Private 5G Networks for Connected Industries

Deliverable D5.1

E2E In-Lab System Integration Report

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Executive Summary

This document reports on the activities of the first nine months of 5G CONNI's Task 5.1: "Realization of the selected use cases". This task aims to integrate an end-to-end system in a lab environment, conducting connectivity and interoperability tests between European and Taiwanese sites.

This deliverable starts with an overview of the general 5G system architecture adopted by 5G CONNI. A functional architecture is defined, based on the motivating use cases (cf. D1.1[1]) and the corresponding models identified in D2.1[2]. This is followed by a presentation of the hardware and software components provided by the partners in order to build the test sites. Next, the initial testbed deployment plan is described, including a presentation of the preliminary integration tests and tools.

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

[2] Cf. 5G CONNI, D2.1, "Intermediate report on private 5G network architecture," Sep. 2020.

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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
AF	Application Function
AMC	Adaptive Modulation and Coding
AMF	Access and Mobility management Function
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
BOSCH	Robert Bosch GmbH (partner of the consortium)
CHT	Chunghwa Telecom Co. Ltd. (partner of the consortium)
CN	Core Network
CNC	Computer Numerical Control
COTS	Common Off-The-Shelf
CP	Control Plane
CPE	Customer-Premises Equipment or Customer-Provided Equipment
CPU	Central Processing Unit
CU	Central Unit
DN	Data Network
DNN	Data Network Name
DU	Distributed Unit
DX.Y	Deliverable X.Y (where X and Y are numbers)
E2E	End-to-End
eMBB	enhanced Mobile Broad Band
EU	European
gNB	gNodeB (5G base station using NR technology)
GPRS	General Packet Radio Service
GTP	GPRS Tunnelling Protocol
GUTI	Globally Unique Temporary ID
HHI	Fraunhofer Heinrich Hertz Institute (partner of the consortium)
HQ	Headquarters
III	Institute for Information Industry (partner of the consortium)
IMSI	International Mobile Subscriber Identity
IMTC	(ITRI's) Intelligent Machinery Technology Center
ITRI	Industrial Technology Research Institute Inc. (partner of the consortium)
I-UPF	Intermediate User Plane Function
KPI	Key Performance Indicator
LAN	Local Area Network
MAC	Medium Access Control

MANO	Management And Orchestration
MEC	Multi-access Edge Computing
MIMO	Multiple-Input Multiple-Output
MNO	Mobile Network Operator
NEF	Network Exposure Function
NG	Next Generation
NGAP	Next-Generation Application Protocol
NIC	Network Interface Controller
NID	Network ID
NPN	Non-Public Network
NR	New Radio
O&M	Orchestration and Management
OTA	Over-The-Air
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
PLMN	Public Land Mobile Network
QoS	Quality of Service
RAM	Random-Access Memory
RAN	Radio Access Network
RLC	Radio Link Control
RRC	Radio Resource Control
RU	Radio Unit
SA	Standalone
SBA	Service-Based Architecture
SCTP	Stream Control Transmission Protocol
SMF	Session Management Function
S/P-GW	Serving/PDN-Gateway
SSD	Solid State Drive
TAU	Tracking Area Update
TCP	Transmission Control Protocol
TW	Taiwanese
UC	Use Case
UDM	Unified Data Management
UDP	User Datagram Protocol
UP	User Plane
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communications
UE	User Equipment
VM	Virtual Machine
VPN	Virtual Private Network
WLAN	Wireless Local Area Network

1 Introduction

The objective of WP5 (Integration, Demonstration & Verification) is the construction of an end-to-end (E2E) trial deployment to demonstrate the technological enhancement developed in the 5G CONNI project for the Smart Industry. To achieve such a target, three steps are envisioned:

1) Design, verification, and testing of the 5G system components, comprising radio access network (RAN), 5G core (5GC), multi-access edge computing (MEC) servers, and over-the-top (OTT) applications in each partner's (or group of partners') laboratory environment;
2) Integration of communication system components to create European (EU) and Taiwanese (TW) continental testbeds;
3) Integration of the E2E intercontinental testbed, implementation of the use case, and performance assessment.

Specifically, during the initial months of work of WP5, the consortium partners have carried out the first actions towards the realization of step 1 by performing in-lab acceptance tests and preliminary integration activities. We want to remark that interoperability and performance tests are in their initial phase and will be conducted systematically throughout the entire duration of WP5 until verification of the entire E2E system functionalities. In particular, these tests will ensure that all the subsystems work together properly for the defined use cases.

1.1 Scope

This document offers a pragmatic description of how the different network components provided and developed by the partners in WP4 are integrated together into the testbed, which is aligned with the use cases defined by the consortium in D1.1[1] (and further developed in D2.2) and based on the inputs provided by the other WPs.

More details on the innovative building blocks of private 5G networks (such as edge computing, industrial application, radio network and core network) are available in the initial specification deliverable (D4.1[3]). WP4 continuously feeds the integrated testbed reported in this deliverable with advanced components. Moreover, while planning the E2E trial, we are considering the outcomes of WP3 concerning the channel models derived from the measurement campaign carried out within WP3. We are also building on the methodologies studied in WP3 to provide an efficient management of radio and MEC resources.

This document:

- Describes in detail the architectural components[4] and system implementation aspects that characterize 5G CONNI's testbeds.
- Focuses on interoperability aspects and details the steps through which we are building our unified intercontinental testbed by connecting the involved EU and TW facilities.
- Provides a description of each partner's technological contributions to the testbeds, from both a hardware and a software point of view.
- Reports on the system integration phases and the initial testing tools.

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[3] Cf. 5G CONNI, D4.1, "Initial specification and implementation of the building blocks," Mar. 2021.

[4] [Note added at the moment of submitting v1.3 of this document, in June 2023] The testbeds' functional architecture proposed here will slightly evolve and be updated in D5.2 and D5.3 to take into account requirements and constraints that raised after D5.1's initial submission.

1.2 Structure

The main structure of this deliverable is summarized as follows. Section 2 briefly introduces the intra- and inter-enterprise scenarios, discussed in D2.2 in more detail. It also characterizes the suitable core network (CN) solutions and overall network architectural deployments for these scenarios. Then, it presents the EU and TW testbeds and how they are merged into a single E2E setup to validate 5G CONNI's conceptual approach and technological solutions. Further, Section 3 is dedicated to an exhaustive inventory of the hardware and software equipment that composes (or is under consideration to compose) the testbeds. Section 4 describes the system integration plan scheduled until the end of 2021 (month 27 of the project); successive integration details and results will be provided in D5.2 and D5.3. Section 4 also lists some preliminary configuration tests that have been carried out on the main fundamental components of 5G CONNI's testbeds. Finally, Section 5 concludes this document and sketches the ways forward for the WP5 activities.

2 High-level E2E Prototype Architecture

This section provides the description of the E2E testbed scenario and the overall networking architectural prototype.

2.1 Scenarios

Different use case scenarios for private 5G inter-site deployments, i.e., having multiple interconnected or integrated 5G network infrastructures at different physical or geographical locations, will be described in 5G CONNI's D2.2. We introduce here some information about them, useful to put in the right context the architectural choices that characterize 5G CONNI's testbeds, presented in Section 2.2, 2.3, and 2.5.

In principle, the scenarios can be grouped into two categories: *intra-enterprise* and *inter-enterprise* scenarios. In intra-enterprise scenarios, user plane data is produced and consumed inside a single enterprise, which nevertheless can have different geographical sites at considerable distance from each other, such as office buildings and production plants. To design a (private) mobile network that serves such scenarios, three general architectural choices can be considered for the CN and its functions. In a first framework, such functions can be distributed across the different locations of the enterprise, for example for increased performance or reliability reasons. Though, this choice comes at the cost of a more complex management. A second possibility consists instead of having all CN functions centralized. This has the benefits of reduced complexity and effort in managing and orchestrating the network across the sites. Finally, a third intermediate stage is conceivable, called a *hybrid* model. In it, a central CN is accompanied by the replication of certain critical control plane functions at specific distributed sites, e.g., in a production plant to enable services like ultra-reliable low-latency communications. Such network functions may include the application function (AF) that, for instance, requires to interact with the 5GC and the manufacturing applications; or, for confidentiality reasons, the user plane function (UPF) in its role as a gateway towards a data network or a (central) database. Data exchange between distributed end points, which are all connected to the respective local private 5G networks, can take place through secured connections either in the same data network or between data networks. Data flows that remain in the same network or security domain can also remain routed inside the 3GPP network by cascading user plane functions and making use of the intermediate UPF (I-UPF) concept[5]. As a matter of fact, from a service-level point of view, there is no practical difference between an approach based either on VPN connectivity or UPF chaining between the edge site and the control center. Anyway, whereas the 3GPP technical specification foresees the enablement of such a UPF chaining approach, it is worth remarking that we are considering the context of non-public networks (NPNs) as opposed to that of public land mobile networks (PLMNs). Thus, not all the features and capabilities described by the technical specifications are applicable to the context of private networks. The UPF chaining approach is one example, as it is more adapted for a nation-wide, stratified/layered network rather than a dedicated, topologically simpler/flattened network. In general, the redundant deployment of CN functions over different sites of the enterprise has to be put in place only if it brings operational benefits that fully compensate the resulting complexification at the network management level.

In contrast to the intra-enterprise scenarios, inter-enterprise scenarios include business cases where the user plane data is shared among different enterprises. In such a framework, communication protocols and network architectural choices must obey even more strict secu-

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[5] Cf. 3GPP, TS 23.501, "System architecture for the 5G System (5GS)".

rity mechanisms. It is possible that in such scenarios different private 5G networks originate from different vendors and are operated by different MNOs or service providers. The standard solution for interoperability and intercommunication is then to establish secured connections between the end points or between services that are part of the data networks of the involved enterprises, such as VPN connections. External, secured databases or a database hosted by one party can be used to exchange information between enterprises. Similar to the intra-enterprise case, some critical control plane network functions should be replicated for reliability and security purposes.

5G CONNI's trial deployment is conceived to demonstrate in a real setting the features of a network architecture that connects different sites and satisfies the functional requirements of the considered scenarios (see also 5G CONNI's D1.1[1] and D2.2). The testbed is made of an EU setup and a TW setup, interconnected into a single innovative intercontinental E2E framework. In the following, we will describe the details of each continental component[4].

2.2 European Setup

The EU setup will interconnect three main sites:

1. Some physical offices at HHI that represent an enterprise's headquarters (HQ).
2. A factory (BOSCH's premises) that represents the enterprise's manufacturing site.
3. A central cloud, separate from the HQ and the manufacturing site.

Over these three sites, as depicted in Figure 2-1, two complementary CN deployments will be put in place to provide the whole setup with the required networking features and functionalities. All CN hardware and software components will be supplied by ATH.

The first deployment is *hybrid* (in the sense described in Section 2.1), and it involves the enterprise's HQ and the central cloud: the control plane network functions of a 5GC reside at the central cloud and a UPF is deployed at the HQ to serve the data traffic generated from or directed there. At the factory, instead, a dedicated *fully on-site* 5GC including both user and control planes is deployed to manage the network of the manufacturing site.

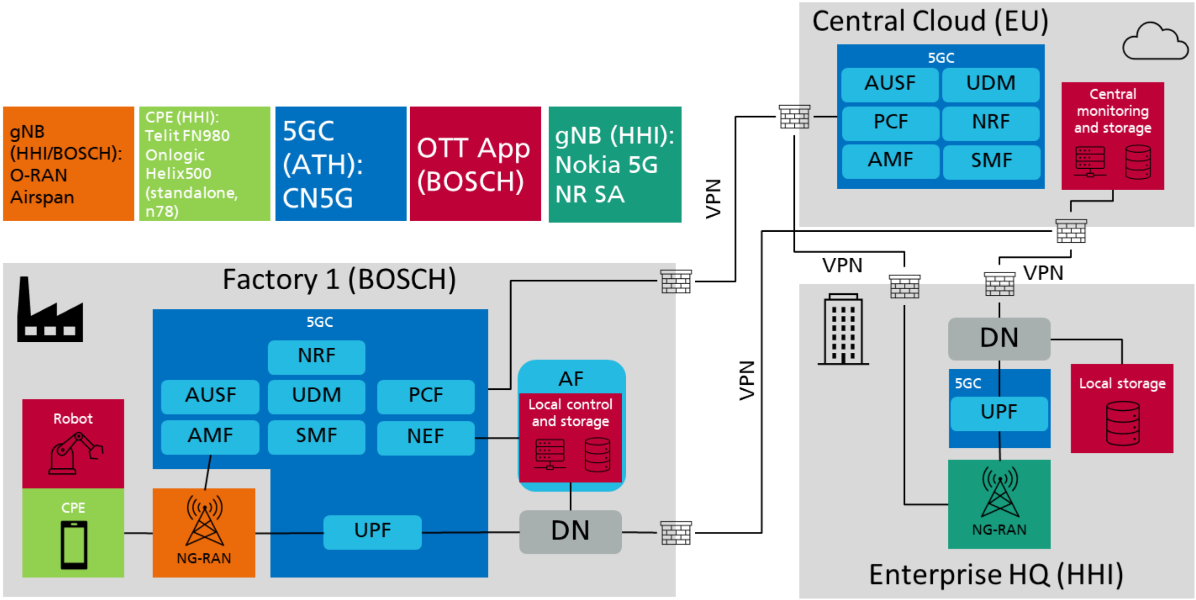

Figure 2-1: EU setup

This architectural choice allows to maintain the factory's traffic local and therefore:

1. To increase the overall plant's security, preventing confidential information from travelling between different sites.
2. To enable edge computing by directly steering the traffic generated by the wireless devices towards the edge servers (and *vice versa*), where a dedicated BOSCH-owned OTT application function (AF) runs.

Notice that the two solutions – fully on-site and hybrid – are respectively the evolution in a 5G framework of the "distributed EPC" and the "distributed S/P-GW" deployment approaches for MEC proposed by ETSI[6].

The traffic local breakout implemented at the factory reduces latencies and, in general, is an enabler for URLLC. Moreover, in such a setup the factory is *de facto* served by two CNs and, in case of failures or malfunctioning of the CN functions deployed on premise, their role can be temporarily taken by the functions of the centralized CN at the cloud (and *vice versa*). This increases the robustness of the network for a streamlined operation of critical automated tasks.

In addition, both the factory and the HQ will be supplied with next-generation (NG) RAN equipment both disaggregated, O-RAN-compliant and not, made available by HHI to support 5G wireless access over the frequencies between 3.7 and 3.8 GHz reserved for private networks in Germany. In line with 5G CONNI's vision, this is another crucial technological choice that guarantees a higher-quality and more performing radio coverage of the two sites, compared to older-generation solutions. A more detailed description of the involved hardware and software for the user equipment (UE), the radio access equipment, the core network, and the edge computing infrastructure is given in the Section 3.

Finally, we will implement VPN tunneling for each point-to-point connection of the transport network between the centralized cloud and the HQ or the factory. Notice that all three sites will have a common PLMN ID and, thus, the same network ID (NID). This is coherent with the intra-enterprise scenario discussed in the previous section. Nonetheless, UEs residing in different sites will be distinguishable by leveraging independent UDM groups.

From the applicative point of view, the use case at BOSCH's factory is being implemented as a robot platform with edge intelligence and control (see UC-3 in 5G CONNI D1.1[1]). The robot control function in the edge cloud is being designed to dynamically adapt to changing conditions of the communication system. Therefore, it communicates with other 5G-specific functions to exchange measurement data, which is then used to improve the robustness, speed, and accuracy of the robot movements. In particular, the control loop cycle time is managed depending on the potentially varying E2E latency of the 5G link between the robot entity and the edge server.

In the case of the enterprise's HQ represented by the part of the network deployed at HHI's facilities, the UPF deployed on the network edge terminates the user plane of the HQ's UE to serve a different kind of traffic compared to the manufacturing plant: this concerns mostly the latency requirements, as the HQ's traffic is more related to monitoring, maintenance or administrative tasks. The transport network interconnecting these locations provides access to components such as a central database or interfaces exposed by, for example, the application functions running at the factory. Notice that in the case of the 5G CONNI system, inter-

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[6] Cf. ETSI White Paper No. 24, "MEC Deployments in 4G and Evolution Towards 5G", Feb. 2018.

connectivity is provided by site-to-site VPNs as described above but might also be provided by other means such as Carrier Ethernet services in practical deployments.

2.3 Taiwanese Setup

The TW setup will interconnect two main sites:

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.

The 5G network logical architecture of the Taiwanese trial site is illustrated in Figure 2-2.

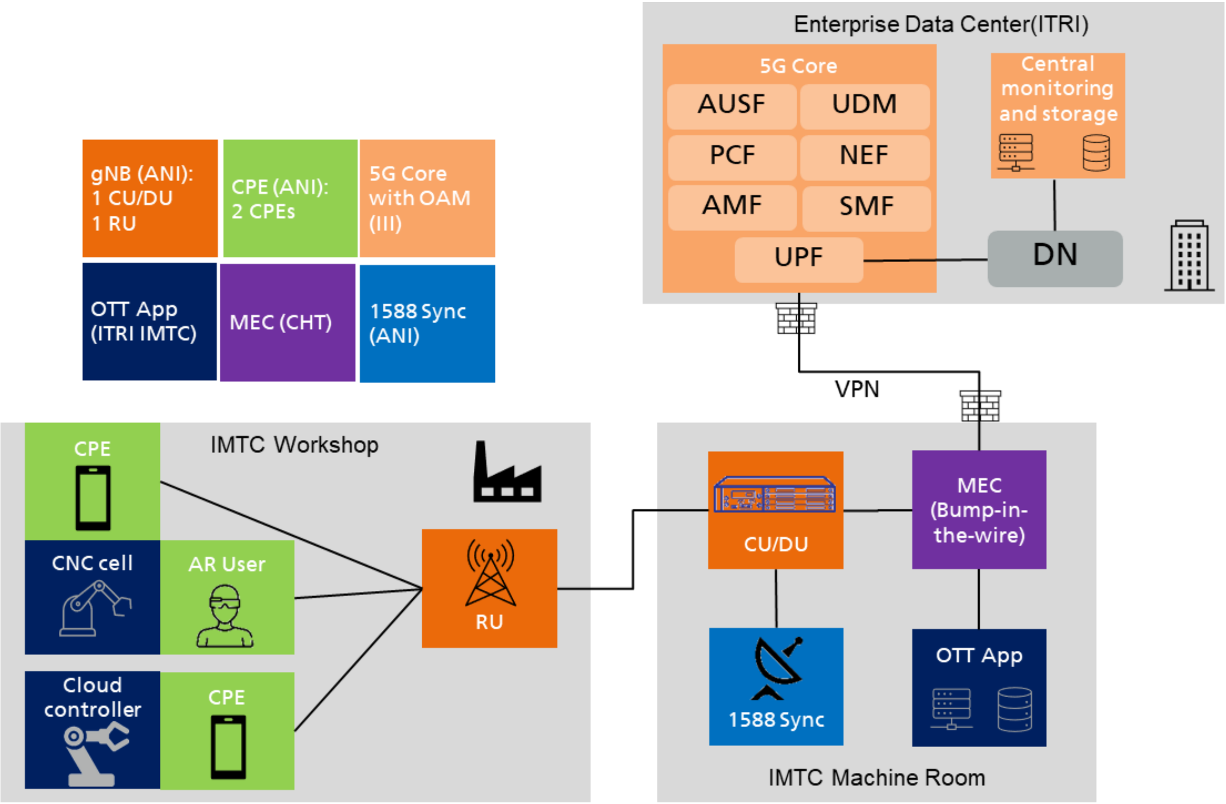


Figure 2-2: Network architecture for the Taiwanese demo site

This setup incorporates RAN, 5G Core, MEC platform, central monitoring system, and vertical applications. The disaggregated RAN system supplied by ANI is O-RAN-compliant and the option 7.2 split is implemented, which consists of a Radio Unit (RU) transmitting and receiving in the range 4.8GHz to 4.9GHz reserved for local private networks in Taiwan and a Central Unit (CU)/Distributed Unit (DU) server running the higher layer protocol. The RU is deployed at the shop floor based on the cell planning in WP3 and connected to the CU/DU located in the machine room via fiber. In addition, a 1588 grand master provides precise synchronization for the RAN through Precision Time Protocol.

The standalone (SA) 5GC supplied by III supports service-based architecture (SBA) and complies with 3GPP Release 15+. Moreover, the 5GC will be deployed at the enterprise's data center and equipped with a central monitoring system which enables five O&M features, namely:

1. Fault Management,
2. Configuration Management,
3. Accounting Management,
4. Performance Management, and
5. Security Management.

In addition to the 5GC, we can integrate other network elements (e.g., base stations, MEC platform, and applications) to the monitoring system through appropriate APIs or northbound interfaces. For URLLC use cases with stringent latency requirements, it is beneficial to monitor QoS information as input for the application to adapt the operational mode.

The local breakout of user-plane traffic is enabled by the MEC platform deployed on the premises of IMTC. By using the bump-in-the-wire architecture, the MEC platform supplied by CHT is transparently integrated between the base station and the 5GC without signaling connections, which makes it easy to deploy. In particular, the MEC routes the selected user-data stream to and from local applications through decapsulation and encapsulation of packets. Since the traffic is terminated locally, data confidentiality and latency are ensured. In addition, the application service is hosted by a dedicated server and will be virtualized and integrated to the MEC platform, which would be beneficial for URLLC applications.

Finally, the secured inter-site connection between the IMTC and enterprise data center will be realized by the VPN and firewall gateway. The detailed hardware and software information of the 5G system will be described in Section 3.

The following use cases will be implemented at IMTC and served by the 5G system described above.

1. Process Diagnostics by CNC and Sensing Data Collection (cf. UC-1 in D1.1[1]): This use case requires eMBB capabilities of 5G network in the uplink direction. Various sensors will be attached on the machine to collect all necessary physical quantities to analyze the machining process. In the meantime, the updated model parameters and threshold values will be transferred back to the on-line monitor system to fit the actual machining parameter.
2. Using Augmented/Virtual Reality for Process Diagnosis (cf. UC-2 in D1.1[1]): This use case tries to utilize the high data rate along with low latency properties of 5G communication and establish a wireless virtual reality or augmented reality system to help process engineers set up work pieces or monitor abnormal conditions during milling process. The process engineer can observe machining conditions in a more intuitive way and shorten the trial-and-error process planning time.
3. Cloud-based Controller for Fixture System (cf. the additional use cases proposed on D1.1[1], Section 2.5): This use case consists of actuators, processes, and sensors, which are equipped at physical machines. A distributed motion controller implements the derivation of the motion commands generated by the interpolator module in the edge cloud, which are sent to the control loop to generate pulse commands to an actuator. Communication KPIs, such as service availability, reliability, packet error rate, end-to-end latency, are crucial to this use case.

2.4 Comparison Between EU Setup and TW Setup

The following table summarizes the main features of the two setups:

	EU Setup	**TW Setup**
Operator model	Fully on-site (Phase 1), then with an additional hybrid configuration (Phase 2)	Fully on-site at the enterprise's HQ
RAN configuration	Disaggregated O-RAN compliant, all-in-one	Disaggregated O-RAN compliant
CN configuration	Fully on-site at the manufacturing site (Phase 1), then with an additional hybrid configuration (Phase 2) involving a private or public cloud (cf. Section 4.1.2) and partial replication of the control plane	Fully on-site (centralized at the company's private cloud)
MEC configuration	Distributed 5GC, distributed UP	Bump in the wire

2.5 Envisioned E2E Prototype Architecture

The 5G CONNI's E2E testbed architecture merges into a single framework the EU and the TW setups presented in the previous subsections, with the goal of building a prototype of intercontinental company network deployment that benefits from the technological innovations developed by the project.

A representation of the E2E system architecture[4] is given in the following figures:

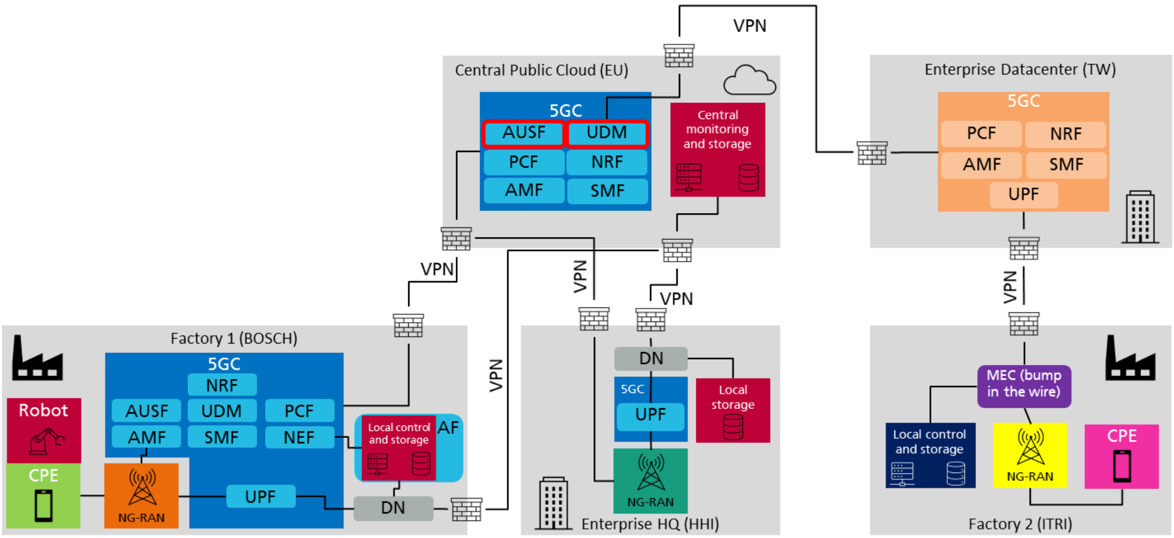
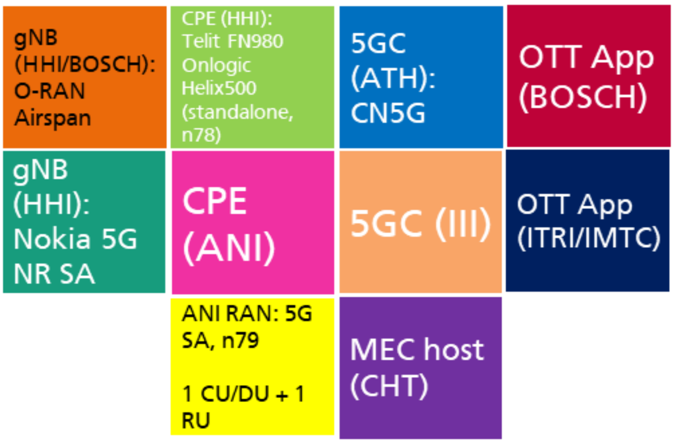


Figure 2-3: EU-TW joint setup



gNB (HHI/BOSCH): O-RAN Airspan

CPE (HHI): Telit FN980 Onlogic Helix500 (standalone, n78)

5GC (ATH): CN5G

OTT App (BOSCH)

gNB (HHI): Nokia 5G NR SA

CPE (ANI)

5GC (III)

OTT App (ITRI/IMTC)

ANI RAN: 5G SA, n79

1 CU/DU + 1 RU

MEC host (CHT)

Figure 2-4: Legend of the architectural components of the EU-TW joint setup

At first glance, a reader may think that the intercontinental setup substantially coincides with the simple juxtaposition of the two continental testbeds. This is not fully true, though. There exists indeed a key integration solution that needs to be leveraged to enable the efficient E2E interconnection of the two deployments: the network authentication modules at the 5GC level will be shared. Concretely, this means that the whole intercontinental setup will depend on a single Authentication Server Function (AUSF) and a single Unified Data Management (UDM), both located at the European central cloud[7]. This solution was devised by the consortium to streamline the integration process of the two setups and minimize the number of required structural adaptations to obtain from them a single networking framework. In spite of this, notice that redundant instances of these modules (and of the other control plane functionalities) will still be available at the EU manufacturing site to maintain the robustness and resiliency deployment choices described in Section 2.2. Then, coherently with the transport network implementation among the different sites of the EU setup, the connectivity between the 5GC at the EU central cloud and that in the TW setup will be realized via VPN tunnelling.

The jointly shared network authentication modules in the 5GC help reducing the configuration effort for the use case of shipping production assets or production lines. As described in D2.2, this cross-border, intra- or inter-enterprise use case can entail shipping entire production lines to other plants, even across countries. Such lines can include a large number of 5G devices, including sensors and actuators, that would need considerable reconfiguration effort in the case where two separate private 5G networks are not designed for interoperability in such circumstances. Once the same AUSF and UDM are reused and provide the pre-configured subscriber and QoS profiles, there is no additional IT and network configuration overhead once the production assets and production lines are reassembled at the new location. Furthermore, the profiles are anyway already aligned with the purpose and type of the production system, particularly in terms of QoS requirement, network slices, etc. Summarizing, the following benefits can be achieved:

- Reduced effort to configure subscriber and QoS profiles.

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[7] [Note added at the moment of submitting v1.3 of this document, in June 2023] As explained in D5.2 and D5.3, this solution has evolved after the initial submission of D5.1, still maintaining the benefits described here. In the final intercontinental testbed architecture, copies of AUSF and UDM will be present at both the EU and the TW sites. Such copies are maintained synchronised via a common provisioning system, designed and implemented in the second part of WP5's work. Such a choice yields a higher tolerance to possible faults (e.g., connectivity losses between the TW site and the central cloud do not cause AUSF and UDM unreachability) and reduced latencies for operations that involve the UDM or the AUSF at the TW site (via the use of the local copies).

- Reduced risk of misconfiguration and employment of production line-specific profiles.
- Short stand-still times of the production assets and lines.

The use case that will be tested over the inter-site setup is an extension of the Augmented/Virtual Reality for Process Diagnosis use case (cf. D1.1[1] and D2.2). We remark the impossibility by the consortium of controlling the transport network that supports the intercontinental traffic exchange. Therefore, latency-critical applications cannot be fully addressed by the intercontinental setup. In the inter-site scenario, a remote expert and a shop floor operator will be located in different countries to simulate a technical support scenario from machine builder to customer or from HQ to overseas production facilities. Secured connection between two sites is the priority, rather than low latency. By doing so, experts from the enterprise's HQ can support manufacturing sites all around the world and:

- Reduce traveling cost for collaboration.
- Quickly deploy new manufacturing sites while keeping the core technology within the HQ and provide necessary support by using digital twins in the cloud computing platform.

Further details on the integration and implementation activity and results about the E2E testbed and the deployed use cases will be provided in D5.2 and D5.3.

3 Hardware and Software Setup

The following subsections provide the component-by-component inventory and the technical specification of the hardware and software equipment involved and integrated (or in consideration to be) in the EU and TW setups, organized as follows:

1. End devices, consisting of both traditional UEs such as smartphones and tablets and robots/workstations integrated with Customer Premise Equipment (CPE).
2. Radio access equipment (two base stations that will be deployed in the EU setup, one in the TW one).
3. Core network and MEC equipment at both sides.

Remark: whenever necessary, the list of hardware and software below may be subject to changes in the coming months, based on discussions among consortium partners and to better fit the use case or deployment requirements.

3.1 End Devices

3.1.1 European Side

At the EU factory (BOSCH), the following robot will be used for the demonstration of UC-3 (robot platform with edge intelligence and control, cf. D1.1[1]):

Hardware	**Software**
Franka Emika Panda Robot • 7-degrees-of-freedom robot arm for research purposes • Ethernet, TCP/IP and UDP/IP for real-time commands • Firmware 1.3.2 • Control sampling frequency: 1kHz between controller and arm (to be extended by an edge cloud-based closed-loop control)	Franka Emika Panda Robot • Libfranka 0.5.0 (C++ Library)
Note: for preliminary implementation and testing purposes, a workstation is used to emulate the edge cloud server to be used in the integrated testbed. The workstation is equipped with a 100BASE-TX network card (Intel I219-V) and uses an Ubuntu 16.04 LTS Xenial Xerus and PREEMPT_RT patched kernel 4.14.78-rt47.	

In order to provide wireless connectivity to the robot, several alternatives are being considered by partners. A final decision will be reached in the coming months of integration. The components under evaluation are:

Hardware	**Software**
Telit FN980 M.2 data card • Qualcomm SDX55 based • 5G 4 × 4 MIMO support • USB 3.1 Gen 2 / PCIe Gen3	Linux with ModemManager, NetworkManager
Robustel R5020 Industrial 5G Router • 5G 4 × 4 MIMO support • 3x 1 GBase-T Ethernet • WiFi 802.11ac • RS232 / RS485 • DiDo	Robustel RobustOS

Hongdian X2 5G IoT Gateway / Router • 5G 4 × 4 MIMO support • 4x 1 GBase-T Ethernet • WiFi 802.11ax	N/A

On the other hand, at the EU enterprise's HQ (HHI), traditional tablets will be used:

Hardware	**Software**
Samsung GALAXY Tab S7 FE 5G • CPU Qualcomm SD 750G • Modem Qualcomm SD X55 • 4 GB RAM	Android 11.0

3.1.2 Taiwanese Side

This section describes the end devices operating at the TW manufacturing site (ITRI).

The CNC cell used to demonstrate UC-1 ("Process diagnostics by CNC and Sensing Data collection") and UC-2 ("Using AR/VR for process diagnosis"), described in D1.1[1], is as follows:

Hardware	**Software**
CNC Machine Tool Travel • Multi-task machine tool with five axes • X-Axis Travel mm 560 • Y-Axis Travel mm ±125 • Z-Axis Travel mm 560+93 • W-Axis Travel mm 910 • B-Axis Rotating Angle degree -20˚~200˚ • C-Axis Rotating Angle degree 360˚ CNC Data Collection for AR/VR and Analysis • Industrial PC • Intel Celeron J1900, 4GB DDR3 LMemory • GbE, 4XUSB	CNC Machine Tool Controller • Siemens 840D Solution Line with OPCUA data interface CNC Data Collection for AR/VR and Analysis • Operating System: Windows 10 Embedded

The cloud-based controller of a fixture system (cf. the additional use cases proposed in D1.1[1], Section 2.5) that operates at the TW factory (IMTC) is described in the following table:

Hardware	**Software**
3X2 POGO ARRAY • Each POGO uses two motors to control 3-degrees-of-freedom for fixture purposes. • Ethernet, TCP/IP for real-time commands.	3X2 POGO ARRAY • L2100 motion controller 109.06.03 (C Library) Cloud Controller (first step for implementation and testing purposes)

- Control sampling frequency: 4kHz between controller and Servo Driver (to be extended by a Ground Controller-based closed-loop control) Cloud Controller (first step for implementation and testing purposes) - Workstation with 1000BASE-TX network card (Intel I210) Ground Controller (first step for implementation and testing purposes) - Workstation with 1000BASE-TX network card (Intel I210)	- Windows Embedded Standard 7 Service Pack 1 - 32-bit operating systems Ground Controller (first step for implementation and testing purposes) - Windows Embedded Standard 7E Service Pack 1 - 32-bit operating systems - INTime version 5.2.14234, Patch level 14234

Finally, the CPEs that provide 5G connectivity to the appliances are described in the following table:

Hardware	Software

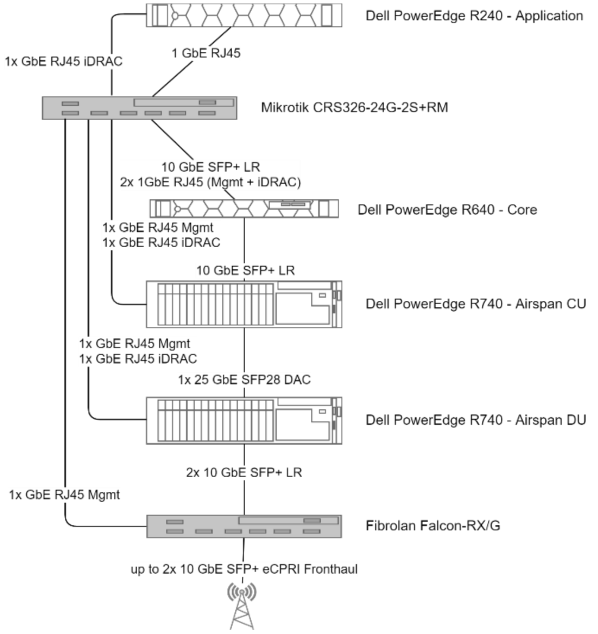
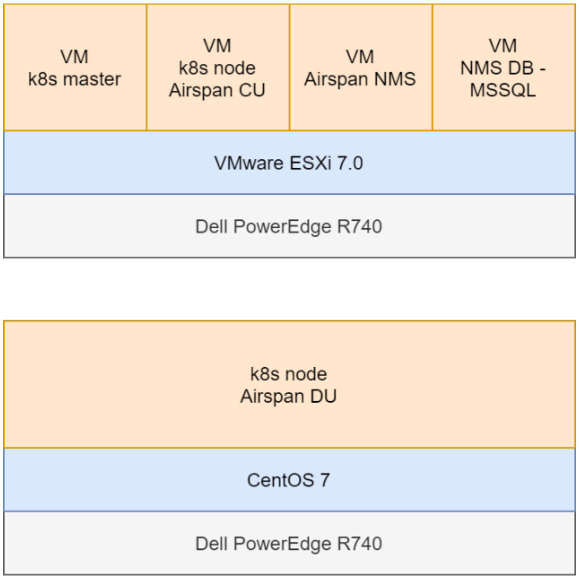
5G NR CPE
- 5G NR Sub-6: Base on Qualcomm SDX55
- CPU: Qualcomm IPQ6010
- WiFi: 802.11ax 2x2
- Interfaces:
  ○ 2X LAN Ethernet- 1GE
  ○ WLAN (802.11ax)
  ○ USB 2.0 Type A
  ○ DIDO
  ○ RS232C/RS485
  ○ Bluetooth 5.0
AR/VR user device
- Microsoft Hololens 2
	5G NR CPE
	- Operating System: Linux
	AR App for Process diagnostics
	- Customized Hololens App developed with Unity3D/C#
	VR App for remote expert
	- Customized App based-on Dassault Systems 3D Experience and 3D Excite developed with C#

3.2 Radio Access Equipment

3.2.1 European Side

The radio access equipment deployed at the EU factory (BOSCH's premises) is described in the following table:

Hardware	Software
O-RAN Rack Physical	O-RAN Rack Virtual Machines

	
RAN Edge Server: Dell PowerEdge R740 • CPU: Intel® Xeon® Gold 5218R • RAM: 160 GB • SSD: 480 GB • 2x Intel® XXV710 (4x 25 GbE) • 1x Intel® XL710 (2x 40 GbE) • 4x 1 GbE	Hypervisor: • VMware ESXi 7.0 Operating System: • CentOS 7/8 Applications: • Kubernetes Master • Airspan OpenRANGE vCU ○ CP/UP Split Deployment via 3GPP E1 Interface • Airspan ACP (NMS) • MS-SQL Database

RAN DU Server: Dell PowerEdge R740
• CPU: Intel® Xeon® Gold 5218R
• RAM: 256 GB
• SSD: 480 GB
• 1x Intel® XXV710 (2x 25 GbE)
• 1x Intel® XL710 (4x 10 GbE)
• Accelerator card: Silicom Pomona Lake
	Operating System:
	• CentOS 7
	Applications:
	• Airspan OpenRANGE vDU
	  ○ 3GPP Split 2 - F1 Interface towards CU
	  ○ RAN Split 7.2x towards RU

Radio Unit: Airspan AirVelocity 2700 • NR Band n78 • 4T4R (4x 250 mW) • 100 MHz Bandwidth • SFP+ port • Synchronization: PTP, SyncE • Power: 48V DC, 50W	• O-RAN Split 7.2a
RAN Switch: Fibrolan Falcon RX/G • 12x SFP+ • 8x SFP28 • PTP, SyncE w/ ITU G.8275.1 profile • GNSS Receiver • External Sync IO (1PPS/10 MHz)	

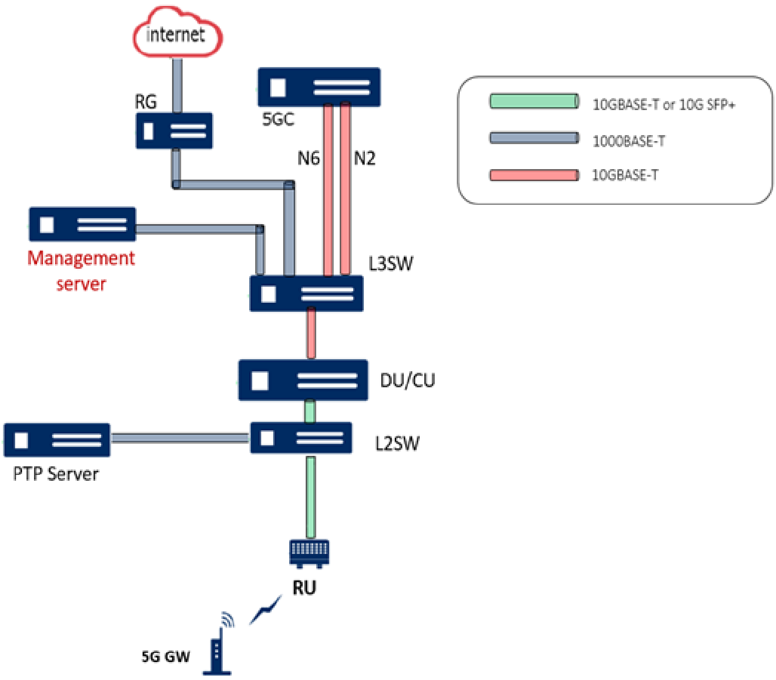
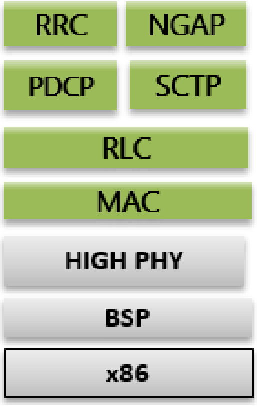
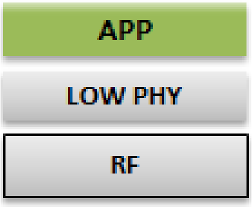
As for the radio access equipment deployed at the EU enterprise’s HQ (HHI), it is described in the following table:

Hardware	**Software**

Nokia AirScale
• AMIA System Module Subrack
• ASIK 5G Common Unit
  ○ 2x SFP28 backhaul
• ABIL 5G Capacity Unit
  ○ 16x8 100 MHz MIMO layers
  ○ 2x SFP28 eCPRI fronthaul
• AEQE mMIMO Radio Unit
  ○ NR Band n78
  ○ 64T64R (64x 35 dBm)
  ○ 100 MHz Bandwidth
	N/A

3.2.2 Taiwanese Side

The radio access equipment deployed at the TW manufacturing site is described in the following table:

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)	CU/DU  RU 

3.3 Core Network and MEC Equipment

3.3.1 European Side

As far as the EU factory environment is concerned, we highlight that the CN and MEC equipment are embedded in the O-RAN rack will provide a fully on-site solution comprising the mobile core and edge computing server close to the RAN equipment. The following figure shows the detail of the O-RAN rack composition.

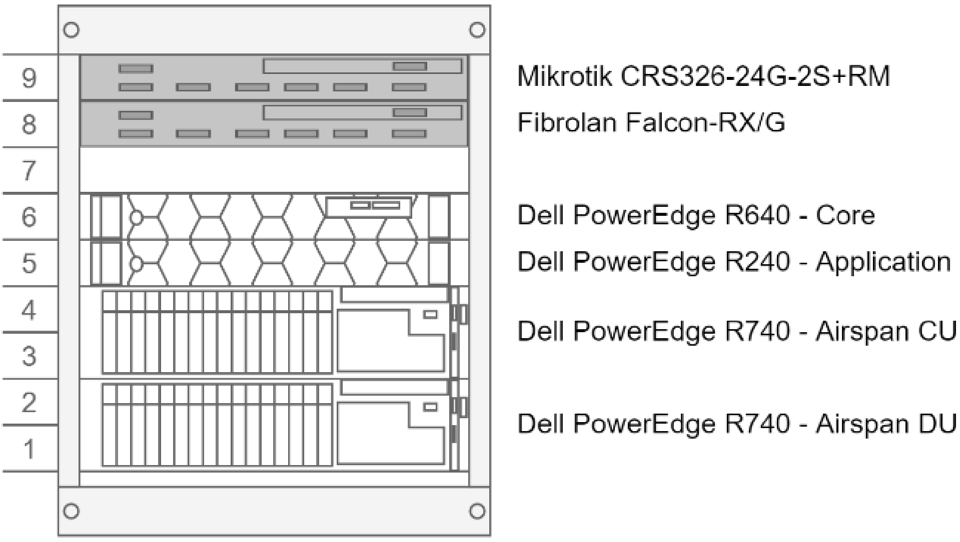


Figure 3-1: O-RAN rack, integrating core network and MEC equipment for the EU factory.

3.3.1.1 Core network

The core network equipment deployed at the EU factory is described in the following table:

Hardware	Software
Dell R640: • Intel Xeon CPU Gold 6140 2.3G, 18C/36T • 128 GB RAM • 2 x 600 GB 15K rpm SAS 12Gbps (RAID 1) • 2 x 32 GB microSD (RAID 1) • 2 x Hot-plug, Redundant Power Supply (1+1), 750W • 2 x 10 GbE • 8 x 1 GbE	VMs: • 5G CN – Athonet's Griffone Hypervisor: • VMware vSphere Essentials Operating System: • CentOS

At the enterprise's HQ, instead, the following CN edge node will be deployed:

Hardware	Software
Dell R640: • Intel Xeon CPU Gold 6140 2.3G, 18C/36T • 128 GB RAM • 2 x 600 GB 15K rpm SAS 12Gbps (RAID 1)	VMs: • UPF/SMF Hypervisor: • VMware vSphere Essentials

• 2 x 32 GB microSD (RAID 1) • 2 x Hot-plug, Redundant Power Supply (1+1), 750W • 2 x 10 GbE • 8 x 1 GbE	Operating System: • CentOS

3.3.1.2 *Multi-access Edge Computing*

As said previously, the MEC equipment hosting the BOSCH AF is integrated in the O-RAN rack that will be deployed at the EU factory, and its specifications are as follows:

Hardware	**Software**
Dell PowerEdge R240 • CPU: Intel® Xeon® E2134 • RAM: 16 GB • SSD: 1 TB • 2x 1 GbE	Hypervisor • VMware ESXi 6.7 Edge cloud controller: • A state-of-the-art-based[8] Motion Application in the edge cloud (written in Python) controls the robot movements at a slightly higher cycle time than 1 ms (acc. 5G CONNI D1.1) Extension of robot SW • Robot movements are interpolated and executed through a Franka Motion Service[8] (written in C++) • Franka Motion Service uses libfranka; see Section 3.1.1

3.3.2 Taiwanese Side

3.3.2.1 *Core network*

The CN equipment deployed at the TW data center is described in the following table:

Hardware	**Software**
5GC Server: Dell PowerEdge R630 • CPU: Intel® Xeon® E5 2600 v4 • RAM: 64GB DDR4 up to 2400MT/s • DISK: 0.96TB hot-plug SATA SSD SmartNIC: Agilio CX 2x10GbE • Interfaces: 2-port 10GbE, SFP+ • Memory: 2GB DDR3 onboard memory	5GC Software Platform: • Kubernetes Scheduler • Kubernetes API server 5GC Application: • AMF/SMF/AUSF/UDM/UPF Operating Systems: • Red Hat Enterprise Linux (RHEL), CentOS, Ubuntu Hypervisors: • Linux KVM

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[8] M. Lind, "Real-time quintic Hermite interpolation for robot trajectory execution," *PeerJ, Computer Science*, 2020.

3.3.2.2 Multi-access Edge Computing

The MEC equipment deployed at the TW manufacturing site is described in the following table:

Hardware	**Software**
Control Node Server: Dell R740xd • CPU: 2*Intel® Xeon® Gold 6254, 3.10 GHz, 18cores • RAM: 256 GB • DISK: 1.2TB • NIC: 4* GE4 port (Intel Chip) Compute Node: Dell R740xd • CPU: 2*Intel® Xeon® Gold 6254, 3.10 GHz, 18cores • RAM: 256 GB • DISK: 1.2TB • NIC: 4* GE4 port (Intel Chip) • 4 port Intel Corporation Ethernet Controller X710 for 10GbE SFP+ • 4 port Intel Corporation I350 Gigabit Network Connection SDN Switch Edge-Core 5812-54X-O-AC-F • 48 SFP + support 10GbE (DAC, 10GBASE-SR / LR) or 1GbE (1000BASE-T / SX / LX) • PicOS	Platform: • ECoreCloud MANO • Openstack Control • Openstack Compute VNF: • Mobile Edge Enabler Control Plane • Mobile Edge Enabler Data Processor

4 System Integration

This section gives an overview of the system integration plan for the EU and TW setups, with a specific focus on the activities that will be carried out until the end of year 2021 (month 27 of the project's lifetime). Further information on this integration and the plan for integration and performance tests during the last nine months of 5G CONNI's will be provided in D5.2.

4.1 European System Integration

The deployment of the EU setup will be carried out via two implementation phases:

1. First, the implementation of the fully on-site 5GC at the factory.
2. Second, the extension towards the proposed inter-site hybrid architecture.

As an additional preliminary phase, in order to push the remote integration of components as soon as they are available, the EU partners are testing their equipment from their own remote labs, before concretely moving to the first phase described above. In the preliminary testing phase,

- ATH provides access to their *Open5G* implementation of the 5GC on AWS[9];
- The base stations for the factory environment and the emulated enterprise HQ (see Sec. 3.2.1) are connected to the 5GC instance on the cloud.

While the 5GC comes already tested internally by ATH, the remote integration requires a series of tests, which is as follows:

Testing Category	Feature Tested
Attach procedures	Attach a user with correct PLMN
	Attach a user with the correct PLMN
	Attach with a valid IPv4 DNN
	Attach with an invalid IPv4 DNN
	Attach with 2 valid IPv4 DNN
	Attach with 1 valid IPv4 DNN and one invalid IPv4 DNN
	Attach with a valid IPv6 DNN
	Attach with an invalid IPv6 DNN
	Attach with 2 valid IPv6 DNN
	Attach with 1 valid IPv6 DNN and one invalid IPv6 DNN
	Attach with a valid IPv4v6 DNN
	Attach with an invalid IPv4v6 DNN
	Attach with 2 valid IPv4v6 DNN
	Attach with 1 valid IPv4v6 DNN and one invalid IPv6 DNN
Idle and Connected State	Go Idle and exit from Idle with one session
	Go Idle and exit from Idle with two sessions
	Go Idle and exit from Idle due to a Paging with one session
	Go Idle and exit from Idle due to a Paging with two sessions
Detach	Detach a user with a session
	Detach a user with two sessions
	Detach for Timeout

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[9] See http://www.open5g.cloud/.

TAU Procedure	TAU Procedure
Traffic	Uplink Traffic
	Downlink Traffic

In future deliverables we will report on the results of these tests.

4.1.1 Phase 1

The fully on-site architecture leverages ATH's proprietary software mobile core, with the following features:

- It runs on common-off-the-shelf (COTS) hardware servers in a virtualized environment.
- Both 4G (EPC) and 5G (5GC) mobile core technologies are supported.
- Base stations (gNBs) from various vendors can be integrated.
- It can support OTT application functions running as close as possible to the mobile core (and BOSCH's in particular), as it integrates an edge computing platform.

At the time of writing, the time plan for the implementation of phase 1 is as follows:

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)
In-lab integration of O-RAN Airspan gNB with ATH's 5GC	**HHI**, ATH	HHI	End of July 2021	Integration should happen between HHI's premises and Open5G on AWS
In-lab integration of Nokia gNB with ATH's 5GC	**HHI**, ATH	HHI	End of July 2021	Integration should happen between HHI's premises and Open5G on AWS
VPN across sites and on-premises integration plan	**BOSCH**, HHI, ATH	BOSCH, HHI, ATH	End of August 2021	/
Shipping of ATH's network-in-a-box to HHI	**ATH**	N/A	End of August 2021/Beginning of September 2021	/
Shipping of O-RAN Airspan gNB and network-in-a-box to BOSCH	**HHI**	N/A	End of September 2021	/
On-premises integration	**HHI**, BOSCH, ATH	BOSCH	End of December 2021	As far as the successful networking configuration and testing is concerned.

4.1.2 Phase 2

The extended hybrid architecture will rely on a centralized instance of ATH's proprietary software mobile core, which could be either hosted by a private cloud infrastructure available at ATH's premises or on the proprietary "BubbleCloud", a solution that allows to deploy 4G and 5G mobile networks as if they were localized "bubbles" from the public Amazon cloud. In particular:

- Each edge mobile network is powered by an ATH edge node and is connected to and managed from the central cloud.
- UP traffic is steered locally within a firewall, thus giving deterministic latency and increased security.
- The support of the remote cloud is typically required for functions such as authentication, mobility and roaming.

4.1.3 Testing Tools

European partners started to test the network equipment they provision to the setup in-lab.

On the one hand, the part of the 5G CONNI network to be deployed at the BOSCH demo site is being commissioned and pre-integrated into an autonomous transportable rack at HHI's lab. It houses a total of four physical servers hosting the RAN, core and application VNFs. One 1 GbE router and one 10/25 GbE switch provide the transport network for O&M, fronthaul and backhaul along with basic infrastructure services required for correct operation of the network functions such as an IEEE 1588 PTP grandmaster clock, DHCP and DNS. Thus, a self-contained and verified 5G network may be shipped for rapid deployment at the demonstration site. Integration testing is performed with Telit FN980 and Quectel RM500Q 5G modem modules on the UE side, allowing for the end-to-end utilization of standard Linux network diagnostic tools such as iPerf and Wireshark. Preliminary tests prior to integration of ATH's 5GC appliance are performed against ATH's Open5G (see below) and a MECSware campus XG core.

On the other hand, the ATH's Griffone 5GC has been internally tested against the following hardware:

- Mobile phones: Xiaomi 10 Pro, Oppo Reno5, Apple iPhone 12;
- gNB: Amarisoft Callbox Mini.

Moreover, as mentioned earlier, towards phase 1, the Open5G testing framework on AWS will be used to pre-integrate the aforementioned NG-RAN and 5GC equipment remotely, thus minimizing the amount of local integration tests among components provided by the distinct EU partners.

4.2 Taiwanese System Integration

This section deals with the TW system integration in the lab environment and the test program to ensure that all the subsystems will work together properly for the selected use cases in a pre-live industrial environment.

4.2.1 In-lab Test Program

As shown in Figure 4-1, system integration and verification of a preliminary prototype in the lab will go through the following phases to make sure that the system is ready for deployment.

- **Vendor implementation (Phase 0)**: The conformance testing may be performed by the vendor itself, which is covered in WP4.

- **Multi-vendor IOT (Phase 1)**: Interoperability testing is to verify the equipment from different vendors works together as defined in the standard.
- **Performance & Stability (Phase 2)**: The aim of this phase is to ensure that the product offers an acceptable level of quality in terms of performance and stability after the product has passed multi-vendor IoT. It distinguishes the product with proven quality from those who passed interoperability tests but without required performance. The main KPI captured in this phase will be TCP/UDP throughput or latency.
- **Validation with realism (Phase 3)**: This phase is going further to determine to what extent the desired performance is achieved for the vertical use cases defined in D1.1[1]. The application traffic could be real or emulated. The main KPI captured here is based on passive analysis to quantify how network imperfections affect the user experience.

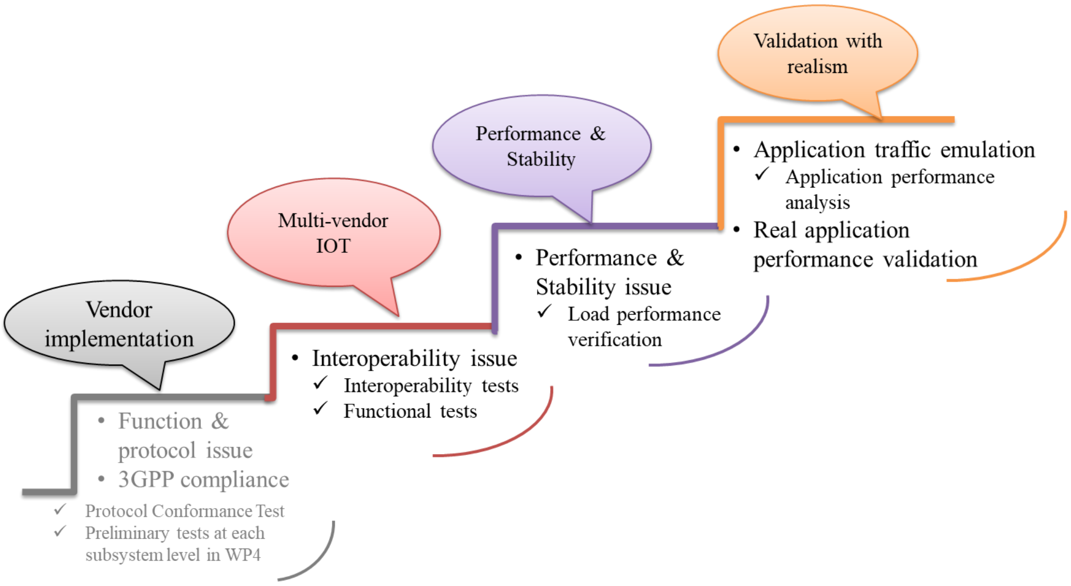

Figure 4-1: In-lab test process

4.2.2 Test Configurations

This subsection describes four system configurations in the test program.

The test configuration A is shown below, which includes the UE, ANI gNB, III 5G Core and application server. In this setup, the UE can be a CPE or Nemo Handy S20+ and the gNB comprises a radio unit (RU) and a server running the central unit (CU) and distributed unit (DU). This configuration is used for multi-vendor interoperability test with a small number of UEs.

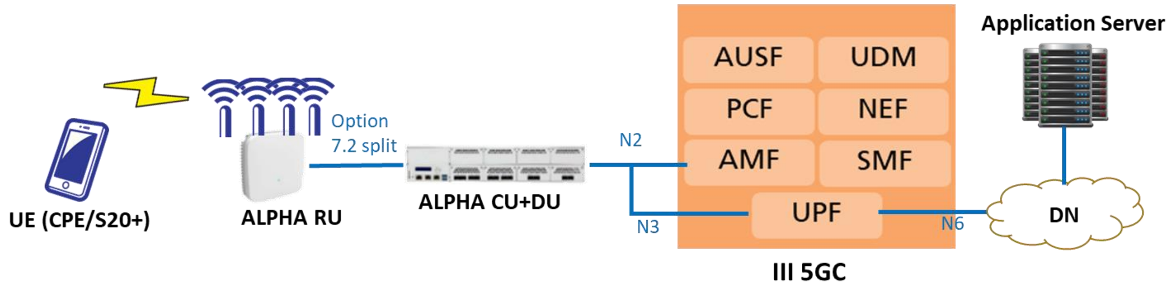

Figure 4-2: Test configuration A

The test configuration B is shown in the figure below, where we have a TM500 to emulate multiple UEs and RF channel conditions. In addition, the traffic generator has been incorporated in the configuration to generate mixed user applications. This setup is used for a wrap-around test of the gNB and real-world network scenario emulation.

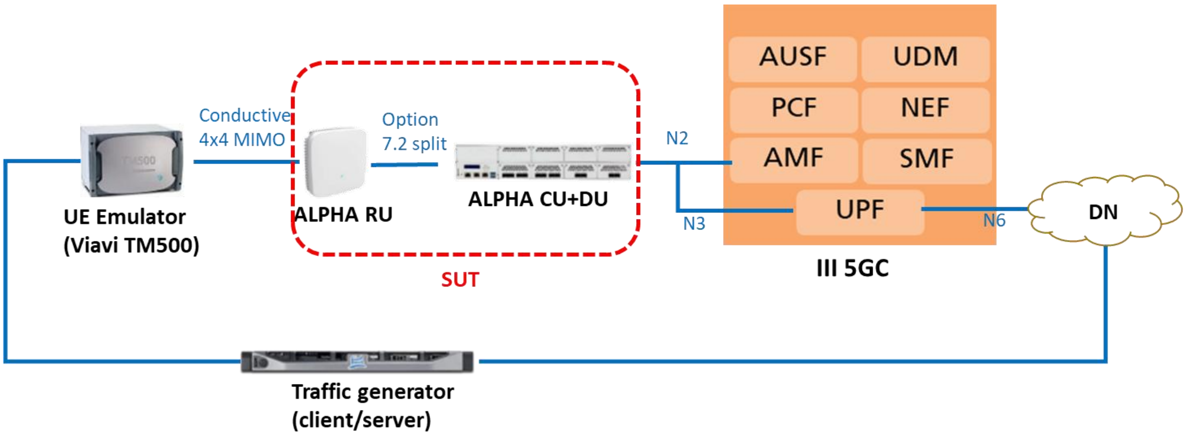

Figure 4-3: Test configuration B

The test configuration C is shown in the figure below, where the MEC platform has been incorporated to steer the application traffic towards a local server. This setup is used for the MEC to test against gNB and 5G core.

The MEC SA (standalone) prototype, described in D4.1[3], supports bump-in-the-wire technology which enables data offload without additional reconfigurations of the base station and core network. This approach intercepts and analyzes the control plane traffic on N2 interface and then performs the traffic filtering, manipulation and redirecting of the user plane traffic on N3 interface.

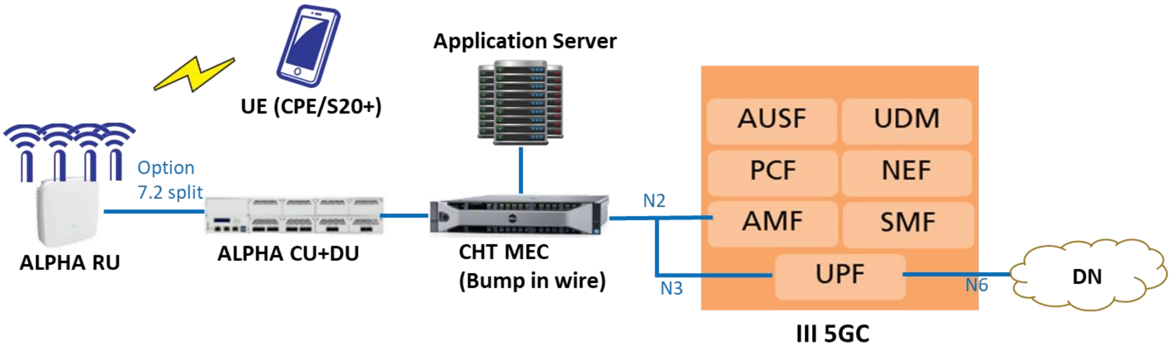

Figure 4-4: Test configuration C

The test configuration D is shown in the figure below, which is similar to configuration B. The only difference is that the local breakout of application traffic via MEC has been incorporated in this configuration. This setup is used to verify that the MEC is able to offload different application traffic.

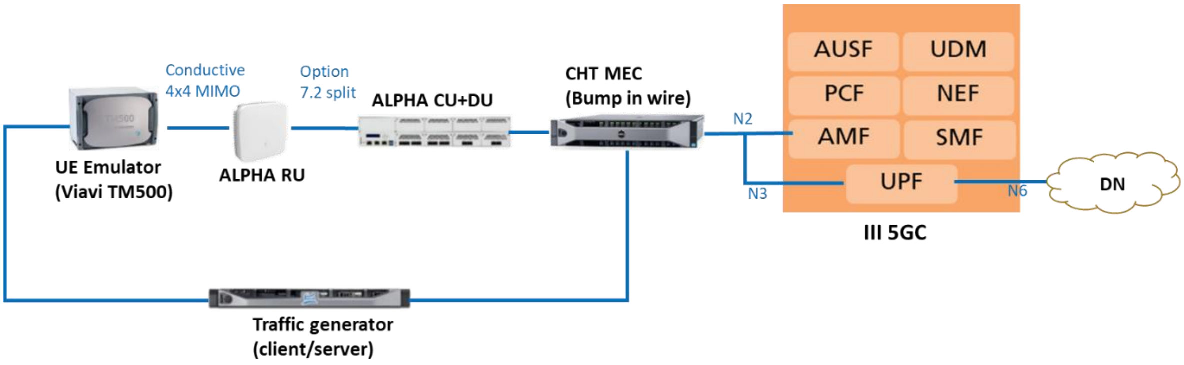

Figure 4-5: Test configuration D

4.2.3 Test Groups

A total of 37 test cases have been compiled and considered in three test groups based on different phases in the test program. Each test case has been assigned to the different test configurations. The results of these tests will be reported in future deliverables of WP5.

1. The Multi-vendor IOT test group includes 12 test cases and applies to the configuration A or C. Test ID 1.1 to 1.8 aim at the procedures when the mobile switches on and registers with the 5G core network. Subsequently, the mobile will establish connectivity with a data network and the network can transfer it between RRC_IDLE and RRC_CONNECTED states depending on inactive or active data transfer. Test ID 1.9 to 1.10 are used to verify QoS differentiation support, which assigns different qualities of service to different applications. Finally, Test ID 1.11 to 1.12 cover the MEC integration with the base station and 5G core to make sure that the application can be reached by the user. Since the MEC using bump-in-the-wire architecture will analyze the control-plane messages on N2 interface, Test ID 1.1 to 1.10 apply to both configuration A and C.

Test ID	Test Item	Test Objective	Test Configuration
1.1	NG Setup	Successful NG interface setup between gNB and 5GC	A/C
1.2	UE Initial Registration with IMSI identity	UE initial registration with IMSI identity	A/C
1.3	UE Initial Registration with GUTI identity	UE initial registration with GUTI identity	A/C
1.4	PDUSession Establishment	Successful establishment of the PDU session	A/C
1.5	UE Deregistration	Successful deregistration procedure triggered by the UE entering flight mode	A/C
1.6	Access Network Release	Successful access network release procedure due to UE inactivity	A/C
1.7	UE-Triggered Service request	Successful mobile-originated service request procedure	A/C
1.8	NW-Triggered Service Request	Successful mobile-terminated service request procedure	A/C
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	A/C

1.10	Management of QoS flow by 5G QoS identifier(5QI)	Successful 5QI configuration of a QoS flow	A/C
1.11	N3 GTP-U processing (GTP decap/encap)	Successful encapsulation or decapsulation of the application packets to or from the UE	C
1.12	N3 GTP-U processing (data forward)	Successful data forwarding to the UPF if the traffic is not offloaded	C

2. The Performance and Stability test group includes 21 test cases and applies to the configuration A or B. The UDP or TCP performance measurements at different channel conditions including cell center, middle and edge have been covered in Test ID 2.1 to 2.12. They aim at single user scheduling including AMC (Adaptive Modulation and Coding scheme), time-frequency resource allocations, MIMO rank, etc. In addition, multi-user scheduling has been evaluated in Test ID 2.13 to 2.16. Finally, the end-to-end round trip latency and long-term stability with heavy loading have been verified in Test ID 2.17 to 2.21.

Test ID	Test Item	Test Objective	Test Configuration
2.1	Average UDP DL Throughput at Cell Center	One UE successfully initiates Iperf UDP DL transfer at cell center with RSRP=-60dBm and record the average TPut	A
2.2	Average UDP UL Throughput at Cell Center	One UE successfully initiates Iperf UDP UL transfer at cell center with RSRP=-60dBm and record the average TPut	A
2.3	Average TCP DL Throughput at Cell Center	One UE successfully initiates Iperf TCP DL transfer at cell center with RSRP=-60dBm and record the average TPut	A
2.4	Average TCP UL Throughput at Cell Center	One UE successfully initiates Iperf TCP UL transfer at cell center with RSRP=-60dBm and record the average TPut	A
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	A
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	A
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	A

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	A
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	A
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	A
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	A
2.12	Average TCP UL Throughput at Cell Edge	One UE successfully initiates Iperf TCP UL transfer at cell center with RSRP=-110dBm and record the average TPut	A
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	A/B
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	A/B
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	A/B
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	A/B
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	A
2.18	Average E2E Round Trip Time at Cell Edge	One UE successfully initiates ping towards the application server at cell edge and record	A

		the average round trip time	
2.19	Long Term (1 hr) Stability with Heavy Traffic	To verify the long-term stability with heavy traffic for 1 hour	A/B
2.20	Long Term (12 hrs) Stability with Heavy Traffic	To verify the long-term stability with heavy traffic for 12 hours	A/B
2.21	Long Term (24 hrs) Stability with Heavy Traffic	To verify the long-term stability with heavy traffic for 24 hours	A/B

3. The Validation with Realism test group includes 4 test cases and applies to the configuration D. This group is dealing with application-layer performance measurements rather than UDP or TCP layer, where the applications can be real or emulated by the traffic generator. The main objective is to ensure that the combined requirements of three use cases can be fulfilled by the same 5G network.

Test ID	Test Item	Test Objective	Test Configuration
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	D
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	D
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	D
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	D

At the time of writing, the time plan for the in-lab test program and on-premise integration are as follows:

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	The regression test focuses on ARP and 5QI test items.
Phase 2 test cases with configuration A and	**ITRI**, ANI, III	ITRI	End of Aug. 2021	Performance tests are performed under Over-The-Air (OTA) or conductive con-

B verified				figurations.
Phase 1 and 3 test cases with configuration C and D verified	**ITRI**, ANI, III, CHT	ITRI	End of Sept. 2021	The MEC platform is integrated to the 5G system.
On-premise integration plan	**ITRI**, ANI, III, CHT	N/A	End of Sept. 2021	It details the physical system architecture of the shop floor (e.g., 5G system, transport network and OT/CT integration).
In-factory system integration	**ITRI**, ANI, III, CHT	ITRI	End of Oct. 2021	Deploy the lab prototype into IMTC plant and all control-plane functions are running live properly.
On-premises E2E system troubleshooting and optimization	**ITRI**, ANI, III, CHT	ITRI	End of Dec. 2021	Selected use cases can be supported by the 5G system.

4.2.4 Testing Tools

TM500 is the 5G NR UE emulator system used for base station development and testing, characterized as follows:

Equipment	Vendor	Product Type	Software Version
Viavi wireless solution TM500 5GNR	Viavi	TM500-C-5G TEST MOBILE	NLA_4_61_0

A Nemo Handy is the Android-based solution for measuring and monitoring the air interface of 5G wireless networks. It uses Samsung 5G Qualcomm X55 UE (S20+) and is characterized as follows:

Equipment	Vendor	Product Type	Software Version
Nemo Handy	Keysight	Nemo Handy Pro	4.21.1295

5 Conclusions

The objective of WP5 (Integration, Demonstration & Verification) is to integrate the E2E system designed in WP2, which covers RAN, 5G Core, MEC, and OTT applications. D5.1 deals with the pre-live lab integration. It describes the EU and TW testbeds and presents some further steps to merge them into an inter-connected private 5G network across two continents, based on a common UDM and AUSF architecture[7]. To this end, different system integration phases, initial test items, and the corresponding integration timeline have been devised and reported. They will ensure that the functionality and performance requirements of the use cases selected in WP1 can be met.

The work of WP5, including integration test results, will be further described in D5.2 (due at the end of month 29 of 5G CONNI's lifetime) and D5.3 (due at the end of the project). The former will provide details and results on the integration of components at each continental manufacturing facility (EU and TW), including a performance evaluation of each setup and its components. D5.2 will also provide initial results on the end-to-end intercontinental inter-site connectivity. D5.3, instead, will cover the full end-to-end performance assessment of the deployed 5G CONNI trial network, including detailed performance measurements and corresponding KPI analyses.