FUDGE-5G

FUlly DisinteGrated private nEtworks
for 5G verticals

Deliverable 4.3

Technical Validation of Vertical Use Cases

Version 1.0
Work Package 4

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Abbreviations

5GC	5G Core
5G-LAN	5G-Based Local Area Network
AMF	Access & Mobility Management Function
ARFCN	Absolute Radio-Frequency Channel Number
AP	Access Point
AWS	Amazon Web Services
BBU	Baseband Unit
BT	Benchmarking Tool
C3	Command, Control & Communications
CBCF	Cell Broadcast Centre Function
CCU	Camera Control Unit
CPE	Customer Premise Equipment
CPU	Central Processing Unit
DASH	Dynamic Adaptive Streaming over HTTP
DL	Downlink
GM	Grandmaster
HD	High-Definition
HTTP	Hypertext Transfer Protocol
ICN	Information-Centric Networking
INPN	Interconnected NPN
IP	Internet Protocol
IT	Information Technology
KPI	Key Performance Indicator
LTE	Long-Term Evolution
LXC	Linux Container
MPEG	Moving Picture Experts Group
NAT	Network Address Translation
NBR	Name-Based Routing
NDMA	Norway Defense and Material Agency
NF	Network Function
NLA	Norwegian Air ambulance (*NorskLuftambulanse*)
NoW	Network-on-Wheels
NPN	Non-Public Network
NR	New Radio
OB	Outside Broadcasting
ONOS	Open Network Operating System
OUS	Oslo University Hospital
OVS	Open vSwitch
PCE	Path Computation Element
PDU	Packet Data Unit
PLMN	Public Land Mobile Network
PNI-NPN	Public Network Integrated NPN

PPDR	Public Protection and Disaster Relief
PTP	Precision Time Protocol
PTT	Push-to-Talk
PTZ	Pan-Tilt-Zoom
QoS	Quality of Service
RAN	Radio Access Network
RCP	Remote Control Panel
RF	Radio-Frequency
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RTT	Round-Trip Time
RX	Reception
SA	Standalone
SBC	Session Border Controller
SCP	Service Communication Proxy
SD	Slice Differentiator / Standard Definition
SDI	Serial Digital Interface
SDN	Software Defined Network
SEPP	Security Edge Protection Proxy
SIM	Subscriber Identity Module
S-NPN	Standalone Non-Public Network
SP	Service Proxy
SPM	Service Proxy Manager
SSH	Secure Shell
SST	Slice Service Type
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TLS	Transport Layer Security
TSN	Time Sensitive Networking
TX	Transmission
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink
UPF	User Plane Function
VNF	Virtual Network Function
VoD	Video on Demand
VPN	Virtual Private Network
VXLAN	Virtual eXtensible Local Area Network

Executive Summary

The following document describes in detail the **final vertical trials** of FUDGE-5G. As described originally in D4.1, **five use cases** have been demonstrated and validated in the context of the project, i.e., concurrent media delivery, Public Protection and Disaster Relief (PPDR), 5G virtual office, Industry 4.0 and interconnected Non-Public Networks (NPNs). While D4.1 focused on an interim technical validation of such use cases, and D4.2 described the validation of specific 5G components that were integrated within the project, D4.3 focuses on the final vertical trials that took place at the end of FUDGE-5G.

For each of the five use cases, a series of test cases and applications have been considered. The document first describes the main setup and the measurement tools for each one of these test cases. This includes the use case **architecture**, deployment information with detailed pictures, and scenarios. Afterwards, the document provides a summary of the execution of the trials, with **detailed results** and/or measured values for the different Key Performance Indicators (KPIs) previously considered in the project. Such results are compared against the requirements defined in D1.1 and discussed in detailed to understand if the use of 5G NPNs and the FUDGE-5G platform fulfills the stakeholders' expectations.

In this sense, the deliverable also collects the **feedback from stakeholders**. For each of the vertical use cases, the stakeholder discusses the main outcomes of the final trials and provides suggestions for improvement, future tests, and the way forward after the project.

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1. Introduction

This deliverable describes in detail the final vertical trials of FUDGE-5G. As proposed originally in D4.1 [1], five different use cases have been validated in the context of the project. Reaching this point in all use cases has not been an easy task. During the project, each use case has followed a specific methodology, as depicted in Figure 1. The methodology includes the following items:

- The definition of a vertical blueprint including KPIs, requirements, main architecture, different phases and test cases. This work was mainly done in WP1 and reported in D1.1 [2].
- Technology design of main innovations and development of 5G services and components such as the FUDGE platform, 5G cores (5GC) and integrated microservice based network functions, as well as 5G devices, done as part of WP2 and reported in D2.3 [3], D2.4 [4] and D2.5 [5].
- Component onboarding, FUDGE-5G platform integration and infrastructure deployment. This can be considered our work related to WP3. It was recently reported in D3.2 [6].
- Component validation in real environments. This item includes the 5G component validation reported in D4.2 [7], and the vertical final trials included in this document.

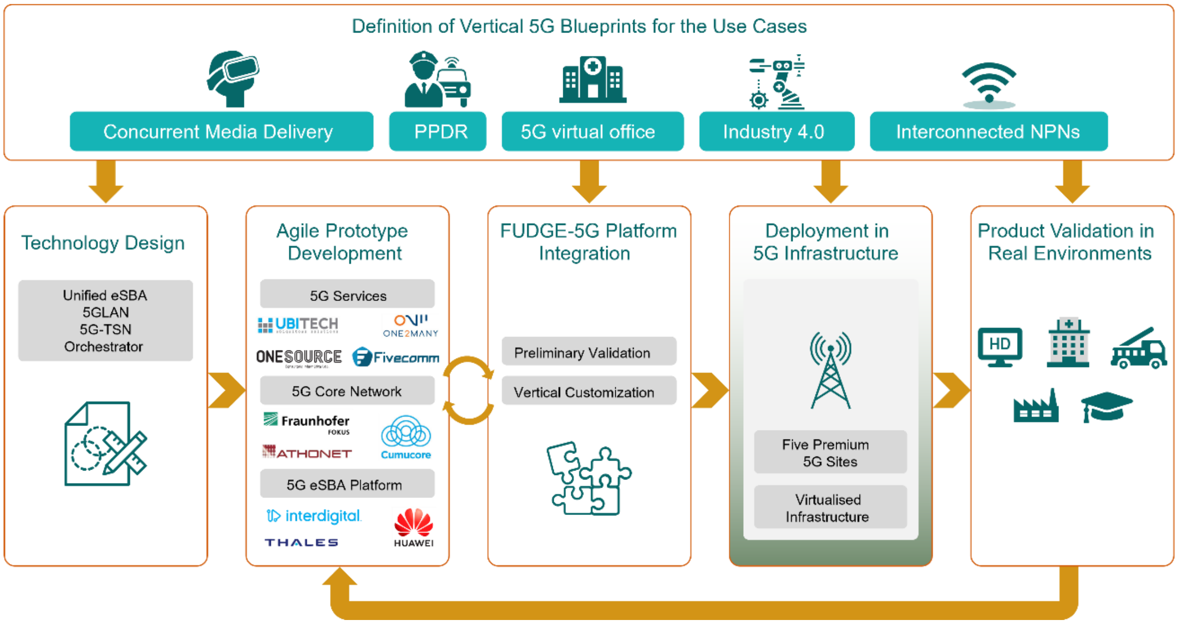


Figure 1. FUDGE-5G use case validation methodology.

As Figure 1 shows, the final vertical trials have been executed for the following five vertical use cases: concurrent media delivery, PPDR, 5G virtual office, Industry 4.0 and interconnected NPNs.

1.1. Objectives

The main objective of D4.3 is to describe in detail the **final vertical trials** performed, to validate the concurrent use of the FUDGE-5G platform and NPNs for vertical applications and services. We have identified three main secondary objectives.

1. Describe the architecture, deployment setup and measurement tools.

D4.3 first describes the main setup and the measurement tools for each one of the test cases done per use case. This includes the architecture, deployment information with detailed pictures, and scenarios (and maps) when needed.

2. Provide validation results for each final vertical trial.

Afterwards, the document describes the execution of the trials and provides detailed results and for the different KPIs considered. Such results are compared against the requirements defined in D4.1 [8] and discussed in detailed to understand if the use of 5G NPNs and the FUDGE-5G platform fulfills the stakeholders' expectations.

3. Collect feedback from stakeholders for future development of FUDGE components.

In this sense, D4.3 also collects the feedback from stakeholders. In each of verticals use case, each stakeholder discusses the main outcomes of the final trials and provides suggestions for improvement, future tests, and the way forward for us after the project.

1.2. Structure

The document is structured in five main chapters, directly related to the vertical use cases mentioned in Section 1.1.

- **Section 2**: Concurrent media delivery, with a total of three test cases, i.e., remote production, media showroom and professional video delivery benchmarking.
- **Section 3**: PPDR, with two related scenarios, i.e., standalone Network-on-Wheels (NoW), and public warning systems.
- **Section 4**: 5G virtual office, which includes two test cases, i.e., ward remote monitoring, and intra-hospital patient transport monitoring.
- **Section 5**: Industry 4.0, which includes indoor 5G network analysis, monitoring and process control, 5G adaptability in industrial environments, and 5G-TSN for industrial scenarios.
- **Section 6**: Interconnected NPNs finally provides results for four test cases, i.e., interconnection of NPNs, home subscriber authentication, visiting subscriber authentication, and access to network services, and additionally results for energy consumption of 5GCs.

Finally, the main findings of this deliverable regarding these trials are provided in **Section 7**.

2. Concurrent media delivery: final trials

The first use case on concurrent media delivery focused on the 5G NPN aspects of multimedia; including media production and multimedia delivery. NRK, the Norwegian public broadcaster, acts as the main stakeholder of this use case. During the project, three test cases were demonstrated, one regarding remote production using the NoW, a portable vehicle deeply detailed in previous deliverables such as D3.1 [9], D3.2 [6] and D4.1 [8]. The second test case, media showroom, includes the experiments of a novel multimedia delivery mechanism which does not rely on Internet Protocol (IP) semantics to perform multicast. The final test cases are an evaluation in laboratory settings of the impact of public 5G networks versus private ones for professional video delivery. Upcoming subsections will provide detail on the setup for each test case and the results obtained.

2.1. Setup and measurement tools

2.1.1. Remote production

This section describes the tests performed in Skien and Bergen to demonstrate the FUDGE-5G remote production use case. NRK and Trippel-M have been involved as stakeholders, meaning the project have helped define the needs for solutions and practical demonstrated use. Furthermore, the major partners in Norway have been the Norwegian Armed Forces, who have built and financed a standalone 5G network together with developers from Telenor and technology from Athonet, Cumucore and Huawei.

In a general view, the project aims to demonstrate concepts where 5G can improve services within several industries divided into different use cases. Specifically, the remote production use cases aim to explore the opportunities that new 5G technology bring to the professional audio-visual content production sector, taking advantage of 5G key features. The project uses the deployment of 5G NPNs, given the opportunities they provide in terms of performance, privacy, data security and compliance. In the process, several tests have been performed, from tests used to get video over 5G to more advanced tests where 5G is used in production.

Particularly, the media use case is about the use of 5G to reduce complexity and setup time of media content production scenarios, while at the same time gaining flexibility. The project defined the use case which takes care of how the media industry can use 5G networks to improve their working methods. In the process, the project had several tests, from only testing whether we get video over 5G to more advanced tests where we use 5G in production. In this use case, a single trial has been performed to test if the proposed technical solution can satisfy the user´s demands, in this case, content producers, i.e., a production testing in the NM-Week event (Skien), June 2022 [10].

2.1.1.1. Main setup

The 5G production in Skien was the first media production within the project where 5G was used on air. Mainly, five wireless cameras were connected to production equipment via a

5G standalone NPN (S-NPN). It was important for NRK to learn from the project and to work on practical solutions that justify the allocation of frequencies for content production. This trial was the first where the team introduced users in a full production flow to the technology. In addition to the technological aspects, the user experience was therefore in focus, and it was important for partners to get feedback from users who used this on air. Figure 2 shows the team setting up a 5G cell, and the same cell being used in the trial.

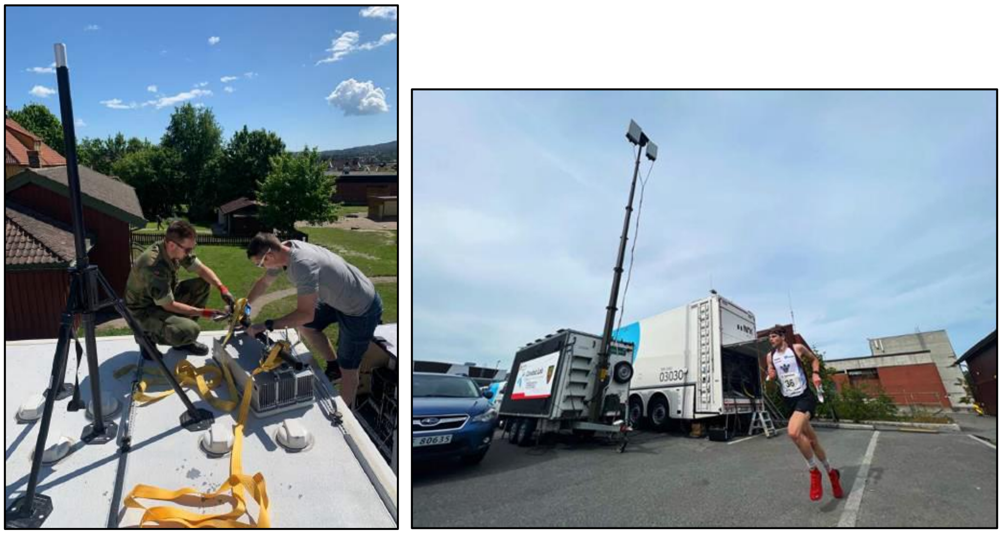


Figure 2. Setting up of one 5G cell (left), which was later used in the trial session (right).

2.1.1.2. Objectives

The specific objectives of this first trial were to:

- Study how to standardize the technology into the external workflows and integrate it with the production Outside Broadcasting (OB) units of NRK, shown in Figure 3.
- Gather user experience to determine where the key pain/points are.
- Test 5G S-NPN in urban environments without a direct line of sight between devices and the cell's antenna.
- Get extended experience with different encoders and modem solutions.
- Get hands-on experience with how camera systems work in remote production.
- Get more hands-on experience with compressed video and IP-based production.

Figure 3. NRK's OB van.

2.1.1.3. Planning

This section describes the planning of the development towards the trials with the required resources and logistics for the use case. The use case is following the expected timeline according to the original project plan. The timeline of the project is shown in Figure 4.

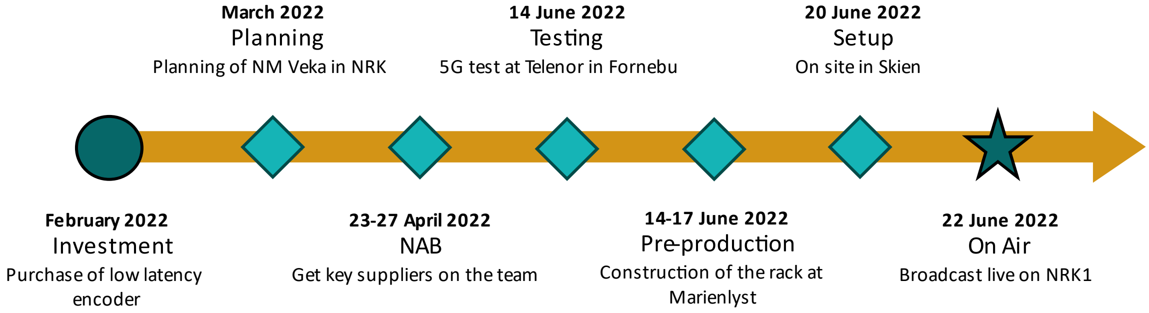


Figure 4. Timeline towards the first trial session.

As it can be seen in the timeline, in February 2022 NRK made the acquisition of 13 low-latency video encoders. VideoXLink was the preferred choice since they combine good compression and low delay over normal IP networks, giving the partners many new opportunities to explore IP-based production.

A new opportunity arose in collaboration with FUDGE-5G when there was interest to test on air. NRK Sporten wanted to try innovative production methods during NM-Week and several large suppliers were willing to lend the project equipment to acquire more knowledge about the possibilities that lie in a 5G production environment. A good collaboration with the sport content producers, who have always been positive about spending time and resources on renewing production methods was relevant. NM-Veka has traditionally been a very good testing ground for this type of projects, thanks to the sport's content producers' good attitude towards new technology.

2.1.1.4. Technical setup deployment on week of June 14-17 (Pre-production)

In the week before the trial, Camera Control Unit (CCU) racks were built. These were made to be placed in locations where power was available, and where all other connections are made via 5G. That is, the CCUs were in the field, i.e., all transmissions between the field and bus were IP-based.

In multi-camera productions, the camera operators need feedback, tally, intercom etc. and the partners tried to make the setup as simple as possible, to focus on testing workflow and user experience to the greatest extent with as few sources of error as possible. The team embedded tally and camera controls over Serial Digital Interface (SDI) and connected this analogically in and out of the CCU. Tally and control data came from a Remote Control Panel (RCP) via an IP tunnel.

Figure 5 shows an illustration of the 5G setup, which only includes this. The total production was composed of 11 cameras, and the other 6 cameras were connected via traditional fiber. Figure 6 also shows the location of the NoW and some of the cameras in a map. Figure 7, on the other hand, shows the different video feeds being sent to the OB.

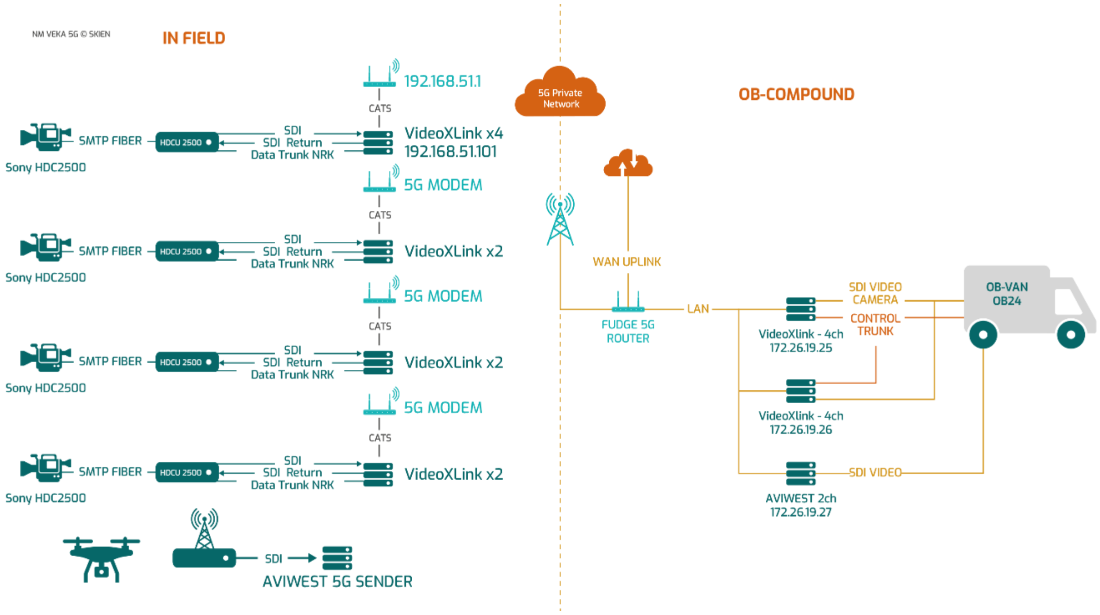


Figure 5. Trial final setup.

From the preparation with the Norwegian Armed Forces' radio experts, the team concluded that 5G in urban areas would be a challenge. Buildings made it impossible to get an unobstructed view.

This environment also proved to be relatively new for the Norwegian Armed Forces to work with, which was the strongest radio-frequency (RF) expertise the project had. The team was well prepared for the other aspects of production, but unfortunately, the planned radio test with the 5G base station was canceled due to challenges with the 5GC, and therefore the team arrived relatively unprepared on-site. As planned, the 5G antenna was placed next to the OB bus, which was in the main OB compound, and racks were placed next to each of the cameras.

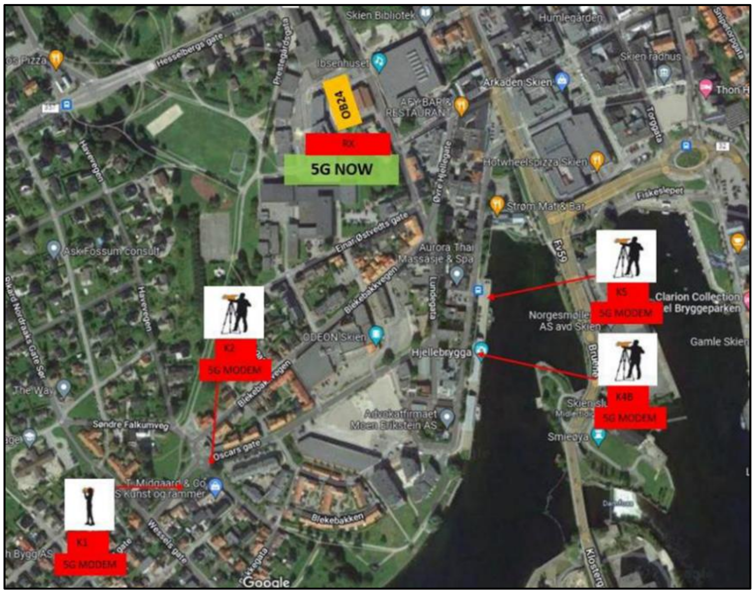


Figure 6. Map with cameras and OB van locations.

It was challenging to test 5G coverage, as the team did not have good instruments to measure actual coverage quality. Even if a Customer Premise Equipment (CPE) or Mobile phone showed that there was relatively good coverage, it could still be a connection with a lot of packet loss and low data transfer. Therefore, the team had to test with the video encoders which could give more data, but this was a time-consuming process with several rigs per site. The team quickly saw that the higher the CPEs, the easier it was to get good coverage. That led to a lot of testing on this matter, where long network cables were used to connect the racks and the CPEs. As a result, a lot of time was spent on communication and structuring testing and troubleshooting.

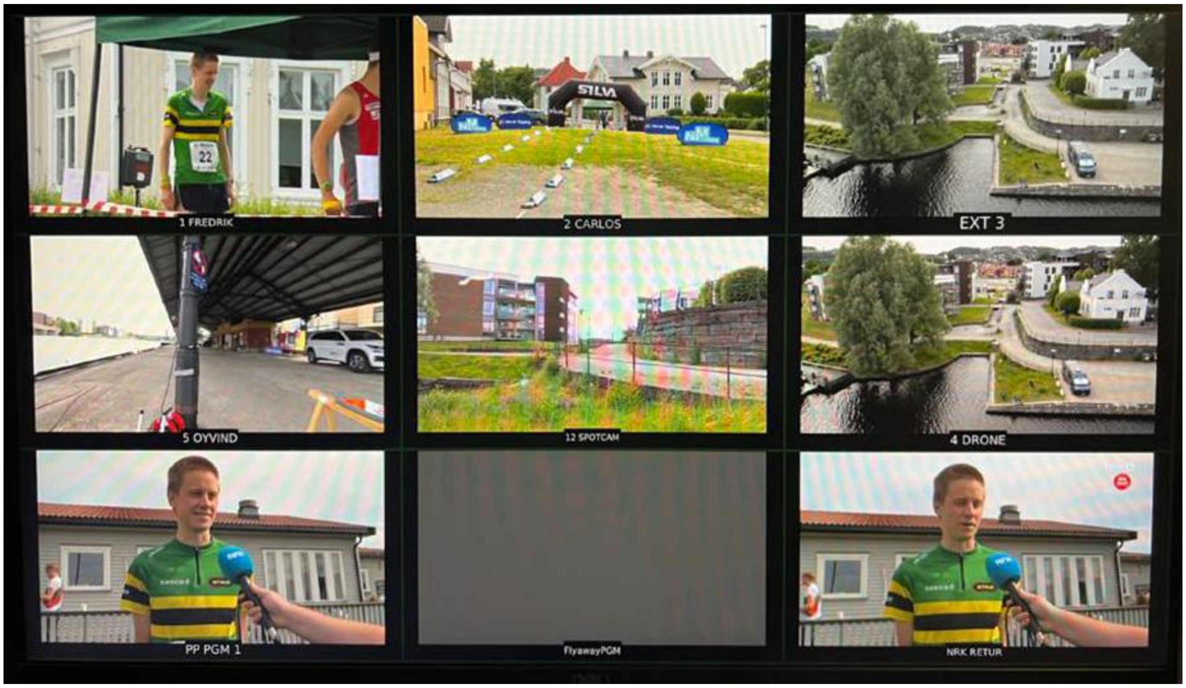


Figure 7. Video feeds from the different cameras.

When NRK had to raise the CPEs, they changed the plan so that they used the same encoders (VideoXlink + CPE) at all locations. That meant that NRK had the Aviwest encoders to spare. The use of a drone in this test was planned with LiveU as a contribution to OB-Van, so the team switched this out with Aviwest on 5G and had the delay reduced by 0.8 seconds, as well as the quality, increased from 20 Mbit to 30 Mbit. This made the cut from the drone look better. By the time the team went to production, most parameters were adjusted to achieve what was expected: quality, stability, and delay.

2.1.2. Media showroom

This subsection describes the set-up of the media showroom test case which uses Name-Based Routing on the User Plane to deliver a Hypertext Transfer Protocol (HTTP)-based Video on Demand (VoD) stream to a fixed set of UEs.

2.1.2.1. Background and Assumptions

Deliverable 1.3 [11] provides a detailed description of the proposal to integrate Name-Based Routing (NBR) on the 5G User Plane with the least amount of changes to the 5G Control Plane. In particular, the request to create/modify/release a Packet Data Unit (PDU) session is remained untouched with a single addition to the procedures within a 5GC. Such approach was chosen to increase the likelihood for standardization.

Figure 8 depicts the architecture of NBR with the orange components representing the core NBR entities, i.e.:

- Service Proxy (SP): Translating IP traffic into Information-Centric Networking (ICN) and vice versa. The SP changes its functionality based on whether it handles requests from clients (SP Client (SP$_{C}$)) or responses from servers (SP Server (SP$_{S}$)).
- Path Computation Element (PCE): This implements the ICN-centric functionalities rendezvous, topology management and path calculation.
- Service Proxy Manager (SPM): This component manages the subscription states for IP addresses and FQDNs each SP$_{S}$ serves. It also exposes an interface to programmatically configure theses subscription states.

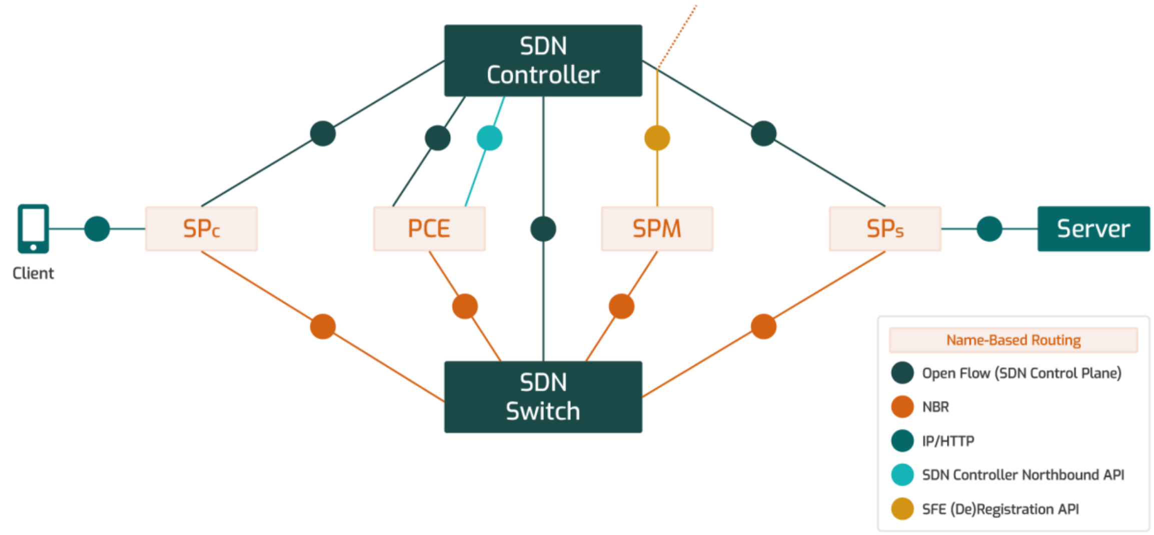


Figure 8: Name-Based Routing

NBR integrates seamlessly with a Software Defined Network (SDN)-based switching fabric, supporting the controllers OpenDaylight, Floodlight and Open Network Operating System (ONOS).

One of the NBR advances over conventional IP is the introduction of multicast for HTTP-based traffic where at each time a response is sent by an SP$_{S}$ to SP$_{CS}$, NBR can deliver them in a multicast fashion through the network, allowing to save networking resources.

2.1.2.2. Experimental Set-up

Figure 9 illustrates the set-up for the NBR User Plane experiment and depicts two clients to the left, connected via individual WiFi access points to separate SP_Cs, and a single SP_S with a video server attached to it. An Open vSwitch (OVS)-based software switch is placed inside the NBR network, forming a branched topology, as seen in many network-related evaluation work.

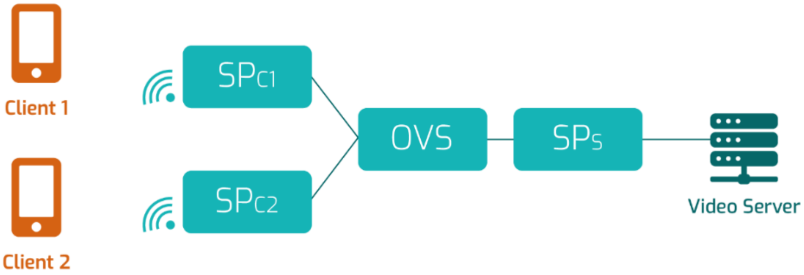


Figure 9: Experimental Set-up

The application is a Dynamic Adaptive Streaming over HTTP (DASH)-based video service where the video server holds a pre-encoded DASH video (Moving Picture Experts Group - MPEG chunks), which are requested sequentially by both clients using HTTP. As NBR implements co-incidental multicast delivery among SPs, both clients are synchronized to request the manifest file from the video server at roughly the same time. Upon parsing the content, both clients start issuing request to the individual MPEG chunks in a rather synchronized fashion. The 60s long video is split into 1s MPEG at a single rate.

2.1.3. Video delivery benchmarking

The third set of tests were executed with the objective of assessing if 5G networks are a good network to carry out media content transmission for production or delivery. The equipment used in these tests is listed below:

- 2 PCs
- 1 VideoXlink X2 encoder
- 1 VideoXlink X2 decoder
- 1 network switch
- 2 5G CPEs
- 5G Telenor commercial NSA network

The setup consisted of the encoder and decoder devices being connected through the 5G network, to perform video transmission over this network. The PCs were connected to the encoder/decoder through the network switch or to the CPEs that gave the encoder/decoder 5G connectivity. The network switch was used to perform packet capture on either side off the network. This can be observed in Figure 10.

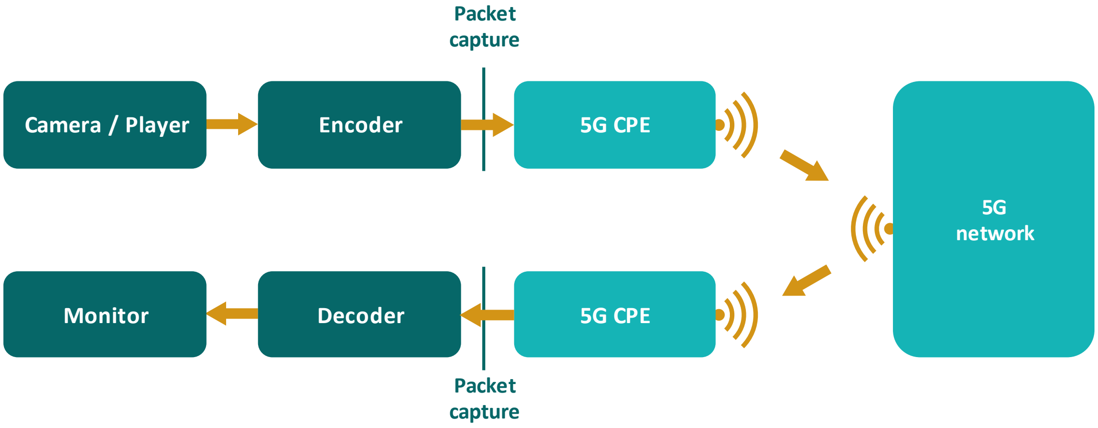
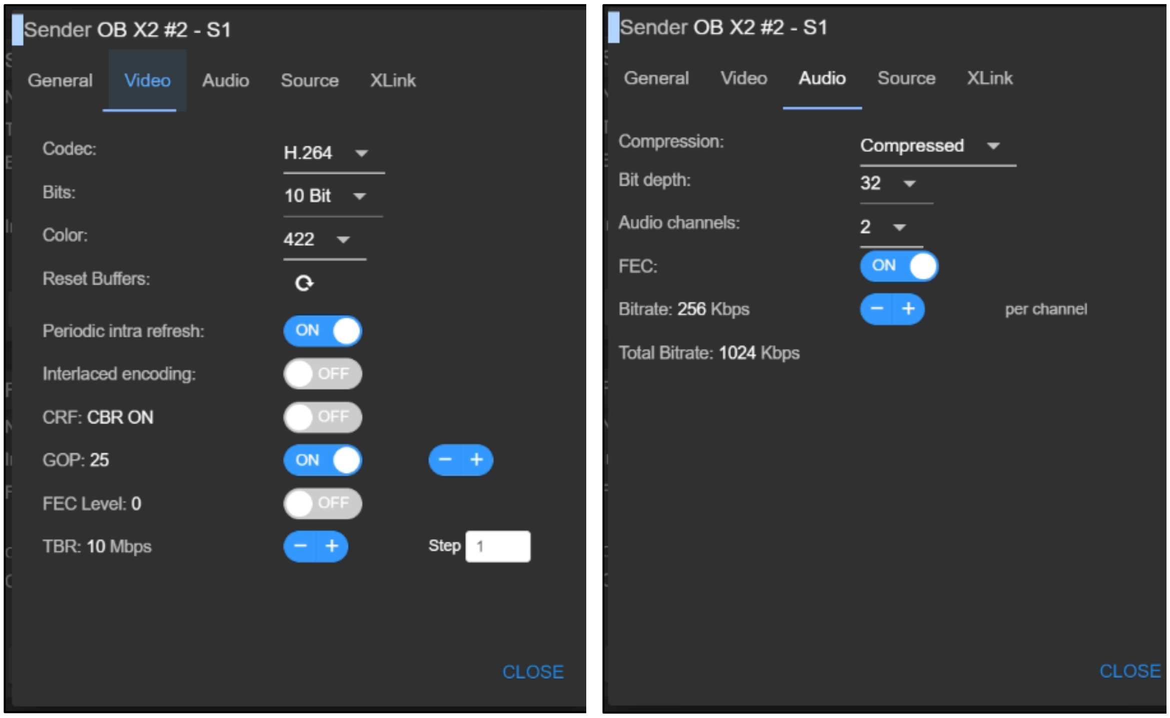


Figure 10. Test setup for video delivery benchmarking.

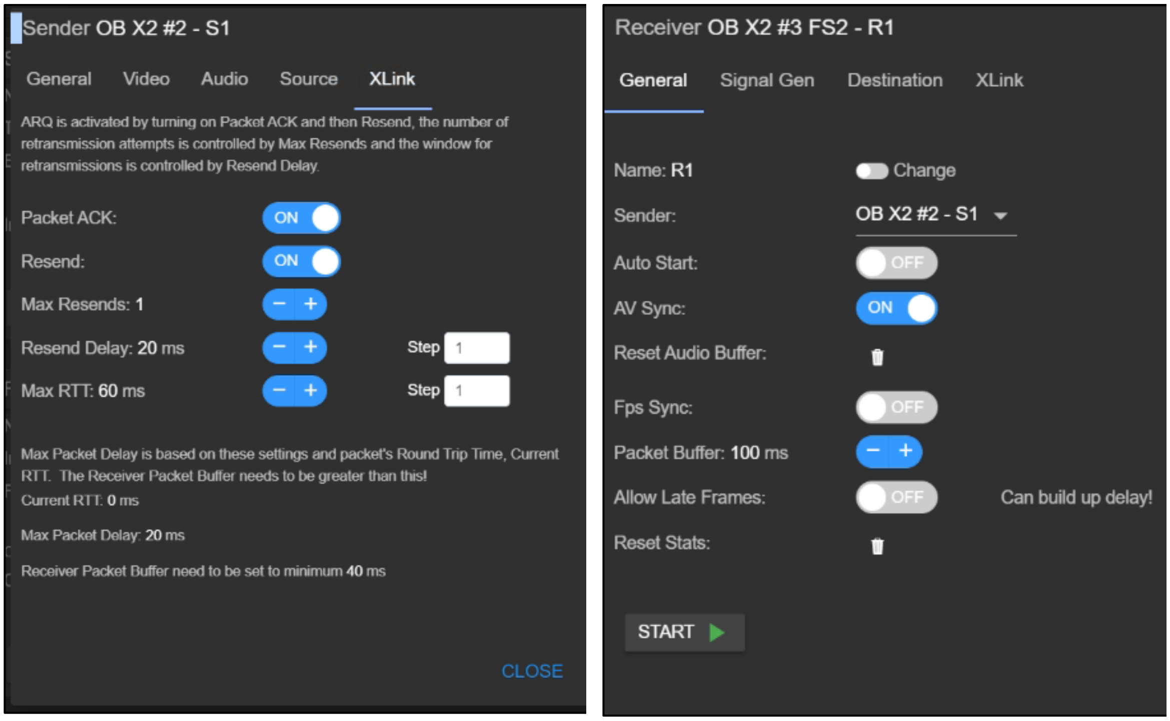
For these tests, the three mechanisms of analysis were, first, extracting the statistics from the Xlink management website, which gives the following information: connection speed between encoder and decoder, total frames transmitted, dropped frames, errors in frames, missing frames. In second place, performing network captures on both the encoder and decoder side (although, not simultaneously). For extracting these statistics, a Selenium script was created to automate the process. From the Wireshark captures, the value which can be extracted is the delta time (interarrival time).

The tests consisted of setting different target output bitrates on the encoder, capturing the statistics and the packets to find out how much the network can support high bitrate applications. The encoder and decoder settings were as shown in Figure 11.



Codec: H.264
Bits: 10 Bit
Color: 422
Reset Buffers:
Periodic intra refresh: ON
Interlaced encoding: OFF
CRF: CBR ON OFF
GOP: 25 ON
FEC Level: 0 OFF
TBR: 10 Mbps
Step 1

Compression: Compressed
Bit depth: 32
Audio channels: 2
FEC: ON
Bitrate: 256 Kbps per channel
Total Bitrate: 1024 Kbps



Sender OB X2 #2 - S1

ARQ is activated by turning on Packet ACK and then Resend, the number of retransmission attempts is controlled by Max Resends and the window for retransmissions is controlled by Resend Delay.

Packet ACK: ON

Resend: ON

Max Resends: 1

Resend Delay: 20 ms Step 1

Max RTT: 60 ms Step 1

Max Packet Delay is based on these settings and packet's Round Trip Time, Current RTT. The Receiver Packet Buffer needs to be greater than this!

Current RTT: 0 ms

Max Packet Delay: 20 ms

Receiver Packet Buffer need to be set to minimum 40 ms

Receiver OB X2 #3 FS2 - R1

Name: R1

Sender: OB X2 #2 - S1

Auto Start: OFF

AV Sync: ON

Reset Audio Buffer:

Fps Sync: OFF

Packet Buffer: 100 ms

Allow Late Frames: OFF Can build up delay!

Reset Stats:

Figure 11. Encoder (sender) and decoder (receiver) settings.

All tests were run with a 1080i50 test input into the encoder, which encodes and transmit in 1080p25 and then the decoder receives this signal and decodes it into 1080i50 again. In Table 1, the planned tests are shown. There are two batches of testing, i.e., one focused on increasing bitrate and measuring parameters and another smaller one with two tests, i.e., finding maximum feasible bitrate and performing speed tests to characterize the network.

#	Resolution	Target bitrate	Duration
A1	1080p25	10	5 mins
A2	1080p25	20	5 mins
A3	1080p25	30	5 mins
A4	1080p25	40	5 mins
A5	1080p25	50	5 mins
A6	1080p25	60	5 mins
A7	1080p25	70	5 mins
A8	1080p25	80	5 mins
A9	1080p25	90	5 mins
A10	1080p25	100	5 mins

Table 1. Video delivery standard tests.

#	Comment	Measurement
B1	Ookla speedtest, 6 times, no load	Ookla bitrate and ping, download and upload
B2	Network breakdown test, increase bitrate until the errors/dropped frames start to appear	Max encoder-decoder bitrate

Table 2. Video delivery additional tests.

2.2. Vertical final trial execution and results

This section documents to which extent the use case KPIs were achieved during FUDGE-5G, according to the trials and measurements. The tests and trials were performed under real conditions to assess to what degree 5G fulfils the specific use-case KPIs and technical requirements. Several metrics and results have been collected to study to which degree 5G fulfils the technical KPIs and requirements of the project use cases.

2.2.1. Remote production

2.2.1.1. Pre-testing (14th June)

In preparation for the next tests, NRK spent time preparing the CCU racks and bringing in new technology from Aviwest to investigate compatibility and potential problems. Two setups were tested:

1. VideoXLink X2 with external 5G CPE from Huawei.
2. Fully integrated units from Aviwest.

After a day of testing and optimization, both setups were working successfully. Telenor and the Norwegian Armed Forces used their 5G network for different use cases, and they occasionally update their 5GC, which meant that the team spent some time getting this solution configured correctly.

An important part of Telenor's changes to the core was that a higher upload speed than download speed was needed. It is expected that in the long term the core will be able to get a frame structure of 2:7. 2:3, which is what the defense has support for in its new equipment now, but on the test in Skien 7:3 was used. This is 50% better in upload throughput than the public 5G network.

2.2.1.2. Trial on 22nd June

From previous experience, it is known that it is better to not test too many things at once. That's why we tried to have so many "known" workflows and as much known equipment as possible. The equipment used were the following: OB24, Sony camera heads, Riedel communication, etc. Thus, different conclusions can be learned from the troubleshooting and the features from the specific elements that were targeted from testing this production.

The main objectives from an equipment perspective were:

- To increase the ruggedness of the video encoder/modem
- To get multi-camera functionality in the remote system. To determine if a CCU is needed. IP native production.

- To determine if suppliers deliver the equipment and to check if they fulfill the requirements.

During the NAB 2022 event, several discussions were addressed with different suppliers to understand their services and equipment offerings. Specifically, video encoders with built-in modems that supported SA 5G networks on the 3300-3400MHz band were explored. Discussions with LiveU, Aviwest, Dejeero and Mobile Viewpoint among others were addressed.

There was great variation in how much focus the suppliers had on 5G S-NPN, and the conclusion is that Aviwest could probably fulfill the technical needs on it. Most of the operators were very focused on bonding, and not on low latency over a modem. One of the great advantages of 5G S-NPN is that you can run everything over one modem and that you can reduce delay.

Furthermore, discussions with several camera manufacturers including Sony, Grass Valey and Panasonic were addressed. What a traditional camera system will need to be integrated easily into a 5G environment is mostly the same features that are needed to bring it into remote production. This mainly involves using fewer analogue interfaces for intercom, tally and program control and more IP-oriented solutions. In addition, the need for a CCU makes things less portable, and will require additional racks outside the cameras.

What we found is that most suppliers continue to base their camera systems on CCU-based architecture. However, Grass Valley has come up with one model where this is not the case (LDX150 model), and even though NRK received such camera right before the production, there was no time to test and integrate this camera into the workflow of this production. The reason for this is standardization, as the rest of the production cameras are Sony in OB24. Also, another matter was the total weight of the camera for hand-held, which was tested on a later occasion.

2.2.1.3. Obtained results

During testing, NRK measured the total bandwidth for sending video at about 40Mbps, but in production in Skien was 70Mbps stable.

NRK had previous experience with VideoXLink and Huawei-CPEs, and the solution eventually worked. A challenge with using the 5G CPEs is that the team depended on the encoder and decoder seeing each other directly on the network, and not being blocked by firewall/Network Address Translation (NAT) routing in the CPE. Although several of the CPE suppliers have support for opening ports in the firewall/routing, the team did not manage to open point-to-point connection before using a CPEs that supported “hardware bridged mode”. This means that the encoder gets its IP from the 5GC and not from the CPE’s own subnet. When this issue was resolved, glass-to-glass delay of 280ms was obtained, i.e., 7 frames delay in 1080i50.

Figure 12. Equipment used during the trials.

On the Aviwest solution, we tested both their high-end transmitter “PRO4” and their simpler “Air320-5G”. In addition, we tested their StreamHub server for reception of the signal on SDI. After relatively quick configuration, the Aviwest devices were connected to the 5G network, and it automatically connected to the correct band with Telenor’s special Subscriber Identity Module (SIM) card. Aviwest has developed a new Ultra-low latency mode where you can get latency as low as 300ms in 1080i50. The suppliers of both solutions claim that by producing in 50P, it will be possible to reduce the delay by a further 100ms.

2.2.2. Media showroom

The results of the NBR experiments for HTTP-based video delivery on the User Plane are provided in Figure 13, which depicts whiskers plots of three independent runs of the experiment. While the x axis shows the number of runs, the y axis shows to how many clients the HTTP response (video chunk) has been sent to.

Figure 13: Gain over Conventional IP

As can be observed in the figure above, the mean across all three runs is stable around 1.71 – 1.79, meaning NBR had a 71 – 79% saving compared to convention IP for delivering the video. Run 1 even depicting the case where both no coincidental multicast was observable between the SPs as an outlier.

2.2.3. Video delivery benchmarking

- **Test B1**: Results are shown in Table 3.

Date	DL (Mbps)	UL (Mbps)	Ping latency (ms)
3/30/2023 15:31	441.06	123.32	22
3/30/2023 15:31	504.53	121.26	17
3/30/2023 15:29	380.15	120.66	20
3/30/2023 15:28	399.44	113.28	17
3/30/2023 15:28	393.42	122.62	17
3/30/2023 15:26	509.31	113.28	17

Table 3. Ookla speedtest results for video delivery.

The results of the tests yield and average speed of 437.985 Mbps in downlink and 120.125 in downlink, with an average latency of 18.33 ms. It is worth noting that the value of downlink is quite variable, even though the tests were closely spaced in time, so the average value is not very accurate. This is not a problem, as the important for video transmission is upload speed (120.125 average with 3.29 standard deviation) and ping latency (18.33 average with 1.88 deviation), which are consistent.

- **Test B2:**

This test was performed during the standard tests. It consisted of finding at which configured bitrate on the encoder, the number of missed or error frames increase with the increase of the number of frames. This means that there is constant missed or error frames, which would render a received video unusable. From observing the obtained statistics from the webpage, from 60 Mbps upwards, the video stream starts to show this behavior.

- **Standard tests (A1 to A10):**

In Table 4, the extracted statistics from the Xlink webpage are shown for each test. A9 and A10 were not performed, as A8 already produced an unusable video stream (the total frames and error frames were the same over the duration of the test).

#	Configured bitrate	Avg. video stream speed (Mbps)	Total frames	Dropped frames	Error frames	Missed frames
A1	10	11.71	7250	0	23	8
A2	20	22.45	7250	0	47	20
A3	30	33.20	7250	0	24	27
A4	40	43.93	7250	0	24	16
A5	50	54.55	7250	0	17	5
A6	60	62.38	7250	0	7132	5
A7	70	68.46	7250	0	7220	0
A8	80	75.40	7250	0	7207	23

Table 4. Xlink statistics results for video delivery.

The test results show that the video stream is usable up to a configured bitrate of 50 Mbps, as the number of error frames is similar to the total frames. This means that almost all frames contain errors at this point. From the video stream average speed, it can be observed that the measured bitrate is similar to the configured bitrate or slightly higher, with the exception of the A7 and A8 tests, in which it starts to be slower, meaning that the network starts to break down and not support such high bitrate stream.

From the Wireshark captures, the interarrival (or delta) time can be extracted. Table 5 shows the results of this metric, with the captured performance in the encoder/decoder side.

#	Packet Average interarrival time encoder (s)	Packet Average interarrival time decoder (s)	Difference %
A1	0.00150	0.00038	2.94
A2	0.00093	0.00161	-0.42
A3	0.00069	0.00113	-0.38
A4	0.00081	0.00088	-0.07
A5	0.00067	0.00069	-0.02
A6	0.00076	0.00047	0.61
A7	0.00063	0.00054	0.16
A8	0.00077	0.00038	1.02

Table 5. Packet capture results.

From these results, it can be stated that the 5G network does not introduce significant variation in interarrival time. This means that the packet timing is mostly maintained through the system, which is beneficial for video transmissions.

2.3. Stakeholder feedback

Previous sections have provided a comprehensive definition of the architecture, tests and components for the considered use cases. Also, it has additionally described the integration process of the different 5G and media components needed for the tests. Several KPIs have been measured to be demonstrated in the tests, as well as the monitoring and measurement tools used have been explained. This section includes a questionnaire forwarded to NRK, with both insights regarding 5G Private Networks and FUDGE-5G specific questions.

After executing the trials, NRK as main stakeholder of this use case, was asked to fill a short questionnaire. The main objective is to get their feedback and understand if the current solutions we provided were useful for delivering their services in real trials. NRK provided the following feedback.

2.3.1. 5G related questions

1. *Please rate your familiarity with 5G technologies:*

Not familiar	Basic knowledge	Fair	Familiar	Expert
			✓	

2. *Can 4G technologies meet yout current service requirements?*

Yes, 4G LTE is enough	No, 5G (public/private) connectivity is needed	No, a 5G private network is needed
		✓

3. *Would you use the current 5G private network components in your workflow from now on?*

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
				✓

4. *If you had to choose only one aspect, what is the most important benefit that a private 5G could bring to your industry.*

Robust and nomadic 5G Islands for remote production, independent of backhaul.

5. *What is, in your opinion, the most challenging issue to overcome by 5G Private Networks?*

Need support for uplink favoring frame structures to utilize the spectrum better.

2.3.2. About the tests and trials

6. *How complicated did you find the 5G system to use, compared to other existing solutions?*

Very easy	Easy	Normal	Difficult	Very difficult
		✓		

7. *Measure the level of current technical competency of your team to operate the 5G NPN. Would you be able to operate it on your own?*

Very low	Low	Normal	High	Very high
		✓		

8. *What is the level of importance of these KPIs when delivering your services?*

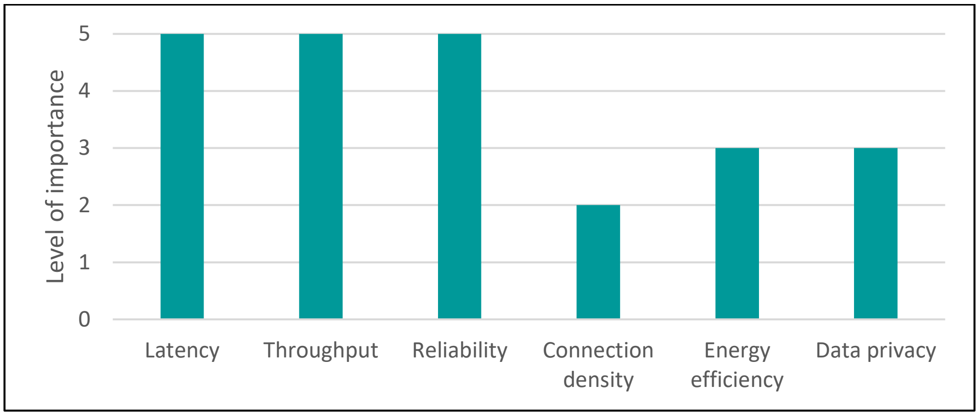


Figure 14. Level of importance of different KPIs in the concurrent media delivery use case.

9. *Were these KPIs met?*

Latency	Throughput	Reliability	Conn. Density	Energy eff.	Data privacy
Yes	Partially	**Yes**	**Yes**	**Yes**	Not tested

10. *Have been the initial expectations met about FUDGE-5G?*

Yes

2.3.3. Suggestions for future tests and way forward

The main suggestion is to keep working across verticals and optimize on common needs in PPDR and media.

It is important to consider the experiences gathered from the use cases to get back to the drawing board for enhancing the technical solutions. Since many of the solutions are also like traditional remote production/IP-based workflow, this is good training for the use case partners to work with. Partners hope they can find similar projects soon where they can continue to do this to streamline and learn more.

A very important part of a 5G network will also be to build a common network and environment for several services that can work across, and not just point-to-point-based communication. This will be a strength that can enable partners to develop the way productions are performed.

The Olympic Broadcasting Service has fixed the requirements for the delay in production over 5G to be a maximum of 60ms. This value corresponds to today's traditional link solutions. As of now, the main challenge to achieve this lies in the encoding and decoding of video that is compressed enough to be sent over 5G. Furthermore, support for Precision Time Protocol (PTP) sync in the network will be important for timing all data packets. This support is written into the 5G standard from Rel-17, but it is not yet known whether the 5G network is accurate enough to handle PTP sync even if the standard supports it. In any case, the partners believe that with all IP-based TV production, this will be the subject of discussion as to what is acceptable for the different user groups and productions.

The following suggestions have been defined for concrete learning outcomes for the next tests:

- Better coverage planning and a plan for where the mobile units will be located.
- More robust solutions in the field of "CCU kit" standardization.
- Increase bandwidth and get more resources on 5G.
- Combining remote production with 5G (this has a greater cultural impact than technical).
- Understand which challenges must be solved related to general network competence in technical specialist groups.

3. PPDR: final trials

3.1. Setup and measurement tools

This section reports the setup for two test cases linked to the PPDR use case, i.e., the standalone (SA) NoW and the public warning system. The trials of the first test case were executed during December 2021, in Rygge (Norway). The objective of the trial was to test the SA 5G NoW to support the emergency responders in the field during the search and rescue operations. The trial was conducted in collaboration with Norway Defense and Material Agency (NDMA), Norwegian Air ambulance (*NorskLuftambulanse*, NLA) and the Norwegian TV broadcaster, NRK. The FUDGE-5G project also aimed to showcase the versatility of the service-based core architecture by integrating the Nemergent 5G Push-to-Talk (PTT) application into the Athonet standalone 5GC network. To achieve this, the MCX application was deployed as a virtual machine on a small server running CentosOS 7. The Nemergent PTT application was successfully tested at the UTLEND conference held in Lom, Norway from September 22-25, 2022.

Another PPDR pilot, related with public warning, was also performed on February 17, 2023, in Fornebu (Norway). This test did not include the NoW but was done on the Telenor campus in Fornebu.

Note that two of the test cases envisaged in D1.1 [2] were not finally tested. On the one hand, the interconnectivity with the remote cloud was removed from our study due to military constraints. The objective of this test case was to provide a full continuity of services with “zero touch” and “zero days” capabilities. The test case has been tested outside the project, and additional activities are currently ongoing for addressing other civil use cases. On the other hand, the coexistence of public and non-public networks has been also left outside this project for the same reason. This is mainly because the Thales Nexium Defense suite, solution offered by this company, is composed of several assets and solutions linked to military usage. As occurred in the previous case, additional activities are currently ongoing for addressing other civil use cases.

3.1.1. Standalone Network-on-Wheels

3.1.1.1. First trial (December 2021)

The FUDGE-5G NoW is a SA autonomous solution that provides a 5G network for connectivity between first responders in case of emergencies. NoW hosts the radio, core and other applications as a one in all mobile solution that can be transported easily. For the reported trial, the 5GC from Athonet and other PPDR relevant applications were deployed in an Amazon Web Services (AWS) snowball edge server, providing a single box solution. To allow remote management and interconnection of the NoW with a remote cloud, it was integrated a multichannel router solution from Goodmill Systems. Similarly, to enhance the operation of field deployed teams for PPDR the OneSource Mobitrust situational awareness platform was installed in the AWS edge along with Triangula application for gunshot detection and other applications like Push to talk for future trials. Figure 15 shows the PPDR architecture in a nutshell. This solution has multiple advantages like providing on demand coverage with guaranteed Quality of Service (QoS), computing at the edge, fully autonomous, possibility of connecting partners edge, secure and ruggedized, quick deployment and while simple in operation.

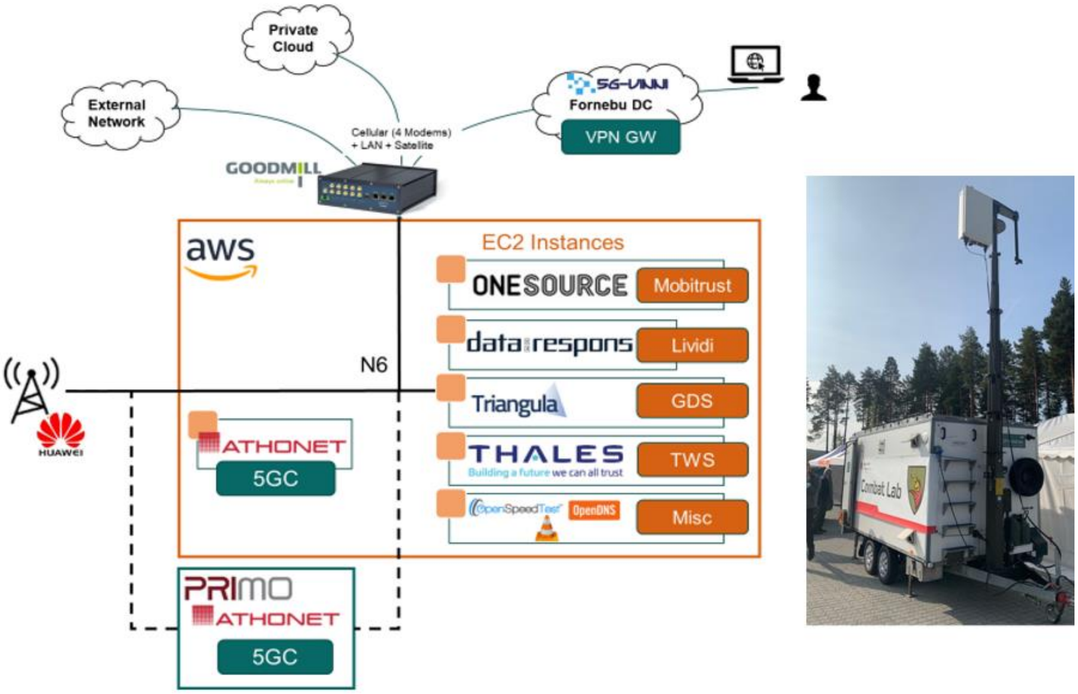


Figure 15. Network-on-Wheels 5G NPN architecture.

Trial deployment narrative and topology

A natural catastrophe (e.g., flooding, avalanche, land slide) has hit a small village situated in the Norwegian mountain ranges destroying multiple buildings, and several people are still missing. The authorities have ordered the evacuation of the village, and launched a rescue mission supervised by the NDMA, NLA and the Red Cross to save missing people. The first responders have reported that public telecommunication infrastructure (both fixed and mobile) is severely damaged.

The FUDGE-5G NoW is instantly deployed in the emergency area to provide connectivity to support communications between first responder teams and starts serving as mobile Command, Control & Communications (C3) hub. During the trial 5G SA powered drones were flown to the accident site broadcasting the live video feed to the rescue personnel along with police control room and NRK’s master control room. After spotting the person in need of help, the relevant team for coordinated search and rescue were dispatched. The team was also equipped with 5G powered situational awareness rescue kits which also live feeds the video from the accident site to emergency service respondents in real time.

3.1.1.2. Second trial (September 2022)

The trial showcased the Nemergent 5G PTT application's use in a simulated search and rescue operation following a natural disaster in a small mountain village. The scenario involved a catastrophic event that resulted in multiple building collapses and missing individuals, leading to an evacuation order by the authorities. The available communication systems, both fixed and mobile, were severely damaged due to the disaster.

The rescue mission was initiated by the NDMA, NLA, and Red Cross to save the missing individuals. The FUDGE-5G NoW was quickly deployed to provide communication support for first responder teams during the rescue mission. The system was used as a mobile C3 hub and 5G SA-powered drones were deployed to broadcast live video feed from the accident site to the control room. Figure 16 shows a high-level topology of deployed narrative during the “Search and Rescue trial. After spotting the person in need of help, the relevant team for coordinated search and rescue were dispatched. The team was equipped with mobile phones with Nemergent PTT client installed on them.

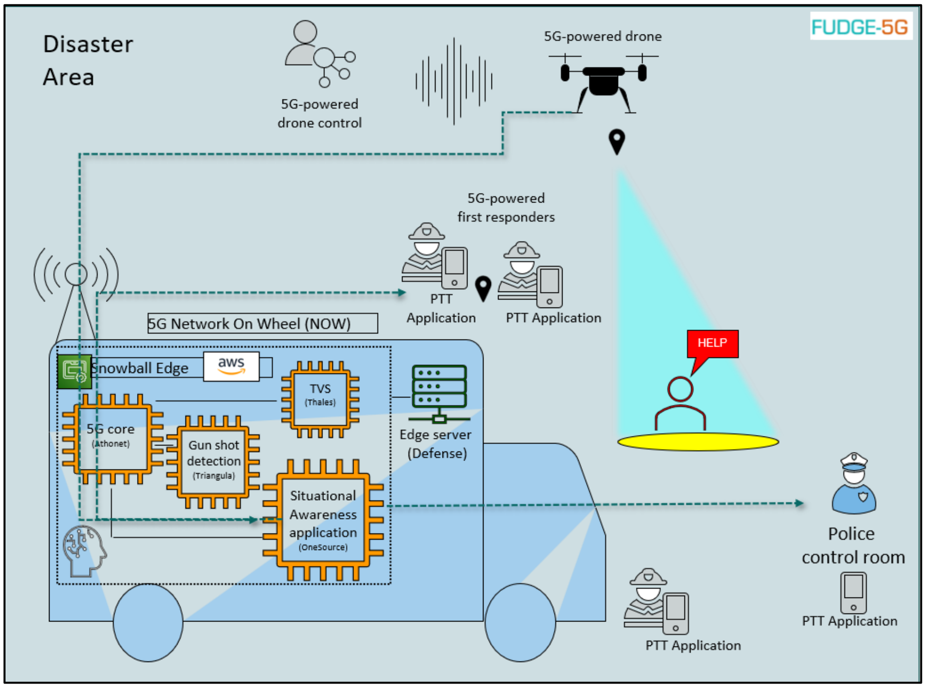


Figure 16. Topology for simulated search and rescue operation.

3.1.2. Public warning system

The second test setup consisted of the Cumucore 5GC deployed in a micro-PC box, on which also the one2many Cell Broadcast Centre Function (CBCF) was deployed. The CBCF only uses the Access & Mobility Management Function (AMF) of the 5GC. The gNodeB was a Huawei LampSite system. Figure 17 shows the real components used during the testing session. The key feature of this scenario is that cell broadcast functionality allows mass notification with a text message delivered within seconds.

Figure 17. O2M CBCF on Cumucore 5GC with Huawei gNodeB on top.

Note that, for this scenario, NDMA was the stakeholder, which was present during the test. NDMA and Telenor provided the 5G phones that were used for the testing.

3.2. Vertical final trial execution and results

3.2.1. Standalone Network-on-Wheels

3.2.1.1. First trial (December 2021)

The main trial objective was to showcase the potential and the ability of a standalone private 5G network to allow broad band capabilities to first responders and special forces. The trial validates the integration of 5G SA components along with the use of PPDR specific vertical applications (OneSource Mobitrust situational awareness platform and video distribution app) within the NoW. Thus, the trial demonstrated the quick and urgently setting up of secured autonomous 5G bubble with all the services capabilities within the area along with showcasing the capability of multiple video flows streams from high-definition (HD) cameras, carried by dismounted operators or the drones, towards a video server hosted at the NoW. The trial also logged the downlink and uplink through put of 433 Mbps and 130 Mbps respectively for the 40 MHz bandwidth along with 6 multiple live HD steams at different locations, shown in Figure 18.

Figure 18. Live video streams from drone and first responders to various locations.

Some of the main achievements related to 5G were:

- Integration of 5GC and different vertical applications in one in all rugged solution in AWS Snowball edge server.
- Use of portable 5G bubble in case of natural disasters or emergency situations like landslides, earthquakes, or floods, for communication and coordination.
- Live broadcasting of multiple video streams to different emergency service centres and personnel.

The complete video of the trial is available at this link.

3.2.1.2. Second trial (September 2022)

The PTT system was configured with three user groups, each with different members and affiliations. Group A consisted of the Search and Rescue mission team, including representatives from the police force, NLA, and NDMA. The first responders were able to communicate effectively with each other through video, text, and voice, as demonstrated in the photos captured during the trial.

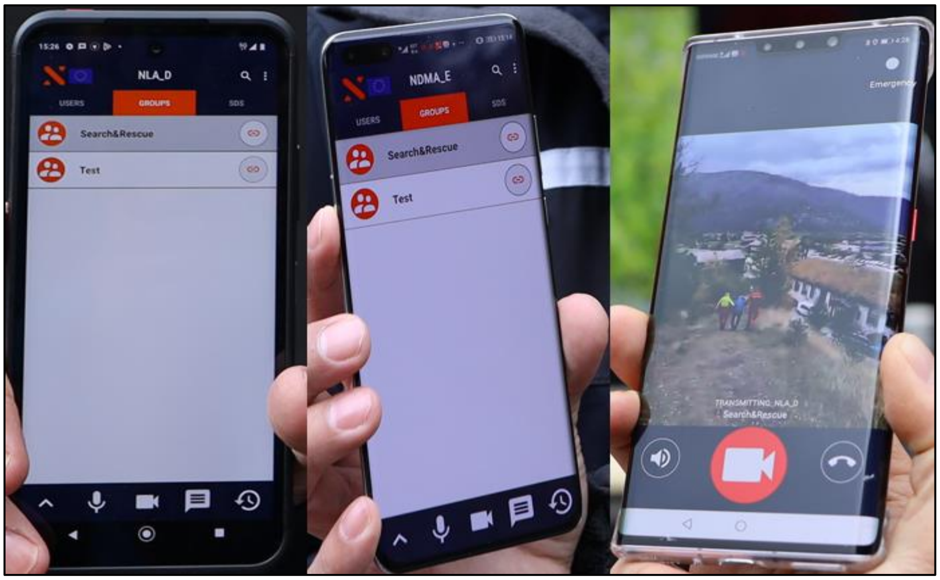


Figure 19. Nemergent PTT application group video call transmission.

The trial was a success and highlighted the effectiveness of the Nemergent PTT application in supporting critical communications during emergency operations, especially when traditional communication systems are unavailable.

Figure 20. Nemergent PTT application group call transmission and drone video on a screen.

3.2.2. Public warning

Several tests were done with the phones all lying on a table. Figure 21 shows that all phones presented the following message simultaneously:

"Fudge 5G test. No further action required".

Figure 21. 5G phones used for mass notification test.

Note that the NoW was not available for the test and therefore neither was a story line was played out during the trial, nor was the trial part of another test case. The purpose of the trial was to show case the potential of a mass notification to the stake holders of the PPDR use case: NDMA. A text message was broadcast within seconds to all available phones. The nature of broadcast allows scaling to a huge number of phones. The complete video of the trial is available at this link.

Table 6 shows the requirements as listed in deliverable D1.1 [2] that are applicable to the public warning trial. Other requirements from deliverable D1.1 are not applicable to the use case or were not implemented as part of the trial.

Requirements
#1 The system shall be able to deploy a full 5G network in the FUDGE-5G autonomous edge. The platform shall be dimensioned for running Radio Access Network (RAN), core Virtual Network Functions (VNFs), and edge applications in a fully standalone configuration
#3 The system shall be able to automate the provisioning of RAN configuration, core functions, and cloud applications
#6 The system shall have the capability to issue public warning messages to all devices in radio coverage
#11 The system shall guarantee security between deployed NFs and between the user and the application instances by using mandatory security mechanisms such as Transport Layer Security (TLS) and OAuth

Table 6. PWS Requirements.

One can confirm that requirement #1 is fulfilled because the system consisted of a CBCF and a 5GC deployed as microservices running in containers. The gNodeB registered itself with the AMF in the 5GC, which is consistent with requirement #3. Requirement #6 was demonstrated in the trial: all mobile devices in coverage of the radio cell presented the warning message (see Figure 21). Regarding requirement #11, it was not fulfilled in the trial since neither TLS nor OAuth was used in the trial.

3.3. Stakeholder feedback

This section includes a questionnaire forwarded to the PPDR stakeholder, i.e., NDMA for gathering some information and feedback about their thoughts on the trials executed.

3.3.1. 5G related questions

1. *Please rate your familiarity with 5G technologies:*

Not familiar	Basic knowledge	Fair	Familiar	Expert
				✓

2. *Can 4G technologies meet yout current service requirements?*

Yes, 4G LTE is enough	No, 5G (public/private) connectivity is needed	No, a 5G private network is needed
	✓	

3. *Would you use the current 5G private network components in your workflow from now on?*

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
			✓	

4. *If you had to choose only one aspect, what is the most important benefit that a private 5G could bring to your industry.*

5G has opened many new frequency bands and made it possible to use private 5G in the field (nomadic network) for PPDR/defense use.

5. *What is, in your opinion, the most challenging issue to overcome by 5G Private Networks?*

Handset compatibility in “non-official” PLMNid´s not working on Samsung and Apple devices.

3.3.2. About the tests and trials

6. *How complicated did you find the 5G system to use, compared to other existing solutions?*

Very easy	Easy	Normal	Difficult	Very difficult
			✓	

7. *Measure the level of current technical competency of your team to operate the 5G NPN. Would you be able to operate it on your own?*

Very low	Low	Normal	High	Very high
				✓

8. *What is the level of importance of these KPIs when delivering your services?*

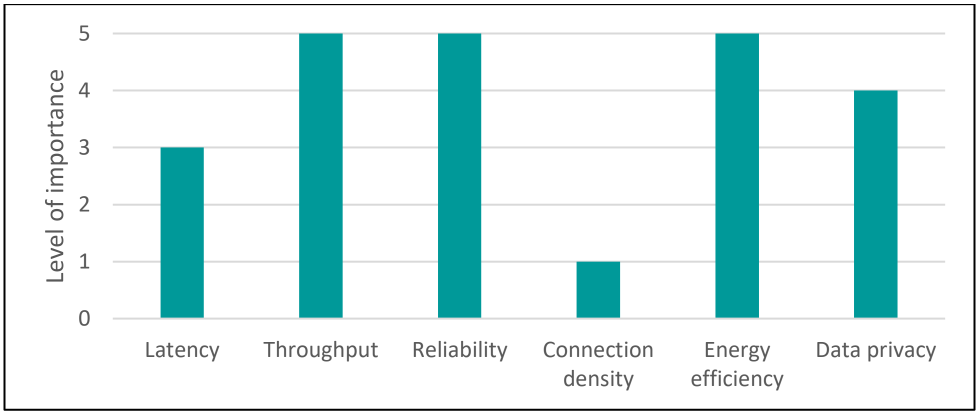


Figure 22. Level of importance of KPIs in the PPDR use case.

9. Were these KPIs met?

Latency	Throughput	Reliability	Conn. Density	Energy eff.	Data privacy
Yes	**Yes**	Partially	Not tested	**No**	**Yes**

10. Have been the initial expectations met about FUDGE-5G?

Yes

3.3.3. Suggestions for future tests and way forward

The main suggestion is to keep working across verticals and optimize on common needs in PPDR and media. NDMA will use the results learned in FUDGE-5G and improve their knowledge in future projects of Horizon Europe such as IMAGINE-B5G, where they also act as stakeholders.

4. 5G virtual office: final trials

Oslo University Hospital (OUS) is a reference hospital, not only for the region of Oslo but also for the entire country of Norway. As stakeholder for the 5G Virtual Office use case, it provided a challenging environment and plenty of expertise to go with it. It was the goal of the trials described hereafter to meet the high expectations of OUS and to attain the FUDGE-5G objectives regarding the usage of NPNs for such scenarios.

Figure 23. Oslo University Hospital

For running these trials, a central location of the OUS campus was selected (see Figure 23). It was at this location that the FUDGE-5G infrastructure was setup, and where the trials took place to perform measurements and gather feedback from both the stakeholder and other Norwegian health sector professionals. For the sake of completeness of the trials in terms of technology exploitation and stakeholder interests, three scenarios were initially proposed in close collaboration with OUS: ward remote monitoring, intra-hospital patient transportation monitoring and ambulance transportation monitoring. However, the latter scenario was later discarded due to low interest from OUS and lack of infrastructure support for the Public Network Integrated (PNI)-NPN.

As for the timeline of the use case trials, there were several delays and changes, mostly caused by the impact of COVID-19 on both equipment availability and ability to travel to the premises by the involved partners. These delays were mostly mitigated by the convergence of scenarios, as well as by additional efforts put into place in the last year of the project. In the end, the outcomes were still highly appreciated by OUS and provided the expected validation of FUDGE-5G technology. In the subsections below, the entire setup and final results will be described in detail.

4.1. Setup and measurement tools

This subsection intends to describe the final setup for the 5G virtual office trials in detail. It focuses encompasses not only on the 5G network infrastructure, but also on the vertical application and corresponding validation tools.

4.1.1. Infrastructure setup

All partners involved in the use case collaborated to setup the infrastructure at the hospital with the support of the stakeholder. This node hosts the 5G NPN, including the 5G New Radio (NR), 5GC and the Vertical Applications, all deployed at the edge server to provide different corporate services. Figure 24 shows the high-level diagram overview of infrastructure deployed at the Hospital, whereas Figure 25 showcases the actual physical setup.

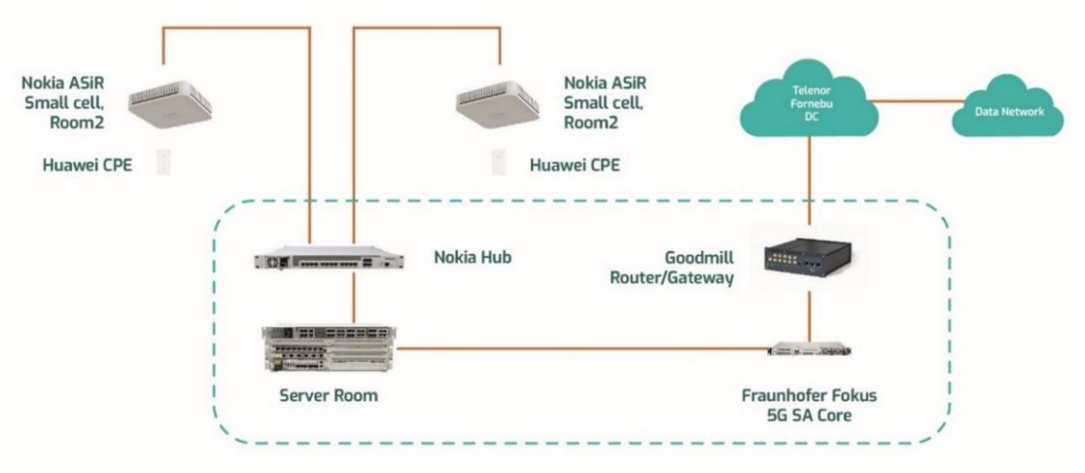


Figure 24. 5G private network Infrastructure deployed in Hospital.

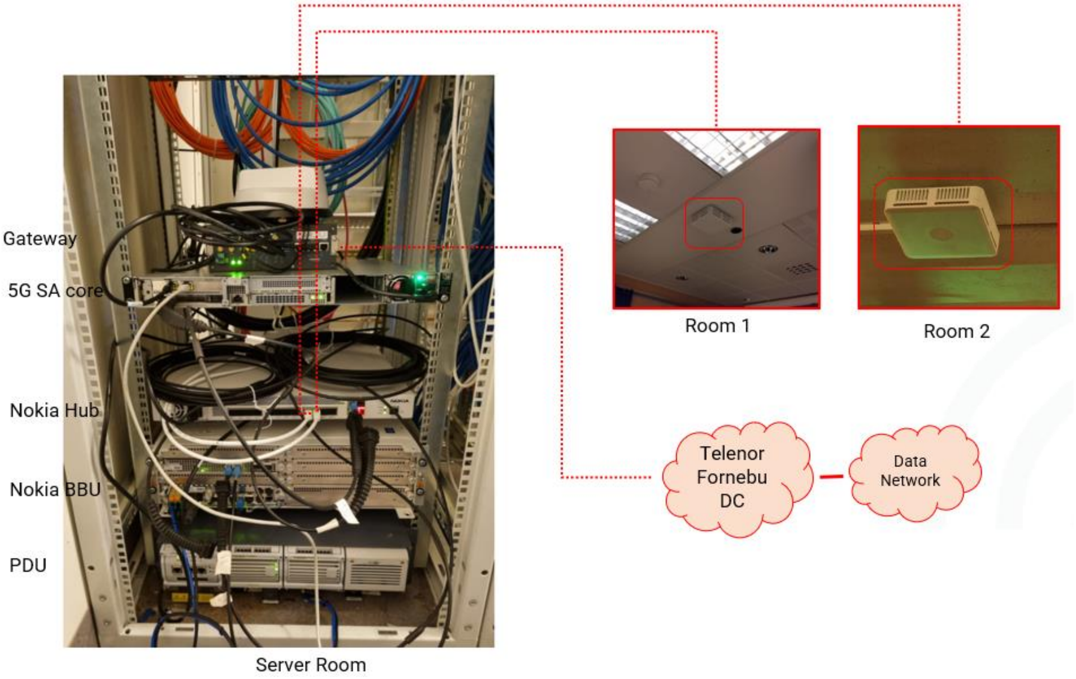


Figure 25. Actual deployment of 5G private network Infrastructure deployed in Hospital

The indoor 5G NPN solution was provided by the Nokia Airscale System module, consisting of a BBU, a HUB and two radio dots from Nokia. Table 7 shows the 5G radio parameters configured in the hospital equipment.

DU Cell ID	Duplex Mode	Physical Cell ID	Frequency band	ARFCN	Frequency	Bandwidth	Subcarrier spacing	Transmit Power (dBm)	TX/RX Mode
1	TDD	1	n78	622668	3340.02 MHz	80 MHz	30 KHz	23	4 Tx and 4 Rx

Table 7. 5G Radio parameters of the Nokia gNB.

The 5GC (Open5Gcore) is provided by Fraunhofer FOKUS and was deployed on bare metal using an HPE DL110 telco server. The telco server hosts both the 5GC and OneSource's Mobitrust Vertical Application. This server is connected to the baseband unit (BBU) via a single mode optical fibre cable. Similarly, to provide Internet access for both management and 5G devices, the server is connected to a Goodmill router with uplink to the 5G commercial network of Telenor, which reaches both the Internet and management network with a Virtual Private Network (VPN) connection to Telenor's Fornebu data centre.

4.1.2. Virtual Office vertical application setup

As mentioned previously, the Mobitrust Vertical Application was deployed at the edge server, in a Docker environment through docker-compose (was further detailed in D3.2 [6]. This application is a platform by itself, composed by multiple microservices, each deployed on their respective Docker container. Figure 26 shows the general architecture of those microservices.

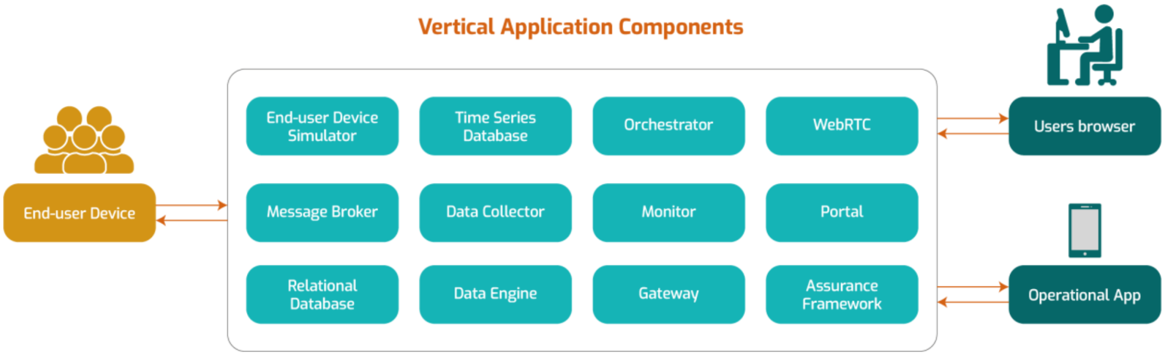


Figure 26. Vertical application components of the virtual office setup.

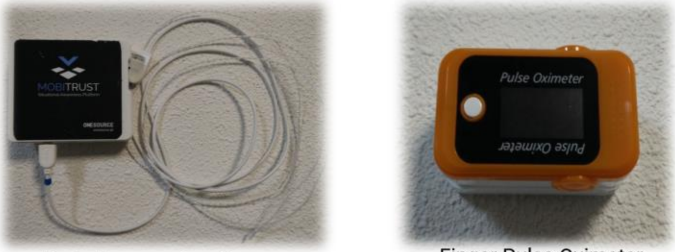
The end user device, or User Equipment (UE), is part of the hardware developed by OneSource. This device consists of a single-board computer coupled with custom PCBs that include a microprocessor, a Telit FN980 5G modem and batteries for operation without mains power. It acts as an interface between the multiple sensors with different communication technologies (serial, Bluetooth, Wi-Fi, etc.) used in the 5G Virtual Office use case and the 5G NPN that relays the communication to the Vertical Application platform. Figure 27 shows a unit of those end user devices.

Figure 27: OneSource end-user devices.

In Figure 28, some examples of the Bluetooth sensors used to monitor the health of the patients are depicted. These were selected based on the requirements and feedback from the stakeholder, and ultimately were very relevant to the assessment of the FUDGE-5G technology applied to health monitoring.

Blood Pressure Monitor

Chest Band with ECG, HR and RR



Body Temperature Sensor

Finger Pulse Oximeter

Figure 28. 5G Virtual office Bluetooth sensors.

Alongside the UE and the sensors, two cameras with Pan-Tilt-Zoom (PTZ) capabilities were integrated and connected to the 5G Network. These had the sole purpose of visually monitoring patients in multiple locations remotely.

4.1.3. Measurements Tools

The main measurement tool was the Assurance Framework integrated in the Vertical Application. The goal of this component is to assure that the Vertical Application and the 5G NPN are working as intended through multiple methods, with the main one being KPI collection and processing. For functional metrics, the process can follow different paths depending on how they are collected, aggregated, and correlated: they can come already as metrics, or they may require pre-processing if obtained through logging systems. Once these metrics are processed, they are visualized in a portal provided by Grafana or Chronograf. Further description of this component can be found in D4.1 [8], as the Assurance Framework also works as a validation tool. Figure 29 shows an example of data processed with the Assurance Framework and visualized through Chronograph.

Figure 29. KPI data collect/processed by the Assurance Framework during the trial.

4.2. Vertical final trial execution and results

On November 17th, 2022, the main trial was carried out at the Oslo University Hospital (*Rikshospitalet*). During the trial, two scenarios were showcased alongside a few presentations from the parties involved: OneSource, Telenor, and OUS. The main objective of the session, besides the validation of FUDGE-5G, was to demonstrate the project's innovations to multiple elements of the health sector in Norway.

As mentioned, the trial consisted of two scenarios: ward remote monitoring and intra-hospital patient transportation monitoring. Two rooms were setup to accomplish the objective of the trial. The "ward", with one patient laying on an hospital bed that had the UE with the sensors wirelessly attached, and the control room, which had multiple screens in order to all the relevant patient information provided by the Vertical Application. A more detailed description of the trial execution is given below with further focus into each of the scenarios.

4.2.1. Ward remote monitoring

The ward remote monitoring scenario, represent in Figure 30, uses the NPN deployment to enable remote monitoring of ward patients using a set of bio sensors. This allows smart processing and analysis to trigger alarms in case abnormal values are detected as well as doctor to patient remote interaction.

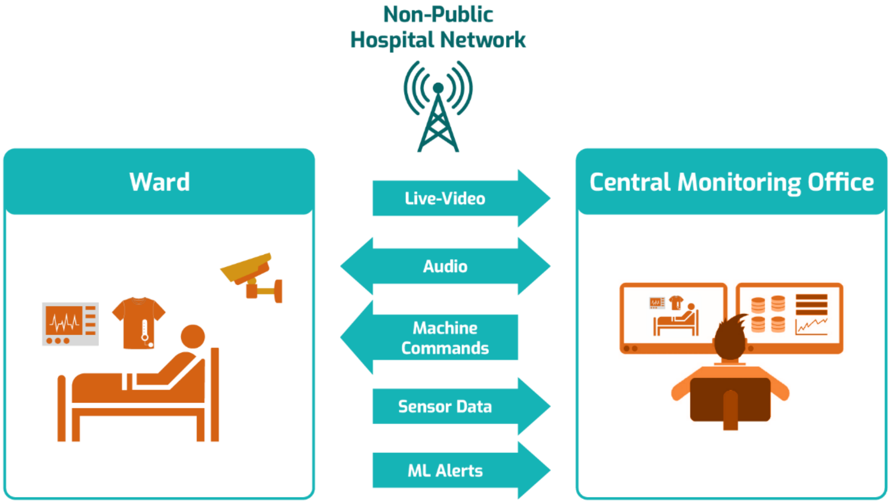


Figure 30. Ward remote monitoring test case depiction.

The story board for this test case is described in Table 8.

Title	Description
The doctor remotely monitors a patient in the ward	The doctor in the office has direct access to all the information arriving from the patient's room at the ward, so it is able to monitor the patient's condition remotely.
Doctor subscribes to alerts from sensors attached to the patient	All the sensors on the patient's room at the ward are connected to the hospital network, so it is possible to subscribe to alerts from sensor readings. A doctor that is responsible for a patient receives these alerts on their own UE, regardless of its location.
Sensor levels move outside typical ranges, or an abnormal pattern is detected, so the doctor receives an alert	Examples: if the SpO2 level drops under the threshold, the system raises an alarm and places an alert to the doctor's UE; if an abnormal electrocardiogram pattern is detected by machine learning, an alert is raised, and a notification is sent to the responsible doctor's UE for further analysis.
Remote medical procedure support	A patient at the ward requires a medical procedure that needs supervision of a specialized doctor. This doctor connects his/her UE to the Vertical Application, selects the correct patient and supports less specialized staff located in the ward.

Table 8. 5G Virtual Office ward remote monitoring story board.

Figure 31 shows the control room, where OneSource is describing to the audience the process of the remote monitoring and showcasing the real time sensor feed. The screen to the right contains the vital signs of the patient and the one to the left shows the video feed from the "ward" room.

Figure 31: Hospital control room during test case 1: ward remote monitoring.

Next to the patient, there were also a medical staff member monitoring in person with a mobile device. This device was connected to the Virtual Application through the 5G NPN and visualising the same information that was shown at the monitoring room, as represented in Figure 32.

Figure 32. Mobile device connected to the Vertical Application.

4.2.2. Intra-hospital patient transport monitoring

The intra-hospital patient transport monitoring scenario, represented in Figure 33, aims to ensure uninterrupted monitoring with quality when patients are transported inside the hospital, in contrast to what current technologies provide.

Figure 33. Intra-hospital patient transport monitoring test case depiction.

The story board for this test case is described in Table 9.

Title	Description
A patient needs to be transported from the ward to the radiology department	A doctor, in the office, connects its UE to the Vertical Application and can see all the information from the patient being transported. Alternatively, it may be subscribed only to alerts to perform a more passive monitoring.
Patient transportation is ongoing	The staff is moving the patient towards the Radiology department. The UE with sensors remains connected and roams from microcell to microcell without any disruption in connectivity or quality.
Supervised medical procedure required	The doctor, monitoring remotely, receives an alert that the patient blood pressure is dropping. Immediately, the doctor request that the appropriated medication is applied and supervises the procedure.
The patient undergoes radiology exam and then is returned to its room at the ward	During the exam and when returning to the room, the doctor can monitor the patient from office, without any connectivity loss. Also, machine learning algorithms always keep processing sensor's data in real time in case no doctor is able to monitor actively.
A patient needs to be transported from the ward to the radiology department	A doctor, in the office, connects its UE to the Vertical Application and can see all the information from the patient being transported. Alternatively, it may be subscribed only to alerts to perform a more passive monitoring.

Table 9. 5G Virtual Office Intra-Hospital Patient Transport Monitoring story board.

Following the first test case on ward remote monitoring, the patient located at the "ward" was moved into a different area of the Hospital. During the entire process, the vital signs of the patient were monitored without interruption in the control room. Figure 34 contains the point of view of the control room, showing the vital signs on the screen to the right and the video feed of the patient being transported on the screen to the left.

Figure 34. Hospital control room during test case 2: intra-hospital patient transport monitoring.

4.2.3. KPI validation summary

During the trial, a number of KPIs were collected in order to validate both the network and the Virtual Office Vertical Application (Mobitrust). Hence, these can be split into application KPIs and 5G network KPIs. The application KPIs are described in the table below.

KPI ID	Description
UC3-K1	End-to-end HD multimedia latency is the elapsed time from the moment HD Multimedia is requested (TS1) by the operator until the multimedia is displayed at the operator screen (TS2).
UC3-K2	End-to-end SD multimedia latency is the elapsed time from the moment SD Multimedia is requested (TS1) by the operator until the multimedia is displayed at the operator screen (TS2).
UC3-K3	Round-Trip Time (RTT) is the elapsed time between the timestamps since a simple request is sent from one component to the UE (TS1) until the moment the response is received (TS2).
UC3-K4	Sensor data latency is the elapsed time between the timestamps of the messages since they are requested from the operator (TS1) until the moment they are received by the operator (TS2).
UC3-K5	Device authentication time is the elapsed time from the moment the device is turned on (TS1) until the moment it receives the acknowledgement (TS2).
UC3-K6	Device battery life. Should last 4 hours while delivering sensor data to the Clinical Care Classification system, since they are turned on (TS1) until the moment they are shut down (TS2).
UC3-K7	Device number of restarts. Should run without restarts.
UC4-K8	Device communication availability. Should be available 99% of the time.

Table 10. Application KPIs for 5G Virtual Office.

The 5G network KPIs are described in Table 11 below.

KPI ID	Description
UC3-K9	Radio signal quality via Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) measured at the UE containing the 5G modem.
UC3-K10	Uplink and Downlink data rates.

Table 11. 5G network KPIs.

Table 12 contains the results of the KPIs measured during the trial. There are two main takeaways from these results. One, the very low latency of the live video feed and sensor data transmission, and two, the fact that it was all uninterrupted for the duration of the trial. This showcases the advantage of NPNs in an Hospital setting, namely the reliability, privacy, and lack of dependability on external providers.

KPI ID	Measurement results
UC3-K1	~350 ms
UC3-K2	-
UC3-K3	~34 ms
UC3-K4	~50 ms
UC3-K5	~8 s
UC3-K6	~6 h
UC4-K7	0
UC4-K8	100%
UC4-K9	RSRP of ~-60 dBm RSRQ of ~-10 dB
UC4-K10	888.1 Mbps of downlink (DL) 65.4 Mbps of uplink (UL)

Table 12. KPI measurement results.

4.3. Stakeholder feedback

The following subsection shows the feedback gathered from the main stakeholder of this use case. In this particular test case, a different althouhg similar questionnaire was provided to workers located in the facility when after the trial execution. The idea was to compile their thoughts and analyse them together as a whole. The main outcomes of this questionnaire, delivered to four people, are shown next.

4.3.1. Main outcomes

1. *What is your role in the organization?*

There was a well-represented number of members in the trial, including:

- Head of radiology
- Head of department
- Head of section
- Section advisor (Information THechnology, IT)

2. *What is your main field of work?*

- Radiology
- Leader and hepato-pancreato-biliary surgeon
- Architecture, design and tenders

3. *Please rate your familiarity with 5G technologies:*

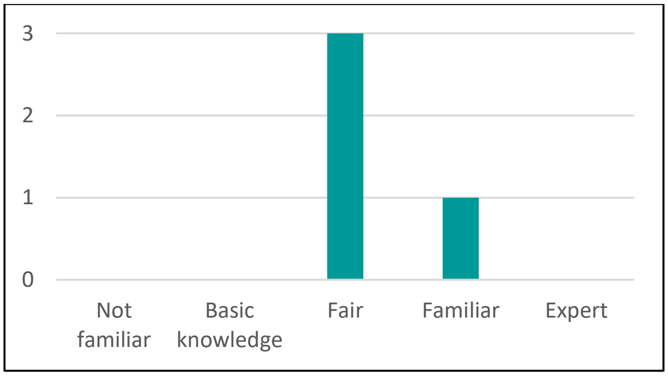


Figure 35. Level of familiarity of the 5G virtual office stakeholder.

4. *From your point of view, what are the most important aspects to be validated in FUDGE-5G trials for hospital deployments?*

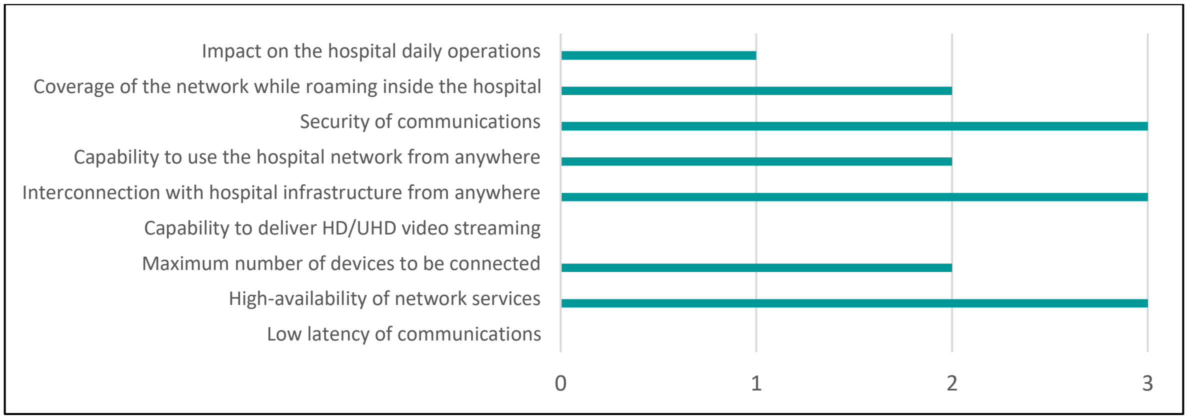


Figure 36. Most important aspects to be validated in the trials.

5. *What types of applications/services do you expect to have running over the 5G network?*

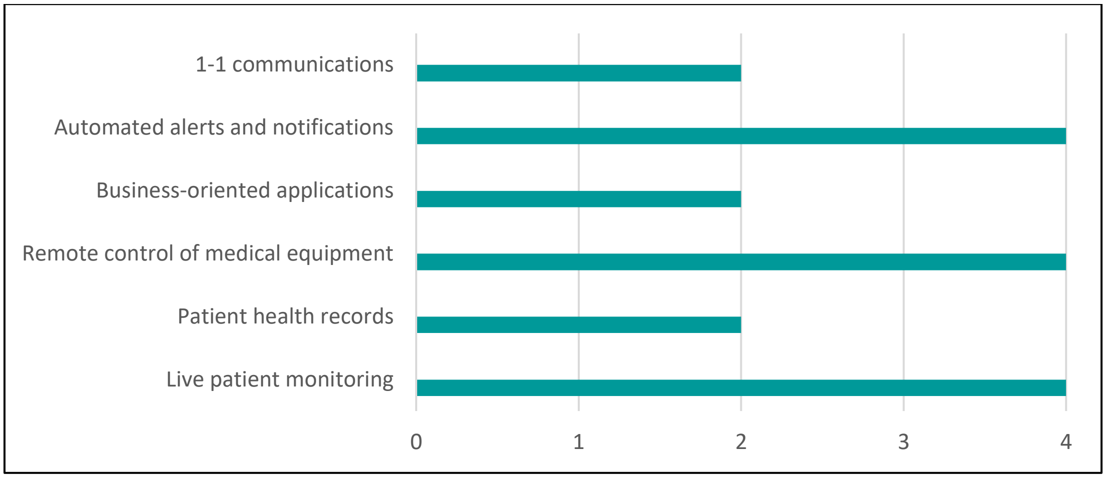


Figure 37. Expected applications and services using 5G services.

4.3.2. About the project

6. *Based on what you saw today, what is the single most important benefit that a private 5G network could bring to a hospital deployment?*

- Better patient care
- Replacing WiFi
- Redundant radio communications
- Quality of service

7. *Based on what you saw today, how likely you will be to follow the progress of the project?*

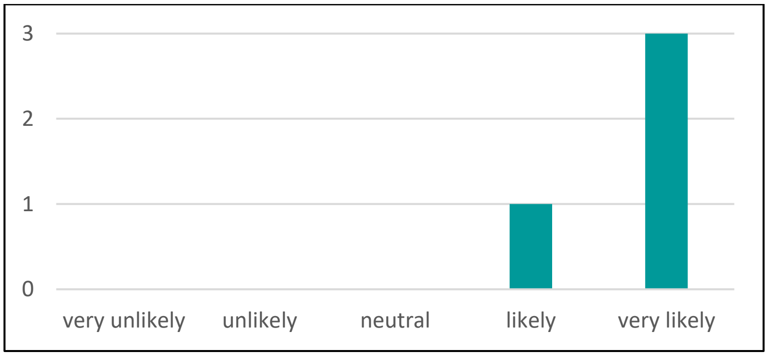


Figure 38. Level of likelihood to keep posted about the project: 5G virtual office use case.

5. Industry 4.0: final trials

The following section describes in detail the final vertical trials performed in FUDGE-5G for the Industry 4.0 use case. As explained in previous deliverables D1.1 [2], D3.2 [6] and D4.2 [7], the trials took place in the technology laboratory of ABB in Fornebu, Norway. The location is shown in Figure 39.

Figure 39. ABB premises location in Fornebu, Norway.

In the following subsections, we first describe the main architecture, component setup and measurement tools used per test case. Afterwards, the trial execution and main outcomes are discussed in detail.

5.1. Setup and measurement tools

The particular use case of the Industry 4.0 has defined the following validation methodology. The first phase of the trials, initially planned for 2021, was postponed due to network integration issues to Q4 2022. After the succesfull execution of these trials, reported in D4.2 [7], the second phase has been performed in Q1 2023.

ABB has always shown special interest in network-related requirements as a baseline for executing their applications. Although D4.2 already included some initial results, D4.3 includes a complete section on additional testing of 5G related KPIs. This report also includes the details and results of several of the application test cases previously considered, that is, monitoring and control as a service, process control, and 5G adaptability in industrial environments. Note that some of the test applications have been analyzed from a network perspective, since they were not possible to execute due to network limitations, as the requirements initially envisioned were too ambitious as of today.

Regarding the tools that have been used to test the performance and user experience of the use case, they are mainly based on industrial devices and host systems, as well as process control software to execute the different test applications here explained. ABB, with the support of Cumucore, Fivecomm and Telenor, has also provided the adequate software and tools to design, provision, commission and operate the 5G NPN with connected devices.

It is important to mention that the trials executed in ABB featured one of the main innovations highlighted at the beginning of the project, that is, 5G-Based Local Area Network (5G-LAN) as one of the features included in the 5GC provided by Cumucore and deployed in their lab. The use of Time Sensitive Networking (TSN) in 5G networks, on the other hand, has been tested as a separate demo in Cumucore premises, shown in Figure 40. The initial architecture presented in D4.2 included a complete setup and time synchronicity results. In this deliverable, the 5G devices provided by Fivecomm have been additionally integrated and validated as part of the demo. More synchronization results, comparing with other devices, are here provided.

Figure 40. Cumucore premises location in Espoo, Finland.

5.1.1. 5G network testing

A first validation of the 5G network to be used in ABB was made separately at Telenor premises. Once the devices and the 5G network were validated, the next step was to move the equipment from Telenor to ABB premises and validate again by following the same procedure. The initial validation results, reported as part of phase-1, are available in D4.2 [7]. The following components were integrated in the Industry 4.0 node.

Figure 41. 5G components (5GC, radio, and devices) deployed at ABB lab.

- **5GC** from Cumucore: bare-metal version with 5GLAN functionality integrated.
- **5G radio infrastructure** from Nokia: BBU, Hub and two radio dots, provided and integrated by Telenor.
- **Two 5G devices** from Fivecomm. Additional 5G CPEs from other companies were also available for testing purposes, although not finally used.

Figure 41 shows how these components look like. Such components have been integrated following a particular end-to-end network diagram for up to four different topologies. Figure 42 shows an advanced version of the third topology used in our measurements. Note that in this setup, a single device was used, while in the rest of topologies two devices were connected to the network. The validation of the 5G network has been based on four main KPIs, whose results are presented in Section 5.2.1. Regarding the measurement tools used during the trials, we used *iperf* and *ping*.

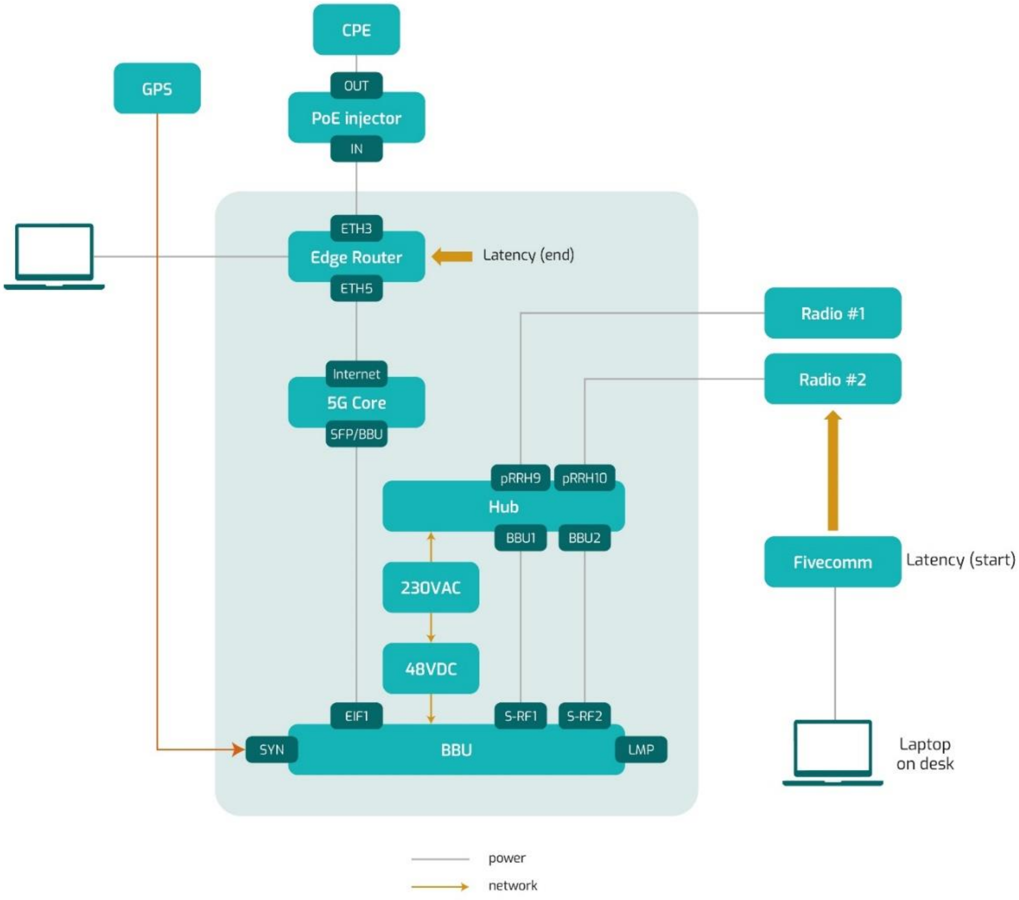


Figure 42. 5G network detailed architecture (topology 3).

5.1.1.1. Topology #1

Topology #1 represents a complete end-to-end system setup as it is expected to be used in an industrial environment. It includes both 5G related delays and delays incurred in test PCs and associated wired networks. End application devices are connected via 5G modems. Figure 43Figure 42 shows a simplified version of this topology employed in the trials.

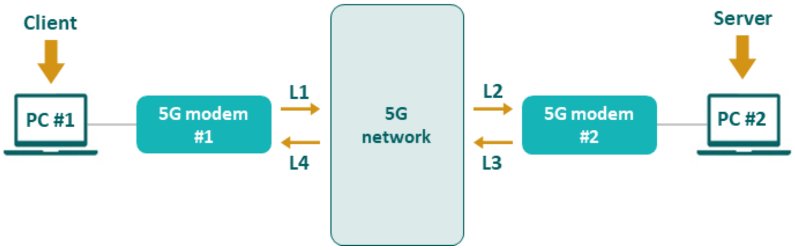


Figure 43. Topology 1 employed in the trials: client on PC #1, server on PC#2, two 5G modems.

Note that L1-L4 represent the different hops in the UL/DL needed to perform an end-to-end test. For this topology, two different KPIs have been measured: throughput when using Transmission Control Protocol (TCP) and throughput plus jitter with User Datagram Protocol (UDP).

5.1.1.2. Topology #2

The second topology is similar to the first one since it is still representing a complete end-to-end wireless NPN based industrial system. It therefore includes both 5G related delays and delays incurred in test PCs and associated wired networks. The main difference relays on where the server is located. In this case, we have an industrial device directly connected via a native 5G component.

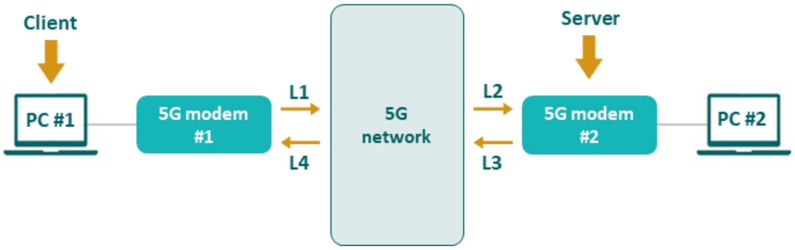


Figure 44. Topology 2 employed in the trials: client on PC #1, server on 5G modem #2.

For this particular topology, up to three KPIs have been measured: throughput with TCP, throughput, and jitter with UDP, and end-to-end latency (minimum, maximum, average). Additionally, this is the topology used to validate the test application on process control over 5G. More details are provided in Section 5.2.2.

5.1.1.3. Topology #3

Finally, the third topology in our 5G network testing setup removed the second modem and connected the second PC directly to the 5G network, through an edge router that in turn is connected to the 5GC. Figure 45 shows a simplified version of Figure 42, where this change can be observed. Additionally, the client was moved to the 5G modem connected to PC #1.

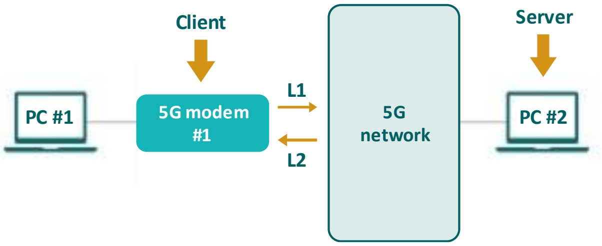


Figure 45. Topology 3 employed in the trials: client on 5G modem #1, server on 5G modem #2.

5.1.2. Monitoring and control

This section has considered three of the four test applications initially described in D1.1 [2], i.e., remote monitoring-as-a-service, remote control-as-a-service, and process control over 5G. The two first ones are conceived as the same setup, shown in Figure 46Figure 26 (left). Process control is also shown in the figure (right).

Figure 46. Remote monitoring-as-a-service / control-as-a-service basic setup (left) and process control over 5G (right).

The first test application is monitoring-as-a-service. The idea was to send 4K video signals streamed using network orchestration and traffic handling with priority levels. Remote monitoring permits a stakeholder to monitor, analyze and report about a specific industrial process or condition under study. As it can be observed in the figure, several video cameras are placed over a moving rail or platform that is also remotely controlled. This represents the second part of the setup, i.e., remote control-as-a-service. The main idea is to control and monitor the different processes taking place under their supervision field.

In this scenario, the main objective of ABB was to quantify how many ultra-HD streaming video data flows in 4K (2160p), with a bandwidth requirement of approximately 25 Mbps, could be sent in the UL at the same time without saturating the 5G NPN for a particular configuration, ideally up to eight. This part of the test was discarded as no more than two cameras could be used with current 5G networks. Regarding control as a service, it has been tested by means of end-to-end latency results, observing if the current requirements of 10 ms are feasible. A similar study has been performed for the third application since it requires very similar latency values.

5.1.3. 5G adaptability in industrial environments

The third identified scenario was the continuous monitoring of signal strength related parameters in several 5G devices, mainly those provided by Fivecomm, as well as other components for industrial environments. The main idea behind this test application was to observe the impact on 5G coverage in the lab, depending on the device position with respect to the 5G dots, which are located as shown in Figure 47.

Figure 47. 5G adaptability basic setup: locations of access point 1 (left) and 2 (right).

The specific device position will naturally have an impact on some signal strength related parameters, such as RSRP, RSRQ, or Signal-to-Interference-plus-Noise Ratio (SINR). Figure 48 shows the map of the laboratory and specific locations of the two dots or Access Points (APs) installed. The figure also shows the 6 different points of reference where the measurements were taken.

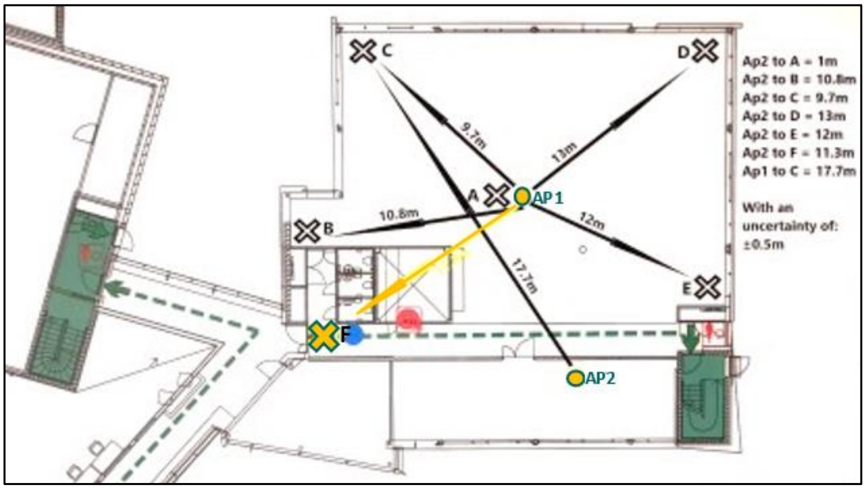


Figure 48. Map of ABB lab, with AP locations and measurement points.

Note that this application test case may be related to transmission power level control for safe operations in hazardous areas, or coverage in dense environments with heavy metal and concrete construction onshore/offshore. Since a particular frequency band n78 was used, this is also related to the impact of 5G spectrum on the use of NPNs. Note that the signal strength parameters are directly obtained from the 5G devices, through AT commands in their operative system.

5.1.4. 5G-TSN for industrial scenarios

As mentioned earlier, the last scenario related to this use case is the use of one of the main innovations of the project, 5G-TSN, in industrial scenarios. Due to the lack of maturity of TSN in 3GPP current releases and unavailabilty of compatible/standardized devices and modules, this part of the use case was moved to Cumucore premises in Espoo, Finland. The main objective was to develop in software the basic synchronization functionalities such as the use of PTP protocols in the network and the devices, as well as their integration and validation in a laboratory environment.

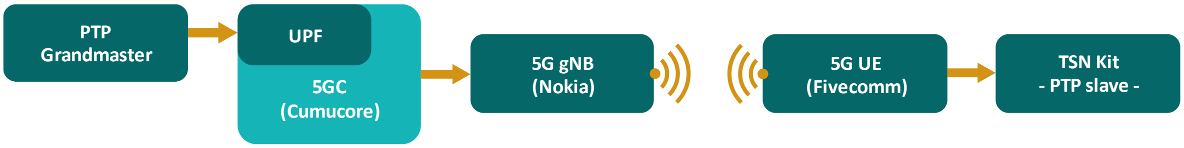


Figure 49. TSN setup diagram used in Cumucore premises.

The setup was first used by Cumucore in ABB Finland, whose results were reported in D4.2 [7]. The final step was the integration and validation of 5G devices developed by Fivecomm. In this case, a different modem from the two modems available in ABB was sent to Cumucore. This particular component comes with the needed modifications in software so it is compatible with the 5G-TSN network provided by Cumucore. In order to perform the measurements, the 5G device implemented the Virtual eXtensible Local Area Network (VXLAN) protocol. The basic setup diagram used for this last TSN testing stage is shown in Figure 49.

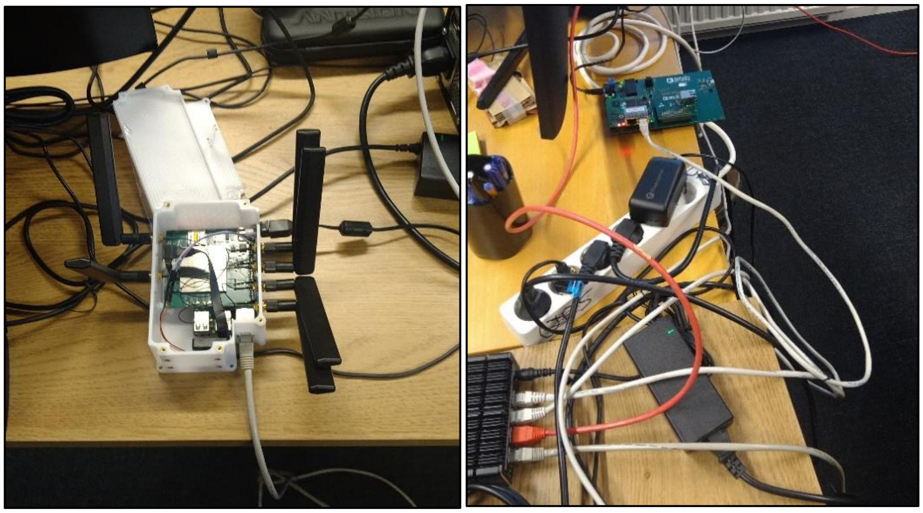


Figure 50. TSN standalone demonstration over 5G: components on the device side.

As it can be observed, the setup was kept simple, as any additional nodes in the layout would have an impact on the results. In this case, we are transmitting the PTP Grandmaster (GM) signal over the User Plane Function (UPF) of the 5GC, and therefore the 5G radio. The 5G modem shown in Figure 50 (left) hence retransmits this information by using the VXLAN protocol to the TSN Kit shown in the same figure (right), which then compares with GM time and calculates the offset.

5.2. Vertical final trial execution and results

5.2.1. 5G network testing

5.2.1.1. Topology #1

Table 13 shows the results obtained for the first topology considered in the measurements, whose setup is described in Section 5.1.1.1.

Test	Traffic	Min. Throughput (Mbps)	Av. Throughput (Mbps)	Max. Throughput (Mbps)
#1	TCP	23.8	42.77	62.9
#2	TCP	18.7	39.81	57.8
#3	TCP	20.9	42.85	62.9

Table 13. TCP throughput results, topology 1.

In this setup, the client is the sender, and the server is the receiver. It involves two UL and two DL, and the test took 300 seconds. The table shows a recorded throughput range of 18.7 to 62.9Mbps.

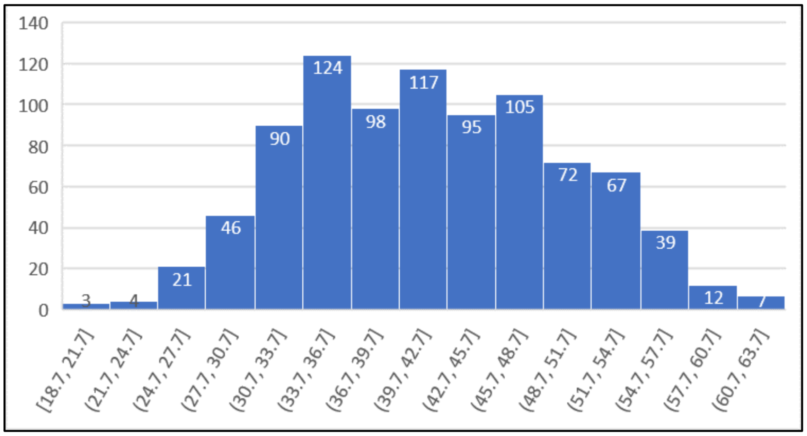


Figure 51. TPC throughput distribution over 5G, topology 1.

The recorded throughput in this case goes from PC 1 to PC 2, with throughput capability at PCs in the order of Gbps. Assuming a throughput (wired) capability at Fivecomm modems of Gbps, and that the 5G UL throughput is expected to be lower than DL throughput, hence the recorded throughput is associated to the UL (UL throughput is the bottleneck in this design). A similar behavior can be observed with UPD packets.

Test	Traffic	Jitter (ms)	Min. Throughput (Mbps)	Av. Throughput (Mbps)	Max. Throughput (Mbps)
#1	UDP	1.917	20.3	33.9	45.4
#2	UDP	2.583	26.6	39.05	48.8
#3	UDP	3.037	23.4	36.07	52.1

Table 14. UDP throughput results, topology 1.

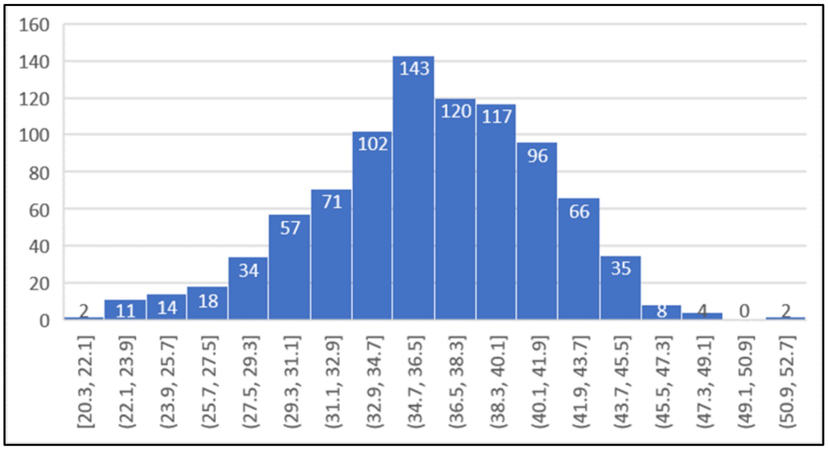


Figure 52. TPC throughput distribution over 5G, topology 1.

As it can be observed, with UDP we obtained a UL throughput range between 20.3 and 52.1Mbps.

5.2.1.2. Topology #2

The results obtained for with the second topology are shown in Table 15 for TCP. In this case, we recorded an UL throughput range between 16.8Mbps and 66.2Mbps. Therefore, it can be observed that no major changes are appreciated when changing the server from PC #2 to the 5G modem.

Test	Traffic	Min. Throughput (Mbps)	Av. Throughput (Mbps)	Max. Throughput (Mbps)
#1	TCP	23.8	42.77	62.9
#2	TCP	18.7	39.81	57.8
#3	TCP	20.9	42.85	62.9

Table 15. TCP throughput results, topology 2.

This behavior is, however, slightly different when obtaining UDP results, as shown in Table 16. It is important to highlight that the jitter has been reduced drastically, from values ranging 2-3 ms to 0.05-0.02 ms, which represents 100 lower values. Regarding the throughput, it has experienced a significant increase up to 75.7 Mbps.

Test	Traffic	Jitter (ms)	Min. Throughput (Mbps)	Av. Throughput (Mbps)	Max. Throughput (Mbps)
#1	UDP	0.101	26.3	55.31	74.1
#2	UDP	0.059	35.8	58.43	75.7
#3	UDP	0.242	28.3	47.12	67.8

Table 16. UDP throughput results, topology 2.

We additionally measured the 5G latency when using this topology. Table 17 and Figure 53 show the minimum, average and maximum values obtained, as well as the distribution respectively. The results show a RTT 5G latency range from 7ms to 28ms.

Test	Min. Latency (Mbps)	Av. Latency (Mbps)	Max. Latency (Mbps)
#1	7	15	23
#2	9	18	26
#3	9	18	28

Table 17. 5G latency results, topology 2.

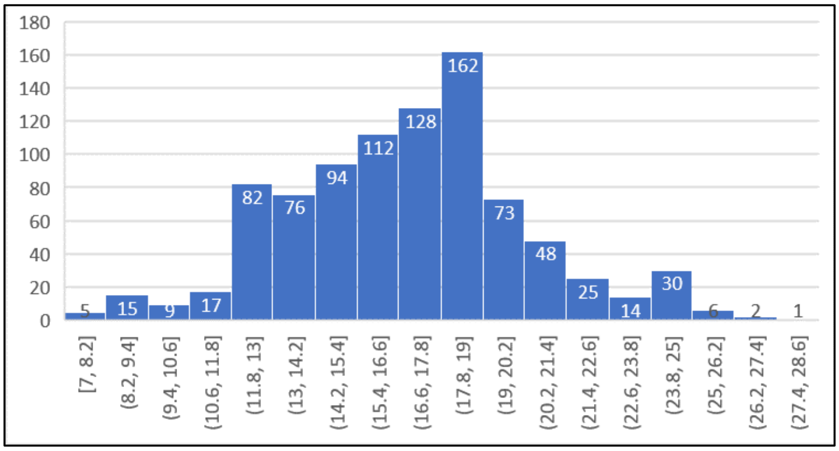


Figure 53. 5G latency distribution (ms) when using 5G, topology 2.

5.2.1.3. Topology #3

The focus in topology #3 was the throughput, by using both UDP and TCP transmissions with a single 5G modem. This was done as the direct connectivity to the network allowed us to differentiate between the two links without having any UL bottlenecks because of the use of two 5G connected modems.

Throughput (Mbps)			
TCP	Downlink	Sender	399
		Receiver	395
	Uplink	Sender	50.2
		Receive	42.9
UDP	Downlink	950	
	Uplink	43.8	

Table 18. Throughput obtained with TCP and UDP transmission, topology 3.

As it can be observed, this topology permitted us to validate that, although the UL throughput values are still similar to the ones obtained in topologies 1 and 2, the DL trhoughput is clearly higher, obtaining an average values of 395-399 Mbps with TCP and 950 with UDP.

5.2.2. Monitoring and control

As mentioned in Section 5.1.2, the demonstration of the monitoring part of this test application was finally not considered, as the UL values observed in the measurements were not as high as expected by the stakeholder. Therefore, we focused on the control part of the application, which was validated by means of 5G latency results.

In this case, we used topology #2, and we observed the number of received packets that were successfully received with a guaranteed 5G latency. In other words, if a packet was received with latency higher thant the specified value, it was discarded with an impact on the overall reliability. Table 19 shows the dependency between these two requirements.

Reliability/latency	50%	70%	80%	90%	95%	99%	99.9%
16 ms	🟧	🟧	🟧	🟧	🟧	🟧	🟧
19 ms	🟩	🟩	🟧	🟧	🟧	🟧	🟧
22 ms	🟩	🟩	🟩	🟧	🟧	🟧	🟧
25 ms	🟩	🟩	🟩	🟩	🟩	🟩	🟧
28 ms	🟩	🟩	🟩	🟩	🟩	🟩	*objective*

Table 19. Control as a service latency vs. availability requirements.

As it can be observed, receiving the 99.9% of the packets sent (requirement set at the beggining of the project in D1.1 [2]) would provide a maximum 5G latency of 28 ms. This means that the 5G network would support industrial control systems with processes that require no more 28 ms. Unfortunately, this is still not close to the 10 ms requirement provided in D1.1, and more research/technolgy improvement is still needed. A summary of the results is provided in Section 5.2.4.

5.2.3. 5G adaptability in industrial environments

The third test case consisted in evaluating the signal strength and coverage in the lab for different configurations. Table 20 shows the minimum, average and maximum values obtained for RSRP, RSRQ and SINR. During the signal quality measurement, stable values were observed.

Point	Min. RSRP (dBm)	Av. RSRP (dBm)	Max. RSRP (dBm)	Min. RSRQ (dB)	Av. RSRQ (dB)	Max. RSRQ (dB)	Min. SINR (dB)	Av. SINR (dB)	Max. SINR (dB)
A	-47	-45,40	-44	-11	-11	-11	35	36,6	38
B	-70	-65,1	-63	-11	-11	-10	30	33,30	35
C	-74	-67.3	-62	-11	-11	-11	23	29.5	36
D	-79	-79.0	-72	-11	-11	-11	25	27.5	31
E	-81	-74.0	-70	-12	-11	-11	19	24.9	30
F	-82	-79.4	-77	-11	-11	-11	16	21.3	31

Table 20. RSRP, RSRQ and SINR obtained values.

- **AP1 test**: Point C had excellent RSRP. However, SINR was lower due to the wall. RSRQ was good for all points, but not excellent.
- **AP2 test**: From the map, points D, E, and F were non-line of sight, with F having the worst signal quality. RSRP and SINR results reveal that D was on the edge of excellent, while E and F were on the edge between excellent and good. Point A, being only 1 meter from the access point, naturally exhibited the best signal quality, with B and C following as the second best due to their clear line of sight with minimal obstructions.

5.2.4. Industrial test cases: main findings

The following table compiles the main finding of this collaborative work between the consortium partners involved and ABB.

Test case and findings	Target KPIs	Recorded KPIs (5G Lab)
Remote monitoring as a service Findings: UL throughput is limiting. Need multiple 5G modems to achieve aggregated UL throughput of 200Mbps.	UL throughput: 200Mbps	UL throughput: 21.1-52.5Mbps
Remote control as a service TSN and localization was not implemented in ABB. Findings: Round-trip latency is still high in 5G.	E2E latency: <10ms	E2E latency: 7ms – 73ms
5G adaptability in industrial environments Findings: Only fixed points. Signal strength was strong and remained stable throughout testing.	RSRP: Good RSRQ: Good SINR: Good	RSRP: Excellent/Good RSRQ: Good SINR. Good
Process control over 5G Findings: Round-trip latency is still high. 5G system availability was not consistent.	UL latency: <2ms E2E latency: <10ms	UL latency: 3ms - 42.6ms E2E latency: 7ms - 73ms

Table 21. KPI and requirement analysis for the Industry 4.0 test cases.

5.2.5. 5G-TSN for industrial scenarios

This subsection shows the time synchronization results obtained in Cumucore premises, following the setup provided in Section 5.1.4. The next tables show the status pages of the TSN evaluation box located after the 5G network, which is synchronized through the 5G modem, as well as the time offset achieved in the first measurement performed.

	Port 1:	Port 2:
Port Role:	Master	Slave
Peer Status:	Not time Aware	Time Aware
Line Delay:	0	1237
Best Master Clock ID:	00:17:47:ff:fe:70:07:61	
Best Master Priority1:	64	
Best Master Priority2:	246	
Best Master Steps Removed:	2	

Table 22. Status page of the TSN kit evaluation box.

Local Time:	1679475652.461237489
Master Time:	1679475652.460635830
Time Offset:	**-601659**

Table 23. Time synchronization (ns) in TSN device connected 5G UE.

These results show a time offset of approximately 601 µs, which is naturally far from the 168 ns obtained through fixed TSN wired devices. This means that the radio contribution is currently in the order of 10^4 to 10^6 compared to the rest of the chain. Note that we repeated this procedure eight times, obtaining the results shown in Figure 54. Such results provide an average time synchronization offset result of **16.5 ms**.

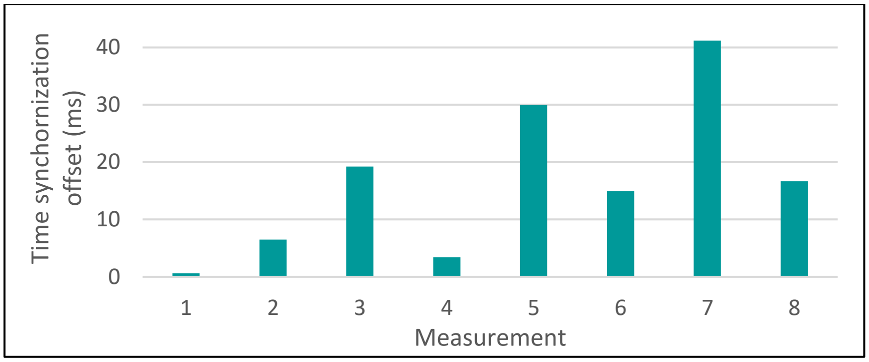


Figure 54. Time synchronization offset results obtained in Cumucore premises.

5.3. Stakeholder feedback

This section includes a questionnaire filled by ABB, who acted as the main stakeholder of the Industry 4.0 use case as explained above.

5.3.1. 5G related questions

1. *Please rate your familiarity with 5G technologies:*

Not familiar	Basic knowledge	Fair	Familiar	Expert
			✓	

2. *Can 4G technologies meet yout current service requirements?*

Yes, 4G LTE is enough	No, 5G (public/private) connectivity is needed	No, a 5G private network is needed
	✓	

3. *Would you use the current 5G private network components in your workflow from now on?*

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
	✓			

4. *If you had to choose only one aspect, what is the most important benefit that a private 5G could bring to your industry.*

Network orchestration and security aspects, which are key in current industrial processes.

5. *What is, in your opinion, the most challenging issue to overcome by 5G Private Networks?*

The support of UEs and 5G devices.

5.3.2. About the tests and trials

6. *How complicated did you find the 5G system to use, compared to other existing solutions?*

Very easy	Easy	Normal	Difficult	Very difficult
		✓		

7. *Measure the level of current technical competency of your team to operate the 5G NPN. Would you be able to operate it on your own?*

Very low	Low	Normal	High	Very high
		✓		

8. *What is the level of importance of these KPIs when delivering your services?*

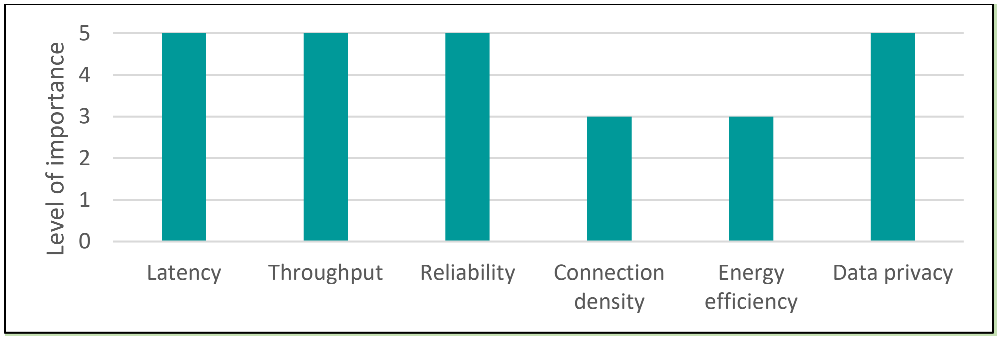


Figure 55. Level of importance of KPIs in the Industry 4.0 use case.

9. *Were these KPIs met?*

Latency	Throughput	Reliability	Conn. Density	Energy eff.	Data privacy
No	Partially	**No**	Partially	Partially	**Yes**

As it can be seen in the table, 5G Rel-15 networks need still improvement for fulfilling the ambitious and critical requirements that industrial scenarios need.

10. *Have been the initial expectations met about FUDGE-5G?*

The initial expectations have been met partially as shown before.

11. *Suggestions for future tests and way forward*

It will be interesting to see large scale testing with new 5G NR releases.

6. Interconnected NPNs: final trials

This section describes the final trials performed for the FUDGE-5G use case Interconnected NPNs. The scenarios described in deliverable D1.1 [2] was realized in phases during the tenure of the project. In the phase 1, distributed authentication framework with local breakout scenario was tested between FOKUS and UPV Interconnected NPN (INPN) nodes. During the 2nd phase the third INPN node Oslo hospital was also added and interconnected with the other two nodes. The same scenarios were validated between the three locations along with the home routed roaming feature during the final trials.

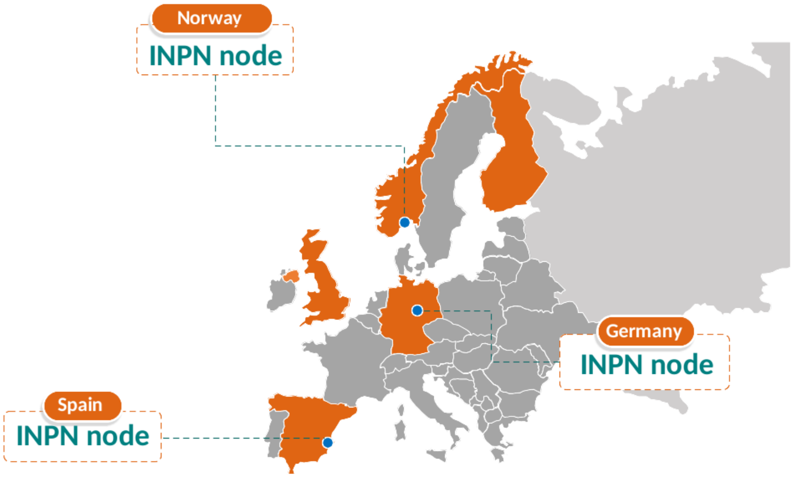


Figure 56. Location of INPN Nodes.

6.1. Setup and measurement tools

The Interconnected NPNs use case is different than the other use cases in the context of feature-based validation and no field trial. This use case is focused on adding new features in the 5GC network to support roaming within small-sized private networks. During the tenure of the project the Fraunhofer FOKUS Open5GCore testbed was extended with a new component Session Border Controller (SBC) to support authentication of roaming users by their home network and home-routed feature to access home network services while roaming. The validation results of these features are already reported in D4.2.

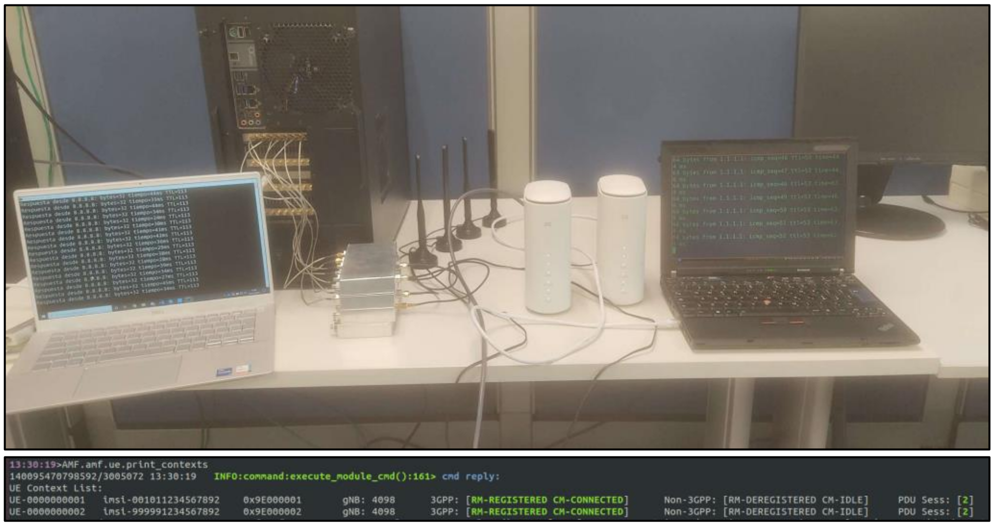
The features were developed for validating the scenarios defined in D1.1 for this use case. The test setup with the 5GC for visited and home subscriber authentication and for home-routed roaming scenarios are illustrated in the following sections.

6.1.1. Interconnection of NPNs

As per D1.1, the plan was to deploy the NPN nodes in the premises of the stakeholders Fraunhofer FOKUS Berlin, UPV Valencia and Telenor Norway. As the third location Telenor Norway was not fully finalized at the first phase of the project, the NPN nodes were first deployed at FOKUS and UPV. In the later phase of the project, the Hospital node in Oslo was added as the third location.

6.1.1.1. Phase-1 Trial

During Phase-1 of FUDGE-5G project, the validation of the use case were performed in phases from September 2021 to September 2022 between UPV and FOKUS node. For the first phase trial, the Fraunhofer FOKUS 5GC with SBC component was deployed in these locations in light weight container system. The two nodes were configured with Public Land Mobile Network (PLMN) number 00101 and 99999 and they were connected via VPN tunnel over a secure shell (SSH). The main motive of the integration work in September 2021 were, to validate the newly developed component SBC which had the feature of Service Communication Proxy (SCP) to route messages between networks and establishing the distributed authentication framework for the roaming subscribers. The overhead of introducing SCP in the 5G registration procedures were captured between 3-8 ms. The Open5GCore from the Fraunhofer FOKUS was integrated with Amarisoft RAN and ZTE modem at UPV lab (reported in D3.1). The setup at UPV and outcome of the verification of the use case is shown in Figure 57 (already reported in D3.1).



```
13:30:19>AMF.amf.ue.print_contexts
140095470798592/3005072 13:30:19   INFO:command:execute_module_cmd():161> cmd reply:
UE Context List:
UE-0000000001   imsi-001011234567892   0x9E000001      gNB: 4098      3GPP: [RM-REGISTERED CM-CONNECTED]      Non-3GPP: [RM-DEREGISTERED CM-IDLE]      PDU Sess: [2]
UE-0000000002   imsi-999991234567892   0x9E000002      gNB: 4098      3GPP: [RM-REGISTERED CM-CONNECTED]      Non-3GPP: [RM-DEREGISTERED CM-IDLE]      PDU Sess: [2]
```

Figure 57. Lab setup at UPV (top); UPV and FOKUS network UE registered at UPV AMF (bottom).

In April 2022 the first trial was performed to capture the 5G procedure related KPIs for home and visited subscribers as reported in D4.1. In September 2022, the tests were repeated between the two nodes to capture all the control plane and data plane related KPIs listed in D4.1. For this trial the UPV and FOKUS nodes were connected through a Wireguard system. The aim of the trials in phase-1 were to test the home subscriber scenarios and visited subscriber scenarios for local breakout. In the first phase, the tests were performed using the real device and with emulated UEs and Benchmarking Tool from Open5GCore platform, to verify the below mentioned processes for both home and visited subscribers-

- The 5G registration, session establishment and deregistration procedures.
- RTT to local data network.
- Local data path capacity.

Objectives:

These test cases were chosen to validate the target of the use case of providing an effective roaming solution for 5G private network by:

- Processing the variation of 5G procedure duration for home and visited subscribers (local breakout).
- Calculating the effective data path capacity for the visited subscribers compared to home subscribers.
- Determining the best-effort backhaul.
- Finding out the overhead induced by the components involved in roaming between private networks.

6.1.1.2. Phase-2 Trial

The final trials for the use case Interconnected NPNs were performed in the second phase of the project. The last trial to cover all the scenarios was performed in February 2023. For the last phase, the third INPN node Oslo Hospital was also interconnected with the UPV and FOKUS node. To increase security of the connectivity between the three network nodes, a Wireguard system was added to connect three edges instead of using internet as the backhaul. The details on the interconnection using Wireguard was reported in D3.1.

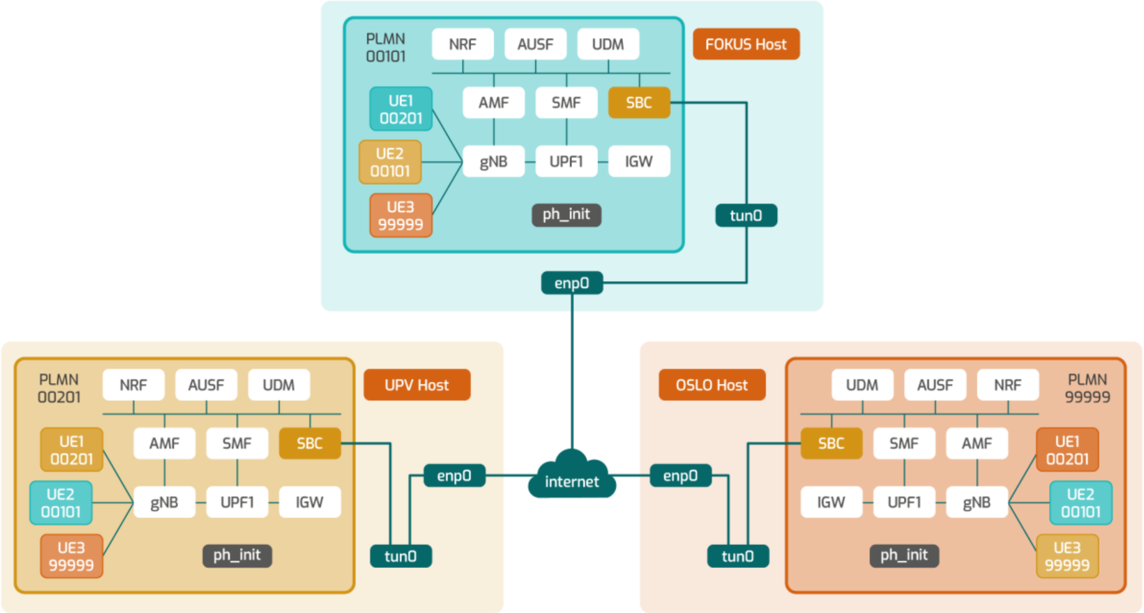
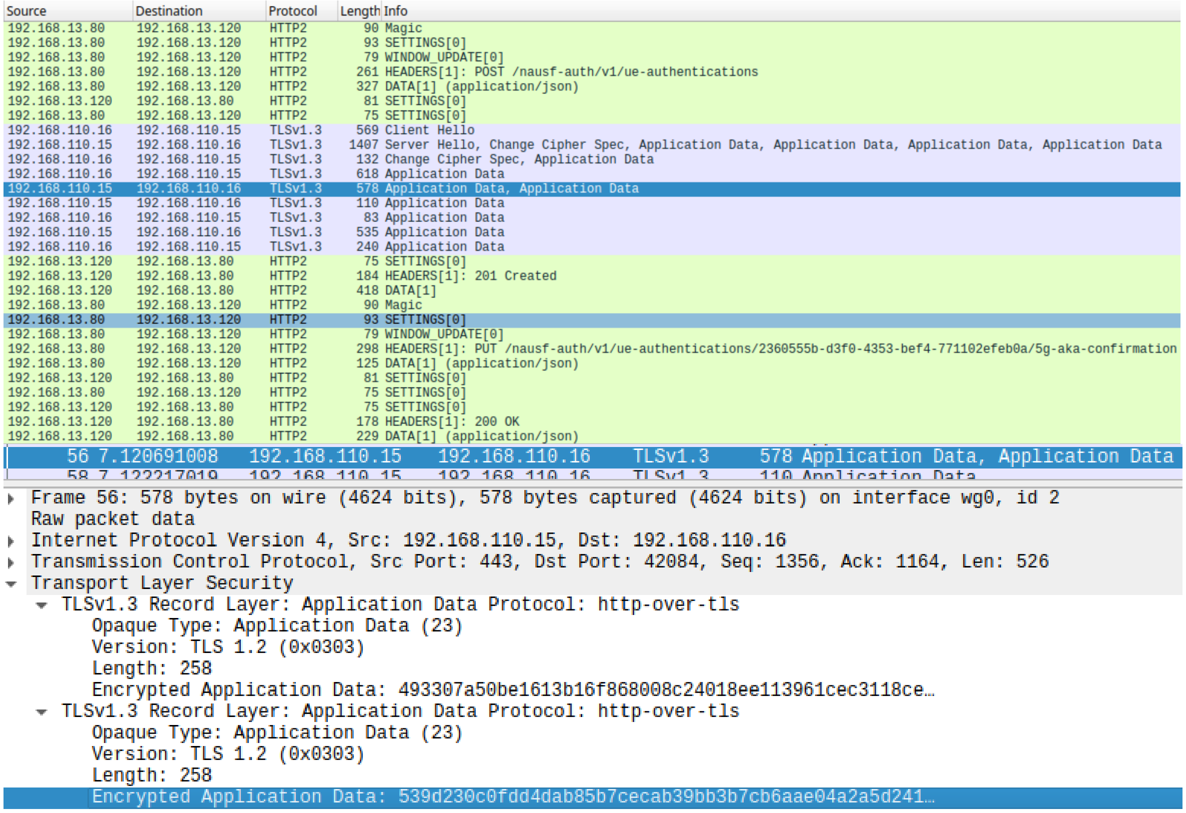


Figure 58. Test setup for Interconnected NPNs with three nodes

The three nodes were configured with PLMN 00101, 00201 and 99999. Each of these networks had UEs belonging to their own and the other networks. The 5GCs in these three location were deployed using lightweight containers. The SBC within the Open5GCore was extended with the addition of some Security Edge Protection Proxy (SEPP) features. In this phase also the home routed roaming feature was onboarded, to allow roaming subscribers having connectivity to home data network and accessing home network services. The setup for the final trials is shown using the Figure 58.

In the final trials, the motive was to route the messages between the private networks through the SBCs to authenticate the roaming users and to establish data bearers for the roaming subscribers with the home network. The message exchange between the private networks are encrypted using SBC and are shown using the Figure 59 (already reported in detail in D4.2).



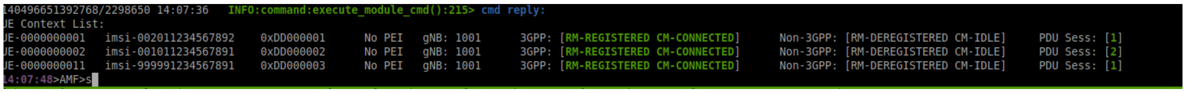
```
Source          Destination     Protocol  Length Info
192.168.13.80   192.168.13.120  HTTP2       90 Magic
192.168.13.80   192.168.13.120  HTTP2       93 SETTINGS[0]
192.168.13.80   192.168.13.120  HTTP2       79 WINDOW_UPDATE[0]
192.168.13.80   192.168.13.120  HTTP2      261 HEADERS[1]: POST /nausf-auth/v1/ue-authentications
192.168.13.80   192.168.13.120  HTTP2      327 DATA[1] (application/json)
192.168.13.120  192.168.13.80   HTTP2       81 SETTINGS[0]
192.168.13.80   192.168.13.120  HTTP2       75 SETTINGS[0]
192.168.110.16  192.168.110.15  TLSv1.3    569 Client Hello
192.168.110.15  192.168.110.16  TLSv1.3   1407 Server Hello, Change Cipher Spec, Application Data, Application Data, Application Data, Application Data
192.168.110.16  192.168.110.15  TLSv1.3    132 Change Cipher Spec, Application Data
192.168.110.16  192.168.110.15  TLSv1.3    618 Application Data
192.168.110.15  192.168.110.16  TLSv1.3    578 Application Data, Application Data
192.168.110.15  192.168.110.16  TLSv1.3    110 Application Data
192.168.110.16  192.168.110.15  TLSv1.3     83 Application Data
192.168.110.15  192.168.110.16  TLSv1.3    535 Application Data
192.168.110.16  192.168.110.15  TLSv1.3    240 Application Data
192.168.13.120  192.168.13.80   HTTP2       75 SETTINGS[0]
192.168.13.120  192.168.13.80   HTTP2      184 HEADERS[1]: 201 Created
192.168.13.120  192.168.13.80   HTTP2      418 DATA[1]
192.168.13.80   192.168.13.120  HTTP2       90 Magic
192.168.13.80   192.168.13.120  HTTP2       93 SETTINGS[0]
192.168.13.80   192.168.13.120  HTTP2       79 WINDOW_UPDATE[0]
192.168.13.80   192.168.13.120  HTTP2      298 HEADERS[1]: PUT /nausf-auth/v1/ue-authentications/2360555b-d3f0-4353-bef4-771102efeb0a/5g-aka-confirmation
192.168.13.80   192.168.13.120  HTTP2      125 DATA[1] (application/json)
192.168.13.120  192.168.13.80   HTTP2       81 SETTINGS[0]
192.168.13.80   192.168.13.120  HTTP2       75 SETTINGS[0]
192.168.13.120  192.168.13.80   HTTP2       75 SETTINGS[0]
192.168.13.120  192.168.13.80   HTTP2      178 HEADERS[1]: 200 OK
192.168.13.120  192.168.13.80   HTTP2      229 DATA[1] (application/json)
```

```
     56 7.120691008   192.168.110.15   192.168.110.16    TLSv1.3     578 Application Data, Application Data
     58 7.122217019   192.168.110.15   192.168.110.16    TLSv1.3     110 Application Data
```

```
▸ Frame 56: 578 bytes on wire (4624 bits), 578 bytes captured (4624 bits) on interface wg0, id 2
  Raw packet data
▸ Internet Protocol Version 4, Src: 192.168.110.15, Dst: 192.168.110.16
▸ Transmission Control Protocol, Src Port: 443, Dst Port: 42084, Seq: 1356, Ack: 1164, Len: 526
▾ Transport Layer Security
  ▾ TLSv1.3 Record Layer: Application Data Protocol: http-over-tls
      Opaque Type: Application Data (23)
      Version: TLS 1.2 (0x0303)
      Length: 258
      Encrypted Application Data: 493307a50be1613b16f868008c24018ee113961cec3118ce…
  ▾ TLSv1.3 Record Layer: Application Data Protocol: http-over-tls
      Opaque Type: Application Data (23)
      Version: TLS 1.2 (0x0303)
      Length: 258
      Encrypted Application Data: 539d230c0fdd4dab85b7cecab39bb3b7cb6aae04a2a5d241…
```

Figure 59. Encrypted message exchange between FOKUS and UPV network

In the second phase, Nov 2022 one trial was performed to validate the feature of SBC to encrypt inter-domain messages. In the final trial, the tests from phase-1 were repeated for the three connected nodes to validate the interconnectivity. Roaming users from UPV and FOKUS were registered at the third location Oslo. In Figure 60, UEs from the three interconnected NPNs registered at Oslo node is shown. In the final trial in February 2023, the tests from phase-1 trials were repeated between the three nodes to capture all the KPIs listed in D4.1.



```
140496651392768/2298650 14:07:36   INFO:command:execute_module_cmd():215> cmd reply:
JE Context List:
JE-0000000001   imsi-002011234567892    0xDD000001      No PEI   gNB: 1001      3GPP: [RM-REGISTERED CM-CONNECTED]      Non-3GPP: [RM-DEREGISTERED CM-IDLE]     PDU Sess: [1]
JE-0000000002   imsi-001011234567891    0xDD000002      No PEI   gNB: 1001      3GPP: [RM-REGISTERED CM-CONNECTED]      Non-3GPP: [RM-DEREGISTERED CM-IDLE]     PDU Sess: [2]
JE-0000000011   imsi-999991234567891    0xDD000003      No PEI   gNB: 1001      3GPP: [RM-REGISTERED CM-CONNECTED]      Non-3GPP: [RM-DEREGISTERED CM-IDLE]     PDU Sess: [1]
14:07:48>AMF>s
```

Figure 60. UE from FOKUS, UPV and Oslo network registered at Oslo AMF.

The aim of the final trials in phase-2 were to test the home subscriber scenarios and visited subscriber scenarios for local breakout between the three connected nodes. Also, to validate home routed roaming scenario for visited subscribers. Same as phase-1 the tests were performed with emulated UEs and Benchmarking Tool from Open5GCore platform. For visited subscribers, the tests consisted of verifying:

- The 5G registration, session establishment and deregistration procedures in case of local breakout.
- The 5G registration, session establishment and deregistration procedures in case of home routed roaming.
- RTT to local data network in case of local breakout.
- RTT to home data network in case of home routed roaming.
- Data path capacity in case of local breakout.
- Data path capacity in case of home routed roaming.

Objectives:

These test cases were chosen to validate the home routed and the local breakout scenario for 5G private network by:

- Processing the variation of 5G procedure duration for visited subscribers (local breakout vs. home routed).
- Calculating the effective data path capacity for the visited subscribers (local breakout vs. home routed).
- Determining the best-effort backhaul.

6.1.2. Energy Consumpion of 5GCs

In line with the European Green Deal [12] the international sustainable development goals [13], and towards green, sustainable, distributed, and inclusive mobile technology [14], research on 5G networks have focused on the efficiency of the network from an energy perspective. Extensive work has been conducted on energy efficiency and consumption in the RAN as the number of micro/macro cells will increase significantly based on infrastructure considerations [15]. Limited work has been done to evaluate the energy consumption in the 5GC and on the 5GC optimization front in 5G and beyond mobile generations.

This work evaluates the core network consumption and compare the power consumption with/without the presence of a proxy function for different loads in context of the 5GC.

6.1.2.1. Testbed Set-Up: 5GC Analysis

UERANSIM is the open source state-of-the-art 5G UE and RAN (gNodeB) simulator. UE and RAN can be considered as a 5G mobile phone and a base station in basic terms. The project can be used for testing 5GC Network and studying 5G System. UERANSIM introduces the world's first and only open source 5G-SA UE and gNodeB implementation. In our experimental setup the 5GC is running as Linux Containers (LXC) in a bare-metal server.

In another machine, we run the UERANSIM as an LXC, with configurations that point to the AMF of the 5GC. The diagram of the setup is shown below.

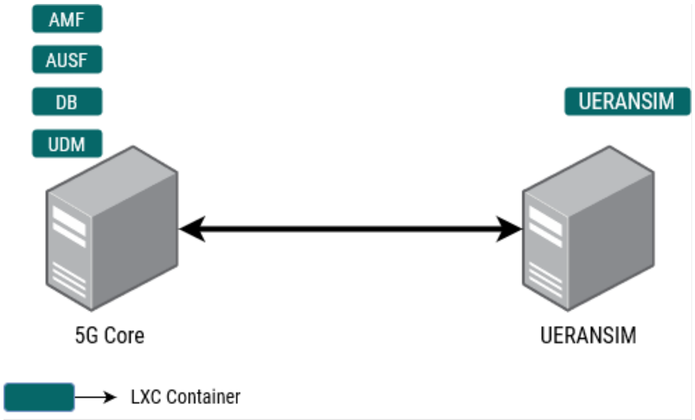


Figure 61. Testbed setup for 5GC power analysis

UERANSIM needs configuration files for UEs and the gNB.

For the gNB we first configure the N2 and N3 interface addresses like below:

```
linkIp: 127.0.0.2
ngapIp: ueransim.lxd
gtpIp: ueransim.lxd
```

Next, we configure the AMF LXC IP address in the server machine to be found by the gNB as:

```
amfConfigs:
   address: 10.130.36.113
   port: 38412
```

We also set the Slice Service Type (SST) to 1 and remove the Slice Differentiator (SD) parameter.

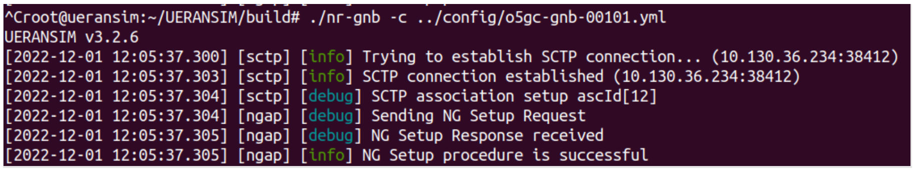
On the UE configuration, the gNB search list is set to the following two IP addresses, as UE and gNB run in the same container:

```
gnbSearchList:
  - 127.0.0.1
  - 127.0.0.2
```

Another part of the configuration file to consider is the section of sessions that is used for PDU session establishment. In our experiments, our UEs don’t make a PDU session, so we comment on this part of the config file.

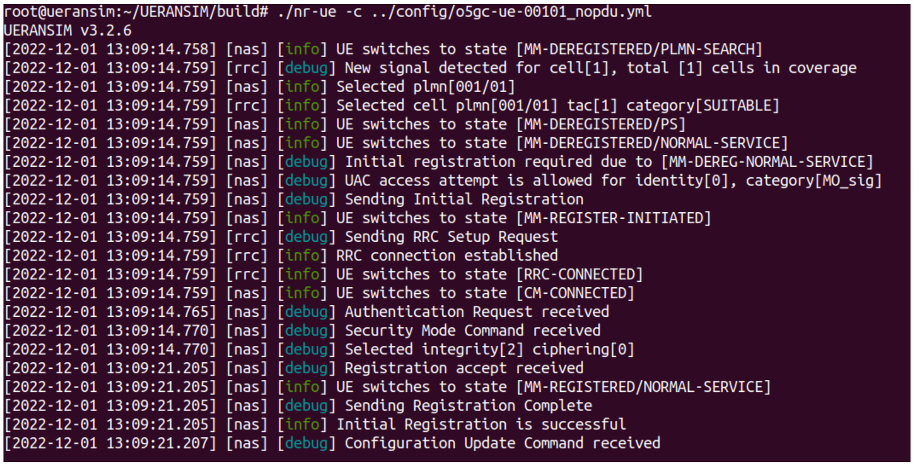
```
sessions:
# - type: ‘IPv4’
# - apn: ‘default’
# - slice:
#         sst: 1
#         sd:  1
```

For the basic usage of the simulator, we first run the executable for the gNB:



```
^Croot@ueransim:~/UERANSIM/build# ./nr-gnb -c ../config/o5gc-gnb-00101.yml
UERANSIM v3.2.6
[2022-12-01 12:05:37.300] [sctp] [info] Trying to establish SCTP connection... (10.130.36.234:38412)
[2022-12-01 12:05:37.303] [sctp] [info] SCTP connection established (10.130.36.234:38412)
[2022-12-01 12:05:37.304] [sctp] [debug] SCTP association setup ascId[12]
[2022-12-01 12:05:37.304] [ngap] [debug] Sending NG Setup Request
[2022-12-01 12:05:37.305] [ngap] [debug] NG Setup Response received
[2022-12-01 12:05:37.305] [ngap] [info] NG Setup procedure is successful
```

And then we can run the executable for the UE with the appropriate configuration file:



```
root@ueransim:~/UERANSIM/build# ./nr-ue -c ../config/o5gc-ue-00101_nopdu.yml
UERANSIM v3.2.6
[2022-12-01 13:09:14.758] [nas] [info] UE switches to state [MM-DEREGISTERED/PLMN-SEARCH]
[2022-12-01 13:09:14.759] [rrc] [debug] New signal detected for cell[1], total [1] cells in coverage
[2022-12-01 13:09:14.759] [nas] [info] Selected plmn[001/01]
[2022-12-01 13:09:14.759] [rrc] [info] Selected cell plmn[001/01] tac[1] category[SUITABLE]
[2022-12-01 13:09:14.759] [nas] [info] UE switches to state [MM-DEREGISTERED/PS]
[2022-12-01 13:09:14.759] [nas] [info] UE switches to state [MM-DEREGISTERED/NORMAL-SERVICE]
[2022-12-01 13:09:14.759] [nas] [debug] Initial registration required due to [MM-DEREG-NORMAL-SERVICE]
[2022-12-01 13:09:14.759] [nas] [debug] UAC access attempt is allowed for identity[0], category[MO_sig]
[2022-12-01 13:09:14.759] [nas] [debug] Sending Initial Registration
[2022-12-01 13:09:14.759] [nas] [info] UE switches to state [MM-REGISTER-INITIATED]
[2022-12-01 13:09:14.759] [rrc] [debug] Sending RRC Setup Request
[2022-12-01 13:09:14.759] [rrc] [info] RRC connection established
[2022-12-01 13:09:14.759] [rrc] [info] UE switches to state [RRC-CONNECTED]
[2022-12-01 13:09:14.759] [nas] [info] UE switches to state [CM-CONNECTED]
[2022-12-01 13:09:14.765] [nas] [debug] Authentication Request received
[2022-12-01 13:09:14.770] [nas] [debug] Security Mode Command received
[2022-12-01 13:09:14.770] [nas] [debug] Selected integrity[2] ciphering[0]
[2022-12-01 13:09:21.205] [nas] [debug] Registration accept received
[2022-12-01 13:09:21.205] [nas] [info] UE switches to state [MM-REGISTERED/NORMAL-SERVICE]
[2022-12-01 13:09:21.205] [nas] [debug] Sending Registration Complete
[2022-12-01 13:09:21.205] [nas] [info] Initial Registration is successful
[2022-12-01 13:09:21.207] [nas] [debug] Configuration Update Command received
```

6.1.2.2. Testbed Set-Up: Impact of Proxy-Usage

All experiments follow the same set of hardware, applications, and communication patterns. This is to limit the unknowns in the experiment and to ensure that all data points obtained through experimentation are repeatable and comparable. The experiments are conducted with HP EliteDesk 800 G1 Tower machines installed with Ubuntu 22.04. The overall experiment is designed with a single consumer (client) and producer (server) and a web proxy as an intermediate node. The communication pattern is illustrated in Figure 62 (left) and the direct communication pattern where no proxy is in use, is illustrated in the same figure (right).

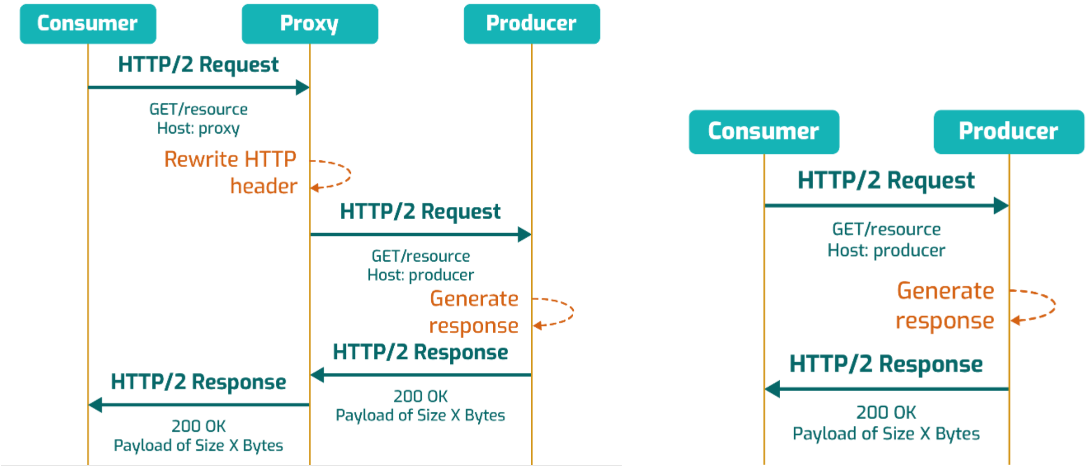


Figure 62. Proxy-Based (left) and Direct (right) Communication Pattern

HTTP is a stateless protocol, but the logical flow within a software component that uses HTTP to obtain information is not. Thus, when putting a system under load, two scenarios must be considered:

- In Scenario 1, the Consumer issues an HTTP request and waits until it receives the response to issue the next one.
- In Scenario 2, the consumer issues as many HTTP requests in parallel as the compute host has Central Processing Units (CPUs) allowing the kernel to place each process on a separate CPU, if deemed necessary.

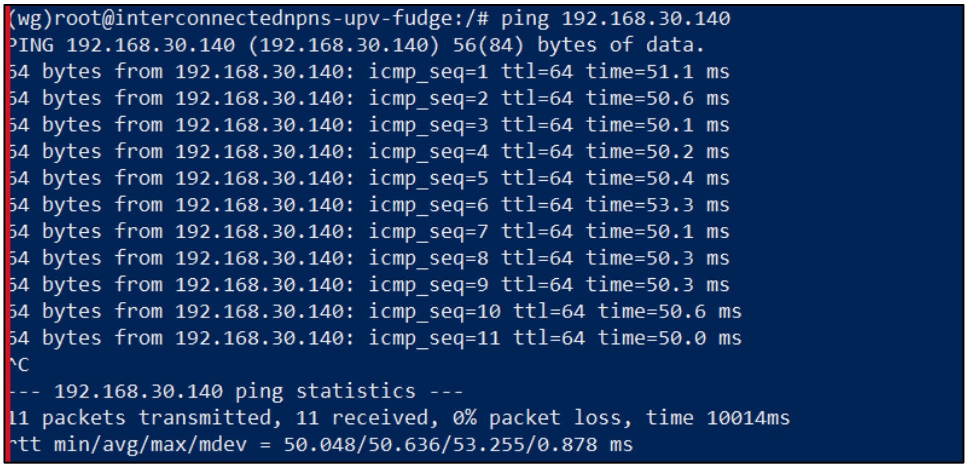
6.2. Vertical final trial execution and results

The final set of trials were performed February 2023. As mentioned earlier, during these trials both home and visited subscribers' scenarios were showcased. The trials were performed between the three interconnected locations UPV, FOKUS and Oslo, in the presence of partners from UPV. The main objective of the trials was to validate the innovations that this use case is bringing to FUDGE-5G by extending 5G core network with a roaming framework for private networks.

The trials consisted of interconnecting the NPNs and performing home subscriber and visited subscriber authentication. For the visited subscribers the ability to access to local network services through local breakout and home network services through home routed roaming were also showcased by creating data bearers to the local and home data network respectively. The setup and validation tools for the trials are already discussed in the previous Section 6.1 and more details on the execution of trials along with the results are captured in the following sections. In addition to that, IDE and AVO academy performed some tests on the energy consumption of 5G core, which are mentioned in Section 6.2.6.

6.2.1. Interconnection of NPNs

As part of the setup for the trials, the interconnection of the NPNs played an important role on the collected KPIs. The three INPN nodes were interconnected via Wireguard as mentioned earlier. In case of home subscribers, all the procedures are executed within the home network only, so there is no message exchange between the home and visited network. In case of visited subscribers, there is message exchange between the home and visited network, so the backhaul between the domains plays a big role in the communication latency. So, before proceeding with the remote procedures the link delay is measured. During the execution of the tests for visited subscribers, the RTT between the domains is measured which has direct influence on the procedure durations. From the trial results, the captured RTT between the UPV and FOKUS edge is shown in Figure 63. The same tests have been performed many times to determine the connectivity and the RTT captured between UPV and FOKUS NPN was on average around 50 to 55 ms. For the third INPN node Oslo hospital, the connectivity was varying a bit frequently and was around 70 to 100 ms.

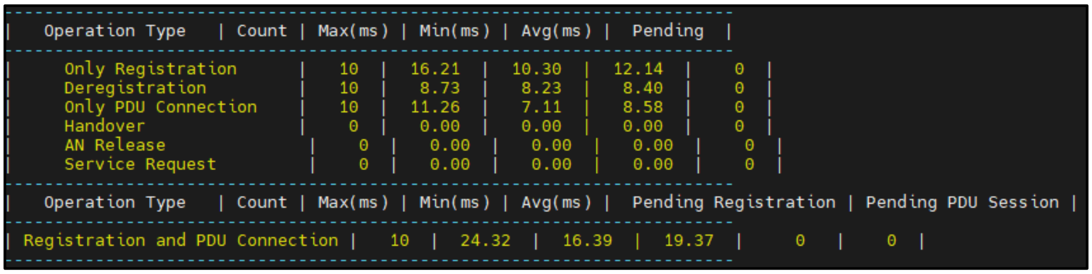


```
(wg)root@interconnectednpns-upv-fudge:/# ping 192.168.30.140
PING 192.168.30.140 (192.168.30.140) 56(84) bytes of data.
64 bytes from 192.168.30.140: icmp_seq=1 ttl=64 time=51.1 ms
64 bytes from 192.168.30.140: icmp_seq=2 ttl=64 time=50.6 ms
64 bytes from 192.168.30.140: icmp_seq=3 ttl=64 time=50.1 ms
64 bytes from 192.168.30.140: icmp_seq=4 ttl=64 time=50.2 ms
64 bytes from 192.168.30.140: icmp_seq=5 ttl=64 time=50.4 ms
64 bytes from 192.168.30.140: icmp_seq=6 ttl=64 time=53.3 ms
64 bytes from 192.168.30.140: icmp_seq=7 ttl=64 time=50.1 ms
64 bytes from 192.168.30.140: icmp_seq=8 ttl=64 time=50.3 ms
64 bytes from 192.168.30.140: icmp_seq=9 ttl=64 time=50.3 ms
64 bytes from 192.168.30.140: icmp_seq=10 ttl=64 time=50.6 ms
64 bytes from 192.168.30.140: icmp_seq=11 ttl=64 time=50.0 ms
^C
--- 192.168.30.140 ping statistics ---
11 packets transmitted, 11 received, 0% packet loss, time 10014ms
rtt min/avg/max/mdev = 50.048/50.636/53.255/0.878 ms
```

Figure 63. Ping Executed between SBC of FOKUS and UPV over the backhaul to capture RTT.

6.2.2. Home subscriber authentication

For the home subscribers, all the requests are handled by the home network. For the subscribers belonging to FOKUS or UPV or OSLO INPN node, the authentication request is processed by their specific node. As there is no dependency on the interconnection of the nodes, for the home subscribers the collected metrics do not vary much. In this project we propose a distributed authentication framework for visited/roaming subscribers and the collection of home subscribers KPIs is important to showcase the differences between the two cases. To collect the KPIs by initiating different 5G procedures for the subscribers, Benchmarking Tool (BT) from the Open5GCore platform was used. BT emulates UEs and gNodeB together in a single component. It is designed in a way such that real life scenarios can be tested, where multiple UEs can connect to the 5G Core through available gNodeBs. To collect the KPIs, we have executed multiple registration, PDU creation, deregistration procedures using BT and collected the statistics from it. The registration, PDU connection, deregistration and registration with PDU connection procedures were executed for multiple subscribers in different nodes. Here we show the results from the tests performed at UPV node for 10 subscribers collected using BT. In Figure 64, for each operation type the number of operations, and their min, max and avg. time is reported. From all the tests performed, the registration procedure latency for home subscribers were around 10 to 12 ms, but for the comparison to the visited subscriber KPIs we will consider the metrics shown in Figure 64 for home subscribers.



```
------------------------------------------------------------------------
|   Operation Type    | Count | Max(ms) | Min(ms) | Avg(ms) |   Pending  |
------------------------------------------------------------------------
|     Only Registration       |   10   |  16.21  |  10.30  |  12.14  |    0   |
|     Deregistration          |   10   |   8.73  |   8.23  |   8.40  |    0   |
|     Only PDU Connection     |   10   |  11.26  |   7.11  |   8.58  |    0   |
|     Handover                |    0   |   0.00  |   0.00  |   0.00  |    0   |
|     AN Release               |    0   |   0.00  |   0.00  |   0.00  |    0   |
|     Service Request          |    0   |   0.00  |   0.00  |   0.00  |    0   |
------------------------------------------------------------------------
|   Operation Type    | Count | Max(ms) | Min(ms) | Avg(ms) |   Pending Registration | Pending PDU Session |
------------------------------------------------------------------------
| Registration and PDU Connection |    10   |  24.32  |  16.39  |  19.37  |      0    |     0   |
------------------------------------------------------------------------
```

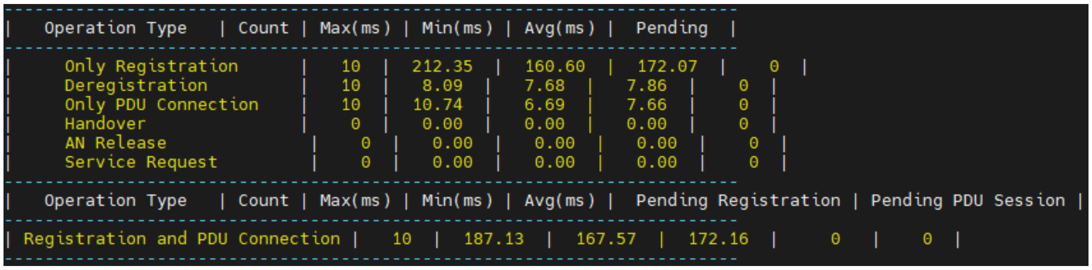
Figure 64. Statistics from BT for Home Subscribers.

6.2.3. Visited subscriber authentication

For the visited subscribers, the authentication request is handled by both home and visited network. As there is dependency on the backhaul between the two networks, the latency between the edge of the networks also needs to be considered while evaluating the KPIs. Same as the home subscribers, for the visited subscribers the 5G procedures were executed using the BT of the visited network (where the roaming users are connected to).

The tests have been repeated multiple times during the trials between FOKUS and UPV nodes and in the final trials also with the Oslo node. For the evaluation of the metrics, the interconnection of the UPV and FOKUS node is considered here. The tests were performed on the visited subscribers (belong to FOKUS node) at UPV node. For the evaluation we took the metrics using BT for 10 subscribers, so that the results can be easily compared with the ones from the home subscribers.

In Figure 65, the statistics for visited subscriber are shown for the same set of operations as the home subscribers. Here the results are captured from the local breakout scenario, so the PDU connection stays to the local data network. As shown by the image, deregistration, PDU connection duration is same as the home network. Only where registration procedure is involved the duration is much higher. Here to evaluate the KPI, the RTT between the UPV ad FOKUS node needs to be considered. For the registration procedure, 3 times there is request going to the home network from the visited network (2 times during authentication and 1 time to fetch subscription information). As shown in Figure 63, the RTT between UPV and FOKUS edge is 50.63 ms. The average duration for Registration procedure here is 172.07 ms for the visited subscribers and the average registration duration for home subscribers is 12.14 ms (shown in Figure 65Figure 64). As per the registration KPI, induced overhead by this distributed authentication framework (from the registration duration) considering the backhaul is- 172.07 - (50.63 *3 + 12.14) = 8.04 ms. From different trials these KPIs have been collected and evaluated. The overhead for roaming subscriber authentication was captured around 3 to 8 ms.



```
-----------------------------------------------------------------------
|   Operation Type    | Count | Max(ms) | Min(ms) | Avg(ms) |   Pending  |
-----------------------------------------------------------------------
|     Only Registration       |   10  |  212.35  |  160.60  |  172.07  |     0  |
|     Deregistration          |   10  |   8.09  |   7.68  |   7.86  |    0  |
|     Only PDU Connection     |   10  |  10.74  |   6.69  |   7.66  |    0  |
|     Handover                |    0  |   0.00  |   0.00  |   0.00  |    0  |
|     AN Release               |    0  |   0.00  |   0.00  |   0.00  |    0  |
|     Service Request          |    0  |   0.00  |   0.00  |   0.00  |    0  |
-----------------------------------------------------------------------
|   Operation Type    | Count | Max(ms) | Min(ms) | Avg(ms) |   Pending Registration | Pending PDU Session |
-----------------------------------------------------------------------
| Registration and PDU Connection |    10   |  187.13   |  167.57   |  172.16   |     0    |     0   |
-----------------------------------------------------------------------
```

Figure 65. Statistics from BT for Visited Subscribers in case of Local Breakout.

The comparison of 5G procedures with respect to the latency is shown using the chart in Figure 66 for home subscribers and visited subscribers.

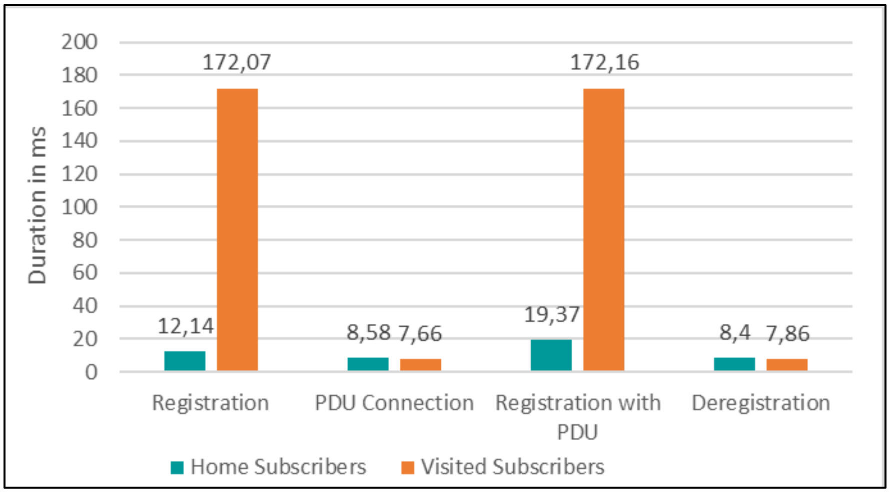
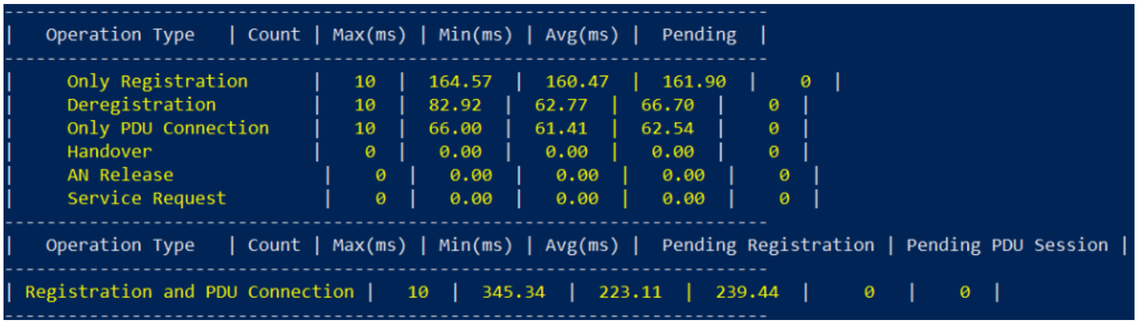


Figure 66. 5G Procedure latency for Home Subscribers Vs. Visited Subscribers (Local Breakout).

6.2.4. Access to network services

This section is focused on the local breakout and home routed scenario for the visited subscribers. The roaming subscribers can access the local network services through local breakout and home network services through home routed roaming. Figure 51 captures the local breakout scenario for the visited subscribers, where PDU connection stays local to the visited network. For the home routed scenario, the PDU session establishment is handled by both visited and home network. The visited network SMF sends request to the home network SMF through the SBCs and receive data path related metrics from the home SMF. The SMFs push rules to the data path in their own network. In the earlier sections the home subscriber and visited subscriber KPIs were compared for authentication between FOKUS and UPV node. Here the KPIs for home routed are evaluated by comparing to the local breakout results.

From UPV network the BT was used to execute the 5G procedures but now the data path is also routed to the home network. In Figure 67, the statistics for home routed scenario are shown. Here we can see the PDU creation and deregistration also have more latency as the registration procedure. As the PDU creation involves the home network, while deregistering the subscriber the session deletion also involves home network. If we compare PDU creation and deregistration of the home routed with regards to local breakout we can also evaluate the induced overhead by the former. For local breakout PDU creation takes on average 7.66 ms and deregistration takes 7.86 ms. For both procedure there is one message exchange between the visited and home network. Therefore, the overhead in this scenario for PDU connection is- 62.54 - (50.63 + 7.66) = 4.22 ms and deregistration is- 66.70 - (50.63 + 7.86) = 8.21 ms.



```
-------------------------------------------------------------------------------
|   Operation Type    | Count | Max(ms) | Min(ms) | Avg(ms) |  Pending  |
-------------------------------------------------------------------------------
|      Only Registration       |  10  |  164.57  |  160.47  |  161.90  |    0  |
|      Deregistration          |  10  |  82.92  |  62.77  |  66.70  |    0  |
|      Only PDU Connection     |  10  |  66.00  |  61.41  |  62.54  |    0  |
|      Handover                |   0  |   0.00  |   0.00  |   0.00  |    0  |
|      AN Release               |   0  |   0.00  |   0.00  |   0.00  |    0  |
|      Service Request          |   0  |   0.00  |   0.00  |   0.00  |    0  |
-------------------------------------------------------------------------------
|   Operation Type    | Count | Max(ms) | Min(ms) | Avg(ms) |  Pending Registration | Pending PDU Session |
-------------------------------------------------------------------------------
| Registration and PDU Connection |   10  |  345.34  |  223.11  |  239.44  |      0    |     0  |
-------------------------------------------------------------------------------
```

Figure 67. Statistics from BT for Visited Subscribers in case of Home-routed roaming.

the chart in Figure 54, clearly represents the comparison of 5G procedures with respect to the latency for local breakout and home routed scenario.

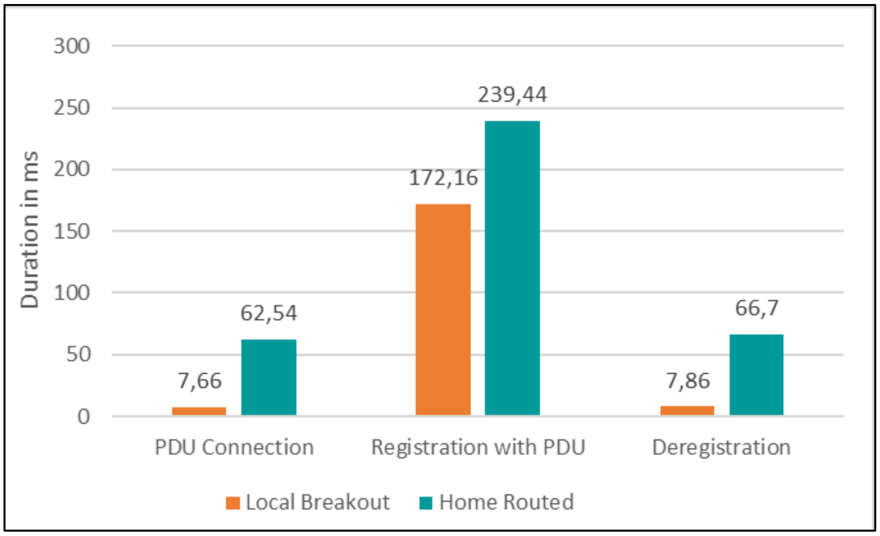
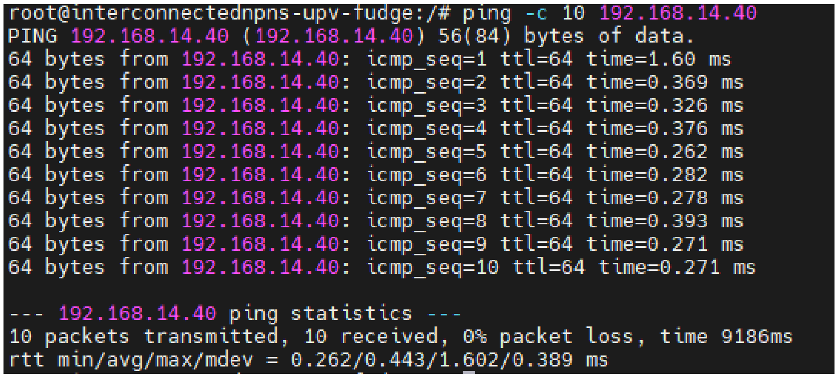


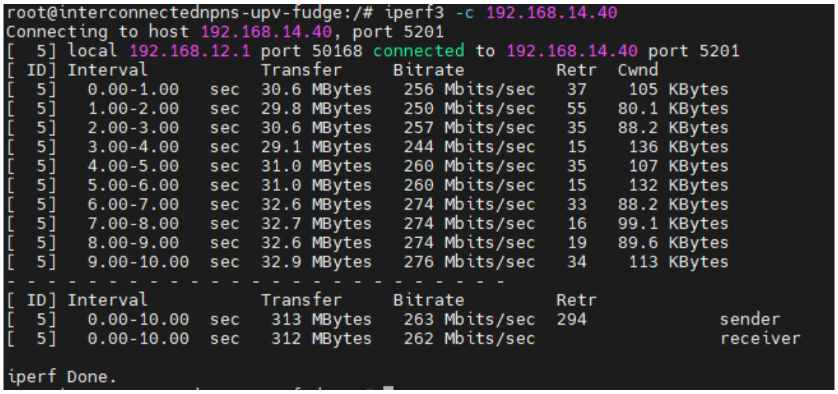
Figure 68. 5G Procedure latency for Visited Subscribers Local Breakout Vs. Home Routed.

To validate the capacity of the data path also ping and iperf tests were done for both local breakout and homme routed scenario. As for local breakout the data path is in the local network, so the outcome is same as home subscribers. In Figure 69, we can see the test results for the local breakout scenario (in the system with 2 vCPUs 4 GB RAM).



```
root@interconnectednpns-upv-fudge:/# ping -c 10 192.168.14.40
PING 192.168.14.40 (192.168.14.40) 56(84) bytes of data.
64 bytes from 192.168.14.40: icmp_seq=1 ttl=64 time=1.60 ms
64 bytes from 192.168.14.40: icmp_seq=2 ttl=64 time=0.369 ms
64 bytes from 192.168.14.40: icmp_seq=3 ttl=64 time=0.326 ms
64 bytes from 192.168.14.40: icmp_seq=4 ttl=64 time=0.376 ms
64 bytes from 192.168.14.40: icmp_seq=5 ttl=64 time=0.262 ms
64 bytes from 192.168.14.40: icmp_seq=6 ttl=64 time=0.282 ms
64 bytes from 192.168.14.40: icmp_seq=7 ttl=64 time=0.278 ms
64 bytes from 192.168.14.40: icmp_seq=8 ttl=64 time=0.393 ms
64 bytes from 192.168.14.40: icmp_seq=9 ttl=64 time=0.271 ms
64 bytes from 192.168.14.40: icmp_seq=10 ttl=64 time=0.271 ms

--- 192.168.14.40 ping statistics ---
10 packets transmitted, 10 received, 0% packet loss, time 9186ms
rtt min/avg/max/mdev = 0.262/0.443/1.602/0.389 ms
```

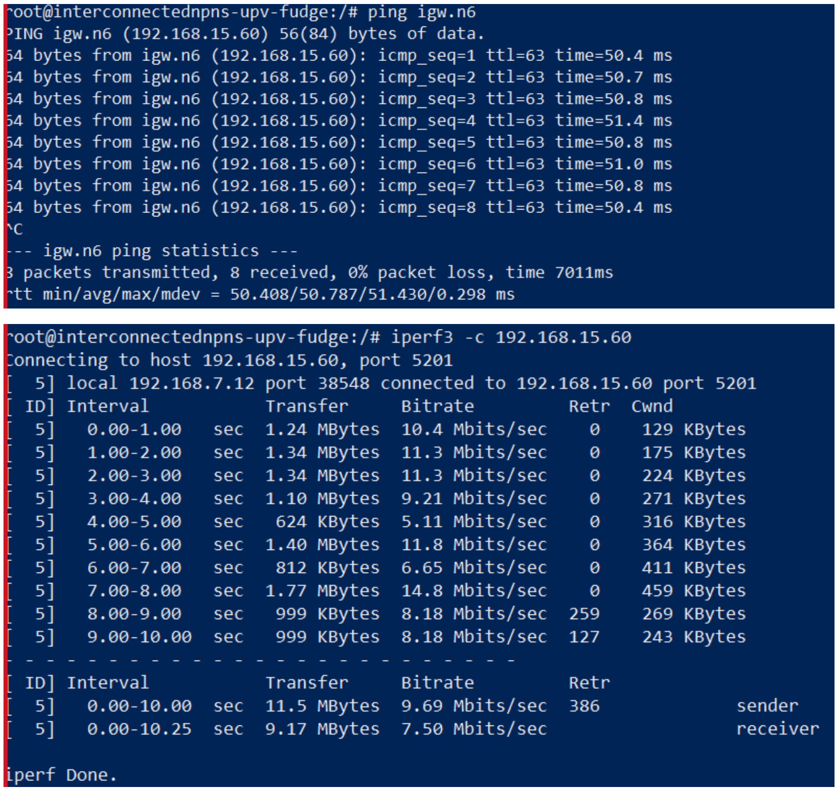


```
root@interconnectednpns-upv-fudge:/# iperf3 -c 192.168.14.40
Connecting to host 192.168.14.40, port 5201
[  5] local 192.168.12.1 port 50168 connected to 192.168.14.40 port 5201
[ ID] Interval           Transfer     Bitrate         Retr  Cwnd
[  5]   0.00-1.00   sec  30.6 MBytes   256 Mbits/sec   37    105 KBytes
[  5]   1.00-2.00   sec  29.8 MBytes   250 Mbits/sec   55   80.1 KBytes
[  5]   2.00-3.00   sec  30.6 MBytes   257 Mbits/sec   35   88.2 KBytes
[  5]   3.00-4.00   sec  29.1 MBytes   244 Mbits/sec   15    136 KBytes
[  5]   4.00-5.00   sec  31.0 MBytes   260 Mbits/sec   35    107 KBytes
[  5]   5.00-6.00   sec  31.0 MBytes   260 Mbits/sec   15    132 KBytes
[  5]   6.00-7.00   sec  32.6 MBytes   274 Mbits/sec   33   88.2 KBytes
[  5]   7.00-8.00   sec  32.7 MBytes   274 Mbits/sec   16   99.1 KBytes
[  5]   8.00-9.00   sec  32.6 MBytes   274 Mbits/sec   19   89.6 KBytes
[  5]   9.00-10.00  sec  32.9 MBytes   276 Mbits/sec   34    113 KBytes
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Retr
[  5]   0.00-10.00  sec   313 MBytes   263 Mbits/sec  294             sender
[  5]   0.00-10.00  sec   312 MBytes   262 Mbits/sec                  receiver

iperf Done.
```

Figure 69. Ping and iperf result for visited subscriber in local breakout.

In case of home routed the data traffic goes over the backhaul, so the interconnection of the NPN nodes has a significant impact on the data path capacity. In Figure 70, the ping and iperf test for home routed data path is shown. The ping results towards the IGW, shows the RTT is similar to the summation of RTT to local data network (local breakout) and the RTT between the edges of the two networks (50.63 ms). Considering the set configuration as local breakout the iperf test shows quite low result for the home routed. So, for home routed scenario the backhaul selection will be very important as it has huge impact on the network bandwidth.



```
oot@interconnectednpns-upv-fudge:/# ping igw.n6
PING igw.n6 (192.168.15.60) 56(84) bytes of data.
54 bytes from igw.n6 (192.168.15.60): icmp_seq=1 ttl=63 time=50.4 ms
54 bytes from igw.n6 (192.168.15.60): icmp_seq=2 ttl=63 time=50.7 ms
54 bytes from igw.n6 (192.168.15.60): icmp_seq=3 ttl=63 time=50.8 ms
54 bytes from igw.n6 (192.168.15.60): icmp_seq=4 ttl=63 time=51.4 ms
54 bytes from igw.n6 (192.168.15.60): icmp_seq=5 ttl=63 time=50.8 ms
54 bytes from igw.n6 (192.168.15.60): icmp_seq=6 ttl=63 time=51.0 ms
54 bytes from igw.n6 (192.168.15.60): icmp_seq=7 ttl=63 time=50.8 ms
54 bytes from igw.n6 (192.168.15.60): icmp_seq=8 ttl=63 time=50.4 ms
^C
--- igw.n6 ping statistics ---
3 packets transmitted, 8 received, 0% packet loss, time 7011ms
tt min/avg/max/mdev = 50.408/50.787/51.430/0.298 ms
```

```
oot@interconnectednpns-upv-fudge:/# iperf3 -c 192.168.15.60
Connecting to host 192.168.15.60, port 5201
[  5] local 192.168.7.12 port 38548 connected to 192.168.15.60 port 5201
[ ID] Interval           Transfer     Bitrate         Retr  Cwnd
[  5]   0.00-1.00   sec  1.24 MBytes  10.4 Mbits/sec    0    129 KBytes
[  5]   1.00-2.00   sec  1.34 MBytes  11.3 Mbits/sec    0    175 KBytes
[  5]   2.00-3.00   sec  1.34 MBytes  11.3 Mbits/sec    0    224 KBytes
[  5]   3.00-4.00   sec  1.10 MBytes  9.21 Mbits/sec    0    271 KBytes
[  5]   4.00-5.00   sec   624 KBytes  5.11 Mbits/sec    0    316 KBytes
[  5]   5.00-6.00   sec  1.40 MBytes  11.8 Mbits/sec    0    364 KBytes
[  5]   6.00-7.00   sec   812 KBytes  6.65 Mbits/sec    0    411 KBytes
[  5]   7.00-8.00   sec  1.77 MBytes  14.8 Mbits/sec    0    459 KBytes
[  5]   8.00-9.00   sec   999 KBytes  8.18 Mbits/sec  259    269 KBytes
[  5]   9.00-10.00  sec   999 KBytes  8.18 Mbits/sec  127    243 KBytes
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Retr
[  5]   0.00-10.00  sec  11.5 MBytes  9.69 Mbits/sec  386             sender
[  5]   0.00-10.25  sec  9.17 MBytes  7.50 Mbits/sec                  receiver

iperf Done.
```

Figure 70. Ping and iperf result for visited subscriber in home routed.

6.2.5. KPI validation summary

In the trials, several KPIs were collected in order to validate the distributed authentication framework, the overhead induced by SBC and the home routed roaming scenario for visited subscribers. The backhaul between the INPN nodes are over the internet (a "best-effort" network) and is not in the control, so for the validation of the KPIs dependant over the backhaul, the backhaul delay is considered. The service KPIs are described in Table 24.

KPI ID	Description
UC5-K0	Control KPI to determine the "best-effort"
UC5-K1	Time taken by the home network UE for completing the registration procedure with the core network as defined by 3GPP in the specifications
UC5-K2	Time taken by the home network UE for completing the PDU session establishment procedure with the given data network
UC5-K3	Time taken by the home network UE for completing the registration and PDU session establishment procedure with the given data network
UC5-K4	Time taken by the home network UE for completing the deregistration procedure with the core network as defined by 3GPP in the specifications
UC5-K5	RTT for data path to home network for home network UE
UC5-K6	Time taken by the Visited UE for completing the registration procedure with the core network as defined by 3GPP in the specifications
UC5-K7	Time taken by the Visited UE for completing the PDU session establishment procedure with the given local data network (local breakout)
UC5-K8	Time taken by the visited network UE for completing the registration and PDU session establishment procedure with the given local data network (local breakout)
UC5-K9	Time taken by the visited UE for completing the deregistration procedure with the core network as defined by 3GPP in the specifications
UC5-K10	RTT for data path to home network for visited network UE (local breakout)
UC5-K11	Time taken by the Visited UE for completing the PDU session establishment procedure with the given home data network (home routed)
UC5-K12	Time taken by the visited network UE for completing the registration and PDU session establishment procedure with the given home data network (home routed)
UC5-K13	Time taken by the visited UE for completing the deregistration procedure with the core network as defined by 3GPP in the specifications (home routed)
UC5-K14	RTT for data path to home network for visited network UE (home routed)

Table 24. Service KPIs for Interconnected NPNs.

The 5G network performance KPIs are described in the table below.

KPI ID	Description
UC5-K15	Data path capacity in the local network for home subscribers
UC5-K16	Effective data path capacity in the local network (local breakout) for visited subscribers
UC5-K17	Data path capacity over the best effort backhaul (home routed) for visited subscribers

Table 25. 5G network performance KPIs for Interconnected NPNs.

Table 26 shows the results of the KPIs measured during the final trials. The results showcase the latency for different scenarios, and the performance on the data path. The main learning from the experiments where the remote operations are highly dependent on the backhaul. Therefore, the takeaway from the experiments will be, local breakout scenario will be more suitable for visited subscribers if required services are available in the visited network. Selection of the backhaul is very important in case the visited subscribers need home routed data traffic to access home network services.

KPI ID	Measurement results (on Avg.)
UC5-K0	~50-55 ms
UC5-K1	~10-12 ms
UC5-K2	~7-8 ms
UC5-K3	~17-20 ms
UC5-K4	~7-9 ms
UC5-K5	~0.44 ms
UC5-K6	~168-200 ms
UC5-K7	~7-8 ms
UC5-K8	~175-205 ms
UC5-K9	~7-9 ms
UC5-K10	~0.44 ms
UC5-K11	~60-71 ms
UC5-K12	~230-300 ms
UC5-K13	~60-67 ms
UC5-K14	~50.78 ms
UC5-K15	~263 MB/s
UC5-K16	~263 MB/s
UC5-K17	~9 MB/s

Table 26. KPI measurement results for Interconnected NPNs.

6.2.6. Energy Consumption of 5GCs

6.2.6.1. Results for Energy Consumption of 5GCs

We want to measure the power dissipation of the 5GC while registering different number of UEs. The experimented number of UEs from the UERANSIM are 100, 200, and 300. The methodology of the experiment is conducted through as in the flow presented of the following diagram.

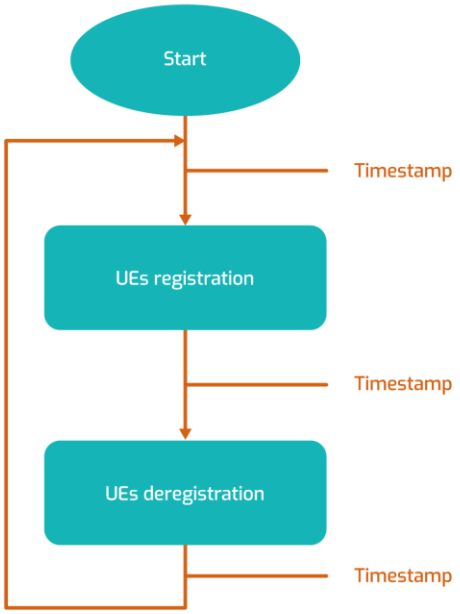


Figure 71. Flow chart of the experimental script execution

Below the power dissipation results are plotted from the 5GC in experiments with 100, 150, 200, and 300 UEs which perform actions of registration/deregistration as described in Figure 2. In each plot we highlight the interval of time correlated with registration/deregistration of UEs.

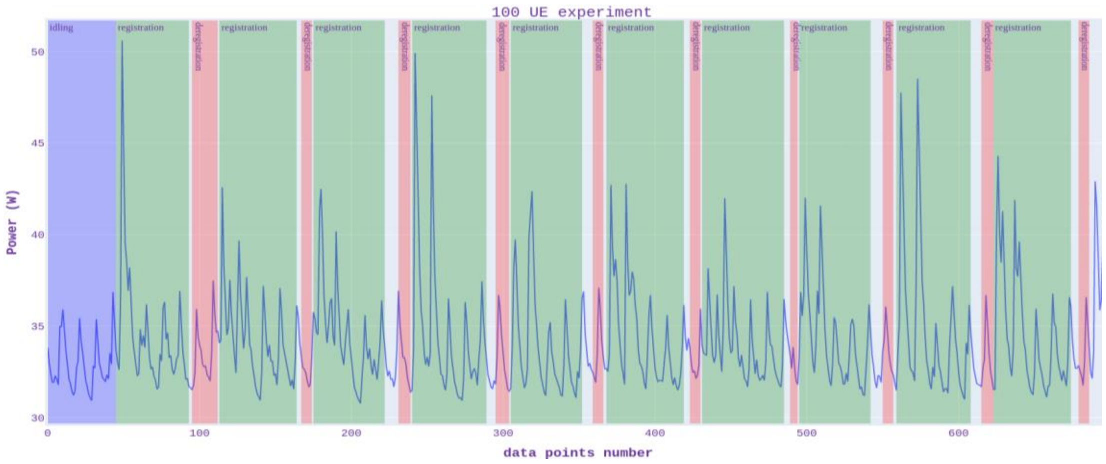


Figure 72. 5GC power profile for 100 UEs registration/deregistration experiment

In Figure 73 we plot the power profile of the 5GC registering/deregistering 150UEs.

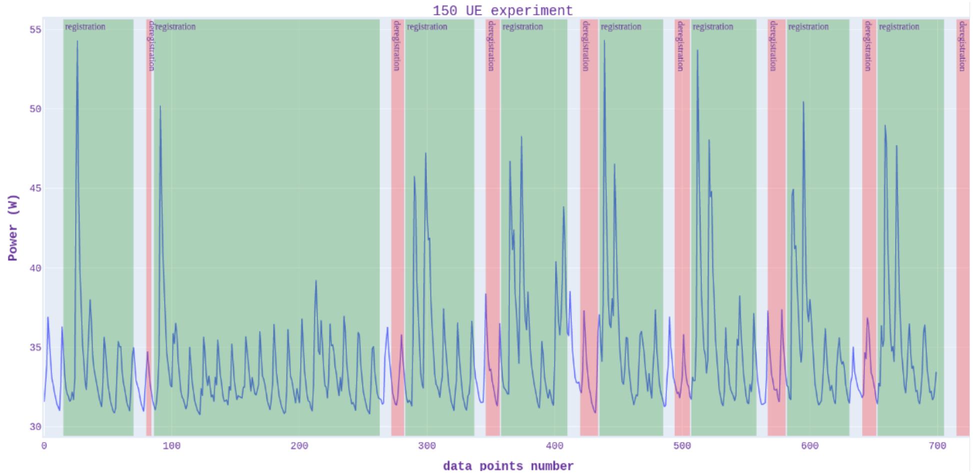


Figure 73. 5GC power profile for 150 UEs registration/deregistration experiment

In Figure 74 we plot the power profile of the 5GC registering/deregistering 200 UEs.

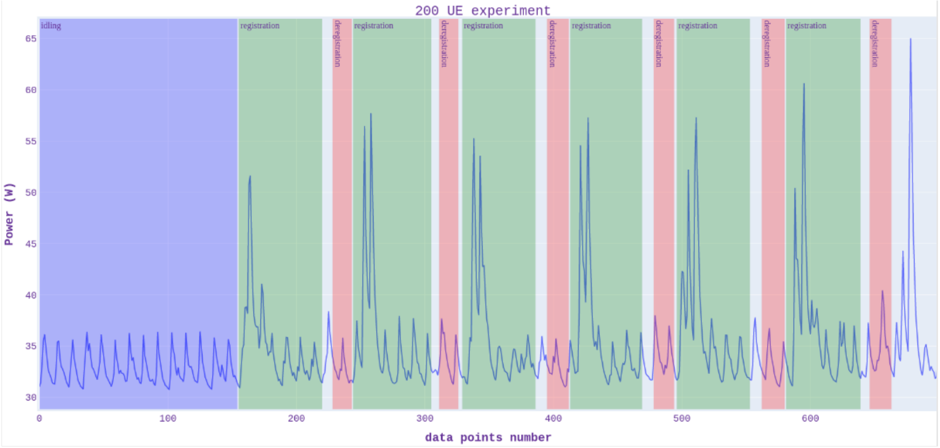


Figure 74. 5GC power profile for 200 UEs registration/deregistration experiment

In Figure 75 we plot the power profile of the 5GC registering/deregistering 300 UEs.

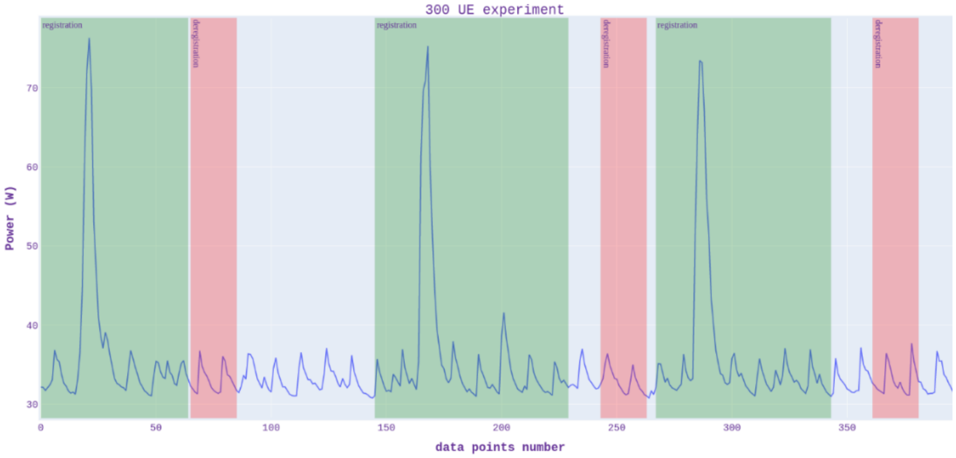


Figure 75. 5GC power profile for 200 UEs registration/deregistration experiment

The results show that increasing the number of UEs registering to the 5GC increases the overall energy consumption in the 5GC, where the maximum energy consumption is 51W for 100 UEs, 54W for 150 UEs, 65W for 200 UEs and 74W for 300 UEs. While we could not increase the number of UEs beyond 300 UEs due to testbed limitations (UERANSIM limitation) the behavior has been consistent within the tested population.

6.2.6.2. Results for Impact of Proxies on Energy Consumption

Under experimental testing, we were able to gather data for the traffic generated by the AMF function in the 5GCore architecture for the process of UE registration. For each UE registration, the Access and Mobility Function sends out two packages by the size of 50 and 252 bytes. The frequency of these packages s shown in the histogram below.

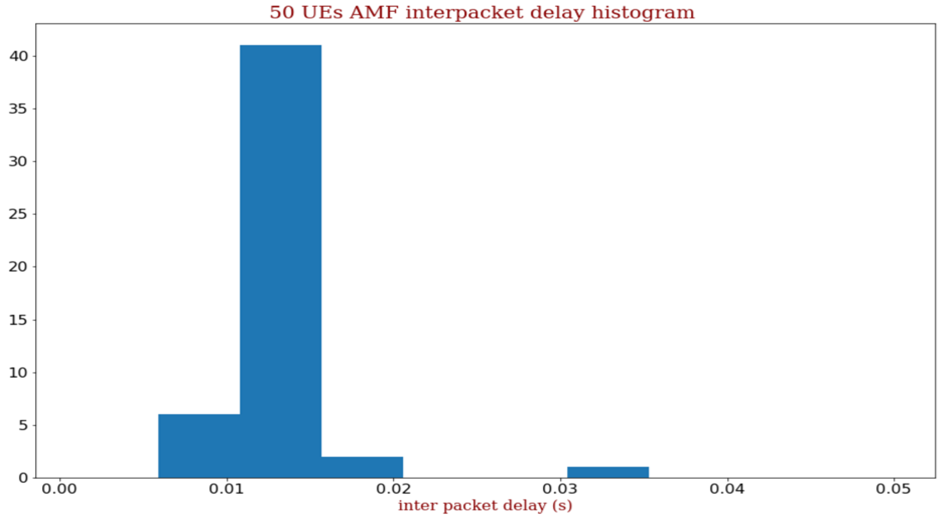


Figure 76. Interpacket delay of the AMF packets in experiments with 50 UE registration.

In our experiments we will reproduce this traffic distribution for generation HTTP/2 traffic, with same package size and frequency as the histogram above.

The experiment is designed to demonstrate any impact of the usage of physical NICs. Thus, the following two modes will be considered:

- Multi Node: All processes operate on dedicated physical compute hosts.
- Single Node: All processes operate on a single physical compute host via the kernel only.

The main library used for generating HTTP/2 traffic in nghttp2, which is an implementation of the Hypertext Transfer Protocol version 2 in C. The framing layer of HTTP/2 is implemented as a reusable C library. Also, there is opportunity to use C implemented version of a HTTP/2 client, server and proxy. The proxy and the server are also based on this library. The version of the library installed is nghttp2/1.48.0-DEV.

A physical Server A transmitting traffic, which uses HTTP/2 as an application layer protocol (HTTP/2 traffic), with certain data rates (reproduced from the histogram above) to Server B through the proxy service.

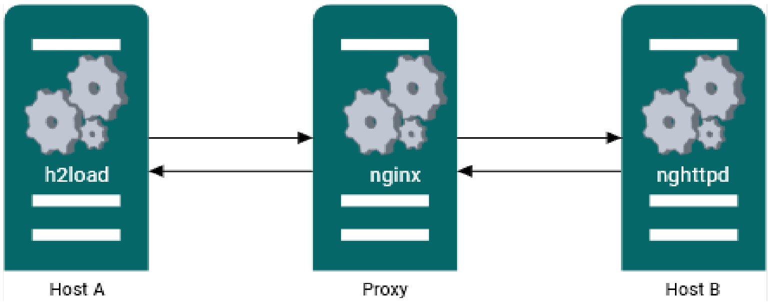


Figure 77. Multi-node Set-up

Process TX in this scenario represents a transmitter that sends traffic using HTTP/2 as an application layer protocol (HTTP/2 traffic) with certain data rates (same as above) to Process RX through Proxy service. It should be noted that all processes are on running in the same physical server and communicated via the localhost (kernel).

In this set of experiments, we measure the power dissipation of the system which consists in two machines running client-server and client-proxy-server scenario. Figures 10, and 11 show the power profiles of the setup with different number of requests sent by the client.

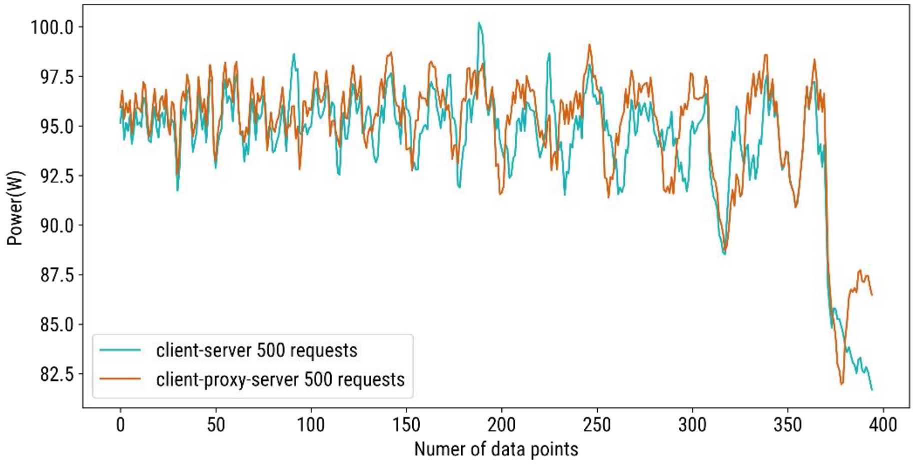


Figure 78. Power dissipation of client-server and client-proxy-server setup with 500 requests.

Figure 79. Power dissipation of client-server and client-proxy-server setup with 1000 requests.

In the following set of experiments, we measure the power dissipation of the system which consists in a single machine running client-server and client-proxy-server scenario. Figure 80 and Figure 81 showing the power profile of the setup with a different number of requests sent by the client.

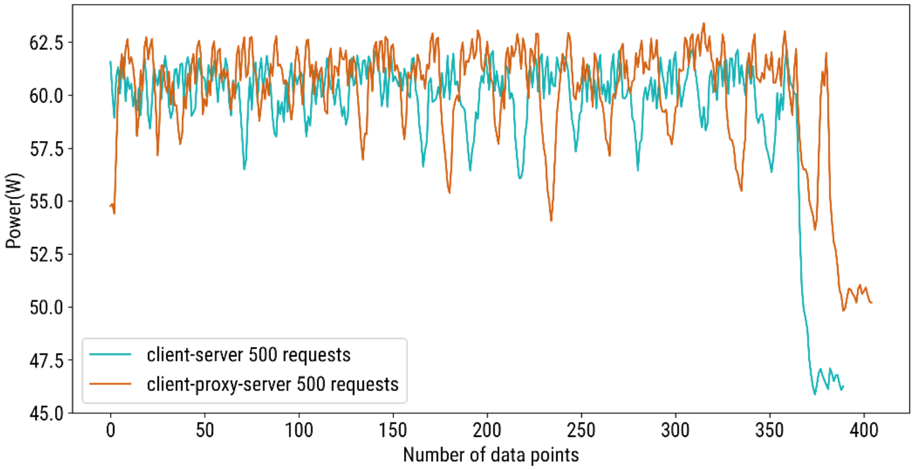


Figure 80. Power dissipation of client-server and client-proxy-server setup with 500 requests

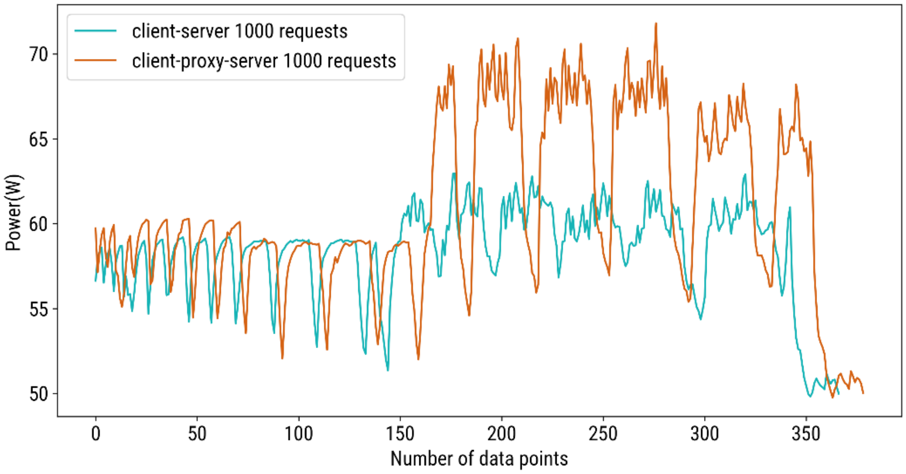


Figure 81. Power dissipation of client-server and client-proxy-server setup with 1000 requests

The results show that using a proxy Network Function (NF) increases the amount of energy consumed in the registration process whether the proxy is used on the same or different machine as NF. For the 500 threads, the energy consumption has slightly increased by around 2 W in the single machine scenario while for the 1000 threads, the increase in the single machine scenario, is approximately 8 W (16%) in comparison to the baseline case (no proxy case). The increase in the multi-machine scenario is around 2W above the maximum baseline value. It has been noticed that the increase is more significant when the proxy is running on the same machine. It is expected that this increase can build up and becomes more significant for one network process such as authentication if there is more than one proxy function is used to perform this process. The results show as well that increasing the number of threads (Load) leads to an increase in the energy consumed by the proxy function.

In the context of the current 5GC architecture, many NFs act as proxy NFs in certain network processes, one of these NFs is the AMF. AMF acts as a proxy NF for many of the network processes, such as UE authentication. In the UE authentication, the AMF contribution is limited to protocol translation (N2 <->HTTP) and some encryption protocol key calculations. The obtained results in this experiment show that removing such NFs, AMF in this case, could save the network a tangible amount of unnecessarily consumed energy.

6.3. Stakeholder feedback

This section includes a questionnaire filled by UPV, who acted as the main stakeholder of the interconnected NPNs use case.

6.3.1. 5G related questions

1. *Please rate your familiarity with 5G technologies:*

Not familiar	Basic knowledge	Fair	Familiar	Expert
				✓

2. *Can 4G technologies meet yout current service requirements?*

Yes, 4G LTE is enough	No, 5G (public/private) connectivity is needed	No, a 5G private network is needed
		✓

3. *Would you use the current 5G private network components in your workflow from now on?*

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
	✓			

4. *If you had to choose only one aspect, what is the most important benefit that a private 5G could bring to your industry.*

The progress on 5G Private Networks and the provisioning of eSIMs could change how we think about interconnected academic networks (or other federated ones), like the existing EDUROAM. At UPV we see a future where we can provide 5G SIM (or electronic SIMs) to our students, teaching staff or researchers and ensure high quality connectivity inside the campus and whenever our staff can roam into other institutions. The current solution is a basic but functional one provided by Wi-Fi over unlicensed spectrum.

5. *What is, in your opinion, the most challenging issue to overcome by 5G Private Networks?*

5G phones are not widespread yet to the point where it is ubiquitous. It is still a small but growing market. Also, the technology behind 5G S-NPNs and eSIMS needs to mature more to provide the Interconnected NPN service at the same level as existing EDUROAM initiatives.

6.3.2. About the tests and trials

6. *How complicated did you find the 5G system to use, compared to other existing solutions?*

Very easy	Easy	Normal	Difficult	Very difficult
				✓

7. *Measure the level of current technical competency of your team to operate the 5G NPN. Would you be able to operate it on your own?*

Very low	Low	Normal	High	Very high
				✓

8. *What is the level of importance of these KPIs when delivering your services?*

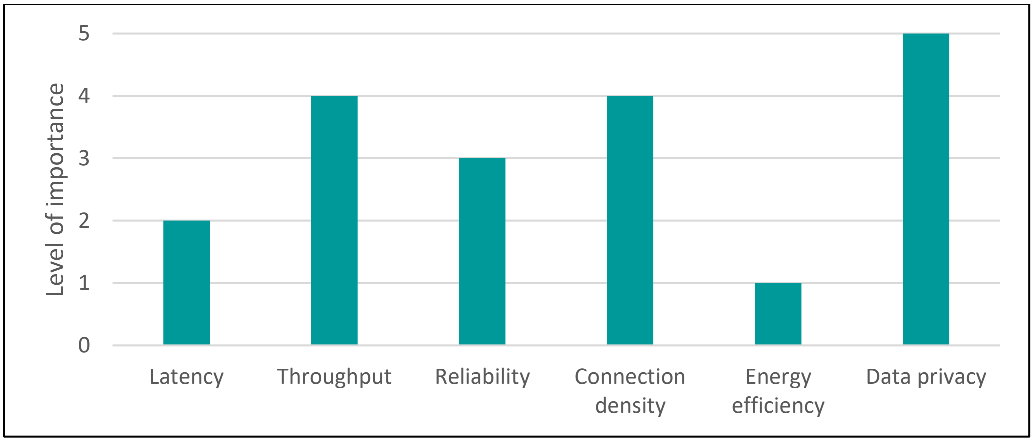


Figure 82. Level of importance of KPIs in the Interconnected NPNs use case.

9. *Were these KPIs met?*

Latency	Throughput	Reliability	Conn. Density	Energy eff.	Data privacy
Yes	**Yes**	**Yes**	Not tested	Not tested	**Yes**

10. *Have been the initial expectations met about FUDGE-5G?*

The Interconnected NPN trial showcased the ability for remotely connected 5GCs to easily cooperate and form a distributed private network that validate users belonging to different private PLMNs. The local breakout capabilities, where the visiting phones were just authenticated once then the data is provided locally, emulates how EDUROAM (or traditional public operator roaming) works currently.

6.3.3. Suggestions for future tests and way forward

The work done in FUDGE-5G is a first step to showcase the capabilities of interconnected private networks. In the future, we would like to see more advanced functionalities being tested, like the testing of private networks using eSIMs; or the automatic migration of services upon authentication. For example, if an UPV student travels to the Berlin node; UPV 5GC should also provide instances of every AF that the student can access locally in Berlin (such as paper access, multimedia recorded lessons, intranet access, etc.). Other topic to explore would be the inclusion of similar paradigm in public operator and private network cooperation like the work done in this project.

7. Conclusion

The present document, D4.3, described in detail the final trials performed in the FUDGE-5G project. The trials were performed in the context of **five vertical use cases**, i.e., concurrent media delivery, PPDR, 5G virtual office, Industry 4.0, and interconnected NPNs. For each vertical, we first described the end-to-end architecture used, as well as the setup and components integrated in the field or laboratory where the tests took place. Once the setup was clear, we provided insights about the trial execution and the results obtained.

Along this document, we also gathered feedback from the vertical stakeholders that did benefit from the 5G services deployed at their premises. A 5G and NPN related analysis, as well as several trial related questions were used as an input to understand their needs and observe if our solutions delivered as expected.

7.1. Concurrent media delivery

The first vertical trials on concurrent media delivery were divided into three tests. The first one was related to remote production. The trial took place in the NM-Week event in Skien (Norway), in June 2022. It was successfully executed, with several components of the project (Athonet, Cumucore, Huawei) as part of the main setup. While latency and reliability requirements were covered, some improvements in the UL bandwidth are still needed. In general, NRK as main stakeholder, provided good feedback and confirmed that their initial expectations were covered.

The second part of the use case is the media showroom. This scenario used NBR on the user plane to deliver a HTTP-based VoD stream to a fixed set of UEs. It was executed in the laboratory as an experiment, observing that NBR had a 71-79% saving compared to convention IP for delivering the video.

Regarding video delivery, it can be concluded that a video stream can be performed through a 5G NSA commercial network, up to 50 Mbps. In the tests, no visual assessment of the video quality could be performed, thus further investigation is needed to conclude is this bitrate value does not result in visual artifacts. The measured packet interarrival values do not change significantly across the 5G network for the measured bitrates, thus reducing the chances of decoding artifacts due to late frames. Due to time constraints, no more analysis of the packet captures, or the statistics could be performed, thus, in the future, further investigation would be required to fully characterize the encoder and network behavior. This would help to understand the use of 5G networks for video transmissions.

7.2. PPDR

The vertical final trials on PPDR were finally divided into two main activities or scenarios, i.e., the use of the so-called NoW, and public warning systems. The first scenario was tested and validated in two different trials. The first trial took place in December 2021, in Rygge (Norway), in collaboration with NDMA and NRK. The objective of the trial was to test the stand alone 5G NoW to support the emergency responders in the field during the search and rescue operations. It was delivered successfully, and the tests went as planned. The second trial consisted of the integration of a 5G PTT application in the Athonet 5GC and its validation. The PTT application was successfully tested at the UTLEND conference held in Lom (Norway) in September 2022.

The second scenario was the delivery of public warning messages to the public. The pilot consisted of the Cumucore 5GC deployed in a micro-PC box, on which also the one2many CBCF functionality was deployed. The purpose of the trial was to showcase the potential of a mass notification to the stakeholders NDMA. A text message was broadcasted within seconds to all available phones, which serves us to validate that, due to the nature of broadcast, this allows us to scale to a massive number of phones.

NDMA, through the questionnaire provided, explained that their initial expectations were also covered. Latency and throughput aspects, as well as data privacy requirements, were fulfilled. However, there is still room for improvement in energy efficiency.

7.3. 5G virtual office

The virtual office trials consisted of two different test cases, i.e., ward remote monitoring and intra-hospital patient transport monitoring. Note that in this particular use case, both trials shared the same setup and infrastructure. The node hosted a 5G NPN including radio equipment from Nokia and a 5GC from FOKUS. The telco server hosted both the 5GC and OneSource's Mobitrust application. The server was connected to a Goodmill router with uplink to the 5G commercial network of Telenor, which reached both the Internet and management network to Telenor's Fornebu data centre.

The first trial used the described NPN deployment to enable remote monitoring of ward patients using a set of bio sensors. In the hospital of Oslo, Onesource described to the audience the process, showcasing a real time sensor feed with vital signs of the patient as well as the wardroom. Next to the patient, there were also a medical staff member monitoring in person with a mobile device, connected to the virtual application through the 5G NPN. For the second trial, the patient located at the wardroom was moved into a different area of the Hospital. During the entire process, the vital signs of the patient were monitored without interruption in the control room.

Both application and network KPIs have been validated in the context of the two trials, obtaining measurement results for latency, signal quality, or throughput, among others. Through the questionnaire, the stakeholder provided positive feedback after the execution of such trials.

7.4. Industry 4.0

The vertical stakeholder of the Industry 4.0 was ABB. The two main innovation that we wanted to evaluate in this project for this use case were 5GLAN and 5G-TSN. A standalone NPN formed by a 5GC from Cumucore, 5G radio from Nokia and 5G devices from Fivecomm was deployed in ABB lab. While several applications have been tested over the 5G NPN with

5GLAN in their premises, the 5G-TSN functionality has been additionally validated in a standalone deployment in Cumucore premises in Espoo (Finland).

Regarding the deployment in ABB, a series of test cases have been validated from November 2022 to March 2023. We conducted together with the stakeholder ABB 5G KPI measurements related to latency, throughput, and signal quality. Results showed that, although some requirements were met, the test cases and applications under study cannot be fully executed nowadays with state-of-the-art 5G Release 15 networks.

In Cumucore lab, a 5G device developed by Fivecomm was integrated in their 5G-TSN network. To perform the measurements, the 5G device implemented the VXLAN protocol. In this setup, a PTP GM signal was sent over 5GC and radio. The 5G modem retransmitted the information to the TSN Kit, which then compared with GM time and calculated the offset. The results showed an average offset of 16.5 ms. Although this result is still not ideal and not yet close to the wired results obtained (~ns), it served as a first approach to the implementation and demonstration of such technology.

7.5. Interconnected NPNs

The interconnected NPN use case focused on adding new features in the 5GC network to support roaming within small-sized private networks. The objective was to deploy the NPN nodes in the premises of the stakeholders Fraunhofer FOKUS in Berlin (Germany), UPV in Valencia (Spain) and the hospital node in Oslo (Norway).

During phase-1, the validation of the use case was performed from September 2021 to September 2022 between UPV and FOKUS nodes. In a second phase, the three scenarios were covered in a trial performed in February 2023. In the final trials, the motive was to route the messages between the private networks through the SBCs to authenticate the roaming users and to establish data bearers for the roaming subscribers with the home network.

The energy consumption of 5GCs has been also evaluated by InterDigital and AVO academy. The aim was to compare the power consumption with and without the presence of a proxy function for different loads in the context of the 5GC. The results show that increasing the number of UEs registering to the 5GC increases the overall energy consumption, where the maximum value is 51W for 100 UEs, 54W for 150 UEs, 65W for 200 UEs and 74W for 300 UEs. The results also showed that using a proxy NF increases the amount of energy consumed in the registration process whether the proxy is used on the same or different machine as NF.

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Annex A: remote production additional findings

Some of the tests carried out by NRK did not use FUDGE-5G components. Nevertheless, they provide useful insights in the use of 5G NPNs for remote production. For this reason, Annex A contains NRK information regarding their experiences in covering an outdoor event using 5G cameras; and their personnel feedback of using 5G for real coverage of events.

National Championships in Terrain Running (Bergen), October 2022

The trials performed in Bergen were performed to investigate: (i) the performance of the 2.3GHz band and whether it fits multiple-camera production, and (ii) how well an upgraded public network would work for media content production. The covered event was the National Championships in Terrain Running and was held on Sunday 09 October 2022. This time the race length (round trip) is 2000 meters, the same length as the lake. Older men will run 5 laps (10 km) and older women 3 laps (6 km).

The planning involved the participation of different stakeholders: NRK and Trippel-M. These stakeholders from FUDGE-5G, are working towards the aim of investigating which use cases 5G can provide increased value in various industries.

The tests carried out so far have been part of the media use case and have been performed using 5 wireless cameras connected to the production chain through Telia's public 5G network. The network was enhanced with additional base stations which provided coverage on the 2.3 GHz band (N40).

NRK is in dialogue with Nkom and the Norwegian Armed Forces about partially or completely disposing of the 2.3 GHz band, also known as the N40 band. These frequencies have not yet been assigned, and this test was the first where this band was tested, with temporary permission from Nkom.

Figure 83. Race route.

Figure 84 depicts the conceptual diagram for the first test of FUDGE-5G media use case for comparison.

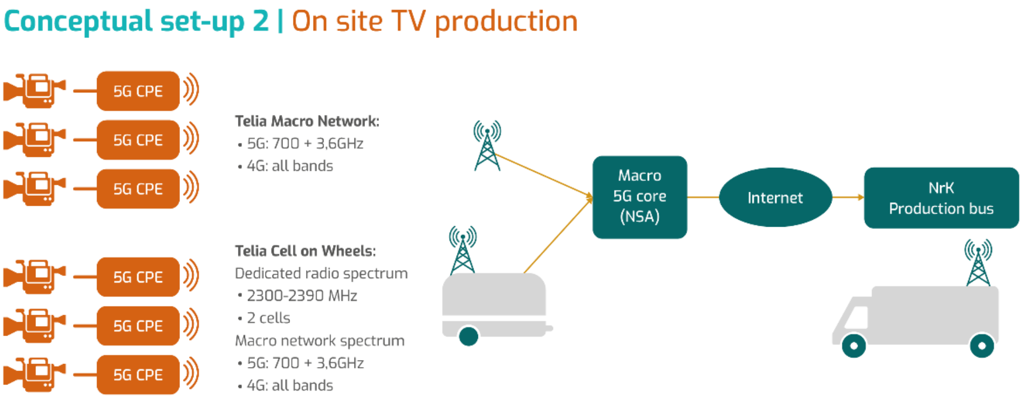

Figure 84. Bergen's testbed conceptual diagram: on site TV production.

This test was done in a relatively small area, which was ideal for testing one mobile cell with many cameras attached to it.

In the image below, NRK had cameras 5, 6, 7, 8 and 9 connected over 5G. Camera 3 was partly connected by 5G since it was both wired and wireless, but it had some performance issues on the encoder. Thus, this camera was not used with 5G for production.

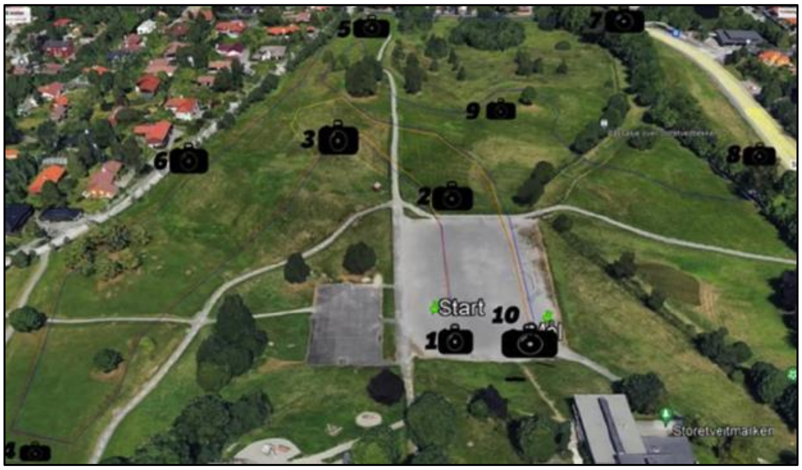

Figure 85. Camera placement overview.

Coverage

One week before the broadcast, the cell was set up and several tests were carried out to verify the coverage in the area.

Figure 86. Cell with 2.3 GHz and 3.6 GHz antennas placed.

An additional concern is the time of setting up the cell since this type of deployment took about 2 days to set up. It should be noted that if this solution is intended be put into production, more efficient solutions should be analyzed and investigated.

NRK understood in previous trials the importance of coverage planning, and this time was no exception. Telia took care of the coverage planning. Topography became a challenge; the small hills and trees affected the coverage. 2.3 GHz had better abilities to get over hilltops and through vegetation than 3.6Ghz.

Figure 87 shows the difference in coverage for low and high frequencies respectively (little coverage for 3.6GHz behind the hill present at the top of the map).

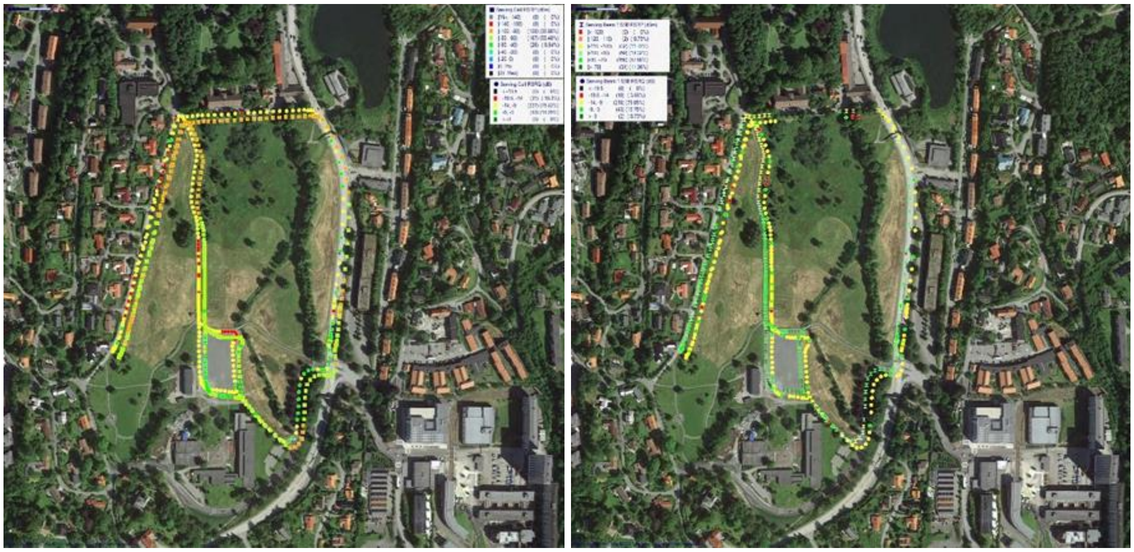

Figure 87. 2.3GHz (left) and 3.6 GHz (right) coverage map. RSRP and RSRQ values.

Double antennas were set up, each one providing a sector. RSRP, RSRQ and DL-UL values for each camera/UE are shown in this figure.

Regarding nomenclature that appears in the caption of the image, “K5 until K6” means movable camera 6 on the way to fixed camera 5 position. Wireless cameras are all on 5G, but only camera 5, 6, 7, 8, 9 are wireless-only and then used for the tests. The rest of the cameras are connected using fiber since they are closer to the OB-van.

It is important to point out that the cameras placed at the transition point between the sectors had lower performance. It was experienced that when the coverage from the NRK cell became too weak, the UEs handover to other cells. This turned out to be a problem, as the capacity on the other cells was not sufficient, thus not getting good enough performance to achieve flawless live video.

This switching meant that the modems had to use 4G for about one second before completing the handover to the other 5G cell. External users accessed the 4G public network while this happened, so unexpected traffic is introduced in this scenario.

Kamera pos.	NR36_RSRP	NR36_RSRQ	DL_Mbit	UL_Mbit
K3	-77	-11	1140	156
K5	-97	-13	1111	112
K5 til K6	-86	-12	1241	150
K6	-90	-11	1269	134
K5 til K7	-106	-13	1216	76
K7	-102	-12	802	64
K7 til K8	-87	-10	1464	114
K8	-82	-10	1546	161

Figure 88. Camera's location and KPIs measured.

When several handovers to other cells were experienced, especially in the area farthest from NRK mast, Telia helped to temporarily turn down the power on nearby cells to avoid the handovers.

It should be noted that throughput tests were done using the website Speedtest.net. The difference between how live video is transferred and Speedtest.net is that video is transmitted using a single session, while Speedtest.net transfers data over several simultaneous sessions. This means that the results from speed tests might not represent the network performance for video applications. The video transmission system (Xlink) is also UDP based, while Speedtest.net uses TCP.

Removable antennas

As stated before, it was concluded that there are great advantages to having a line of sight from the receivers to the cell. This greatly improved performance and ensured noticeably less packet loss and signal interference. To achieve this, the antennas were movable and did not have to stand right next to the cameras.

In this setup, 5G receivers (CPEs) were used and could be moved some distance away from the camera. On camera 7 (which was the furthest away) this was the solution to get stable coverage. This receiver had a built-in antenna and support for POE. NRK could therefore run a single network cable to this, about 60 meters away from the camera.

Remote management of the CPE

In contrast to previous tests, this time NRK had the opportunity to remotely control the CPEs from the OB, and this turned out to be a very big advantage. It was possible to speed test, check the coverage and restart them, which made the testing much easier and clearer.

Three different camera types were used in these tests:

- Sony HDC-2500 camera chain
- Sony HDC-P50
- Grass Valley LDX 150

For the tests, all cameras were Sony HDC-2500 except the movable camera K6 (HDC-P50) and the IP controlled camera: Grass Valley LDX-150.

The Sony HDC-2500 camera is a traditional broadcast camera that relies on CCU. The CCU is the endpoint for both network (RCP control and tally), communication and video (send and return). Dedicated racks had to be built to contain interfaces for all the above.

The racks contained a VideoXLink for broadcast video and return video. This device also creates a layer 2 trunk network that allowed the CCU and RCP to communicate. Furthermore, there was a receiver (CPE), which was connected to an external antenna. For powering these racks, a generator was used to create electricity. Here, it is desirable to find a solution with mobile batteries in the long term. From this set-up, one camera fiber went to the camera, and the operator had all the functions needed: monitoring of video returns, tally and communication.

Figure 89. Camera operator on scaffolding and the camera rack on the floor (camera 5).

Figure 90 defines the diagram of the camera rack.

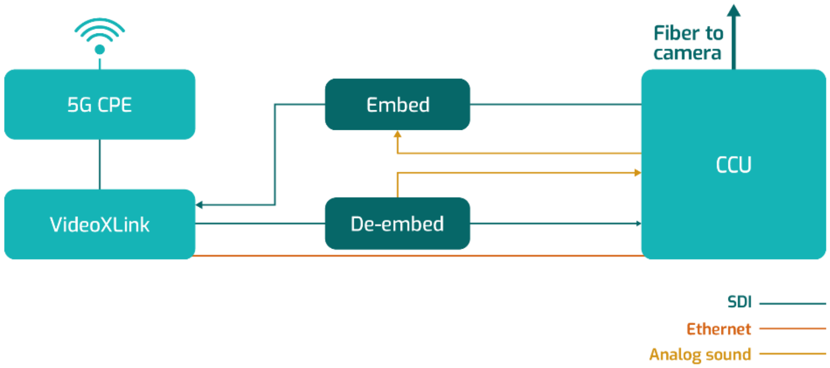

Figure 90. Diagram of setup in "field CCU kit".

In addition, Figure 91 shows a Sony HDC-P50 camera, designed for use on remote contribution scenarios and a steady cam. This camera is controlled from the RCP over the network. The camera operator was placed in the OB and had screens and a communication panel. Also, the driver of the car had a radio communication to hear the director and camera operator.

Figure 91. Sony HDC-P50.

As with the HDC-2500 setup, NRK used VideoXLink's layer 2 data trunk for the transmission of RCP control data. The control signals to the remote camera head were transported over the same link. This worked well over 5G and solved a problem that has previously been struggled with, as traditional video links previously tested do not have dedicated data trunks.

In contrast to the HDC-2500 rigs, NRK used VideoXLink X2 with a specially made battery adapter on this camera. This meant that it could be used as a normal camera battery with

D-TAP out. The camera and remote-controlled head received power from a car battery that was located at the back of the it.

Another one of the cameras used was the Grass Valley LDX150. The big advantage of this camera is that it was not necessary to use a CCU. It directly has SDI in and out. Thus, the communication for audio and control is embedded in the SDI stream, being possible to directly connect an RCP to it.

Field test

It was a big advantage that the "CCU field kits" (the camera racks) were built and tested in advance. This saved a lot of time compared with previous production experiences. The racks themselves are quite large and heavy but building these in a simpler and lighter way will probably have great advantages. Pre-configuration of VideoXLinker also saved a lot of time.

Figure 92. Car with a 5G phone on a mast.

Problems with receivers and 2.3 GHz

The initial plan was to lock the CPEs to specific bands, 3 of them to 2.3 GHz and 3 to 3.6 GHz (It later turned out that the CPE was dependent on 700 MHz on 4G which Telia turned off as it was difficult to isolate). It was found that The CPEs only connected to the 3.6GHz band, due to a misunderstanding with the chip manufacturer, so the devices didn't support 2.3 GHz band.

As an alternative, Telia informed that a small number of smartphones on the market today support this band, and after some research, three compatible phones were found. NRK tested if USB tethering between the smartphone and the VideoXLink was possible, which it was. This way, the encoder was provided with 5G, and the phone was provided with power. The behavior of this connection was not stable, and the USB cable occasionally fell out of the phone, so mobile phones are not an ideal field modem.

Furthermore, Telia also made 2.3 GHz the priority band in the area, as the mobiles could not control the prioritization of bands. This fact had negative aspects: it meant that many other users (UEs which were not part of the test) were using the 2.3GHz band, so the frequency band was not exclusively available for the tests as it was initially envisioned. Figure 24 shows the first tests with a phone on a mast, and VideoXLink in a car, connected via USB-C.

It was finally decided to run 2 cameras with a mobile phone and 1 test stream with 2.3 GHz connectivity, and 3 cameras at 3.6 GHz. Particularly, K3, K6 and K9 cameras were using 2.3GHz, hence they had to run on mobile phones since N40 NSA was not supported on the professional CPEs. (When 4G 700 MHz was turned off). K5, K7 and K8 cameras were using 3,6G Hz on professional CPEs. This was done to distribute the load and test the capacity of the network.

Through the tests it was concluded that there were quite large variations in ping and RTT, probably because the 5GC was located far away from the base stations and UEs.

Camera number	Band	Placement	Comment
3	2,3 GHz	Tripod camera, clear view to mobile cell	Due to some performance challenges this streamed only as a test (not on air)
5	3,6 GHz	Tripod camera, slightly behind a hump, antenna moved to have a clear view of the mobile cell	Worked fine on the air
6	2,3 GHz	In the car	Good performance, but some "tearing" on the video-image when changing sectors in the north-west corner of the production area
7	3,6 GHz	Tripod camera, slightly behind a hump and some trees, antenna moved to have a clear view of the mobile cell	Worked fine on the air, we saw somewhat higher packet loss when it was far away from cell towers
8	3,6 GHz	Tripod camera, clear view to mobile cell	Worked fine on the air
9	2,3 GHz	Crane, clear view to mobile cell	Worked fine on the air

Table 27. Description of used cameras.

The phones managed to get up to 40 Mbps uplink without problems, but above this, it was observed that they drop to a performance level that was not good enough and the video started to block/stutter, probably due to some lack of resources on the phone.

Remote control of a mobile phone

It was possible to install TeamViewer Host on the phones and set them up in such a way that the remote user could log in without pressing anything on the phone. This way, the phone could be remotely controlled and monitored in combination with an application that gave coverage and connected cell information.

Problems with communication

Several camera operators reported problems with communication to the camera. The problem was initially thought to be solely the 5G network, but it turned out to be a more complex issue, which was a combination of packet loss in the 5G network and a synchronization problem between the CCU and VideoXLink in the rack. As soon as we disconnected the ref cable, the problem became far less.

NRK personnel additional feedback

Some contributions from users were gathered from test case 1, whose views have been appropriately reflected in the report.

- Producer Øivind Nyborg:

"I noticed that the cameras over 5G had a higher delay than the other cameras, but low enough that it did not significantly affect my workflow. It felt stable and worked well. It would be desirable to have a higher capacity to be able to have half the latency".

- Photographer Carlos Belseth:

"Felt very nice to me. Can't remember sitting with any feeling that the delay compared to the rest of the production was a hindrance or something I thought about during production. Is of course quite early technology considering that in principle we had a patchland/spriter with racks and a lot of boxes to get tally/control/returns etc. When/if you get to make a little more less specialized solutions, something in terms of size between a sprinter and a Liveu backpack, then you can become even more mobile and maybe open up even more areas of use, but racks are much more mobile than an OB bus already, so very positive about where this can end. Very good with tally, return, sound and controll vs. e.g., LiveU backpack/other 4G solutions with their own limitations"

- Camera controller Eirin Frøen:

"The delay was acceptable for my work here, but could cause major problems with, for example, greater variations in NLOS/LOS zones. In the event of an error in the solution, we had to involve those who worked with the network to check what was wrong."

- Photographer Fredrik Løvgren Bryn:

"The delay was not a problem in the area in relation to the work tasks that were performed, […]. Communication between the producer and the camera operators worked as expected."

NRK additional feedback

In tackling the pre-production challenges, some lessons and learning points have been extracted. Below there is an overview of the biggest challenges encountered:

1. Coverage planning and placement of the 5G network's main antenna was the hardest challenge. Initially, the approach was the idea that this should stand next to the OB bus,

but costs could have been reduced by placing it elsewhere and also it could have been an opportunity for a point-to-point link for data transmission to receivers in OB.

2. The Defense's core is placed in a trailer, but it would also have been an advantage if this core was more rack-based and could be placed on, for example, a rooftop. Unfortunately, the coverage inspection was cancelled, and the data basis with visualization of the coverage in the city center was received too late to redo the rigging plan.
3. It would also have been interesting to try out setups in which several 5G antennas were used, but more equipment was not available at the time.
4. Due to the 2 selected locations with 2 cameras at each location, it was chosen to co-locate encoders/CCUs in one combined rack for each camera pair. Unfortunately, the setups are dependent on CCUs, which is something to be avoided. In these tests, a development from the camera manufacturers eliminating the need for a CCU would be helpful. It was concluded that the racks should be as small as possible, preferably in a case with only power input and a network with POE to CPE. Then, it could be more flexible in the field, and easily placed near the camera with the best coverage. In urban areas, the CPEs often have to be lifted above the ground. In these tests, for example, a simple telescopic pole could have been used instead of lamp posts and a lift.
5. To exploit the capacity in the 5G network, it will also be advantageous to have some distance between each CPE. This will ensure that the antenna's "sector" architecture is utilized in the best possible way (Spatial multiplexing: if the angle difference is large enough towards the 5G antenna, then each CPE can get its own beam and reuse the entire spectrum several times, so they do not have to share the capacity). With a massive MIMO 64x64 antenna, it was possible to have 16 beams/layers, i.e., 16 cameras/CPEs that utilize almost the entire spectrum at the same time, if they are well spaced between them. This technology obviously raises costs, but it is important to consider that all investments in RF technology will serve the entire 5G ecosystem, i.e., all devices/cameras, rather than one-to-one links as in today's radio systems.
6. Better access to a tool for measuring 5G capacity would be helpful. Defense has also had challenges with this in the past. Aviwest provided slightly better graphs than XLink in the area, because it could be clearly seen that when the RTT increased, high packet loss was observed. On the other hand, XLink's statistics solution was good for measuring the data capacity over time.
7. NRK aerial photography can probably contribute to a more effective measurement of coverage conditions. A drone can, for example, lift an XLink that simulates video traffic (with CPE). It would save considerable time in the lift.

In addition, the general conclusions extracted from the tests conducted on 14 June and the setup developed are presented:

1. This test session was a good and full-fledged test in the field. It could be clearly seen how much is gained from implementing full-scale system and the collaboration between technology, editorial and production teams.

2. NRK is pleased to have anticipated and eliminated most of the challenges with the user experience as the main objective so that production could be carried out.
3. When the coverage challenges were resolved, the 5G network delivered the expected capacity and we never had to use backup solutions that were in place.
4. Once improved some of the technical solutions regarding the IP connections, the 5G network will help to increase flexibility in production, and in the long run it could make rigging time more efficient.
5. The greatest potential for improvement concerns the infrastructure of the TV equipment before 5G is ready for production.

The key outcomes from these tests have been summarized in the following table.

Objectives	Lessons learned
To standardize the technology into the external workflows and integrate towards the production units of NRK (OB24)	It is relatively difficult to get all functions over IP-based workflow in the field. The racks are quite time-consuming to build for each production, and it will be cost-effective to standardize these for both remote production and 5G workflows. If the camera manufacturers do not come up with a "CCUless" workflow, the operations team is completely dependent on building setups outside the cameras.
Obtain information about where key pain points are for users (what do users complain about the most)	From the tests performed, it was encountered that latency is the most noticeable problem of doing productions over 5G. In this case, the obtained end-to-end delay is acceptable for most productions.
Testing 5G S-NPN in urban environments without direct line of sight to the antenna	This requires preparation and testing. Mapping of coverage and well-thought-out antenna and camera positions are necessary.
Expand NRK´s experience with different encoders and modem solutions	Aviwest proved a viable solution and it proved to be a simple "plug and play" solution that clearly shows that it is possible to make things more rugged. The test shows that there can be great advantages in splitting up the CPE and encoder, but this can perhaps be solved in the future with an external antenna.
Get hands-on experience with how camera systems work in remote production	The camera systems mostly worked well. Additional interfaces other than analog connection were missed, but it is possible to create robust solutions around this. Several similarities between the challenges in 5G and remote production were appreciated.
Get more hands-on experience with compressed video and IP-based production	As mentioned above, delay is the most notable KPI to take care of. NRK received few concrete feedback about large delay differences in video with the different solutions.

Table 28. Key outcomes of the test cases in remote production.

Following, the general outcomes of the tests conducted in the final trial are presented:

1. Logistics in the field and associated rigging time is still a challenge.
2. Power consumption for more equipment in the field is a problem and aggregates are not an ideal solution.
3. Tests competed in practice with the simplicity and capacity of video over fiber. These kinds of setups are the ones that set the bar for what the project is trying to achieve.
4. With better capacity, control and flexibility, the presented setup can work to an acceptable level.
5. Easier mobile solutions are desired.
6. Several conclusions can be extracted from network behavior and latency times.

VideoXlink was used to measure all network parameters but also recorded the difference between a fibre-connected camera (uncompressed, no latency) and a wired camera with a phone filming the two receiving monitors. By counting the difference in number of frames we could calculate glass to class latency introduced by encoding and wireless transport. In the tests performed, a latency of approximately 350ms on video. This value was not noted as a problem by the specialist operators, but it is desirable to find encoders that can get below 100ms.

It should be noted that some limitations have been found when using public networks. Throughout the following paragraphs, an assessment of public networks for low-latency broadcasting is addressed. During the week in Bergen, several issues have demonstrated that the use of public 5G networks for broadcasting in this setup is not enough. It might work well for newsgathering, similar to the 4G remote contribution scenarios today with LiveU and similar systems, but in a multi-camera context with a need for low delay, capacity, stringent requirements, and functionalities, it is not sufficient.

Some of the problematic points encountered with public networks are the following:

1. Data capacity: little or no control over how many devices use the network simultaneously. High capacity is demanded to support multiple cameras simultaneously and operate connected to the NPN, ensuring seamless transmission between all of them with no timing glitches or visible artifacts.
2. Handover: limited ability to control handover since it is controlled by the base stations. During handovers between base stations, the performance drops below an acceptable level. In standalone networks, it is expected that the handover will be faster and will affect performance to a much lesser extent.
3. Timing grid: at 3.6GHz, it is not possible to set a frame structure that provides good performance on upload.
4. The main issue was that without a local core we were not able to get control over who had access to the frequency/capacity. Then, changes were made to the main network and not to the local network. It was intended to set priority on 3,6 GHz so that all cell phones used by the audience in the area would utilize that capacity instead of 2,3 GHz (N40 was supposed to be the production-band reserved for NRK), but this failed as the phones we had that supported N40 could only attach to a band with priority (not possible to set band manually). Only the professional CPEs were able to select a

different band manually but they did not support N40 NSA (when 700MHz was not used in 4G signaling). In addition, we had to turn off some public base stations to avoid handover to other networks (to avoid loss of frames on the moving cameras). Mobile phones supporting N40 also had too limited resources to provide high quality uplink. In conclusion, we lack control and cannot get optimal performance when we're not able to use professional CPEs (seem to work fine on N40 SA, Confirmed by FFI). Standalone NPN with a local core (like previous trials) is therefore preferred.

5. RTT/latency: by sending the data to the centralized core, RTT and latency times vary greatly over time.
6. Coverage: if there is poor coverage on 5G, UEs can fall back to 4G, which is not desirable.