Private 5G Networks for Connected Industries

Deliverable D5.2

E2E In-Factory System Integration Report

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Executive Summary

This report is the second deliverable associated with 5G CONNI's WP5. It covers the period between month 22 and 29 of the project's lifetime, which corresponds to the second part of the activities of Task 5.1 "Realization of the selected use cases", the first part of those of Task 5.2 "Test and evaluation in real-world production environments", and the very beginning of Task 5.3 "E2E performance measurement and KPI analysis."

This document describes the advancements in the deployment of 5G CONNI's end-to-end trial network that will interconnect both the European and Taiwanese manufacturing facilities, as a prosecution of the work previously described in the first deliverable of this WP. In particular, this report focuses on the evolution of the testbed's architecture and hardware/software equipment, and on the status of the transition from in-lab integration to the factories. A time plan is included, with both concluded and scheduled activities towards the completion of WP5.

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List of Acronyms

3GPP	3rd Generation Partnership Project
5G	5th Generation of mobile networks
5GC	5G Core
5G CONNI	5G for Connected Industries
5QI	5G QoS Identifier
AF	Application Function
AMF	Access and Mobility management Function
AMI	Amazon Machine Image
ANI	Alpha Networks Inc. (partner of the consortium)
API	Application Programming Interface
AR	Augmented Reality
ATH	Athonet Srl (partner of the consortium)
AUSF	Authentication Server Function
AWS	Amazon Web Services
BBU	Broadband Unit
BOSCH	Robert Bosch GmbH (partner of the consortium)
CBC	Cloud-Based Control
CDF	Cumulative Distribution Function
CHT	Chunghwa Telecom Co. Ltd. (partner of the consortium)
CN	Core Network
CNC	Computer Numerical Control
CP	Control Plane
CPE	Customer-Premises Equipment or Customer-Provided Equipment
CPU	Central Processing Unit
CU	Central Unit
DCA	Distributed Control Architecture
DHCP	Dynamic Host Configuration Protocol
DL	Downlink
DN	Data Network
DNN	Data Network Name
DNS	Domain Name System
DU	Distributed Unit
DX.Y	Deliverable X.Y (where X and Y are numbers)
EoIP	Ethernet over IP
E2E	End-to-End
eMBB	enhanced Mobile Broad Band
EU	Europe/European
FCAPS	Fault-management, Configuration, Accounting, Performance and Security
GM	Grandmaster
gNB	gNodeB (5G base station using NR technology)
GPRS	General Packet Radio Service
GPS	Global Positioning System
GTP	GPRS Tunnelling Protocol

GUI	Graphical User Interface
GUTI	Globally Unique Temporary ID
GW	Gateway
HHI	Fraunhofer Heinrich Hertz Institute (partner of the consortium)
HQ	Headquarters
HW	Hardware
IEEE	Institute of Electrical and Electronics Engineers
III	Institute for Information Industry (partner of the consortium)
IMSI	International Mobile Subscriber Identity
IMTC	(ITRI's) Intelligent Machinery Technology Center
IP	Internet Protocol
ITRI	Industrial Technology Research Institute Inc. (partner of the consortium)
ITU-T	International Telecommunication Union - Telecommunication
KPI	Key Performance Indicator
LAN	Local Area Network
MA	Motion Application
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MCU	Motion Control Unit
MEC	Multi-access Edge Computing
MIMO	Multiple-Input Multiple-Output
MS	Motion Service
N/A	Not Applicable
NEF	Network Exposure Function
NF	Network Function
NG	Next Generation
NGAP	Next-Generation Application Protocol
NMS	Network Management Station
NR	New Radio
NRF	Network Repository Function
O&M	Orchestration and Management
OAM	Operations, Administration, and Maintenance
OP	OPerator code
OPC	Derived OPerator Code
OTT	Over-The-Top
O-RAN	Open Radio Access Network
PCF	Policy Control Function
PDCP	Packet Data Convergence Protocol
PDU	Protocol Data Unit
PHY	Physical Layer
PREEMPT RT	Preemptive Real Time
PTP	Precision Time Protocol
QoS	Quality of Service
RAM	Random-Access Memory
RAN	Radio Access Network

RCU	Robot Control Unit
REST	REpresentational State Transfer
RF	Radio Frequency
RLC	Radio Link Control
RRC	Radio Resource Control
RSRP	Reference Signal Received Power
RTC	Real-Time Constraint
RU	Radio Unit
SA	Standalone
SCTP	Stream Control Transmission Protocol
SMF	Session Management Function
SSD	Solid State Drive
SW	Software
TCP	Transmission Control Protocol
TDD	Time-Division Duplex
TW	Taiwan/Taiwanese
UC	Use Case
UDM	Unified Data Management
UDP	User Datagram Protocol
UE	User Equipment
UI	User Interface
UL	Uplink
UP	User Plane
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communications
UE	User Equipment
VPN	Virtual Private Network
vRAN	Virtualized RAN
WP	Work Package
WPX	Work Package X (where X is a number)

1 Introduction

This deliverable builds upon the results provided in [1], and it describes the activities conducted within WP5 from month 22 to 29 of the project's lifetime. The main goal of WP5 is to construct an end-to-end (E2E) trial deployment to demonstrate the technological enhancement developed in the 5G CONNI project for the Smart Industry.

During the initial development phase, as reported in [1], the consortium partners had mostly focused on designing the overall system architecture, on deciding how to practically assemble the technological components provided and developed in WP4, and on carrying out initial integration and testing activities at an in-lab level, either each partner independently or grouped in small clusters in Europe or in Taiwan. The main results of such work were:

- A consolidated overall architectural framework of the E2E demo, conceived to support an extension of the Augmented/Virtual Reality for Process Diagnosis use case (cf. [2] and [3]).
- A thorough analysis of the required hardware (HW) and software (SW) equipment.
- A definition of the roadmap to follow towards the integration of the European (EU) local setup (divided in two main phases) and of the Taiwanese (TW) local system (divided in three main phases).
- A description of the testing tools and initial available test results.

The present document reports on the further advancements of WP5's work, in a transitioning phase from the fully in-lab integration activities of the first months and the fully in-factory operational deployment that will be reached at the end of the project's lifetime.

1.1 Scope

This document consolidates D5.1's pragmatic description of how the different network components provided and developed by the partners in WP4 are integrated together into the testbed [1]. More precisely, this document:

- Provides a key architectural update: the description of the solution chosen to implement the shared authorization and authentication modules to interconnect the EU and TW private networks into a single intercontinental framework.
- Revises the description of the HW and SW equipment involved in the testbed.
- Provides a detailed description of the status of the EU and TW testbeds at the present moment, both from the networking and the application points of view.
- Defines the planned remaining activities until the end of the project.

Globally, the activities carried out in the last eight months have allowed the partners of the project to validate the technical choices made in the first period, to carry out the component integration process (which is still ongoing, as per the plan reported in Table 4-3, Table 4-4, Table 4-9, and Table 4-10), and to begin the in-factory deployment.

1.2 Structure

The deliverable is structured as follows. Section 2 briefly summarizes the main characteristics of the system architecture of 5G CONNI's E2E demo. Then, it focuses on the technical solution selected for the implementation of a unified user provisioning system and for AUSF/UDM synchronization between the EU and the TW networks. Further, Section 3 updates the inventory of the HW and SW equipment that composes the testbeds, initially provided in [1]. Section 4 reports on the progress of the EU and TW system integration, with a low-level description of the networking plan at both sites, pictures of the deployed equipment, some performance results at a networking and application level, and the list of planned activities until the end of the project. Section 5 concludes this document and sketches the ways forward for the WP5 activities. Finally, Section 6 lists the internal and external supporting documentation referenced throughout this deliverable.

2 System Architecture Update

This section starts by recalling the main features of 5G CONNI's demonstrational setup, which will interconnect the EU and the TW testbeds, and which was introduced in full detail in [1]. Further, we specify the solution that has been chosen to implement the authentication and provisioning modules that are shared between the two testbeds.

2.1 Recall of the E2E architecture

We briefly recall here the main characteristics of the E2E architecture of 5G CONNI's inter-continental demo, which is depicted in Figure 2-1 and Figure 2-2. The E2E testbed merges into a single framework the EU and the TW setups, with the goal of building a prototype of intercontinental company network deployment.

The overall framework features three 5GC instances: two local deployments – one in EU and one in TW – dedicated to serve two industrial sites (BOSCH and ITRI's premises), and a central 5GC with the control plane functionalities instantiated over a public cloud and a distributed user plane. Such a control plane will be deployed over Amazon Web Services (AWS, see also Section 3.3.1.1), whereas the user plane will be deployed as an "edge node" at HHI's premises, playing the role of the simulated company's headquarters. The centralized 5GC will act as the "main" core network, interconnecting all the other three testbed locations (the two industrial sites and HHI's premises), which are each endowed with their own 5G radio access equipment. In particular, the network authentication modules at the 5GC level are shared between the centralized EU instance and the TW instance. All information about the specific solutions deployed at the 5GC, RAN, and edge computing level within the testbed is available in [1] and further down in this document.

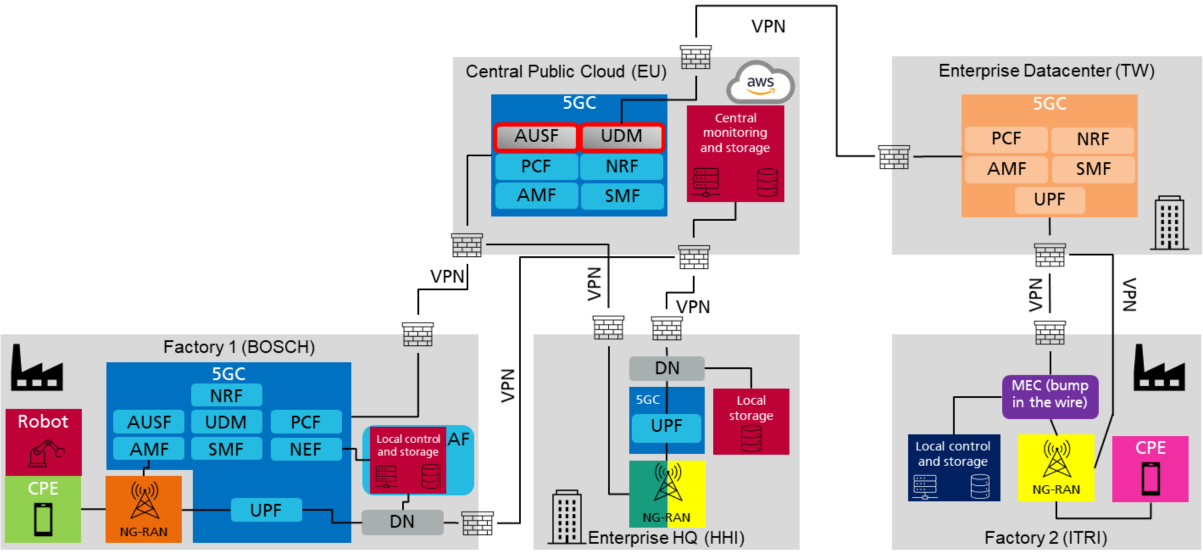


Figure 2-1: EU-TW joint setup.

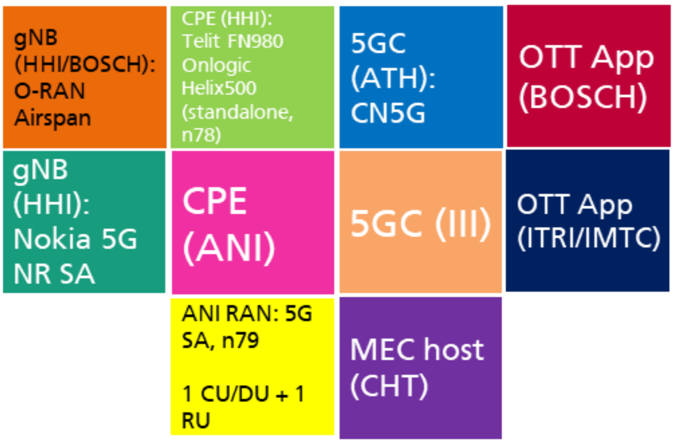


Figure 2-2: Legend of the architectural components of the EU-TW joint setup.

2.2 Centralized Provisioning System

To practically implement the authentication modules that are shared between the TW and the on-cloud centralized 5GC instances (with the benefits highlighted in [1]), we will realize the solution depicted in Figure 2-3. More precisely, we are instantiating within the TW setup a logical replica of the on-cloud AUSF and UDM. Functionally and from the point of view of the managed and stored data, the central functions and their replicas are indistinguishable. This is guaranteed by the fact that they are always kept synchronized by a *unified centralized provisioning system*, through which subscribers are provisioned and configured. From the 5GC architectural perspective, such an implementation choice has two main benefits: ensuring redundancy of critical subscription data (physically available at both continental sites) and improving the performance of the control plane network functions (NFs) of the TW setup (making the UDM always locally reachable).

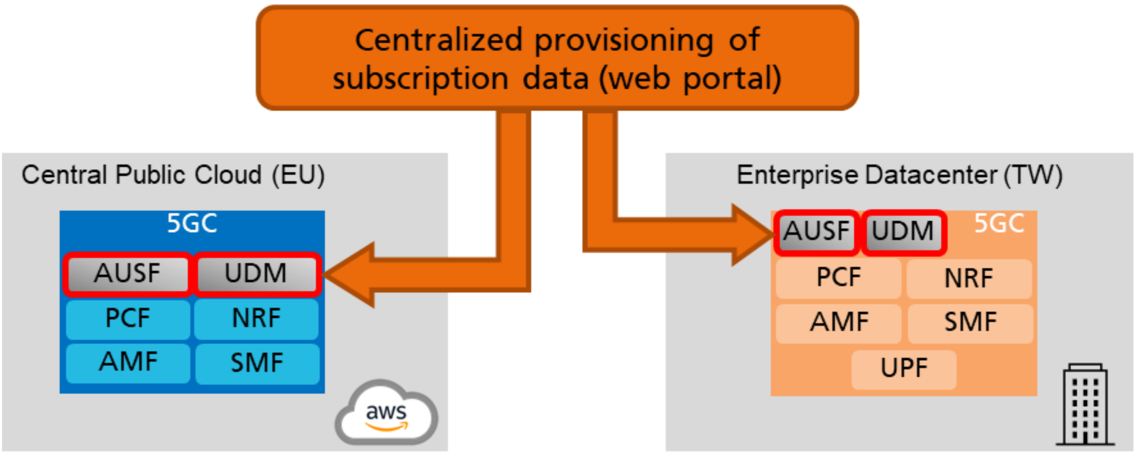


Figure 2-3: Realization of the shared authentication modules via a centralized subscriber provisioning system.

Then, the centralized provisioning will be practically carried out through III's Operations Administration and Maintenance (OAM) solution, described in the following.

2.2.1 OAM System and User Equipment Management

The 5G private network OAM solution is based on the needs of private network operations. FCAPS categorizes the working objectives of network management into five levels. The five levels are fault-management (F), configuration (C), accounting (A), performance (P) and security (S). OAM is very important to improve the stability and efficiency of private networks.

The 5GC OAM system under development will provide comprehensive management for 5G network components. OAM system can be used to monitor the health of the network and detect problems before users call for help. III's OAM system also provides a dashboard analysis function, which helps to find solutions quickly.

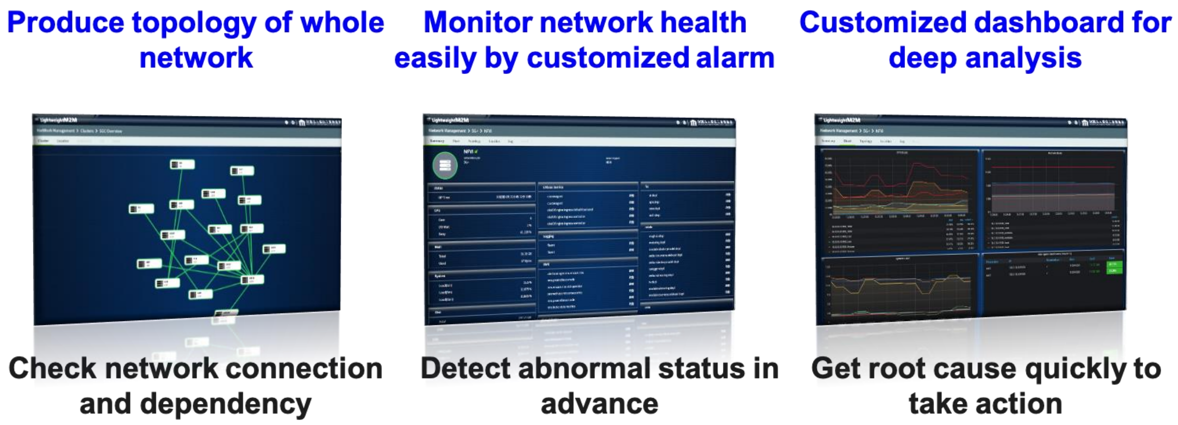
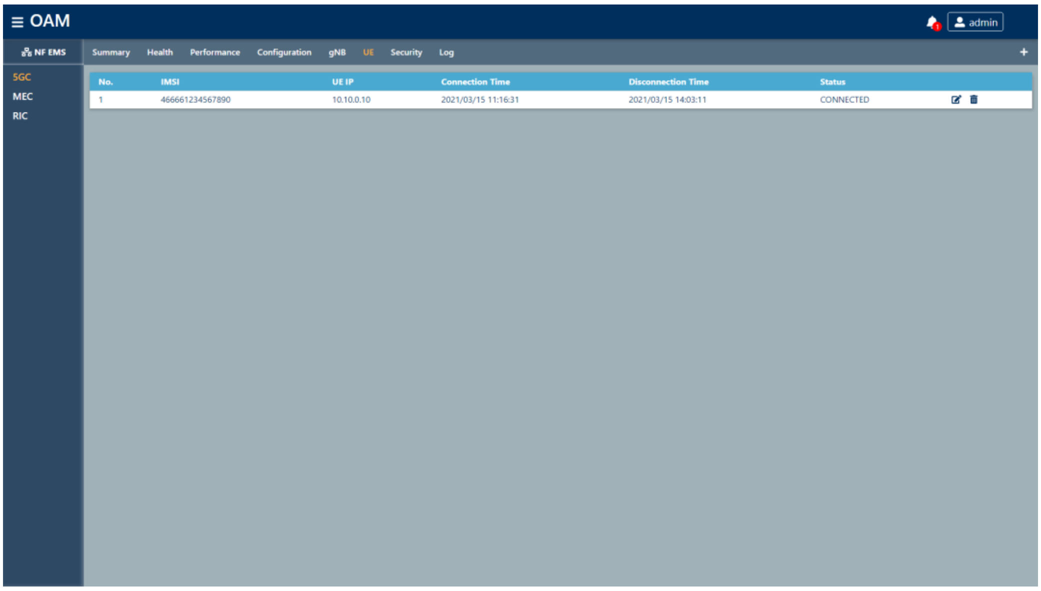


Figure 2-4: OAM Functions in 5GC.

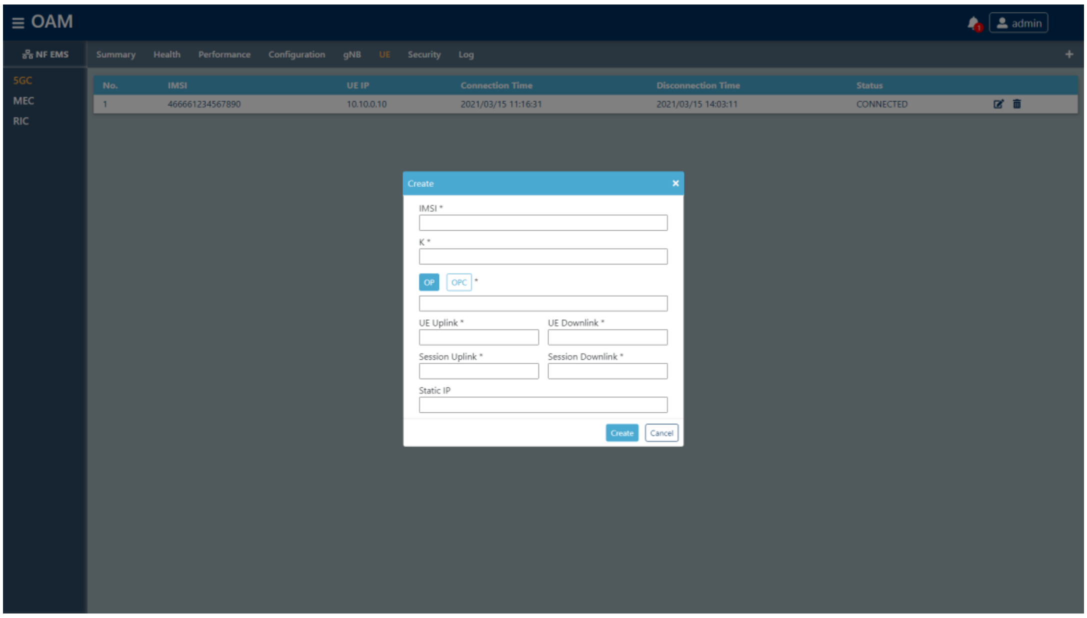
Figure 2-5 shows the User Equipment (UE) status. By using the OAM system, all UEs registered in 5GC are shown in the UE management list. The detailed information, including UE IMSI, connection time, disconnection time, IP, status, and operation management is also provided. When the joint UE provisioning function will be developed and integrated in the OAM system, common UEs that are served both by III and ATH's 5GCs will be visible in this system.



No.	IMSI	UE IP	Connection Time	Disconnection Time	Status
1	466661234567890	10.10.0.10	2021/03/15 11:16:31	2021/03/15 14:03:11	CONNECTED

Figure 2-5: UE Status in 5GC OAM.

Figure 2-6 shows the UE creating User Interface (UI). The IMSI, key K, OP/OPC codes, UE Uplink, UE Downlink, IP and other information will be sent to both III and ATH's 5GC. The system will then confirm that the UE was correctly provisioned in both core networks.



No.	IMSI	UE IP	Connection Time	Disconnection Time	Status
1	466661234567890	10.10.0.10	2021/03/15 11:16:31	2021/03/15 14:03:11	CONNECTED

IMSI *

K *

UE Uplink *

UE Downlink *

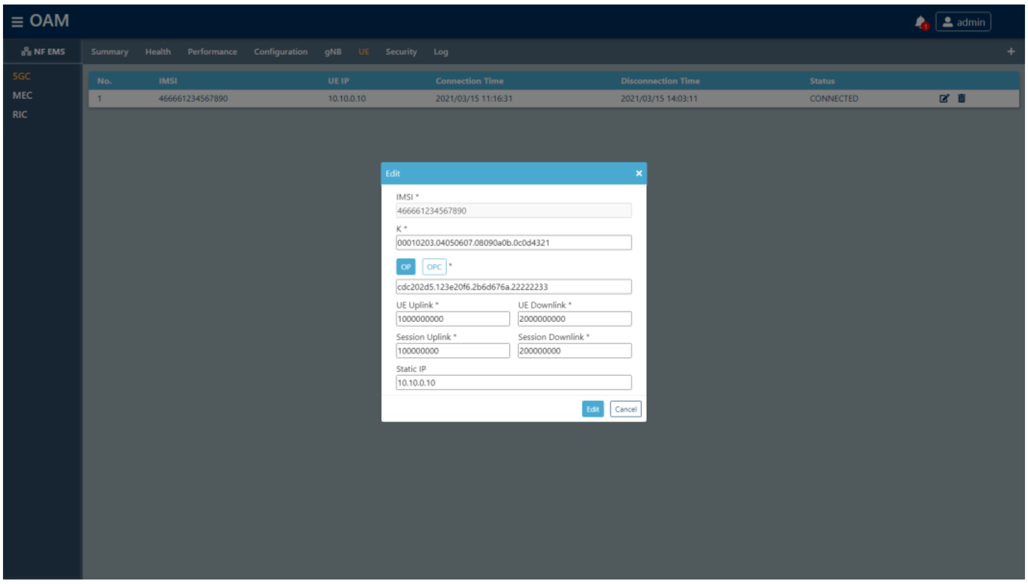
Session Uplink *

Session Downlink *

Static IP

Figure 2-6: 5GC OAM Create UE.

Figure 2-7 shows the UI to input optional information for a newly added UE. It allows the user to add extra information to describe the UE.



No.	IMSI	UE IP	Connection Time	Disconnection Time	Status
1	466661234567890	10.10.0.10	2021/03/15 11:16:31	2021/03/15 14:03:11	CONNECTED

IMSI * 466661234567890

K * 00010203.04050607.08090a0b.0c0d4321

OP * cdc202d5.123e20f6.2b6d676a.22222233

UE Uplink * 1000000000

UE Downlink * 2000000000

Session Uplink * 100000000

Session Downlink * 200000000

Static IP 10.10.0.10

Figure 2-7: 5GC OAM UE optional information input.

Figure 2-8 shows the 5GC OAM login screen. The account and password should be provided. The system supports the establishment of new accounts, and it will check the password complexity to prevent information security incidents.

Figure 2-8: 5GC OAM login screen.

5GC OAM provides front-end graphical user interface (GUI) portal. Users can use the browser to log in to the web page for direct management. It is convenient for administrators to conduct private network management and control. Management attributes and modules are classified in different tabs. In addition, the front-end will provide a northbound interface, which is convenient for the third-party applications or services. The northbound interface is established by RESTful API and Pub/Sub dual channels. The non-immediate information can be accessed through the relevant internal parameters of the RESTful API. The real-time messages and subscribe to messages can be accessed through Pub/Sub. By using this mechanism, polling performance reduction is eliminated, and system performance is improved.

3 Hardware and Software Setup Update

In this section, we preserve the same structure as Section 3 of [1], reporting only on the updates with respect to the original HW and SW equipment plan.

3.1 End Devices

3.1.1 European Side

No updates.

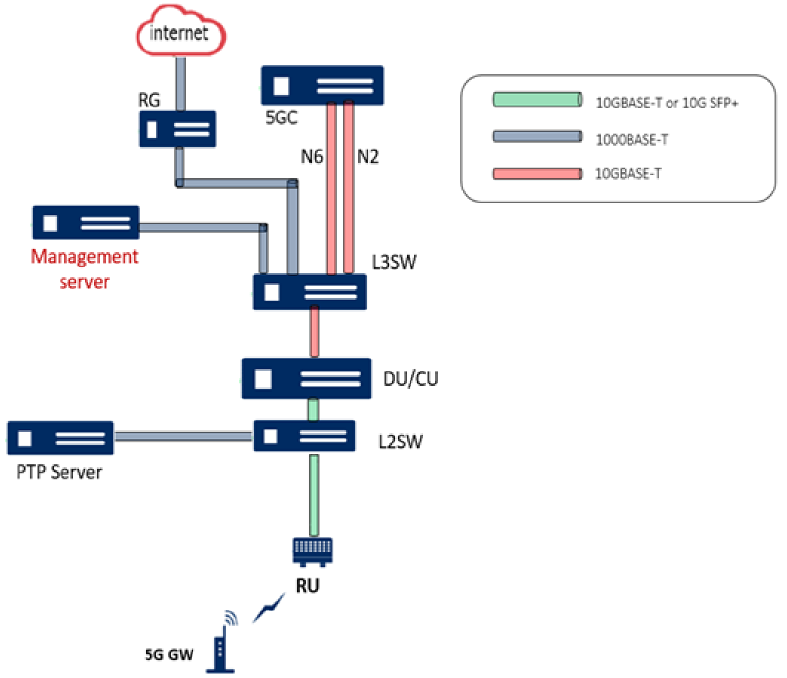
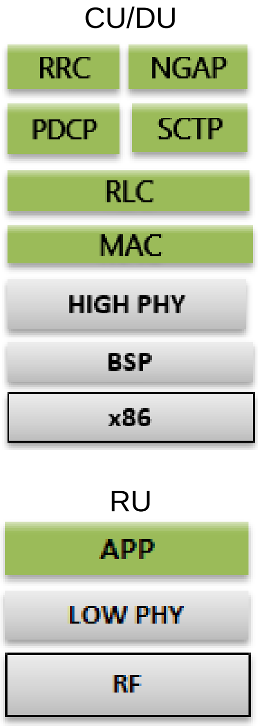
3.1.2 Taiwanese Side

No updates.

3.2 Radio Access Equipment

3.2.1 European Side

Other than the O-RAN Airspan gNB for the EU Factory and the Nokia gNB for the emulated Enterprise HQ, a new piece of radio access equipment will be added to the Enterprise HQ premises.

Hardware	**Software**
RAN structure  CU/DU • CPU: Intel Xeon and C627 PCH • L1 acceleration: Xilinx XCKU060 • Interface: SFP+ 10GbE(fronthaul) and QSFP+40GbE(backhaul) RU • SoC: Xilinx XCZU9CG • RFIC: ADI 9371 *2 • Interface: SFP+ (Data), PoE (Power)	

3.2.2 Taiwanese Side

No updates.

3.3 Core Network and MEC Equipment

3.3.1 European Side

3.3.1.1 Core network

ATH’s 5GC is adapted to run on several hyperscalers and cloud stack including VMware, AWS and Google Cloud. One of the best examples of deployment consists in the 5GC running on top of AWS EC2 and AWS SnowBall Edge HW. For this reason, as mentioned in Section 2.1, the role of the Central Public Cloud for the central 5GC instance is played by AWS, in addition to the instances on premises at the EU Factory (BOSCH) and Enterprise HQ (HHI). Such a solution leverages the new Athonet Open5G platform that makes open standards and interfaces of 3GPP, allowing to bring up a 5G network by connecting an on-premises RAN network to the 5GC instance in AWS over an Internet connection, protected by a VPN tunnel. This solution provides a highly scalable and automated platform and opens ATH’s 5G system to new radio vendors, device vendors, application providers, academy, and research institutions. Furthermore, due to the required interworking between the 5GC and the edge infrastructure solutions like those deployed at BOSCH and HHI, the user plane is kept local, and applications and services run as close as possible to where data is created and consumed, in order to deliver intelligent and real-time responsiveness. The deployment of a 5GC instance on AWS needs to have access to the AWS EC2 console, after logging into AWS and selecting the account and region of instantiation. An Amazon Machine Image (AMI) is then ready for deployment on AWS EC2. The 5GC does not require SSH access since the core is completely configurable by accessing the GUI (Figure 3-1).

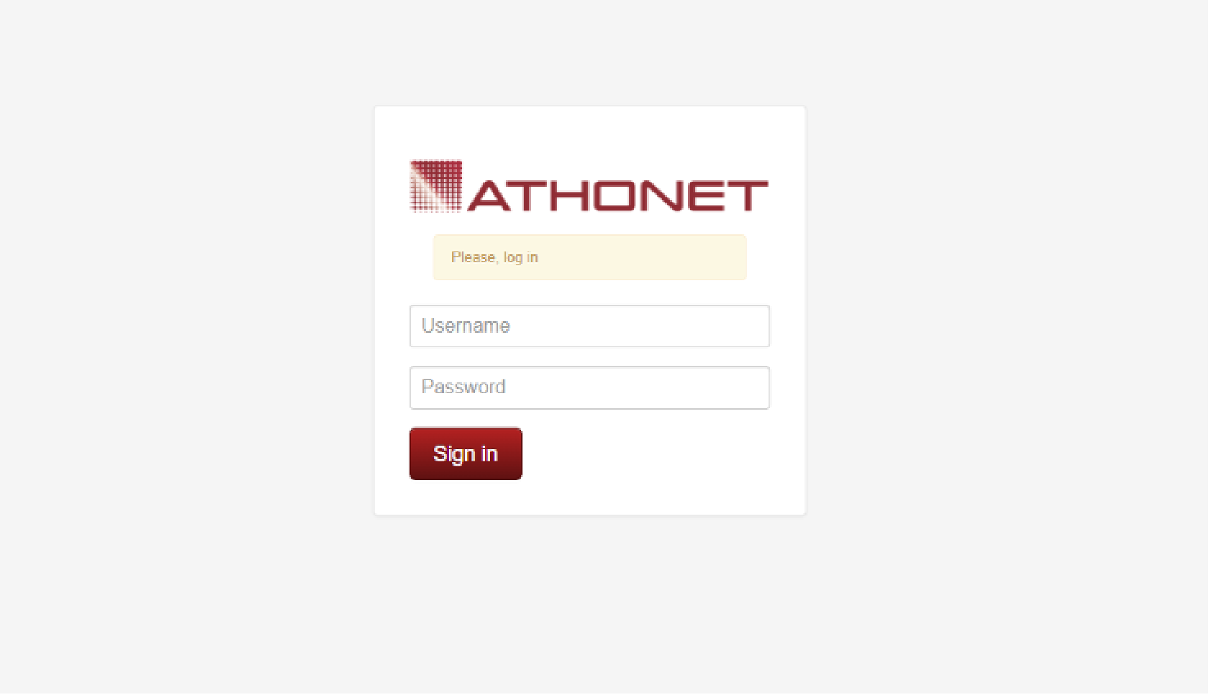


Figure 3-1 - The login page of Athonet’s 5GC GUI.

3.3.1.2 Multi-access Edge Computing

No updates.

3.3.2 Taiwanese Side

3.3.2.1 Core network

No updates.

3.3.2.2 Multi-access Edge Computing

No updates.

4 System Integration Progress

In this section, we present the progress in the EU and TW continental systems integration activities, comprising different physical sites. Preliminary validation and test results are provided as well. The time plans for the continental testbeds are updated with respect to [1] and extended until the scheduled end of the 5G CONNI project. Finally, the time plan for the inter-continental pilot is provided, after having consolidated the overall architecture – see Section 2.2.

4.1 European System Integration Progress

Let us start with the EU system integration activities. In the following, we describe the network and robot integration activities carried out and planned, both in lab as well as on premises, following the time plan for Phase 1 – see Section 4.1.4. At present, Phase 1 is completed, except for the transportation of the network equipment to a second BOSCH site, where the final performance tests will be carried out. Notice that, as part of Phase 1, the remote integration tests listed in Section 4.1 of [1] were successfully completed too (tests on attach procedures, idle and connected states, detach, TAU, and traffic).

4.1.1 Network Integration

The 5G system to be used on the European side of 5G CONNI's demonstrator will eventually consist of three separate sites: the factory premises at BOSCH, hosting the industrial application, HHI's Berlin campus representing an enterprise HQ, and a central cloud providing network functions common to both locations. As of integration Phase 1 (see description in [1]), a high-level overview of the implemented system is shown in Figure 4-1. It consists of a fully self-contained 5G network at the factory site covering RAN, 5GC, and MEC, thus implementing the *fully private* on-site deployment model [1], [4]. At the enterprise HQ site, there is currently only one gNB. Both sites are interconnected via an IPsec VPN tunnel, thus logically acting as one larger network.

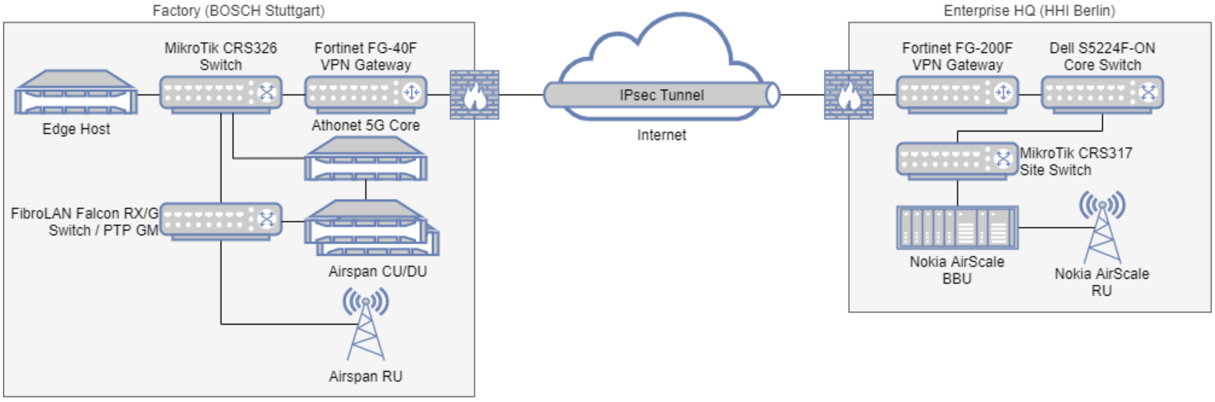


Figure 4-1: Phase 1 high-level structure of the EU multi-site 5G network.

The 5G network deployment for the factory premises (BOSCH) consists of four main components:

- O-RAN compliant virtualized RAN (vRAN) supplied by Airspan Networks (partially virtualized),
- 5GC supplied by Athonet (virtualized),
- Mobile edge host for virtualized industrial application deployment,
- Transport network & support infrastructure.

The RAN is fully disaggregated into the components radio unit (RU), distributed unit (DU) and central unit user-plane/control-plane (CU-UP/CU-CP) as per O-RAN specification and implements the O-RAN fronthaul interface with lower-layer split option 7.2, the 3GPP F1 midhaul interface (higher layer split 2) and the O-RAN O1 OAM interface. While the RU is the only physical network function, the DU, CU-CP and CU-UP are implemented as kubernetes software services running on two general purpose servers. The dedicated DU server is additionally equipped with an ASIC compute accelerator card for channel coding. The server hosting the virtualized CU network functions also runs the master node of the vRAN kubernetes cluster and the RAN's network management system.

A detailed view of the factory premises network is depicted in Figure 4-2. RAN mid- and fronthaul transport is provided by a FibroLAN Falcon RX/G 10/25 GbE switch, which also acts as a GPS-locked IEEE 1599 PTP grandmaster clock, providing ITU-T G.8275.1 profile time synchronization to the DU and RUs according to O-RAN LLS-C3.

The remaining transport network and support infrastructure consists of a MikroTik CRS326 router/switch for OAM and DN connectivity, also providing the DNS and DHCP services required by the system's components. Site-to-site interconnectivity is established via a Fortinet FG-40F VPN gateway.

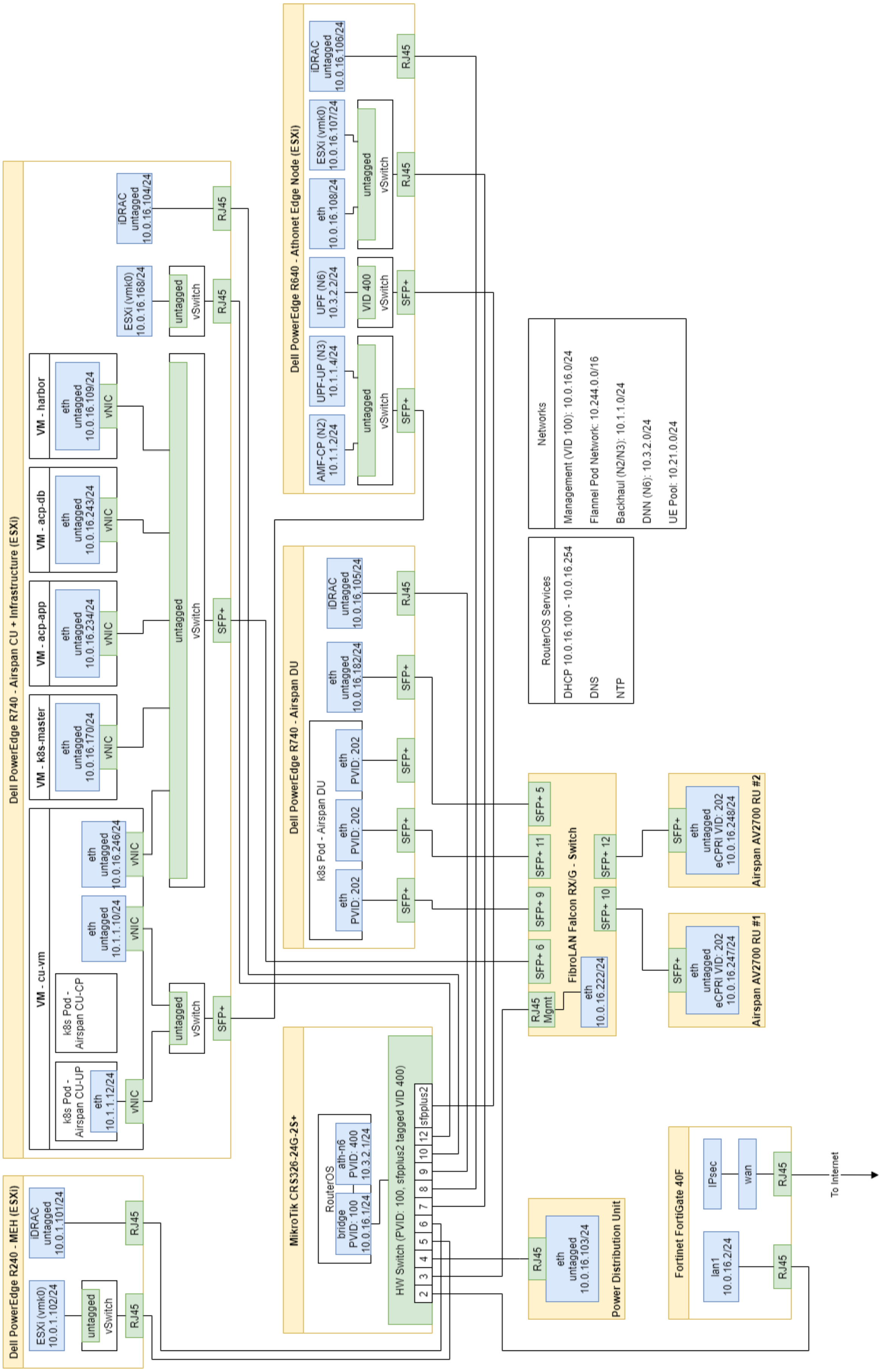


Figure 4-2: Network topology of the EU in-factory 5G network.

All components of the factory premises 5G network are mounted in a rugged, transportable case for ease of deployment as shown in Figure 4-3.

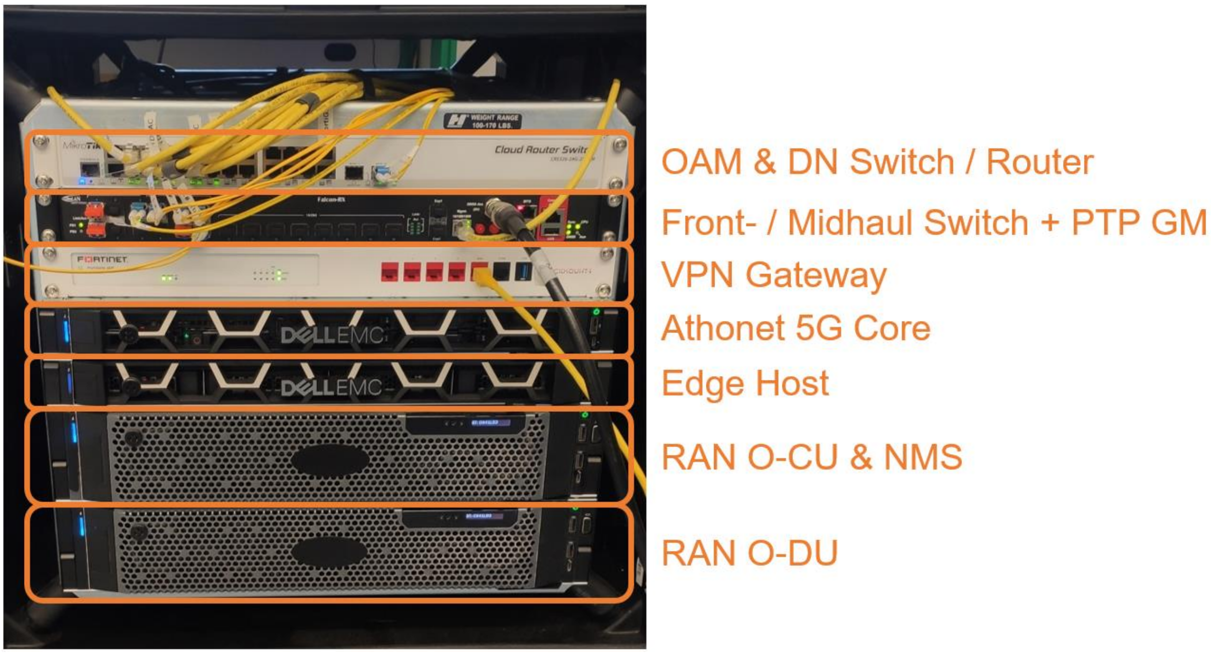


Figure 4-3: Physical layout of the factory premises 5G network.

The basic parameters of the factory premises RAN are summarized in Table 4-1.

Table 4-1: Factory premises RAN parameters.

Parameter	Value
Center frequency	3750 MHz (Band n78)
Channel bandwidth	100 MHz
Subcarrier Spacing	30 kHz
Frame structure	7DF2U
Flexible slot format	Format 2
Max. Tx power	26 dBm
Downlink Layers	2

The RAN on the enterprise HQ consists of a Nokia AirScale gNB that is connected via a series of switches to the VPN gateway. When moving towards system integration Phase 2, it will be connected to the 5GC in the central cloud location (AWS). The physical deployment at enterprise HQ site is shown in Figure 4-4.

a) HHI Datacenter

b) HHI Rooftop Equipment Room

Figure 4-4: 5G Network on HHI premises (EU Enterprise HQ).

4.1.1.1 Preliminary Performance Results

Preliminary performance tests were conducted in a lab environment on the pre-integrated fully private 5G network to be deployed on the EU side factory premises as shown above in Figure 4-2 and Figure 4-3. For this purpose, a virtual machine was set up in the system's mobile edge host to serve as endpoint for ping roundtrip time and iperf3 based throughput measurements (both TCP and UDP). On the UE side, a Robustel R5020 industrial 5G router was registered on the network. RSRP at the UE was -77 dBm and measurement duration was 60s. Measurement results are shown in Table 4-2.

Table 4-2: Performance measurement results for EU side factory 5G system

#	Test Item	Results
1	Avg. UDP DL TPut	130 Mbits/sec
2	Avg. UDP UL TPut	45.2 Mbits/sec
3	Avg. TCP DL TPut	153 Mbits/sec
4	Avg. TCP UL TPut	42.5 Mbits/sec

#	Test Item	Results
5	Ping RTT stats (min/avg/max/mdev)	12.513/22.648/32.0003/5.987 ms

It should be noted that downlink throughput is lower than expected. A nearly identical RAN by the same equipment vendor deployed on HHI's premises achieves more than twice the throughput reported here, which is in line with what can be expected for two-layer downlink transmission. The cause for this behavior has been traced to a problem in the DU server in the current release of Airspan's vRAN system software, where DL throughput degrades on RLC layer. It is currently being investigated with the system's vendor.

4.1.2 Robot Integration

With the motive to remove cabling from the control system, replace it with wireless communication, and control the device remotely, one of the critical parameters for a closed-loop control system is cycle time. The cycle time is traditionally a predefined fixed value and configured during the design phase which does not change during the process. A wired system is generally configured in a way that it can guarantee timely transmission according to this cycle time. A wireless system however can generally not support very low cycle times with absolute guarantees. A solution towards it is still in research. In general, cycle time requirements can be fulfilled by the URLLC key enabler of the 5G network when there is no influence of external environmental factors. However, in the factory environment, when robotic control functions are offloaded and communicated over a wireless network such as 5G, the cycle time of such closed-loop control may vary due number of reasons and could lead to the stop of the entire production processes. There are many mechanisms to overcome this challenge, such as higher quality of service of the network, retransmission of the signal, but they are limited to the network side. Another approach would be to make the control functions of robots adaptive to latency, which helps dealing with imperfect networks at the controller side. This latter approach is considered to develop a concept of dynamic adaptation of a distributed control logic when the 5G communication system is used in smart factories.

4.1.2.1 Concept

Therefore, the target is an innovative and dynamic split of a control function between a robot application instance running off-device, e.g., in an edge cloud (which realizes all the intelligence of robot trajectory planning and control, i.e., the control logic) and a lightweight controller at the robot (executing in a non-complex way and including the interpolator). An interpolator is introduced to receive the command from the application at a higher cycle time and interpolate a piecewise spline to provide the control commands at a faster rate as required by the real-time constraint (RTC) of the FRANKA robot (see specification in [1]).

Figure 4-5 shows the distribution of control functions for an industrial robotic application with a 5G network. The distributed control architecture (DCA) is divided into three main layers: field level, communication level, and edge level. The field level consists of the robot with sensors and actuators and a control unit known as a robot control unit (RCU). The default monolithic control functions of the robotic system are split to offload high computational functions to the cloud. The RCU can still have some safety features and basic control functions to account for situations when a loss in communication to the edge controller occurs.

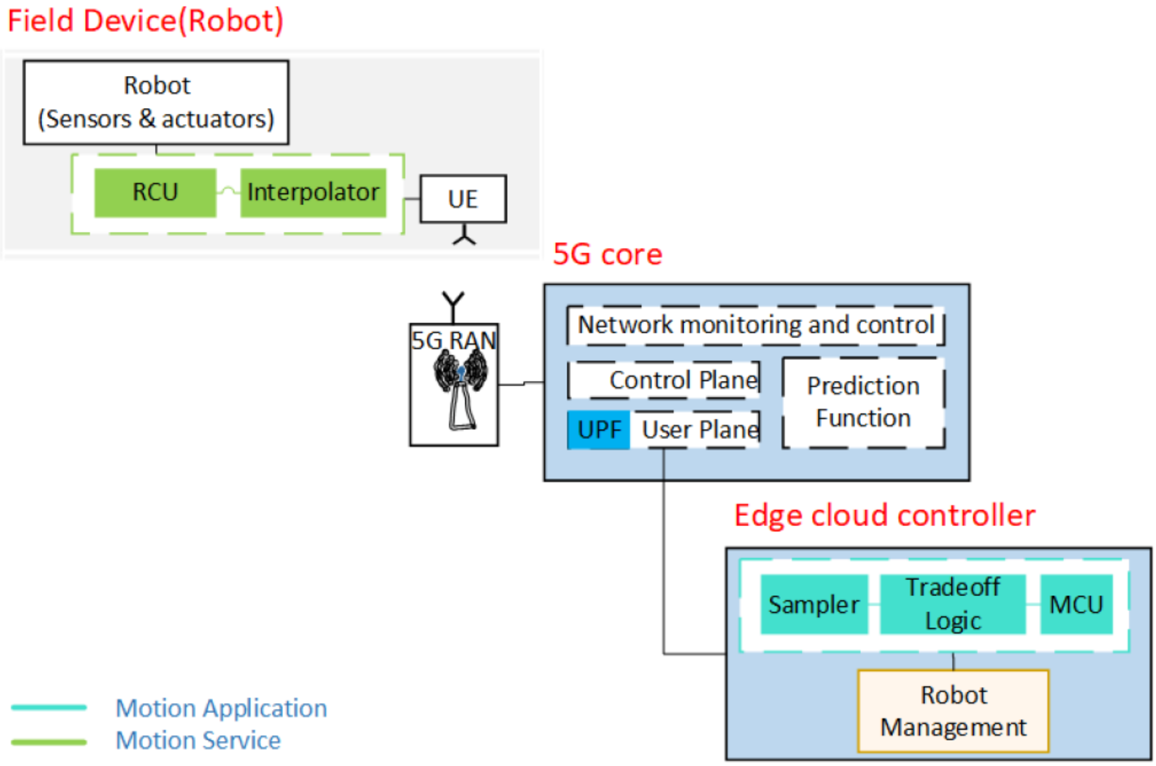


Figure 4-5: Dynamically Split Control System Architecture.

The concept is as follows: the RCU and an interpolator are represented under a motion service (MS). The MS is connected to the UE over a wired connection. Further, the UE is connected to gNB or RAN wirelessly and further to an application running on the edge cloud. The control functions such as motion planning or other computational algorithms are outsourced to an edge cloud controller represented as a motion control unit (MCU). The MCU, along with trade-off logic and sampler, comes under Motion application (MA). The motion planning functions in MA generate the path for the robot to follow, which is sent to the MS over the 5G network and further computed to get the desired trajectory by the RCU. If there is no latency between the MS and MA, the given motion can be directly forwarded to RCU, skipping the interpolation. However, due to the imperfect 5G network or higher cycle time, an interpolator computes the missing points with an interpolated spline between two consecutive commands. Once the target values are received at higher cycle time to the MS, the Interpolator computes a piecewise spline between those target values at the required sample rate by the robot. Hence, interpolating the samples on the field equipment can assist in accounting for delayed or untimely messages over the wireless channel and reduce each control message's latency/jitter requirements. Even though such an Interpolator is used, there is still room for altering control parameters such as velocity and precision to obtain optimum performance of factory processes in order to keep the production line alive. The dynamic adaptation of the controller logic to varying network conditions is recognized through four well-defined stages to account for varying latency capabilities of the imperfect 5G network between the MA and the MS.

The terms MA and MS as well as the interpolation method (piecewise, quintic Hermite interpolation) are taken from [5], which implements the baseline concept (originally targeting at using high-level programming languages like Python for low latency robot control algorithm). This is extended by accommodating for fluctuating latency, i.e. varying spline lengths, as well as pro-active adaptation of the cycle time and the control logic likewise on the basis of knowledge of historical latency and/or jitter information. This leads to the schematic as displayed in Figure 4-6.

The inner loop comprises the real-time closed-loop control of the robotic applications. Every robot has a fixed RTC, which is fulfilled by this inner loop, and it runs at the lower cycle time as per the constraint to the update frequency. If the outer loop, which includes the 5G network, has a high cycle time due to network latency, the interpolator in the MS will account for it and calculates the position values at a high sampling rate with variable spline length. Due to variance in the uplink and downlink delay, the produced interpolated splines have different lengths, and the interpolator is designed in a way to precisely accomplish this.

Here, T_c denotes the cycle time of the outer loop. The cycle time T_c between two consecutive control messages is the sum of the uplink (t_{UL}) and downlink latency (t_{DL}), the processing time of the MA (t_{MA}), the processing time of the MS (t_{MS}), inner loop control time (t_{rt}) and a variable update time (t_{U}). The update time (t_{U}) has been included to artificially increase the outer loop cycle time, which eventually adjusts the relative jitter (the jitter induced through varying uplink and downlink latencies relative to the cycle time T_c).

$$T_{\mathrm{c}} = t_{\mathrm{UL}} + t_{\mathrm{DL}} + t_{\mathrm{MA}} + t_{\mathrm{MS}} + t_{\mathrm{rt}} + t_{\mathrm{U}} \tag{1}$$

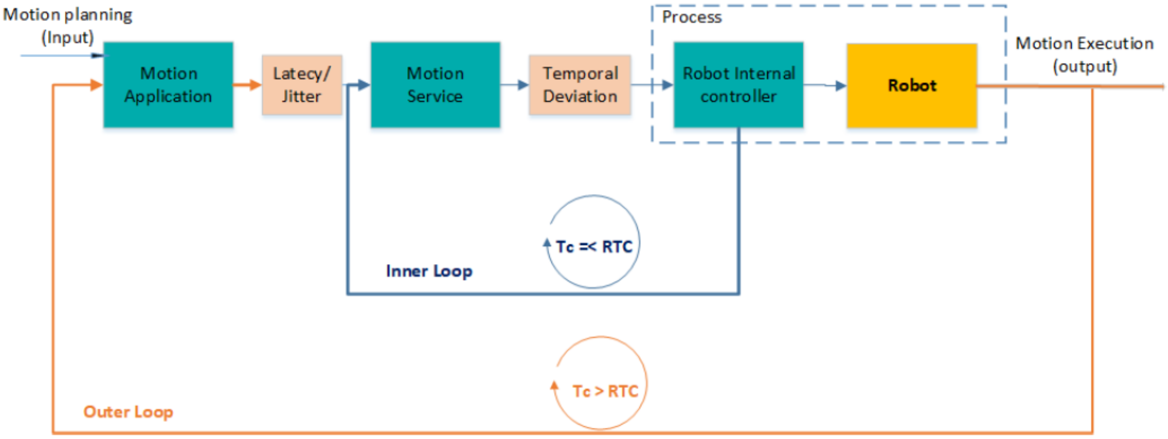


Figure 4-6: Inner and Outer Control Loop Architecture.

4.1.2.2 Implementation and Evaluation Setup

For initial verification and performance testing, the concept has been implemented on a single workstation with separated MA and MS according to Figure 4-7. The communication over these two nodes is over a UDP/IP socket system. The MA node is assigned with the static IP address of 127.0.0.1 and communicated over 9999 port. This port number is chosen as it is not a fixed assigned port number in the socket based communication and can be changed as per users’ liking. The robot controller is provided with the static IP address of 172.16.0.2, which can be also changed in the network section of graphical user interface of the robot (Desk). As instructions provided in the user manual of the Franka Emika robot, the PC has been assigned with static address of 172.16.0.1 in the IP4v setting. The CPU of workstation should be kept to performance mode by disabling frequency scaling to get the desired results. For current setup, the compatible version of Libfranka 0.5.0 is used. If the operating system is upgraded further from 3.2.0 (current operating system version of the robot controller), then the compatible Libfranka version should be used. Installation of preemptive real time (PREEMPT RT) kernel is critical to set the real time permissions for its process. All services run as independent nodes and the MA running separately on another workstation PC can also be implemented as required. Once the MA, MS and RaaS were up and running, a 5G emulator is used as the 5G network is not present yet. In this particular case, a simple function has been implemented to generate (randomly distributed) latency/jitter on the link between the MS and the MA.

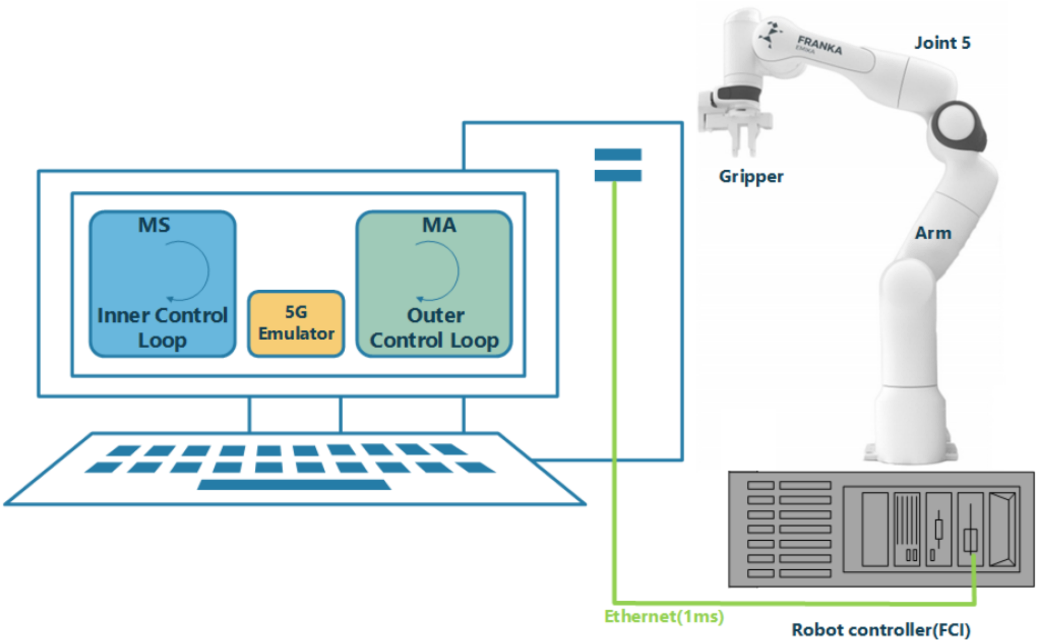


Figure 4-7: Implementation Setup for Preliminary Tests and Evaluation.

Figure 4-8 provides a more detailed view on the implementation. Individual services communicate with each other to formulate the closed-loop control. The concept of the split of control functions for real-time control loops can include various components such as the robot controller, motion service, communication module (to exchange information over some platform and motion application to execute high computational tasks), and motion application. The four layers introduced earlier of a DCA of a closed-loop robotic system are implemented as follows.

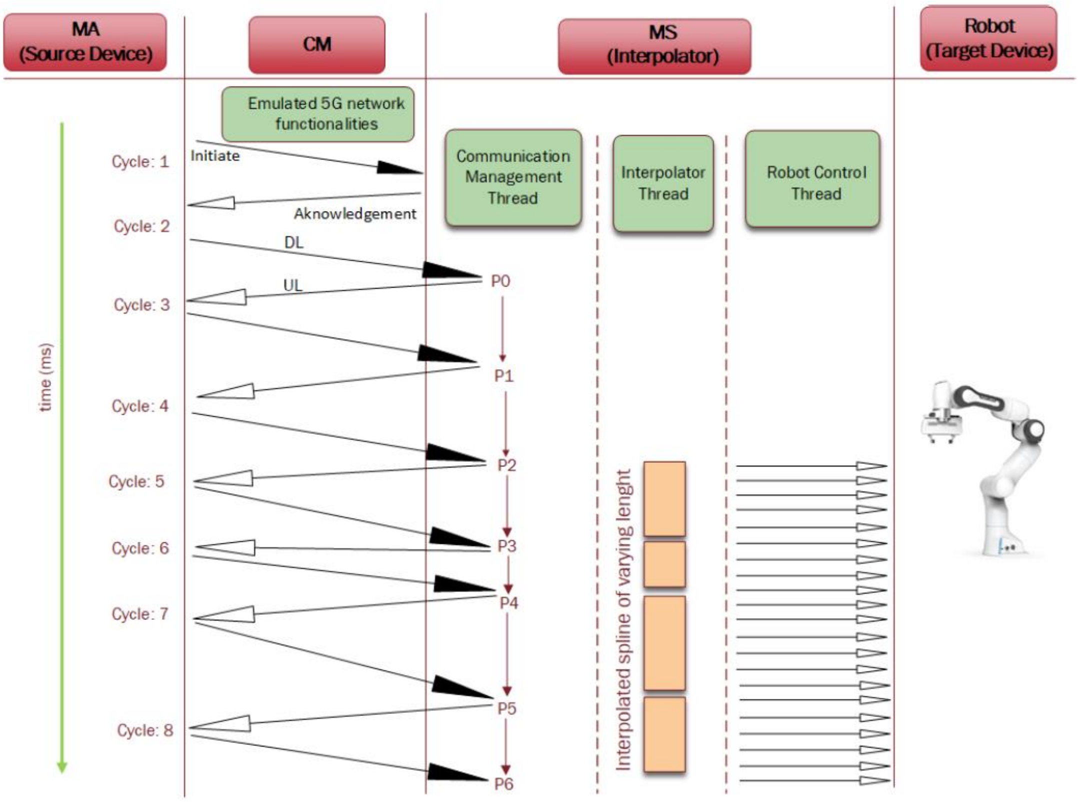


Figure 4-8: Exchange of Messages Between Various Layers of the DCA.

The RCU is used as a service running on a separate node for a service-based architecture. This controller considers dynamic parameters of the robot such as Jacobian matrix, inertia matrix, Coriolis and centrifugal vector, and gravity vector for all robot joints. This RCU detects the violation of limitations and provides feedback to the MS (including executed values, such as joint positions).

The algorithms with threaded programming implementation for DCA are taken from [5] as it gives us several advantages. The MS contains such three threads running in parallel to assure smooth motion of the robot over the imperfect network: A Communication Management Thread, an Interpolation Thread modified to cope with varying spline lengths, and Robot Control Thread.

In the following, the general behavior of the DCA is illustrated. Figure 4-9 shows the response time of the robot, which causes a temporal deviation between the commanded and executed joint angles. This deviation originates from the fact that the interpolator required three values to interpolate a spline between the first two of them, hence being a multiple of the cycle time. Figure 4-10 displays the tracking delay for a step response.

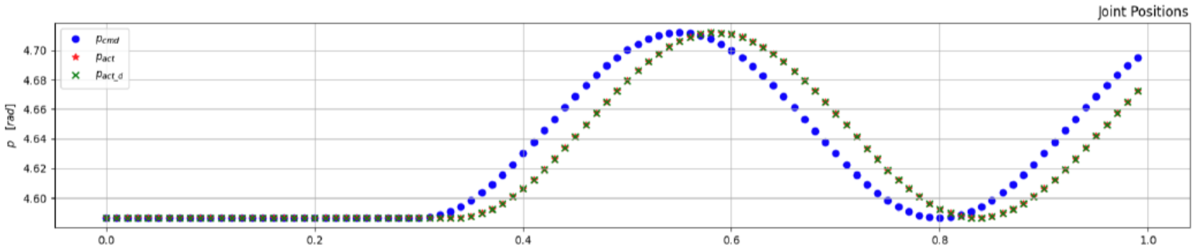


Figure 4-9: Response Time of the Robot.

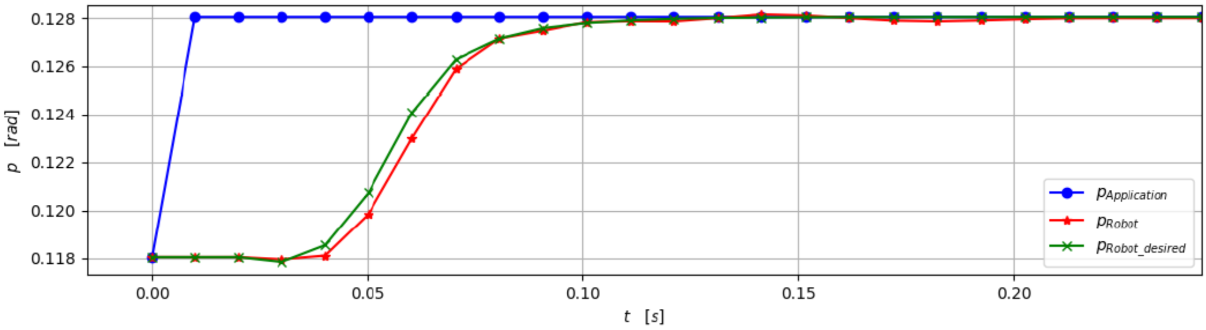


Figure 4-10: Tracking Delay for Step Response.

Figure 4-11 shows the angle of one of the robot's joints as a cosine trajectory (at low speed for testing purposes) for two cases: the ideal planned curve (black) and the actual executed one compensated by the temporal delay mentioned above. Due to induced latency and jitter, the cycle time T_c is between 10 and 16 ms. Thanks to the implementation of the DCA, the spatial deviation between the two curves can be tracked for each and every commanded value of the inner control loop, i.e. every 1 ms. This is shown in Figure 4-12 as the relative spatial deviation in percent over time. In what follows, the statistics of the relative spatial deviation of a joint angle depending on cycle time fluctuations (due to uplink and downlink latency and jitter influencing the accuracy of the interpolation) are used to study the impact of the wireless 5G System between the robot (RCU) and the edge controller (MCU).

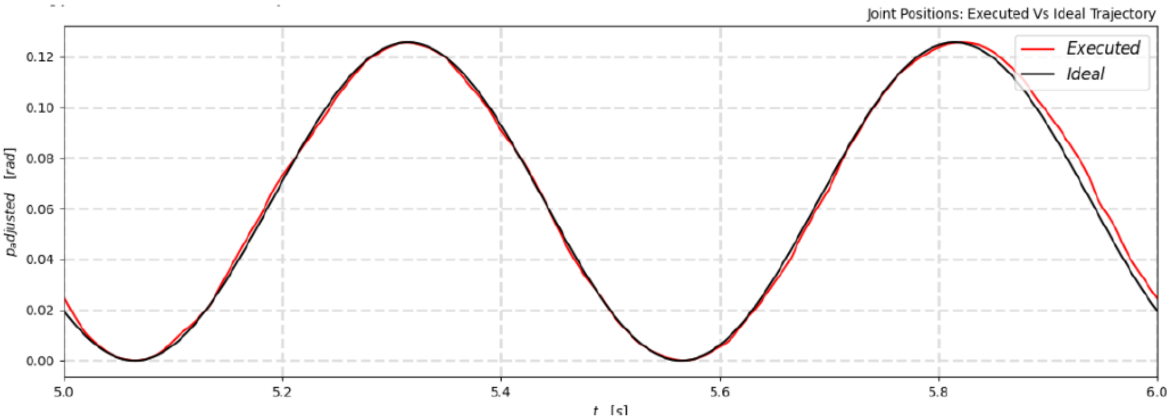


Figure 4-11: Comparison of Executed vs. Ideal Robot Trajectory.

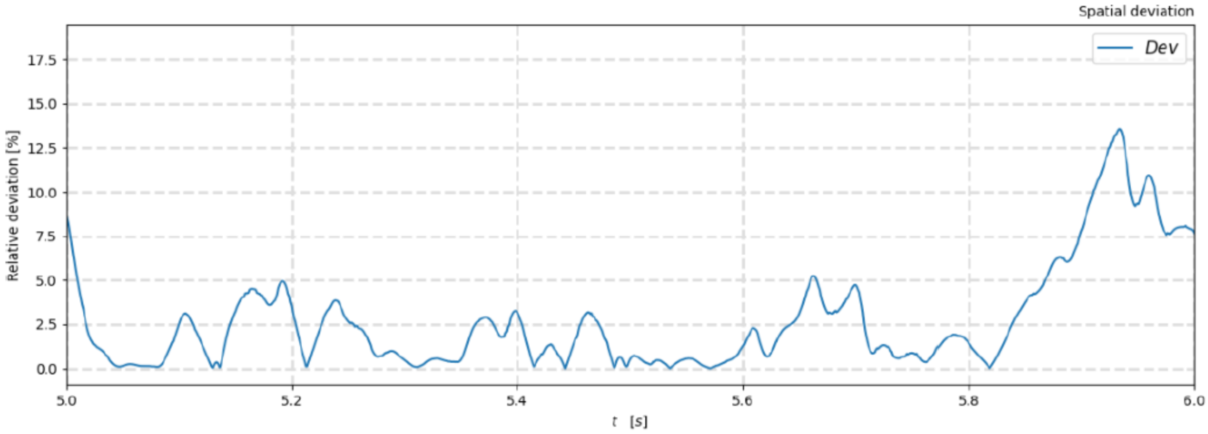


Figure 4-12: Tracking of the Relative Deviation.

4.1.2.3 Preliminary Performance Results

Figure 4-13 shows the empirical cumulative distribution function (CDF) of the relative spatial deviation in percent for a constant angular speed of 0.12 rad/s and for different communication latencies ($t_{\mathrm{UL}} + t_{\mathrm{DL}}$, $t_{\mathrm{U}} = 0$). It becomes apparent that considerably high latencies cause higher relative deviation, especially leading to some increased spikes. While the deviation of the medians is not very significant, higher network latency can cause higher relative deviation peaks, i.e. larger values for the higher percentiles and maxima. In conclusion, further increase of the uplink and downlink network latency leads to higher spatial deviation by degrading the accuracy of the executed robot trajectory.

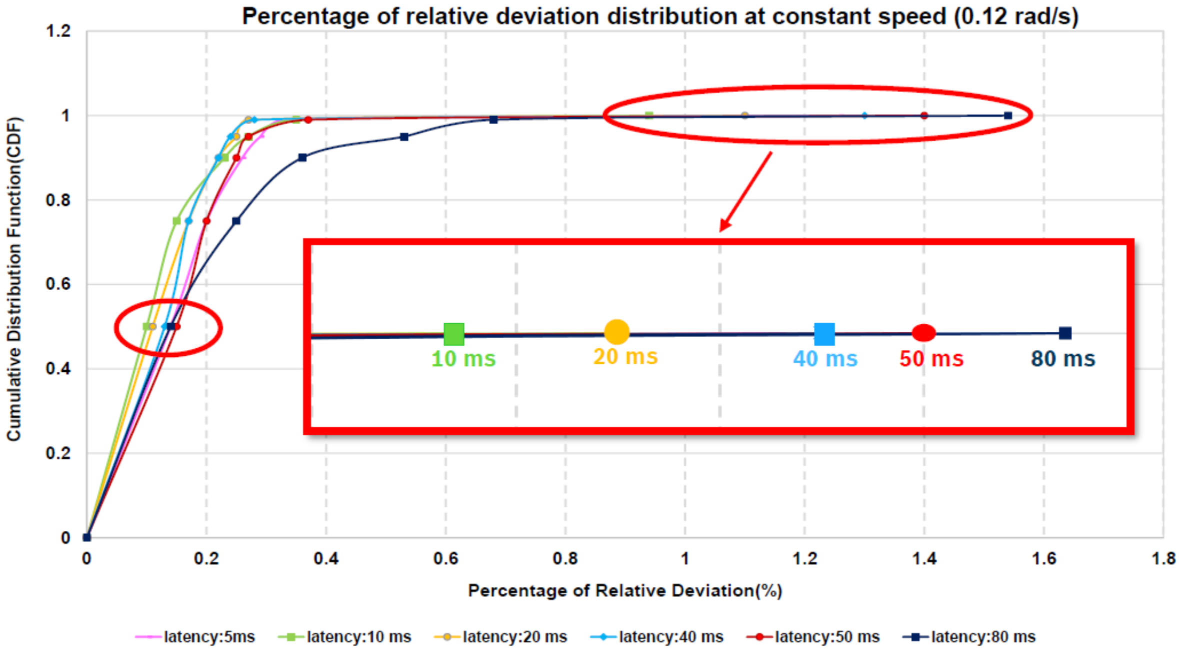


Figure 4-13: CDF of Relative Spatial Deviation in Percent for Various Latencies.

In Figure 4-14, the curves present the medians and 99th percentiles (solid and dashed lines, respectively) of the relative angular spatial deviation of a robot joint for increased latency (x-axis, constant part of $t_{\mathrm{UL}} + t_{\mathrm{DL}} + t_{\mathrm{U}}$) and for varying jitter (represented by the different colors, varying part of $t_{\mathrm{UL}} + t_{\mathrm{DL}}$). Note that the relative spatial deviation is displayed on a logarithmic scale and that the maximum angular speed is increased to 0.5024 rad/s. The following observations can be made: An increase of latency (above 40 ms) causes a higher inaccuracy of the robot's executed trajectory, which is even more obvious for higher percentiles, i.e. the 99th percentile in this case. However, for lower latency, i.e. increased relative jitter except for the red curve, the behavior is less clear but there are indicators that the curves tend to be bowl-shaped, which means that an increase of T_{U} can help compensate the negative impact of a high relative jitter on the trajectory accuracy up to the point, where the latency itself causes a deterioration of the joint precision that overweighs the compensation. Independent of this observation, it also becomes apparent that a very high jitter also dramatically decreases accuracy rendering a proper robot execution virtually infeasible.

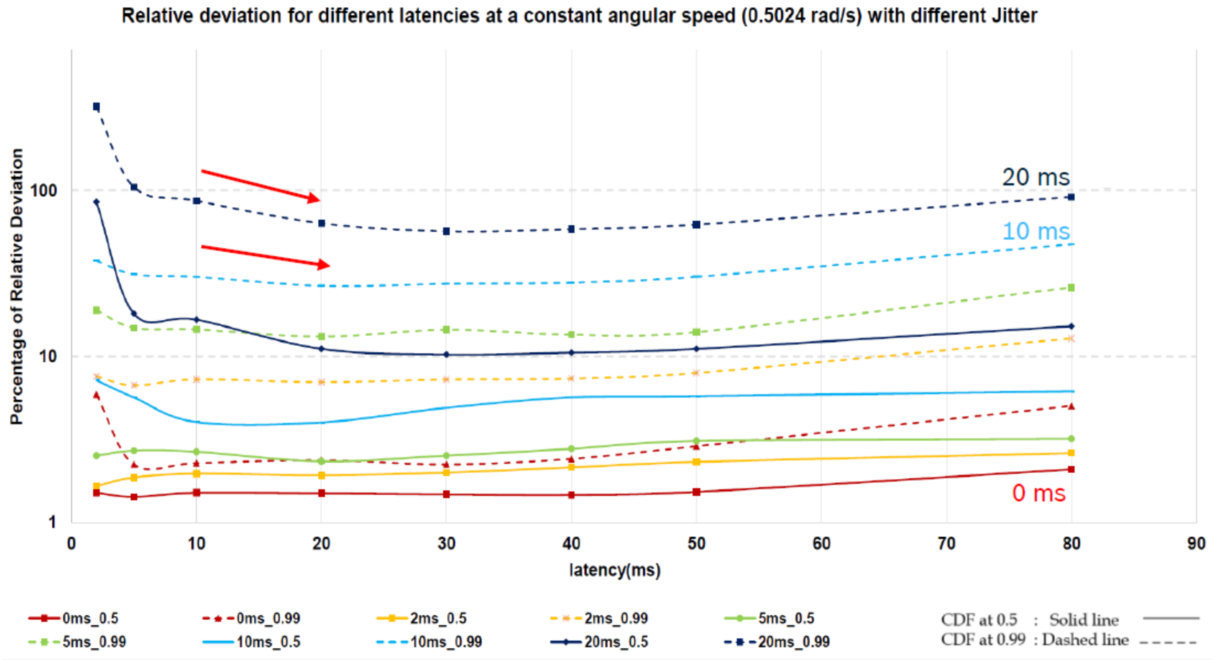


Figure 4-14: Percentiles of Relative Spatial Deviation in Percent by Varying the Absolute Jitter.

The performance evaluation framework illustrated above will be used for the performance assessment of the end-to-end system, which will be installed in the factory environment.

4.1.3 In-Lab Integration of Robot and Network

The 5G System for the European partners has been installed in the BOSCH Renningen research lab in March 2022 for in-lab integration testing with the FRANKA Emika robot. Figure 4-15 shows the overall system setup composed of the network in-a-box (see Section 4.1.1), an Airspan RU and the FRANKA robot.

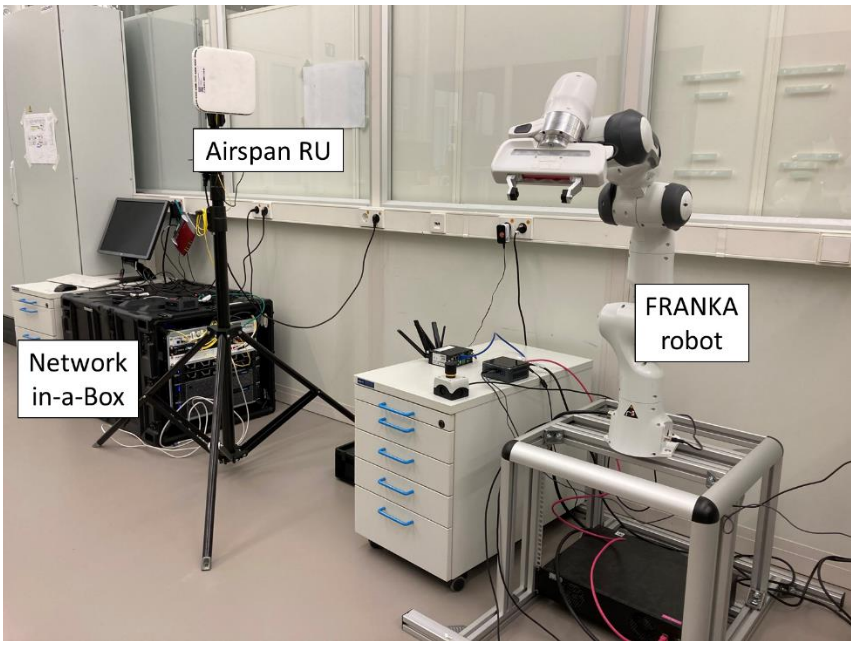


Figure 4-15: Overall System Integration of the Network and the FRANKA Emika Robot.

Figure 4-16 provides some more details of the system installation. The right picture shows the FRANKA arm and gripper, which are connected to the FRANKA Control unit. The Motion Service runs on an Intel NUC (#1) and is attached to the FRANKA Control unit, while the combination of the MS and the FRANKA Control unit is configured in a way, such that the Robot Control Thread of the MS sends packets to the FRANKA Control unit with a cycle time of 1 ms at maximum. The FRANKA Control unit employs all safety related functionalities. The Motion Service communicates receives the motion commands from the Motion Application via a Robustel R5020 5G Router. The left picture displays the network in-a-box including Athonet's 5G Core and Airspan CU and DU. At the moment, the Motion Application, i.e. the actual intelligence of the FRANKA robot, runs on another Intel NUC (#2) and is attached to Athonet's 5G Core via the MikroTik switch.

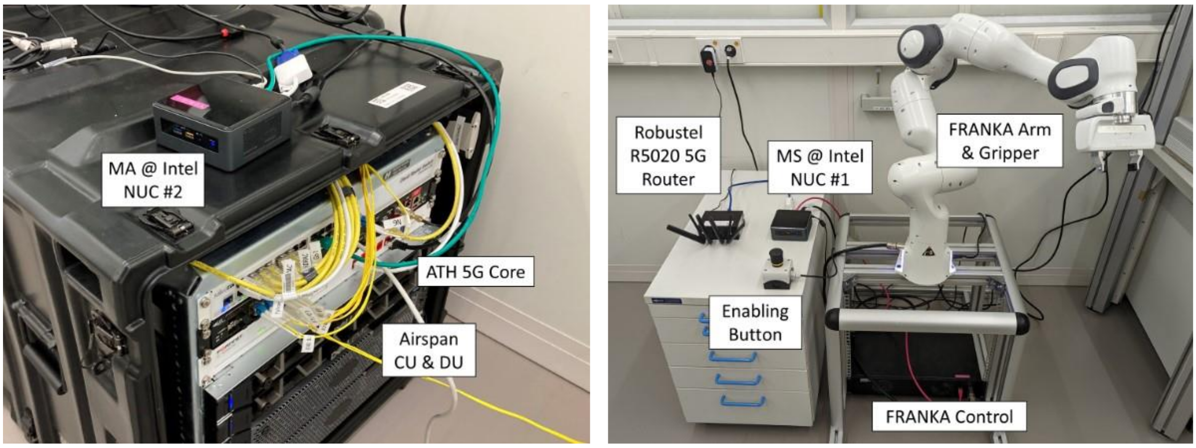


Figure 4-16: System Setup on the Network Side (left) and the Robot Side (right).

Integration and first performance test are being conducted in the Renningen lab environment before the entire system will be moved to the BOSCH factory floor.

4.1.4 Updated Time Plan

4.1.4.1 Phase 1

As per [1], Phase 1 entails ensuring interoperability between the NG-RAN infrastructure and the 5GC network as well the deployment of the all-in-one solution on EU Factory premises. While the interoperability activities were completed with both available gNBs and the 5GC-in-a-box, the on-premise installation of the solution was postponed to allow internal renovation activities of the BOSCH plant in preparation of pilot activities.

At the time of writing, the progress report and up-to-date time plan for Phase 1 is as follows:

Table 4-3: Time plan for Phase 1.

Task	Task owner (in bold) and responsible partners	Labs	Deadline	Notes
Initial bootstrap of O-RAN Airspan gNB	**HHI**	HHI	Completed	Preliminary testing of the apparatus (requires integration with a CN to work properly)
Shipping of ATH's network-in-a-box to HHI	**ATH**	N/A	Completed	/
In-lab integration of O-RAN Airspan gNB with ATH's 5GC	**HHI**, ATH	HHI	Completed	Integration with 5GC-in-a-box solution succeeded.
In-lab integration of Nokia	**HHI**, ATH	HHI	Completed	Integration with 5GC-in-a-box solution suc-

gNB with ATH's 5GC				ceeded.
VPN across sites and on-premises integration plan	**BOSCH**, HHI, ATH	BOSCH, HHI, ATH	Completed	Overall IP plan/service granting/traffic separation under discussion between BOSCH/HHI/ATH
Integration of O-RAN Airspan gNB and network-in-a-box at BOSCH Renningen	**HHI**	BOSCH	Completed	First deployment will be in the BOSCH factory of Renningen.
Moving to BOSCH Feuerbach	**BOSCH**, HHI, ATH	BOSCH	Postponed – scheduled within May 2022	Final deployment will be in BOSCH factory of Feuerbach. Integration activities will continue until the end of the project.

4.1.4.2 Phase 2

In parallel with the completion of Phase 1 activities, Phase 2 has officially started in January 2022. The objectives of this phase comprise:

- Setting up and configuring the Central Public Cloud, to be hosted by AWS and powered by Athonet's 5GC;
- Installation of ATH edge node at the enterprise HQ (HHI's premises).

Moreover, in addition to the original plan, to foster collaboration among the EU and TW partners, an additional gNB by ANI will be integrated at HHI.

The time plan for Phase 2 is as follows:

Table 4-4: Time plan for Phase 2.

Task	Task owner (in bold) and responsible partners	Labs	Deadline	Notes
Integration of 5GS with robot application at BOSCH Renningen	**BOSCH**	BOSCH	End of Apr. 2022	/
Setup of AWS Central Public Cloud solution powered by ATH 5GC	**ATH**	ATH	End of Apr. 2022	/
Remote integration of ANI's n78 gNB with ATH's 5GC	**ANI**, ATH	HHI	End of May 2022	Remote pre-test integration of ANI's n78 gNB with ATH's 5G core.

Shipping of ANI gNB to HHI	**ANI**	N/A	End of Jun. 2022	/
Shipping of ATH edge node to HHI	**ATH**	N/A	End of Jun. 2022	/
Integration of ANI gNB and ATH edge node in HHI's datacenter	**HHI**, ATH, ITRI, ANI	HHI	End of Jul. 2022	The control plane of the 5GC will be hosted on the Central Public Cloud as per the envisioned architecture – cf. Sec. 2.1.

4.2 Taiwanese System Integration Progress

This section is dealing with the TW system integration in the live industrial environment. It will describe the end-to-end system integration on the premises and followed by the work on inter-site use case: Remote expert support for process diagnosis.

4.2.1 Network Integration

Regarding the on-premise integration, the physical system architecture of shop floor is illustrated in Figure 4-17, which includes the 5G system, transport network and OT/CT integration. The setup will interconnect two main sites via VPN.

1. The facility at ITRI that represents an enterprise's data center.
2. The pilot production site (ITRI's IMTC, Intelligent Machinery Technology Center) that represents the enterprise's manufacturing site. It involves a machine room to host most of the network elements and a metal workshop.

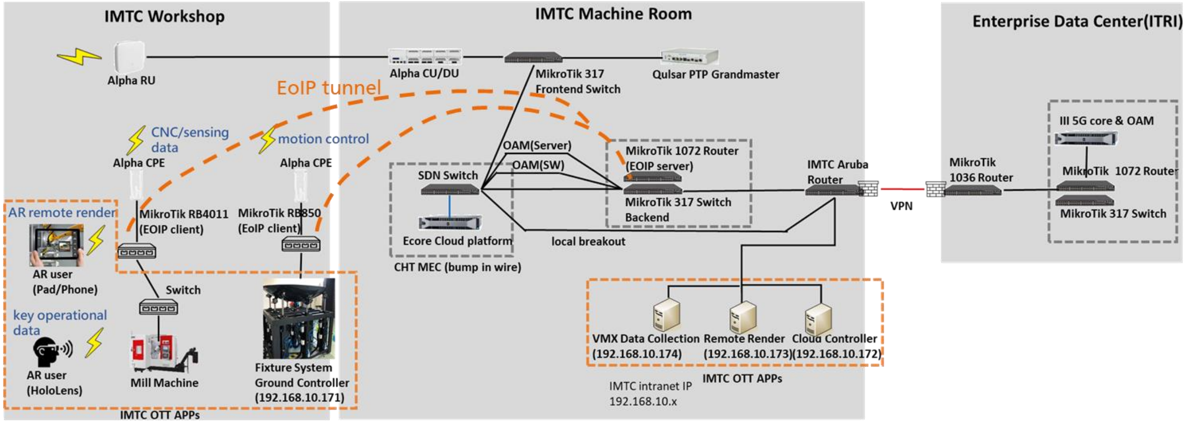


Figure 4-17: E2E network architecture of TW setup.

Figure 4-18 is the satellite map that shows the exact locations of ITRI and IMTC in TW, which are approximately 100 kilometers apart.

Figure 4-18: Satellite map.

The testbed covers RAN, 5G Core, MEC platform, transport network and vertical applications – see also [1]. The disaggregated RAN system is O-RAN-compliant and option 7.2 split is implemented. It consists of an RU running the low PHY and radio functions and a CU/DU server running the high PHY and higher layer protocols. The RU is mounted against H-shaped steel beam with around 4 meters high at the shop floor and operates at 4849.86MHz with 100MHz bandwidth, which is reserved for local private networks in Taiwan. The CU/DU is deployed in a controlled environment at IMTC machine room. 5G NR CPEs are used to provide wireless connectivity to the mill machine, fixture system and AR user.

The standalone (SA) 5G Core is hosted at ITRI that emulates the enterprise data center to cover the control-plane functions, which may include UE registration, security, session management, etc. In addition, O&M platform has been incorporated in the 5G Core to support network management. By using the bump-in-the-wire architecture, the MEC platform is transparently integrated between the base station and 5G Core, in the sense that it's not required to establish signaling connections with 5G network elements. In particular, the MEC routes the selected user-data stream to and from local OTT applications through decapsulation and encapsulation of packets. Since the traffic is terminated locally, data confidentiality and latency are ensured.

Regarding the transport network, in order to integrate the 5G network with the existing IT/OT infrastructure, Ethernet over IP (EoIP) tunnels have been established between two routers as shown in Figure 4-17 to support L2 tunneling integration. Re-configuration of shopfloor's existing wired networks including IP plan is minimized. In particular, the EoIP protocol encapsulates Ethernet frames and sends them to the remote side of EoIP tunnel, which enables the applications to exchange data in the same layer 2 domain.

The aforementioned 5G system has been deployed into the factory. Figure 4-19 shows pictures taken from the IMTC premises, where we can see the III 5G core network at the enterprise data center on the right, Alpha CU and DU of gNB and CHT MEC at the machine room in the middle. In addition, the radio unit is installed at the workshop.

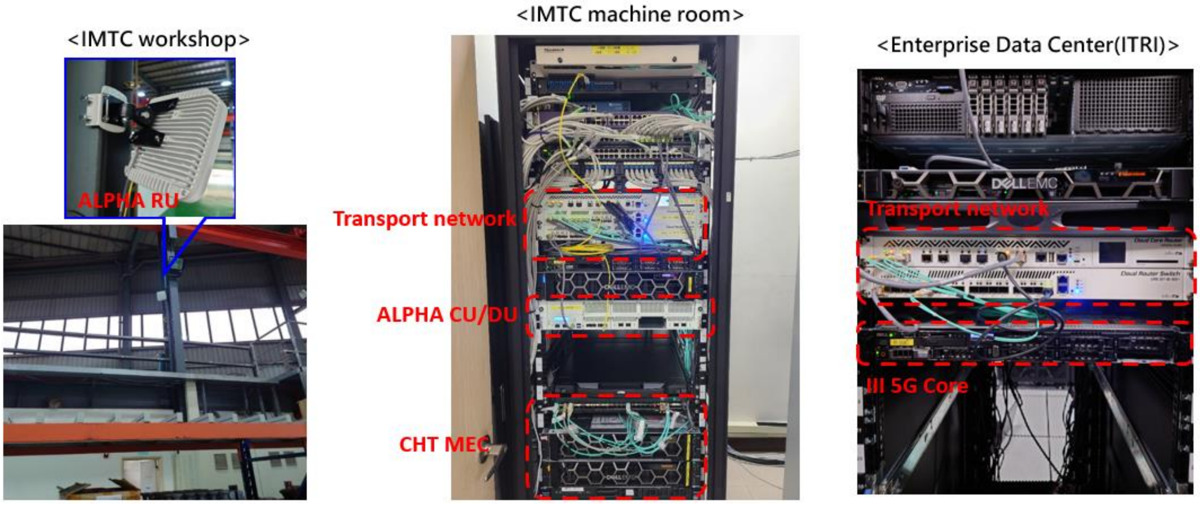


Figure 4-19: Taiwan in-factory integration.

Finally, three use cases have been selected and implemented at IMTC, which have been described in [6], namely:

1. Process Diagnostics by CNC and Sensing Data Collection (cf. UC-1 in [1],[2]).
2. Process Diagnosis Using Augmented/Virtual Reality (cf. UC-2 in [1],[2]).
3. Cloud-Based Controller (CBC, cf. [1] and the additional use cases proposed in [2])[2].

Figure 4-20 shows the area where the use cases are implemented. The radio unit of base station is marked with a purple cross and provides 5G connectivity to end devices. At the time of writing, these applications have been developed and tested via ethernet or Wi-Fi connections but have not yet been integrated with the 5G system. The end-to-end system is expected to be integrated after Phase 3 (cf. [1]) of the test program is concluded.

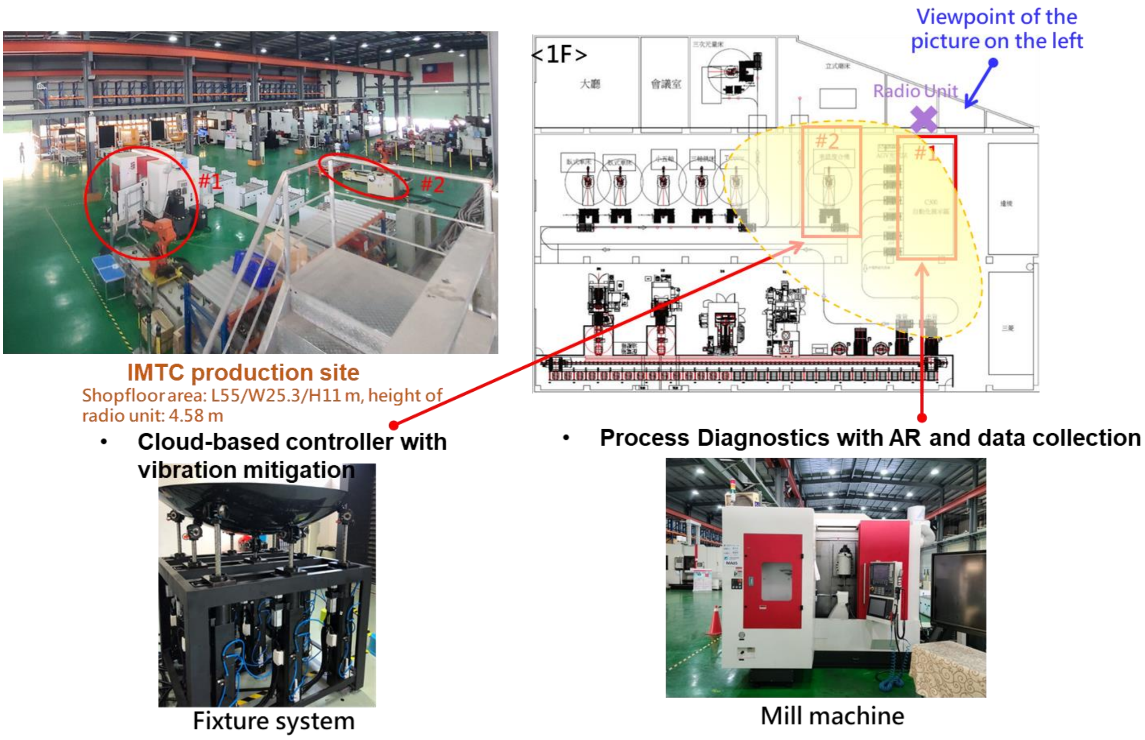


Figure 4-20: IMTC production site organization.

4.2.1.1 Preliminary Performance Evaluation

In this report, we have prioritized our test items for initial performance evaluation based on the test program proposed in Section 4.2.3 of [1], whose collected results we report in Table 4-5 (except for a selection of less relevant tests, as explained below). As detailed in Table 4-5, the Phase 1 test group includes 9 test cases that deal with essential procedures when the mobile device initiates and registers with the core network. It also verifies data offload and forward capabilities via the MEC platform and tests the transmission of L2 frames on top of the 5G system.

Our Phase 2 test group includes 8 valid test cases that focus on UDP/TCP performance measurements and round-trip latency between the User Equipment (UE) and applications. It is worth noting that both Phase 1 and Phase 2 test groups encompass in-lab and in-factory test results.

An important point to emphasize is our selection criteria for these test cases. In [1], a comprehensive list of items was proposed. However, for D5.2, we selected items that are critical and relevant to actual field conditions. For instance, test cases 2.5-2.16 deal with throughput at moderate-to-poor signal points, which are not particularly relevant in our practical field scenario where coverage is within a small range with strong signal points. Therefore, these items were not specially tested in the end.

Moreover, we have collected several essential parameters of the base station, which may influence the performance, in Table 4-6. Our rigorous approach ensures that our testing covers critical areas of performance under conditions that most closely resemble our actual field environment.

Table 4-5: Tests of Phase 1 and Phase 2.

Test ID	Test Item	Test Objective	Test Results
1.1	NG Setup	Successful NG interface setup between gNB and 5GC	Pass
1.2	UE Initial Registration with IMSI identity	UE initial registration with IMSI identity	Pass
1.3	UE Initial Registration with GUTI identity	UE initial registration with GUTI identity	Pass
1.4	PDUSession Establishment	Successful establishment of the PDU session	Pass
1.5	UE Deregistration	Successful deregistration procedure triggered by the UE entering flight mode	Pass
1.6	Access Network Release	Successful access network release procedure due to UE inactivity	Pass
1.7	UE-Triggered Service request	Successful mobile-originated service request procedure	Pass
1.8	NW-Triggered Service Request	Successful mobile-terminated service request procedure	Pass
1.9	Management of QoS flow by Allocation and Retention Priority (ARP)	Successful ARP configuration of a QoS flow, including ARP priority level, pre-emption capability, pre-emption vulnerability	Pass
1.10	Management of QoS flow by 5G QoS identifier(5QI)	Successful 5QI configuration of a QoS flow	Pass
1.11	N3 GTP-U processing (GTP decap/encap)	Successful encapsulation or decapsulation of the application packets to or from the UE	Pass
1.12	N3 GTP-U processing (data forward)	Successful data forwarding to the UPF if the traffic is not offloaded	Pass
1.13 (Additional)	L2 traffic via EoIP tunnel	Successful L2 data transfer on top of the 5G system	Pass
2.1	Average UDP DL Throughput at Cell Center	One UE successfully initiates Iperf UDP DL transfer at cell center with RSRP=-80dBm and record the average TPut	650Mbps
2.2	Average UDP UL Throughput at Cell Center	One UE successfully initiates Iperf UDP UL transfer at cell center with RSRP=-80dBm and rec-	60Mbps

Test ID	Test Item	Test Objective	Test Results
		ord the average TPut	
2.3	Average TCP DL Throughput at Cell Center	One UE successfully initiates Iperf TCP DL transfer at cell center with RSRP=-80dBm and record the average TPut	376Mbps
2.4	Average TCP UL Throughput at Cell Center	One UE successfully initiates Iperf TCP UL transfer at cell center with RSRP=-80dBm and record the average TPut	39.6Mbps
2.5	Average UDP DL Throughput at Cell Middle	One UE successfully initiates Iperf UDP DL transfer at cell center with RSRP=-90dBm and record the average TPut	Not tested due to strong signal strength within the small range of actual field coverage
2.6	Average UDP UL Throughput at Cell Middle	One UE successfully initiates Iperf UDP UL transfer at cell center with RSRP=-90dBm and record the average TPut	Not tested due to strong signal strength within the small range of actual field coverage
2.7	Average TCP DL Throughput at Cell Middle	One UE successfully initiates Iperf TCP DL transfer at cell center with RSRP=-90dBm and record the average TPut	Not tested due to strong signal strength within the small range of actual field coverage
2.8	Average TCP UL Throughput at Cell Middle	One UE successfully initiates Iperf TCP UL transfer at cell center with RSRP=-90dBm and record the average TPut	Not tested due to strong signal strength within the small range of actual field coverage
2.9	Average UDP DL Throughput at Cell Edge	One UE successfully initiates Iperf UDP DL transfer at cell center with RSRP=-110dBm and record the average TPut	Not tested due to strong signal strength within the small range of actual field coverage
2.10	Average UDP UL Throughput at Cell Edge	One UE successfully initiates Iperf UDP UL transfer at cell center with RSRP=-110dBm and record the average TPut	Not tested due to strong signal strength within the small range of actual field coverage
2.11	Average TCP DL Throughput at Cell Edge	One UE successfully initiates Iperf TCP DL transfer at cell center with RSRP=-110dBm and record the average TPut	Not tested due to strong signal strength within the small range of actual field coverage
2.12	Average TCP UL Throughput at Cell Edge	One UE successfully initiates Iperf TCP UL transfer at cell center with RSRP=-110dBm and rec-	Not tested due to strong signal strength within the small range of actual field

Test ID	Test Item	Test Objective	Test Results
		ord the average TPut	coverage
2.13	Multi-UE UDP DL at Cell Center, Middle and Edge	Three UE successfully initiates Iperf UDP DL transfer at cell center, middle and edge respectively and record the average TPut	Not tested due to not aligning with practical application scenarios
2.14	Multi-UE UDP UL at Cell Center, Middle and Edge	Three UE successfully initiates Iperf UDP UL transfer at cell center, middle and edge respectively and record the average TPut	Not tested due to not aligning with practical application scenarios
2.15	Multi-UE TCP DL at Cell Center, Middle and Edge	Three UE successfully initiates Iperf TCP DL transfer at cell center, middle and edge respectively and record the average TPut	Not tested due to not aligning with practical application scenarios
2.16	Multi-UE TCP UL at Cell Center, Middle and Edge	Three UE successfully initiates Iperf TCP UL transfer at cell center, middle and edge respectively and record the average TPut	Not tested due to not aligning with practical application scenarios
2.17	Average E2E Round Trip Time at Cell Center	One UE successfully initiates ping towards the application server at cell center and record the average round trip time	min/avg/max= 15/35/50 ms; loss rate=0%
2.18	Average E2E Round Trip Time at Cell Edge	One UE successfully initiates ping towards the application server at cell edge and record the average round trip time	min/avg/max<= 15/35/50 ms; loss rate=0%
2.19	Long Term (1 hr) Stability with Heavy Traffic	To verify the long-term stability with heavy traffic for 1 hour	Pass
2.20	Long Term (12 hrs) Stability with Heavy Traffic	To verify the long-term stability with heavy traffic for 12 hours	Pass
2.21	Long Term (24 hrs) Stability with Heavy Traffic	To verify the long-term stability with heavy traffic for 24 hours	Pass
3.1	Performance Evaluation using Traffic Profile of the AR Use Case	To assess the system performance using the traffic profile of the AR use case	22Mbps downlink transmission per UE and one-way delay below 15ms is required for a smooth user experience

Test ID	Test Item	Test Objective	Test Results
3.2	Performance Evaluation using Traffic Profile of the Data Collection Use Case	To assess the system performance using the traffic profile of the data collection use case	270 ms on average
3.3	Performance Evaluation using Traffic Profile of the Cloud-Based Controller Use Case	To assess the system performance using the traffic profile of the cloud-based controller use case	The objective is to suppress the vibration introduced by a shaker with frequency under 500 Hz. The test results show that 80% of the vibration has been mitigated in terms of magnitude
3.4	Performance Evaluation using Traffic Profile of the Combined Use Case	To assess the system performance using the traffic profile of all vertical applications at IMTC	Pass

Table 4-6: Parameters of the base station.

Parameters	Value
Center Frequency	4849.86MHz
Channel Bandwidth	100MHz
Subcarrier Spacing	30KHz
RU max Tx power	18dBm
RU Rx gain	15dB
Downlink MIMO layers	4(OLSM)
Uplink MIMO layers	1(Diversity)
TDD UL-DL config.	DDDSUU DDDD
TDD switching slot config.	D6G4U4
DL/UL MCS	20/20 or dynamic

The test results show that the basic control-plane function and user-plane data transfer of the 5G system are running live properly. In addition, the downlink and uplink TCP throughput requirements of the use cases have been fulfilled, while the critical latency requirements imposed by motion controls have not been met (see also 5G CONNI's [7]). In future integration, we plan to optimize the end-to-end latency and integrate the 5G network with vertical applications. QoS differentiation will be investigated to support diverse QoS requirements of different use cases.

4.2.2 Workshop Integration

The implementation of three aforementioned use cases have been described in 5G CONNI's [6]. This section deals with the update on the inter-site use case, namely: Remote expert support for process diagnosis, which is the extension of UC-2 (Process Diagnosis Using Augmented/Virtual Reality) by exchanging digital twin data across the two continental sites. Table 4-7 shows two proposed implementation options. As we can make use of the Dassault system for remote rendering, option 1 is preferred at the time of writing.

Table 4-7: Proposed architectures for inter-site use case.

Architecture	Implementation Requirements
Option 1: Remote Rendering with NVIDIA CloudXR SDK (with Dassault Soft license) (*CloudXR 3.0 not support Hololens 2)	• Workstation PC (NVIDIA Pascal GPU) with Dassault 3DExperience, linked with MEC. Use the Dassault product as-it-is. • Development effort base on Dassault SDK is required to link 3Dexcite with WebApi from ITRI • CloudXR developer license is required
Option 2: Remote Rendering with NVIDIA CloudXR SDK (without Dassault Soft license) (*CloudXR 3.0 not support Hololens 2)	• Workstation PC or rack server (NVIDIA Pascal GPU) , linked with MEC. • CloudXR developer license is required • Development effort based on CloudXR SDK • Development effort based on Unity or Unreal to develop SteamVR compatible Apps to show 3D scene of ITRI site

System architecture based on Option 1 has been implemented at ITRI site using dedicated wifi network to validate feasibility and functionality as shown in Figure 4-21. 3D models for ITRI demo site have been constructed in Dassault Systems software (the 3D Excite APP in the Dassault Systems 3D experience platform). When the 3D models were loaded in a workstation PC with NVIDIA GPU and the remote rendering package from NVIDIA (the CloudXR SDK), the 3D views can be rendered in the workstation PC and streamed to iPad in terms of video. The iPad in this use case was acting as a viewport of the 3D scene. When the user moved around the shop floor, the viewport is updated according to the IMU sensor from iPad. In this preliminary test, the measured network traffic for the video streaming of 3D views from workstation PC to iPad was 25Mbps/UE.

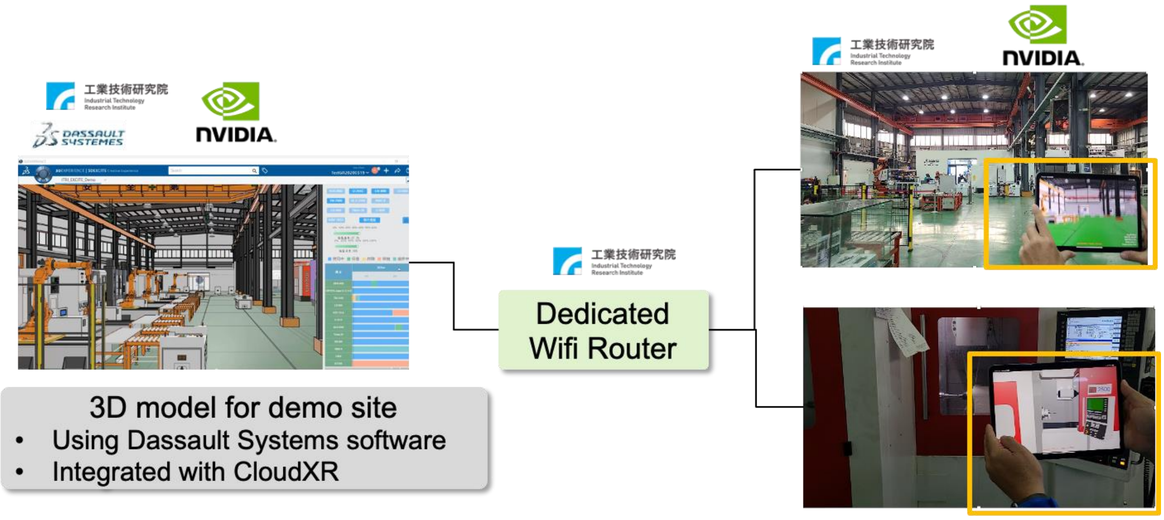


Figure 4-21: 3D model for ITRI demo site streamed to iPad.

4.2.2.1 Preliminary Performance Evaluation

In order to evaluate the impact of various 5G network impairments on UC-2, a network emulator is introduced to simulate bandwidth throttling, latency and packet loss. Figure 4-22 illustrates the network architecture where the emulator is integrated between the iPAD and render server. By default, it does not introduce any impairments and acts as a simple Ethernet bridge. Both server and iPAD are in the same layer 2 domain. Four test cases shown in Table 4-8 are designed to check the stability or performance of UC-2 with three different real-world impairments. The objective is to identify the non-functional requirements of the use case prior to integration with 5G network.

Table 4-8: test cases for preliminary performance evaluation

Test ID	Test Item	Test Objective
1	Remote render over ideal transport network	To record the baseline performance of UC-2
2	Remote render with simulated bandwidth throttling	To check the performance of UC-2 with simulated bandwidth throttling
3	Remote render with simulated latency	To check the performance of UC-2 with simulated latency
4	Remote render with simulated pack loss	To check the performance of UC-2 with simulated packet loss

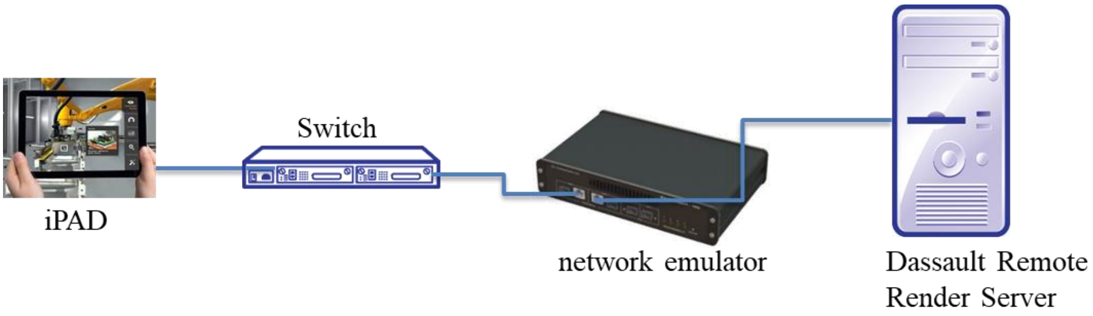


Figure 4-22: Network architecture for impairments emulation.

Figure 4-23 shows the preliminary test results over the ideal transport network. The dominant traffic is in the downlink direction and the throughput fluctuates between 2 and 18 Mbps, which depends on the movement, frames per second and resolution. In future work, we plan to incorporate the 3D model and introduce the impairments to evaluate the impact on the user experience of UC-2.

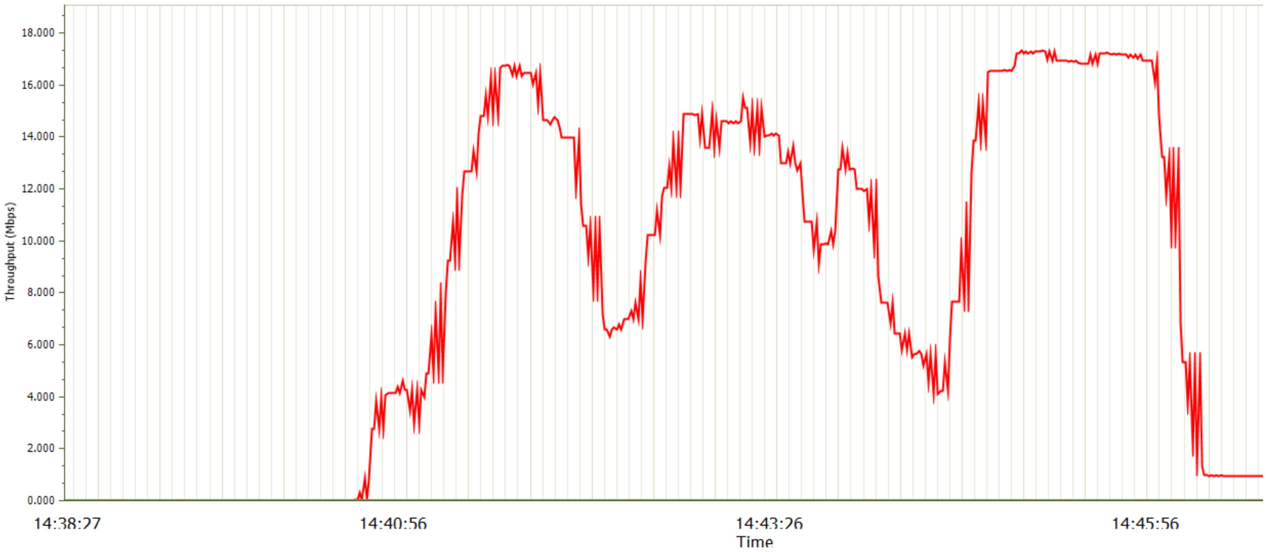


Figure 4-23: Preliminary traffic results.

4.2.3 Updated Time Plan

The time plan for in-lab and on-premises integration (see [1] for the definition of testing configurations A, B, and C) has been updated as follows:

Table 4-9: Time plan for in-lab and on-premises integration.

Task	Task owner (in bold) and responsible partners	Labs	Deadline	Notes
Phase 1 test cases with configuration A verified after 5GC upgrade	**ITRI**, ANI, III	ITRI	Completed	Phase1 and 2 with configuration A and C have been verified to ensure the E2E system is working properly, which covers RAN, 5G core and MEC.
Phase 2 test cases with configuration A verified	**ITRI**, ANI, III	ITRI	Completed	
Phase 1 and 2 test cases with configuration C verified	**ITRI**, ANI, III, CHT	ITRI	Completed	
On-premises integration plan	**ITRI**	N/A	Completed	The physical system architecture of the shop floor has been identified, which includes 5G system, transport net-

				work and OT/CT integration.
On-premises 5G system integration	**ITRI**, ANI, III, CHT	ITRI	Completed	The 5G network has been deployed into IMTC plant and basic control-plane and user-plane functions are running live properly.
Phase 3 test cases verified on the premises	**ITRI**, ANI	ITRI	End of Apr. 2022	Incorporate the traffic profile of use cases to make sure the throughput and latency requirements will be met.
Software of additional UC (cloud controller) virtualized and integrated to MEC platform	**ITRI**, /CHT	CHT, ITRI	End of Apr. 2022	The industrial KPIs will be monitored by CHT's ECoreCloud platform via SNMP protocol.
Integration of 5G with UC-1 and additional CBC UC	**ITRI**, ANI, III, CHT	ITRI	End of May 2022	/
Integration of 5G with UC1, UC-2, and additional CBC UC	**ITRI**, ANI, III, CHT	ITRI	End of Sep. 2022	/

4.3 E2E System Integration Time Plan

As reported in the previous sections, the consortium has been working towards the completion of the two continental in-factory testbeds featuring a fully operational local 5G system and applications. The remaining time until the end of WP5's activities will be devoted to finalizing the implementation of the centralized provisioning system and cross-testbed network interconnection, to fully deploying the Augmented/Virtual Reality for Process Diagnosis use case (cf. [2] and [3]), and to gathering the final validation and performance results. Table 4-10 summarizes the roadmap towards this goal.

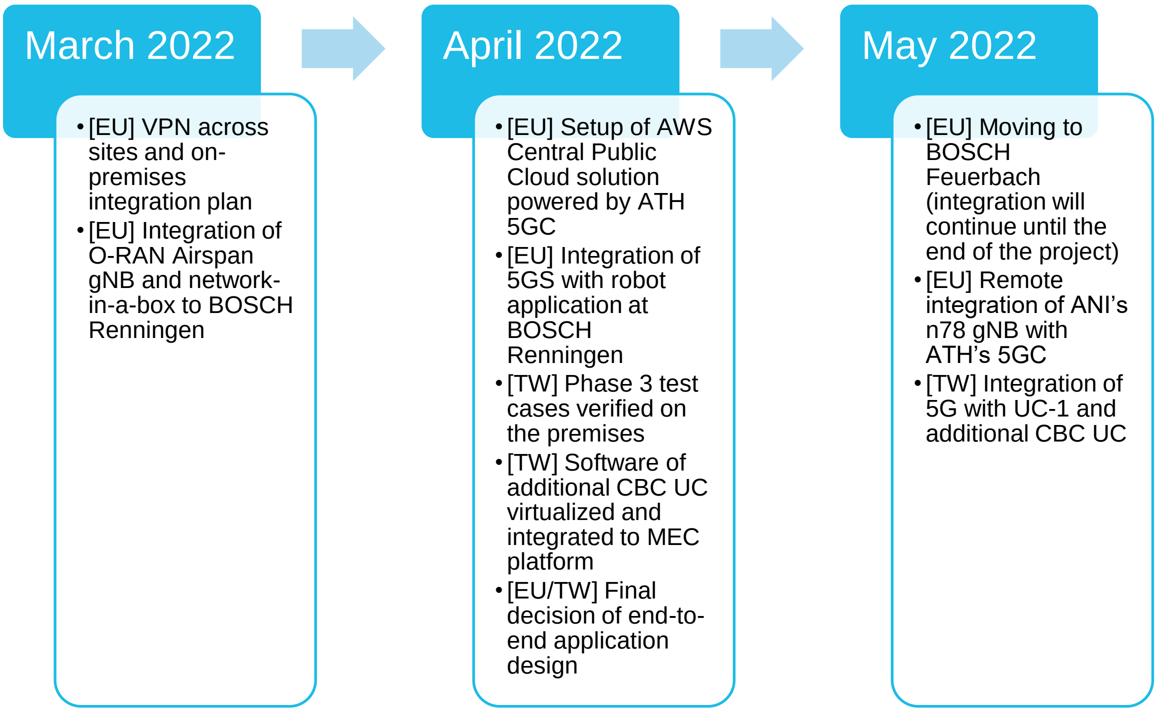
Table 4-10: End-to-end integration plan.

Task	Task owner (in bold) and responsible partners	Labs	Deadline	Notes
Final decision on end-to-end application design	**ITRI**, **BOSCH**	N/A	End of Apr. 2022	Alignment needed between the owners of the workshops (IMTC and Bosch Factory)
End-to-end application up and running at both workshops	**ITRI**, **BOSCH**	ITRI, BOSCH	End of Jul. 2022	/
Integration of centralized UE provi-	**III**, ATH, ITRI	III, ATH	End of Aug. 2022	The web portal developed by III is able to

sioning with III and ATH's 5G core				provision subscription data into III and ATH's UDMs via RESTful APIs.
Start of inter-site use case integration with local 5GS	**ITRI**, **BOSCH**	ITRI, BOSCH	End of Sep. 2022	Integration of application and 5GS at trial site.
Start of D5.3 preparation	**ALL**	N/A	End of Sep. 2022	/
E2E testbed validation	**ITRI**, ANI, III, CHT, BOSCH, ATH, HHI	ITRI, BOSCH	End of Oct. 2022	Validation of the EU-TW end-to-end 5G testbed with the inter-site use case.
Preliminary experimental results collection	**ITRI**, ANI, III, CHT, BOSCH, ATH, HHI	ITRI, BOSCH	End of Oct. 2022	The results may comprise local wireless link performance, edge computing functionality, and inter-connectivity capabilities. All of these results will be reported in D5.3.
Finalization of trials and D5.3 report	**ALL**	N/A	End of Nov. 2022	/

4.4 Summary of the time plans

This subsection contains a joint graphical summary of the time plans reported in Table 4-3, Table 4-4, Table 4-9, and Table 4-10.



March 2022

- [EU] VPN across sites and on-premises integration plan
- [EU] Integration of O-RAN Airspan gNB and network-in-a-box to BOSCH Renningen

April 2022

- [EU] Setup of AWS Central Public Cloud solution powered by ATH 5GC
- [EU] Integration of 5GS with robot application at BOSCH Renningen
- [TW] Phase 3 test cases verified on the premises
- [TW] Software of additional CBC UC virtualized and integrated to MEC platform
- [EU/TW] Final decision of end-to-end application design

May 2022

- [EU] Moving to BOSCH Feuerbach (integration will continue until the end of the project)
- [EU] Remote integration of ANI's n78 gNB with ATH's 5GC
- [TW] Integration of 5G with UC-1 and additional CBC UC

June 2022

- [EU] Shipping of ANI gNB to HHI
- [EU] Shipping of ATH edge node to HHI

July 2022

- [EU] Integration of ANI gNB and ATH edge node in HHI’s datacenter
- [EU/TW] End-to-end application up and running at both workshops

August 2022

- [EU/TW] Integration of centralized UE provisioning with III and ATH’s 5G core

September 2022

- [TW] Integration of 5G with UC1, UC-2, and additional CBC UC
- [EU/TW] Start of inter-site use case integration with local 5GS
- [EU/TW] Start of D5.3 preparation

October 2022

- [EU/TW] E2E testbed validation
- [EU/TW] Preliminary experimental results collection

November 2022

- [EU/TW] Finalization of trials and D5.3 report

5 Conclusions

The objective of WP5 (Integration, Demonstration & Verification) is to integrate within a single intercontinental testbed the components developed in WP4 within the E2E system designed in WP2, which covers RAN, 5G Core, MEC, and OTT applications, and considering the outcomes of WP3. [1] focused on the operational planning of the whole demonstrational setup and on the initial networking integration tests carried out at consortium partners' laboratories.

The present document, instead, reported the activities conducted in the second third of WP5, which covers a transitioning phase from in-lab testing to on-premises deployment. We provided further technical and implementation details on the local and end-to-end connectivity aspects, and the actual solution that 5G CONNI is exploiting to interconnect the EU and TW 5G core network instances. Moreover, we dove deeper into the specific implementations of the networks of the UE and TW setups. We also discussed the progress on the robot integration at BOSCH's premises, including some first performance results.

The work of WP5 will be further described in D5.3, due at the end of the project. It will cover the full E2E performance assessment of 5G CONNI's trial network, including detailed performance measurements and corresponding KPI analyses.

6 References

[1] 5G CONNI, "E2E in-lab system integration report," D5.1 report, WP5, June 2021.

[2] 5G CONNI, "Report on use cases & requirements," D1.1 report, WP1, July 2020.

[3] 5G CONNI, "Final report on private 5G network architecture and operator models," D2.2 report, WP2, September 2021.

[4] 5G CONNI, "Intermediate report on private 5G network architecture," D2.1 report, WP2, September 2020.

[5] M. Lind, "Real-time quintic Hermite interpolation for robot trajectory execution," *PeerJ computer science,* p. 13, 2020.

[6] 5G CONNI, "Final specification and implementation of the building blocks," D4.2 report, WP4, December 2021.

[7] 5G CONNI, "Report on measurements & network planning methodology," D3.1 report, WP3, August 2021.