the main KPIs. Many of the demos were also presented as pre-recorded videos at various events.

The work done on the intracontinental demos also contributed significantly to the intercontinental PriMO-5G system integration activity. In this context, the objective was to interconnect PriMO-5G testbeds between Europe and Korea. These intercontinental end-to-end system demo scenarios have also mapped to PriMO-5G firefighting scenarios and use cases of deliverable D1.1 [PRIMO-D51]. This deliverable report provided details of the background, integration of the components and an evaluation report with the results on the main KPIs. Moreover, the intercontinental PriMO-5G system integration effort and the results were also documented in a magazine article, which is still under preparation at the time of the writing of this deliverable.

Additionally, some partners still had some stand-alone experimental activities taking place during the final year, that have served to provide further validation of key PriMO-5G technologies. Three such component demos were discussed with descriptions of the demo background, developments of the demo and the final results.

Finally, the exploitation of PriMO-5G technology in other verticals was considered. A generic analysis of possible other verticals was given. More importantly, details were provided on a use case where PriMO-5G technology was used for remotely controlling a robot in an industrial facility.

In summary, the system integration and demonstration activities developed over the life span of the project have been notable in highlighting the potential of 5G for supporting demanding and critical operations. These activities have contributed to the development of technological innovations, as well as created new collaborations among the partners. The main achievements have been documented in several articles and demo videos showcased in various events.

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