



Demonstration of **5G** solutions for **SMART** energy **GRIDs** of the future

Deliverable D.3.4

Smart5Grid platform integration and HIL testing activities

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Executive summary

The Smart5Grid project proposes four comprehensive use-cases (demonstrators) as applications which make use of the latest advancements and capabilities of the 5th Generation (5G) wireless technology for the energy vertical. The main scope of those demonstrators refers to development, deployment, and testing of Network Applications in actual power grid operational environments. These use-case specific Network Applications provide tailored services to energy stakeholders aiming at supporting essential functions of the broad concept of smart grids by internalizing the abstraction of the 5G telecommunication layer used for bidirectional transfer of information between field sensors from the power grid (e.g., phasor measurement units, smart meters, remote terminal units, cameras, etc.) and the energy service (Network Applications). Specifically, the Smart5Grid project proposed and developed Network Applications to enhance some functionalities aligned to the smart grid concept, such as:

- (i) Monitoring of an advanced automatic power distribution grid fault detection system through a 5G communication layer to ensure scalability and flexibility of deployment of this system in other parts of the power grid (Italian demo);
- (ii) Remote inspection of automatically delimited working areas using 5G technology, advanced cameras and artificial intelligence-based detection algorithms to improve safety of workers in high voltage power distribution substations (Spanish demo);
- (iii) Millisecond-level precise monitoring and control of distributed renewable power generation to enhance the potential of those units to provide in real-time flexibility services to the power grid (Bulgarian demo);
- (iv) Real-time wide area monitoring of cross-border power flow which aims to enhance the accuracy of real-time observability of large power networks managed by more than one transmission system operator (Greek-Bulgarian demo).

This deliverable, D3.4 (*Smart5Grid Platform Integration and HIL testing*), reports on the activities carried out as part of Task 3.4 (*Pre-piloting via Hardware-In-the-Loop (HIL) demonstration*) in terms of providing advanced testing facilities (pre-piloting testbeds) that enable testing of the key functional requirements of early versions of the use-cases' specific Network Applications in a realistic and controlled environment before they are deployed in the actual pilots. Those functional requirements are two-fold: those related to the impact they might have to the power grid operation (e.g., how the energy vertical service to be provided by the Network Application might affect the operation of the grid) and those related to the Network Application connectivity tests with the 5G-network.

This deliverable elaborates on the pre-piloting tests carried out for each of the four use-case specific Network Applications (early versions), as preparatory steps before the final versions of the Network Applications get verified and validated within the Smart5Grid Platform using the automated Verification and Validation (V&V) framework, and before they are onboarded and deployed in the production environments related to the actual power grid demonstration pilots. It is worth mentioning that all the activities related to the development of the main components of the Smart5Grid Platform and the integration of the platform with the 5G infrastructure, and the energy infrastructure is detailed in two other

deliverables of the WP3: D3.1 (*Interim report for the development of the 5G network facility*) and D3.2 (*Final report for the development of the 5G network facility*), respectively. Specifically, this deliverable is:

- Defining two different approaches for pre-piloting testing considering the energy vertical and the 5G connectivity aspects.
- Determining the methodology to be followed in the pre-piloting testing of each use case considering four common phases related to:
 - Describing the different setup/testbeds developed for each use case to facilitate the pre-piloting testing considering a detailed analysis for each component and interface, and their role in the testbeds.
 - Integrating the corresponding Network Application and other energy-focused control applications in the pre-piloting testbed of each demonstrator. Assumptions and preconditions and differences between the pre-piloting conditions and the actual pilots are analysed during this integration of the early versions the Network Applications.
 - Defining the corresponding scenarios that have been used to test, validate and evaluate each use case during the pre-piloting investigation.
 - Analysing and evaluating the pre-piloting results to determine if the functional requirements have been met and if the Network Applications are able to provide effective services to the smart grid.

It is worth highlighting that a major effort within Task 3.4 (*Pre-piloting via HIL demonstration*) was dedicated to the development and testing of digital-twin models and power controllers for two of the proposed Smart5Grid demos. Specifically, the Bulgarian demo and the Greek-Bulgarian demo make use of Real-Time (RT)-HIL technology for their pre-piloting testbeds. This approach has been considered in these two use-cases to investigate additional testing scenarios related to closed-loop control applications, which cannot be directly performed on the actual grid (e.g., distributed resources to provide in real-time ancillary services to grid operators in the absence of national regulatory framework for this type of services, or wide area protection schemes, among others). The other two use-cases (related to the Italian and the Spanish demos) imply applications which involve pre-piloting testbeds focusing on the 5G connectivity only. Thus, no HIL technology was used in the pre-piloting stage for these latter use-cases. As such, the deliverable was structured focusing first on the Bulgarian and Greek-Bulgarian demos and then on the Italian and Spanish demos, especially to reflect this additional effort allocated for the development of digital-twin models and control applications which were then integrated in the RT-HIL setups for realistic proof-of-concept of the 5G technology impact on control-in-the loop type of applications for smart grids.

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1. Introduction

This deliverable is the fourth technical output from a series of four deliverables of WP3 (*Integrated 5G Network Facility and Open Repositories*). It deals with the elaboration on the pre-piloting testing activities of each of the four use-cases of the Smart5Grid. An emphasis is also given on the development of tailored digital-twin models and specific hardware implemented controllers integrated in Real-Time (RT) control Hardware In-the-Loop (HIL) setup (pre-piloting testing environment) needed for realistic proof-of-concept for two of the demonstrators (the Bulgarian demo and the cross-border Greek-Bulgarian demo, respectively).

To put this deliverable into context it has to be mentioned that all the tasks and deliverables reflecting the work of Work Package 3 (WP3) are to a large extent interrelated and interdependent. Their common ground concerns elaborating on the full development and integration of the Smart5Grid Open 5G experimentation platform, including functional aspects such as end-to-end slicing, service orchestration and automation for efficient deployment and operation of the 5G network which supports the requirements set up by the project use-cases. The Network Application concept is the linking block between the Smart5Grid platform, the 5G telecommunication infrastructure, and the service to be delivered to the energy infrastructure.

The development and integration of the Smart5Grid platform components and their integration with the 5G infrastructure and with the energy infrastructure corresponding to each of the four use-cases is the scope of deliverables D3.1 (*Interim report for the development of the 5G network facility*) and D3.2 (*Final report for the development of the 5G network facility*), respectively. These two deliverables detail the work carried out in Tasks 3.1 (*Smart5Grid network access/core platform building and orchestration*) and in Task 3.3 (*Platform integration and Interfacing between 5G and energy infrastructure*). Deliverable D3.3 (*Open Service Repository*) details the work carried out during Task 3.2, for the development of this important component of the Smart5Grid platform, which is the entry point for developers and consumers of the Smart5Grid Network Applications. All these tasks ran in parallel with Task 3.4 (*Pre-piloting via Hardware-In-the-Loop (HIL) demonstration*). The latter (Task 3.4) is the scope of this document. Thus, it is worth mentioning that any details regarding the Smart5Grid open experimentation platform integration (including integration with the 5G telecommunication infrastructure and the energy related infrastructure), are left out of the scope of this deliverable, because they are detailed in the other above-mentioned deliverables.

This deliverable elaborates on the work carried out as part of Task 3.4 (*Pre-piloting via HIL demonstration*) by describing in detail the advanced pre-piloting testing environments that have been developed within the Smart5Grid project. The pre-piloting environment considers testbeds based on the HIL framework and setups focused on connectivity testing. In this HIL approach, a large-scale power grid is emulated in a real-time simulator using digital twins based on high-fidelity models and by considering field measurements, while Network Applications are integrated in the loop by exchanging information with the digital twin through a hardware network emulator able to realistically mimic the physical communication links of a smart grid application. In this context, Network Applications are integrated using Control-HIL approach, while the Power-HIL framework is facilitated by incorporating actual power device(s) driven by the digital twin through a power amplifier. On the other hand, setups for connectivity testing focus on incorporating the actual 5G network infrastructure to ensure the proper connectivity between physical devices (that will

be located in the field) and the Network Applications (that will be located in the Smart5Grid platform). It has to be noted that the final scope of the pre-piloting is to perform functional tests for the early versions of the Network Applications developed for each of the four use cases, using controlled environment and advanced pre-piloting testing facilities which might need different types of hardware and software blocks (able to replicate both the 5G network infrastructure and the energy infrastructure), however specifically tailored to the scope and the needs of the specific use-case.

1.1. Scope of the document

The scope of this deliverable is to elaborate on the pre-piloting testing which offers realistic and controlled environments able to mimic the actual operating conditions of the four pilots proposed by the Smart5Grid project.

Based on the scope and the functional requirements defined for the use-case specific Network Applications [1], [2], two types of pre-piloting testing architectures were identified:

- (a) ***Vertical-service pre-piloting testing environment using RT-HIL technology*** to be applied for the Network Applications and for new control applications developed for the Bulgarian Demo (UC3: *Millisecond level precise distributed renewable generation monitoring and control*) and for the cross-border Greek-Bulgarian Demo (UC4: *Real-time Wide Area Monitoring (WAM)*).
- (b) ***5G connectivity pre-piloting testing environment*** for applications that are more focused on monitoring the Quality of Service (QoS) of the 5G communication infrastructure for functional tests of the use-case specific Network Applications. This type of pre-piloting architecture was used for the Italian Demo (UC1: *Automatic power distribution grid fault detection*) and for the Spanish demo (UC2: *Remote inspection of automatically delimited working areas at distribution level*).

A major goal and effort of Task 3.4 (*Pre-piloting via HIL demonstration*) was dedicated to the development of tailored digital twins for power grids and related energy infrastructures and the use of the digital twins to formulate realistic and non-invasive HIL testbeds for testing, validating and evaluating the Network Applications developed within this project. These activities were particularly focused on the scope of UC3 and UC4, where new controllers have been additionally developed to highlight the benefits of new potential closed loop applications when integrated through 5G communication technology. It is worth mentioning that the advantage of using HIL approaches is mainly useful when control applications are investigated while the benefits when testing monitoring applications are limited. Therefore, the integration of the corresponding Network Application and the new control applications developed for enhancing the scope of UC3 and UC4 are included in this pre-piloting investigation and thus, this effort is also reflected on the structure and the amount of content dedicated to those two use-cases.

UC1 and UC2 share many similarities in terms of the type of functional tests performed for the early version of the Network Applications and of the type of pre-piloting infrastructure used. Both use cases focus on monitoring aspects (of the protection system and of the working area) and therefore their pre-piloting testbeds mainly focus on connectivity tests between the field equipment and the Network Application, while the HIL framework is not necessary in these use cases since they are mainly based on open loop applications. On one hand, UC1 focuses on the monitoring aspects of the power distribution grid fault detection system using 5G communication, and not on the protection operation functionality of this grid system. On the other hand, UC2 does not need such type of HIL testing environment because the

proposed application does not need any sort of observation on the dynamic behaviour of the grid operation.

As it was previously explained, this deliverable focuses to a large extent on the use of real-time hardware in the loop (RT-HIL) technology as an advanced testing and validation environment for power system applications. This technology is especially useful for those power systems applications that involve the development of innovative controllers for distributed renewable energy resources (DER), or those that need to simulate the dynamic behaviour of large power systems, among others. Thus, it is to be highlighted that most of this deliverable details *the development, integration and validation testing of digital-twin models and new controllers* which were run using *customized RT-HIL pre-piloting, in controlled testing environments*. They were *specifically designed for advanced vertical-service pre-piloting testing aiming to further investigate the impact of new potential control applications in the operation of the energy domain*.

The power infrastructure considered in the RT-HIL framework was realistically emulated (following a non-invasive approach) through a digital replica (digital twin) running in a real-time simulator and by incorporating actual power device(s) connected in Power-HIL configuration. Further, the 5G communication infrastructure, which forms the communication carrier of the data exchange between power grid sensors and the use-case specific Network Applications, is introduced in this setup through a hardware network emulator, which is a macroscopic model of the communication network. The testing approach is used to further validate the correct operation of the monitoring-type Network Applications. In addition, through this HIL testing procedure, the impact on the overall power system operation can be investigated when new control applications (e.g., for coordinating the operation of flexible DERs during disturbances) make use of different types of communication infrastructures (e.g., 4G, 5G).

The 5G connectivity testing procedure, used in the case of pre-piloting testing for the Italian and Spanish demos, make use of actual 5G infrastructure with similar or identical components between the pre-piloting testbeds and the pilots. The testing approach is focused on proper communication between the 5G enabled sensors and the 5G infrastructure, and between the sensors and the use-case specific Network Application.

The deliverable also aims to summarize all the preparatory steps fulfilled so far to *enable advanced testing of the early version of use-case specific Network Applications*, as well as for enhancing their ability to fulfil the functional requirements of respective use-cases. The scope of these tests is *to allow fine tuning in the development of use-case specific Network Applications* before they are to be verified and validated using the automatic V&V framework of the Smart5Grid platform. The V&V is the scope of WP4 and it takes place beyond the pre-piloting stage of the project.

It is to be reminded that the full *Smart5Grid platform development and integration with the 5G infrastructure and with the energy infrastructure* is the scope of another deliverable (D3.2: *"Final report for the development of the 5G network facility"*), which details the work carried during Task 3.1 (*"Smart5Grid network access/core platform building and orchestration"*) and Task 3.3 (*"Platform integration and interfacing between 5G and energy infrastructure"*). The Deliverable D3.2 was submitted concurrently with this deliverable, D3.4. Thus, the scope of this document is fully dedicated to reporting on the activities and testing results obtained during Task 3.4. (*Pre-piloting via HIL demonstration*).

The pre-piloting testing, detailed in this deliverable, refers to the functional tests of early versions of the use-case specific Network Applications, and where relevant, to the analysis of their possible impact on the power grid operation.

In summary, the scope of this deliverable aims to:

- Elaborate on the pre-piloting testing facilities tailored to the needs of each of the four demonstrators aiming to ensure the realistic testing conditions with the actual operation environment of the four pilots.
- Define a common testing methodology for the two types of pre-piloting testing procedures (energy focused and 5G connectivity focused).
- Develop, where relevant, digital-twin models of the larger grid components (portions of the grid, or control-in-the loop models) and new control applications which enhance the scope of UC3, and to some extent of UC4, and which could not be otherwise tested in the actual operation environment of the pilot, due to the possibly invasive nature of this type of tests.
- Elaborate on the connectivity and functional requirements tests (5G technology focused) for Network Applications which provide monitoring services to the energy stakeholders, but do not have a direct impact on the dynamic behaviour of the power grid (UC1 and UC2).
- Summarize the results of functional and integration tests carried out by each of the use-cases on the early versions of the Network Applications as intermediate milestones before they are further tested and evaluated in the automatic V&V framework of the Smart5Grid platform, and before they are deployed in the production testing environments of the pilots.

It has to be noted that the pre-piloting testing is complementary to the testing and validation of the Network Applications within the V&V Framework of the Smart5Grid Open Experimentation Platform, which will be detailed in several deliverables of WP4 (D4.1 – *“Development and deployment of Network Applications for the energy vertical sector”*, due M27, and D4.2 – *“Verification and validation framework based on DevOps practices”*, due M30). However, high-level elaboration on the expected energy services to be provided by each of the use-case specific Network Applications, type of input data used in the development stage for the early versions of the Network Applications which are tested using the pre-piloting testing facilities, among others, are summarized within this deliverable.

1.2. Relationship with other Tasks and Deliverables

This deliverable builds on the previous work performed during WP2 related to the elaboration of use-cases and system requirements (D2.1) [1], and to the definition and specifications for the Network Application concept in the Smart5Grid project, aligned with the overall architectural design and technical specifications for the Smart5Grid Open 5G experimentation platform (D2.2) [2].

Specifically, the first technical report, *“D2.1: Use cases, system requirements and planned demonstrations”* [1] provided an initial description of the design of the use-cases, and of their functional and non-functional requirements, as well as the identification of the fundamental limitations addressed, envisaged innovations and key system requirements. This deliverable also provided relevant information needed for the selection of the type of pre-piloting architecture relevant for each of the four use-cases. This deliverable also gave the first definition of the functional requirements of the use-case specific Network Applications.

The second technical report that provides input for the current deliverable is *“D2.2: Overall Architecture Design, Technical Specifications and Technology Enablers”* [2], which, as its name suggests, provided the

technical specifications of each of the main components of the Smart5Grid platform, the specification of the Network Application concept used in the Smart5Grid project, as well as the technological choices for both the platform development and for the Network Applications. This deliverable enhanced the level of detail on the functional and non-functional requirements for the use-cases specific Network Applications, which indicate the type of tests to be performed during the pre-piloting tests for the early versions of those Network Applications.

As previously mentioned, the current document complements two other deliverables of the WP3, namely D3.1 (*Interim report for the development of the 5G network facility*) and D3.2 (*Final report for the development of the 5G network facility*), respectively. The latter is providing the details on the finalized process of development and integration of the relevant components of the Smart5Grid platform. The same deliverable is also summarizing the process of integration and interfacing between the Smart5Grid platform, the 5G infrastructure and the energy infrastructure, all tailored to the needs of each of the four use-cases.

The current document provides an insight for further testing and fine tuning of the use-case specific Network Applications, which is the scope of two future deliverables of WP4, (D4.1 – “*Development and deployment of Network Applications for the energy vertical sector*” and D4.2 – “*Verification and validation framework based on DevOps practices*”, respectively).

1.2.1. Notations, abbreviations and acronyms

Table 1: Acronyms list

Item	Description
4G	4 th Generation wireless communication
5G	5 th Generation wireless communication
AC	Alternating Current
AGFDS	Automatic Grid Fault Detection System
API	Application Programming Interface
APN	Access Point Name
BBU	BaseBand Unit
BSS	Battery Storage System
CB	Cross-border
CO	Control Operator
CT	Current Transformer for measurement purposes
CPE	Customer Premises Equipment
CPU	Central Processing Unit
DC	Direct Current
DER	Distributed Energy Resources
DRES	Distributed Renewable Energy Sources
DoW	Document of Work (Grant Agreement)
DSO	Distribution System Operator
EE	Entra Energy – Bulgaria
EN	Edge Node

Item	Description
ESO	Elektroenergien Systemen Operator – Bulgaria
FACTS	Flexible Alternating Current Transmission Systems
FFR	Fast Frequency Response
GA	Grant Agreement
GPS	Global Positioning System
HV	High Voltage
HVDC	High Voltage Direct Current
HW	Hardware
HuT	Hardware-under-Test
I2Cat	Internet i Innovacio Digital a Catalunya – Research Center – Spain
ICMP	Internet Communication Message Protocol
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
I/O	Input/Output
IP	Internet Protocol
IPTO	Independent Power Transmission Operator – Greece
KPI	Key Performance Indicator
LV	Low Voltage
LTE	4G Long Term Evolution
MEC	Multi-access Edge Computing
MQTT	Message Queuing Telemetry Transport Protocol
MPTCP	Multi-Path Transmission Control Protocol
MV	Medium Voltage
MW	Mega Watt
NAC	Network Application Controller
NAC_FE	Network Application Controller Frontend interface
NBC	NearBy Computing – Spain
NSA	Non-Standalone (5G architecture)
OSI	Open System Interconnection
OSR	Open Service Repository
PC	Personal Computer
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
PTP	Precision Time Protocol
PV	Photovoltaic plant
QoS	Quality of Service
RAN	Radio Access Network
RES	Renewable Energy Sources
REST-API	Representational State Transfer
RGDM	Enel's standardized MV protection system
RMS	Root Mean Square values
ROCOF	Rate Of Change Of Frequency
RR	Ramping Rate
RRL	Ramping Rate Limit

Item	Description
RRU	Remote Radio Unit
RRV	Ramping Rate Violation
RTLS	Real-Time Location System
RTPM	Real-Time Energy Production Monitoring
RTS	Real-Time Simulator
RTT	Round-Trip Time
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition System
SIM	Subscriber Identity Module
SOM	System On Module
S/P-gateway	Serving gateway/Packet gateway
SSH	Secure Shell
SUT	System Under Test
SW	Software
TDOA	Time Difference Of Arrival
TLC	TeLeCommunication Team of ENEL
TCP	Transmission Control Protocol
TSO	Transmission System Operator
UCY	University of Cyprus – KIOS CoE Research Centre - Cyprus
UWB	Ultra-WideBand
UC	Use-Case
UE	User Equipment
UI	User Interface
URLLC	Ultra Reliable Low Latency Communications
vPDC	virtual Phasor Data Concentrator
VPN	Virtual Private Network
VT	Measurement transformers for voltage
WAC	Wide Area Control
WAM	Wide Area Monitoring
WP	Work Package

2. RT-HIL technology for power systems

2.1. State of the art in research and industry practice

2.1.1. RT-HIL technology

The use of Real-Time Hardware-In-the-loop, often called HIL-technology or sometimes power-HIL has become increasingly popular in recent years for testing and validation of novel power system applications. In simple words, HIL is a technology that allows engineers to simulate the behaviour of a system (hardware-based systems) in a real-time virtual environment, allowing engineers to test and debug the system without the need for the full physical hardware of the real system (e.g., the entire European transmission power grid).

Real-time (RT) simulation is recognized as a highly reliable and accurate method, which makes use of the most recent advancements in parallel computing to solve complex differential equations which characterize the dynamics of large and complex systems, such as power grids. The difference between offline type of simulation platforms (non real-time digital simulations) and the digital RT simulators is that for the latter, the time it takes to solve the system equations and deliver back the output results is exactly the same with real-world system clock (the system that it simulates) [4]. Back in the 90's, and the first decade of the current millennium, the RT simulations for power systems applications were mainly orientated towards tests for protection systems for transmission grids using transient analysis models [5], for static VAR compensators (SVC) and Flexible alternating current transmission systems (FACTS) [6], or controllers for HV direct current (HVDC) [7].

More recently, RT simulation is increasingly used for broad range of applications within distribution grids, active distribution grids, and microgrids which incorporate DER and RES via power electronics converters [8], [9].

A natural evolution from the RT simulations to power hardware-in-the-loop (HIL) techniques took place when more and more interest was shown on impact studies on grid integration of DER and RES among research and academia and among power systems operators, energy regulators and promoters of RES, alike, due to the society drive on greener and more sustainable economy [10], [11].

In summary, sometimes the concept of RT simulation may refer to both:

- 1) **fully digital real-time simulation environment** which may include one or more of the following: model-in-the-loop, software-in-the-loop, or process in-the-loop. It is understood that for a fully digital RT simulation, all the components of the entire system, is modeled inside the simulator without involving external interfacing or inputs/outputs (I/Os).
- 2) **RT-HIL simulation environment** refers to the simulation environment where some parts of the fully digital real-time simulation are replaced with the actual physical components (e.g., an actual protection relay, or an actual power electronics inverter). Thus, the RT-HIL simulation process integrates the power component under test. The latter also is called in the literature the hardware-under-test (HuT). The HuT is connected to the RT-HIL environment through I/O interfaces, such as electronic filters, digital-to-analogue or analogue-to-digital converters and signal conditioners.

In this way, the user of the RT-HIL testing environment can execute user-defined real-time control inputs to either the power equipment under test (HuT) or to the larger system modelled in the RT simulator, in order to analyse the control response.

In conclusion, HIL techniques enhanced the previous RT simulation methodology by integrating real-hardware systems (e.g., power equipment) and software models in a closed-loop RT simulation environment [12]. The RT-HIL configuration is especially useful when one needs to execute the control software within the same time step as the real system and to apply the control actions on the real hardware. Furthermore, the operator of this testing environment has also visibility on the measurements and the parameters of the system. This kind of environment combines the flexibility of simulation with the use of real power devices. Such an opportunity for testing equipment or control strategies in realistic operating conditions is a powerful evaluation tool that a designer can use to rapidly advance from the initial design phase to the prototype.

2.1.2. RT-HIL technology for power systems applications

The use of real-time hardware in the loop (HIL) for power system applications has become increasingly popular in recent years. HIL is a technology that allows engineers to simulate and validate systems before they are deployed into the real world, resulting in improved performance and reliability. This technology can be used for developing controllers, distributed energy resources (DERs), as well as testing control algorithms.

One of the most common applications of HIL for power system applications is in the development of power system controllers for power electronic inverters which interconnect DER, including RES within the power grid [12] - [16]. By using RT-HIL, engineers can simulate the behaviour of a power system controller in a virtual environment, allowing them to test and debug the controller before it is deployed in the real world. This allows engineers to develop controllers that are more reliable and efficient, resulting in improved performance and reliability of the power system.

Another application of RT-HIL for power system applications is in the development of distributed energy resources (DERs). DERs are small-scale, decentralized sources of electricity that can be used to supplement or replace traditional grid-based power generation. By using HIL, engineers can simulate the dynamic behaviour of a DER and its interactions with other components in the power system, allowing them to develop more efficient and reliable systems [9], [10], [16].

Finally, HIL can also be used for testing and validating control algorithms for power system applications. Control algorithms are used to regulate how a system behaves in response to external inputs or changes in internal conditions. By using HIL, engineers can simulate the behaviour of a control algorithm without having to deploy it on physical hardware. This allows them to test and debug their algorithms before they are deployed in the real world, resulting in improved performance and reliability of the control algorithm.

2.2. RT-HIL Testbed, components, and their role (Smart5Grid example)

This section is a brief recap and summary from D2.1 [1] and D2.2 [2], about the Power Systems Testbed of the KIOS Research and Innovation Centre of Excellence (KIOS CoE) of the University of Cyprus (UCY), which

was used for the pre-piloting testing using HIL technology in the Smart5Grid Project. It is to be noted that this type of advanced and flexible testing environment of UCY shares several similarities in terms of major block components with other specialized facilities owned by other power research groups in both academia [11], [14], [17] and power systems industry [17].

The general architecture of the RT-HIL testing facility of UCY is shown in Figure 1. What is common for such type of architectures is the flexibility they offer by design, such that multiple customized re-configurations could be made in order to investigate the specific testing scenarios defined for the system to be tested, in our case by the Smart5Grid UCs.

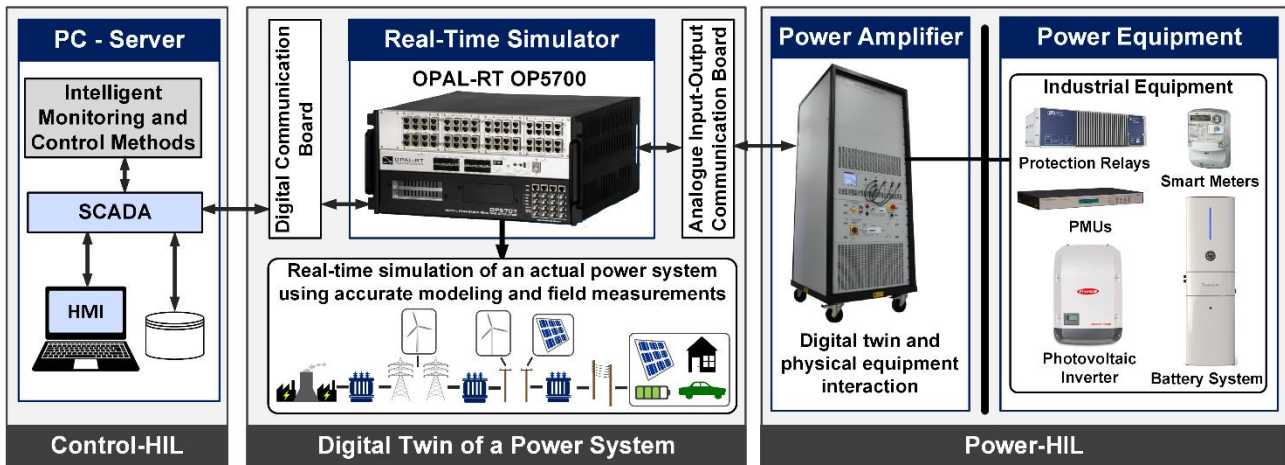


Figure 1: General architecture of a power system testbed

This RT-HIL testing environment is composed of three main architectural blocks, out of which only part might be used, depending on the UC and the specific operation scenario to be tested and validated. These three components are:

1. **Digital twin implementation of a power system:** The role of this block is to develop and implement accurate power system models in the real-time simulator making use of field measurements and parameters of the actual power grid or section of the power grid that it mirrors.
2. **Control-Hardware In the Loop (Control-HIL):** The role of this block is to offer a development framework where detailed models of the power system (or small-scale prototype plant) under test is included in the loop with the developed controller.
3. **Power-Hardware In the Loop (Power-HIL):** The role of this architectural block is to offer a framework to investigate the interaction between the digital twin of a power system and the physical plants (i.e., prototype or commercial inverters of PV or of a wind turbine, and/or of a Battery Storage System (BSS), industrial equipment used in power grids such as protection relays, smart meters, phasor measurement units (PMUs), etc.).

2.2.1. Control-HIL

As it was briefly discussed in the previous section, a Control-HIL block of the RT-HIL framework refers to the component where the new/innovative developed controllers are included in the loop with the digital-twin power system implemented in the real-time simulator.

To consider the complexity of the power system in real time, either a small-scale prototype plant or the digital twin of the actual power plant can be used. Thus, the controller is able to receive measurements and send control set-points to the power grid under test (digital twin), emulating realistic conditions for the demonstration. In actual systems and in control-HIL framework, the real-time responsiveness of the controller is crucial for the stability of the whole system besides any communication or processing delays.

2.2.2. Digital twin of a power system

A digital twin of a power system refers to a realistic digital replica of an actual power system which captures the actual dynamic behaviour of the real system. A dedicated Real-Time Simulator (RTS) is required for the development of a digital twin of a power system. For our specific case, a computational powerful RTS (OPAL-RT OP5700 [18]) is used to allow the execution of high-accuracy simulations in real time. It is to be noted that it is a common practice to use actual field measurements (collected from actual power plants, either online or through measurement campaigns) in order to accurately replicate the operation of selected power systems as digital twins. Furthermore, the use of a digital twin of an actual power system allows advanced investigations on the impact of new controllers, and/or new hardware and/or software components to be integrated in actual power grids by observing in real time the dynamic operation of a smart grid without risking the integrity of the actual critical infrastructure.

2.2.3. Power interface

The role of the power interface to be used in the RT-HIL framework is to enable the interconnection between the RT simulators and the actual power hardware (HuT). Thus, in our case a power amplifier is used as power interface for the investigation of the interaction between the power grid under test (digital twin) and a market available or a prototype plant (HuT) to be integrated in the smart grid according to the needs of each of the UCs. Specifically, the power amplifier replicates, in every solution step of the digital twin (e.g., every 50 μ s), the voltage conditions of the selected bus, and this voltage supplies the power equipment. The operation of the power equipment (power exchange with the amplifier) is considered by the digital twin to accurately emulate the interaction between the two.

2.2.4. Power-HIL

The Power-HIL block of the RT-HIL framework investigates the interaction between the power grid under test (digital twin) and a physical power equipment in the loop (HuT). This allows the testing of how a prototype, or a commercial equipment will operate when connected to a specific location within an actual power system. Therefore, the dynamics of the power systems are replicated in a realistic way to investigate the operation of physical equipment under a relevant environment. Examples of physical power equipment are Photovoltaic (PV) plants, Battery Storage System (BSS), the electrical installation of a building, Wind-Turbines, among many others. It is important to highlight that the power-HIL component of this testing framework is crucial to validate and demonstrate how new power equipment will properly operate when connected to an actual power plant.

3. Architecture for the pre-piloting

From the description of the use-cases provided in D2.1, it emerged that two types of pre-piloting architectures could be defined in Smart5Grid based on their major scope:

- 1) ***Pre-piloting architecture to validate the functional requirements of the energy service(s) to be provided by the Network Applications that have an impact on the actual operation of the grid*** (UC3: *Millisecond level precise monitoring and control of distributed renewable energy sources*, and UC4: *Wide area monitoring of cross-border power flow and wide area-protection*); and
- 2) ***Pre-piloting testbed to validate functional requirements of early versions of Network Applications from the monitoring point of view of 5G connectivity*** (UC1: *Automatic power distribution grid fault detection*, and UC2: *Remote inspection of automatically delimited working areas at distribution level*)

It is to be noted that the control application related to the Bulgarian demo (UC3: *Millisecond level precise monitoring and control of distributed renewable energy sources*) refers to extensions of the initial scope of the pilot, as it was defined in the Document of Work (DoW). The scope is to close the control-loop of the applications defined in the DoW (extension from passive monitoring of RES power production) and provide an advanced proof-of-concept for active control and management of the distributed power RES units for providing real-time ancillary services to the relevant grid operators, such as the Distribution System Operator (DSO) or the Transmission System Operator (TSO). It is to be noted that these extensions are tested and validated only in the pre-piloting testing environment and not in the actual pilots. This is because the testing scenarios might be invasive to the normal operation of the grid (e.g., creating a fault in the grid to test the wide area protection scheme, for the pilot of UC4) or because the current regulations in Bulgaria do not yet allow the RES units (even in hybrid setups with energy storage units) to provide such type of ancillary services to the grid (for the pilot of UC3).

3.1. Architecture 1- focusing on energy operation

This first pre-piloting architecture refers to an RT-HIL framework which allows to realistically investigate the possible impact of energy related services (integrated in early versions of the use-case specific Network Applications) which might send actuation signals to power devices which could change the dynamic operation of the grid. It is important to highlight once again that this architecture is used for the pre-piloting testbeds for the Bulgarian Demo (UC3: *Millisecond level precise distributed renewable generation monitoring and control*) and for the cross-border Greek-Bulgarian Demo (UC4: *Real-time Wide Area Monitoring*), only.

The proposed general pre-piloting architecture using RT-HIL technology is presented in Figure 2. The major blocks of this RT-HIL testbed are: the Control-HIL component, the component that implements the digital twin of the actual power system (or the plant under test, such as a wind farm for example), the Power-HIL component, and the power interface consisting of a power amplifier. They were already detailed in the previous section of this report (section2).

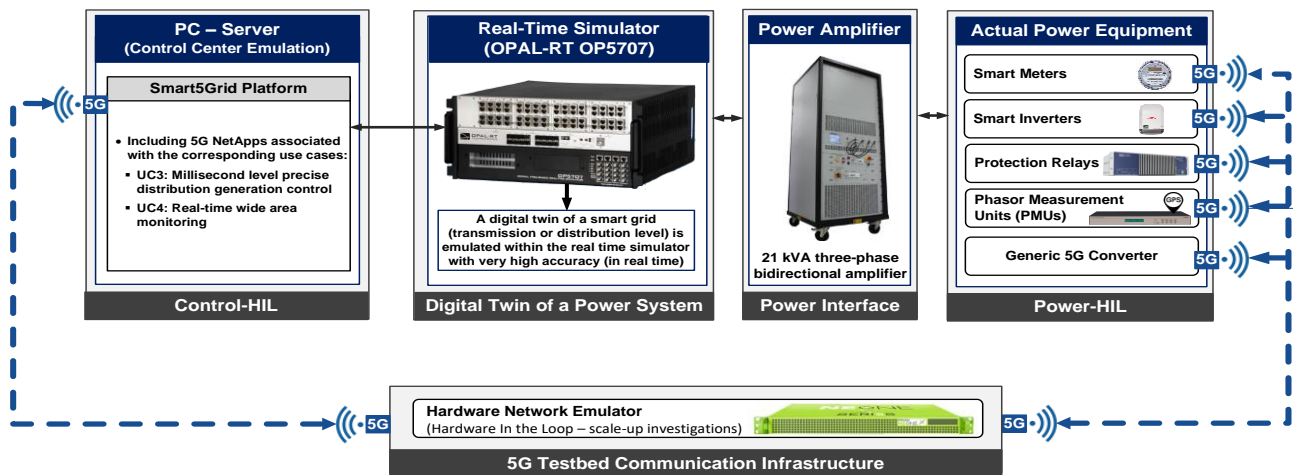


Figure 2: Generic pre-piloting architecture focusing on energy operation (UC3 & UC4)

This specific pre-piloting architecture also integrates in the RT-HIL framework another block related to the 5G communication infrastructure, in our case a Hardware Network emulator. This block provides the needed macroscopic dynamic behaviour of actual 5G infrastructure via the settings of relevant network parameters such as latency or loss of packets, among others.

3.2. Architecture 2 - focusing on 5G connectivity

The second type of pre-piloting architecture refers to 5G connectivity testing framework which allows to realistically investigate functional requirements of use-case specific Network Applications which provide services to the energy stakeholder, but do not have a direct impact on the dynamic behaviour of the power grid. Within this category lies the pre-piloting testing for early versions of the Network Applications for the Italian Demo (UC1: *Automatic power distribution grid fault detection*), and for the Spanish Demo (UC2: *Remote inspection of automatically delimited working areas at distribution level*).

The second architecture of the pre-piloting testbeds for the Smart5Grid is presented in Figure 3. This architecture is composed of three major components: (1) a component which is responsible to host and run the early versions of the Network Application (which is denoted here as Smart5Grid platform), (2) a component which is related to the 5G infrastructure involved in the respective use-case testing, which integrates actual 5G equipment which is most relevant for the data transfer between the Network Application and the field devices from the grid infrastructure; and (3) the component which incorporates all the relevant field devices from the energy infrastructure which constitutes source and/or receiver of data to/from the use-case specific Network Application. It is to be understood that all the necessary interfaces that make these three components work with each other are to be detailed when the implementation of this architecture is tailored to the particularities of the use-case.

It is worth mentioning that these two architectures share common blocks which relate to the integration of early versions of the Network Applications in the loop with emulated (architecture 1) or with actual 5G network infrastructure (relevant components only for the architecture 2), and the use of actual field devices which constitutes the source of data for the Network Applications (from the energy infrastructure of the relevant pilots).

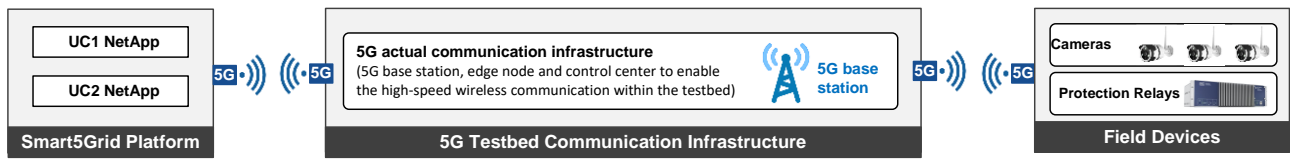


Figure 3: Generic pre-piloting architecture focusing on 5G connectivity (UC1 & UC2)

4. Methodology for pre-piloting testing

The methodology for testing and validation of the functional requirements of the pilots in the pre-piloting setups is composed of four phases. The first phase relates to the choice of hardware and software to be used in each of the pre-piloting setups, along with the assumptions considered to create the realistic operation conditions of the actual pilots. The second phase describes the Network Application integration process with the pre-piloting setup. The third phase defines the testing scenarios along with the relevant KPIs that those scenarios intend to validate. The last phase of the pre-piloting methodology refers to the actual tests where all scenarios are run and where the results obtained are summarized and discussed. Further details of each of these phases are provided below.

4.1. Phase 1: Create realistic conditions to replicate the UC operational environment:

This first phase of pre-piloting testing methodology refers to the details, assumptions and pre-requisites that were taken into account when the pre-piloting testbed was created, in order to ensure that it mimics as realistically as possible the real operation environment of the actual pilot.

In the case of the use of the RT-HIL type architecture for pre-piloting testing, most of this section covers the development of the digital-twin models of the actual system which in essence are advanced dynamical models of the actual systems implemented using modelling simulators (e.g., Simulink Matlab), and translated into simulation models readable by the digital RT simulator (e.g., OPAL -RT).

In the case of the 5G connectivity type of pre-piloting architecture, the realistic operation conditions are mainly related to the creation of similar operational environment of the 5G infrastructure component of the pre-piloting testbed with the behaviour of the same component or group of components operating in the actual pilot.

4.2. Phase 2: Network Application integration

This phase details the process of integration of the Network Applications (the early versions available for testing at the pre-piloting stage) with the pre-piloting testing infrastructure (testbeds), and where available with the corresponding Network Application Controller (NAC) for each of the four use-cases. It is to be noted that based on the proposed timeline of implementation of the Smart5Grid Project, the development and integration of the open Smart5Grid experimentation platform took place in parallel with the activities related to the pre-piloting (Task 3.2 and Task 3.3 of the Work Package 3). Furthermore, a key component of the platform, in charge with the Verification and Validation (V&V Framework) of the Network Applications, is still under development (Task 4.2). In summary, it is to be noted that the differences on the level of integration of the Network Applications with the pre-piloting testbed is highly dependent on the level of deployment of 5G infrastructure and platform integration into the actual pilot.

To overcome this challenge the Network Application integration phase focus on all the steps and tests performed in order to encapsulate the energy services (components of each use-case specific Network Application) into the form of Network Application, as it was defined by the Smart5Grid project, Deliverable D2.2 [2].

The canonical Smart5Grid way is to onboard the Network Application into the Open Service Repository (OSR) and trigger the Validation and Verification (V&V) framework. During the verification, the V&V framework will use the Network Application Controller Frontend (NAC_FE) interface (see Table 2-6 in D3.1 [3]) to onboard and test the Network Application deployment. For the OSR instance the endpoints are hosted at <https://osr-dev.s5g.gos.y-cloud.eu/>. However, because the development of the OSR took place in parallel with the pre-piloting testing, this path of Network Application onboarding could not be followed.

In UC1, UC3 and UC4 where the NAC is NearbyONE (a commercial product of Smart5Grid partner NearBy Computing (NBC)), it is also possible to onboard the Network Applications by manually using the NAC_FE interface of NearbyONE [3], by invoking a Representational State Transfer Application Programming Interface (REST-API), which is hosted at https://smart5grid.nearbycomputing.com/adapters/smart5grid/Network_Applications/. Once a Network Application is onboarded, it can either be deployed always with the NAC_FE or via the web User Interface (UI) of NearbyONE. In the second case, users also have the possibility to change part of the Network Application Descriptor to quickly iterate and do many tests. In this second case, we might still use the OSR's registry to pull artifacts from, or when not possible – for instance where Internet connectivity is not yet available – we can use local instance of the OSR's registry so to replicate as much as possible the production environment.

4.3. Phase 3: Defining the testing scenarios

This phase deals with the details of the pre-piloting tests, by defining specific testing scenarios and their related testing methodology, as well as the corresponding KPIs they are targeting by each of these testing scenarios. Sample tables for collecting this type of information in a unified manner were elaborated in collaboration with the involved partners in the task. They are provided below, including explanation on the expected type of input.

Table 2: Sample table for collecting the list of use-case specific pre-piloting testing scenarios

Scenario ID	Scenario Title	Testcase type	Description
PP – UC# – S1	Provide a short title for the scenario	Indicate the type of testcase the scenario refers to (connectivity, communication or Network Application functionality)	Detail the possible methodology to be used in performing the testing scenario
PP – UC# – S2			
.....			

This table collects the full list of testing scenarios for each of the four UCs in the pre-piloting testing phase. The first column allocates a specific ID for the testing scenario for later reference in joint tables within this document, as well as for easy identification in future testing reports and deliverables (e.g., those related to use-cases validation and verification under V&V framework testing or those related to the final pilot tests). The second column indicates a brief title for the scenario, while the last column offers more information about the scenario (where not fully covered by the title). The third column indicates the type of testing (if it relates to connectivity tests, components integration tests within the pre-piloting testbed or Network Application functional tests).

Table 3: Sample table for the definition of the functional requirements and the targeted KPIs for each of the testing scenarios

Scenario ID	Functional requirements	Targeted KPIs
PP - UC#- S1	Explain what type of functional requirement is investigated by this testing scenario	Provide specific, measurable KPIs for this testing scenario which could indicate if the test was successful or not.
.....		

This table provides information related to the aims of the testing scenario in terms of verification of a specific functional requirement associated with one or more targeted, measurable Key Performance Indicators (KPIs).

Table 4: Sample table for collecting additional information about the type of functional requirements to be investigated by each testing scenario

Functional requirement Name	Brief description of each functional requirement
Short name for the functional requirement investigated	Elaborate on how this functional requirement needs to be tested, what methodology can be used to test it and why.
.....	

This table is intended to collect further information on the methodology to be used for testing the specific functional requirement indicated for each specific testing scenario.

4.4. Phase 4: Validation and evaluation

The last stage of the proposed pre-piloting testing methodology refers to the validation and evaluation of the testing results. Again, we have organized the collection of the testing results following the same uniform approach as described in Phase 3. Thus, an integrated sample table was used in this scope, as it is shown in Table 5. The information reflects the scenario ID, the type of test, a comparison between the targeted KPIs and those obtained after tests. The last column intends to collect further comments, especially of the tests that did not pass as expected or when a large difference between the targeted and obtained KPI after the test was observed.

Table 5: Summary of testing results for the pre-piloting phase of UC #

Scenario ID	Type of test	Targeted KPIs	Real KPIs in tests	Comments
PP – UC# – S1	Connectivity test	KPI1, KPI2, ...		Test passed successfully. If not, please explain why.
.....				

Besides the testing results, this section also provides the actual proof of the testing results, such as screenshots, log snippets, etc. A brief analysis of the obtained results concludes this section.

5. Pre-piloting for the use-cases that use RT-HIL testing architecture

5.1. UC3: Millisecond Level Precise Distribution Generation Control

5.1.1. Phase 1: Pre-piloting testbed description and realistic conditions to replicate the UC operational environment

5.1.1.1. Introduction

The scope of the pre-pilot setup for the Bulgarian demo (UC3: *Millisecond level precise distributed renewable generation monitoring and control*) focuses on “**vertical-service pre-piloting testing**”, where digital twin and Hardware In the Loop (HIL) setups are used to validate the related Network Application and to further investigate the impact of two new potential control applications in the operation of the energy domain.

Particularly, the power infrastructure is considered in this framework in a non-invasive manner through a digital replica (digital twin) running in a real-time simulator and by incorporating actual power device connected in Power-HIL configuration, the 5G communication is introduced through a hardware network emulator, and the Network Application and two related additional applications are able to be tested under realistic and relevant conditions. The testing approach validates the correct operation of the monitoring Network Application. In addition, through this HIL testing procedure, the impact on the overall power system operation can be investigated when a new control application [21] for coordinating the operation of flexible DERs during disturbances is incorporated, and when different communication infrastructures are used to integrate this application in the smart grid framework. Moreover, another control application able to provide ramping rate control functionalities between a wind farm and a battery storage system located far away is investigated by utilising the real-time monitoring Network Application to facilitate the data exchange. In this case, the objective is to ensure strict ramping rate limitation by the combined DERs, considering MW/sec rates, compared to the MW/min rates that are currently considered.

5.1.1.2. Description of the pre-piloting testbed

The pre-pilot architecture for UC3 tries to create a realistic framework with real-time conditions related to the specific UC in order to test and validate the developed Network Application that facilitates the precise monitoring of Distributed Energy Resources (DERs). In addition, the same pre-piloting framework is used to examine some additional control functionalities (beyond the initial purpose of the project) to demonstrate how the advanced features of 5G technology can beneficially affect the operation of the power system when closing the loop in control applications. It is noted that the two additional control applications are only demonstrated in the pre-piloting stage, since several technical and regulatory restrictions are preventing the large-scale deployment of such control schemes in real life applications. Hence, the pre-piloting phase of UC3 aims to:

- Test and validate the deployment, operation and accuracy of UC3 Network Application for monitoring the DERs.
- Investigate the impact of two new control applications enabled by 5G technology on the operation of a smart grid.

The UC3 of the Smart5Grid project is related to the monitoring (and control) of distributed energy resources. Therefore, a digital twin has been developed to emulate in real-time the operation of a power system with high penetration of DERs. The digital twin of the power system and the DERs is connected in a Power Hardware In the Loop (Power-HIL) configuration with actual measuring/actuator devices (or virtual meters/actuators that are emulated within the digital twin) in order to enable the interaction with the Network Application or other control applications. Therefore, the digital twin, with actual or virtual meters/actuators, is connected in a Control Hardware In the Loop (Control-HIL) framework with the UC3 Network Application (or the additional control applications) through a network emulator. In this context, the network emulator can be configured with different settings to emulate the performance of a 5G, 4G, or 3G communication infrastructure, allowing an interesting investigation where the Network Application performance or the impact on the power system operation can be evaluated under different communication infrastructures. An overall diagram of the pre-piloting testbed for the UC3 is demonstrated in Figure 4, while detailed description about each key component of the pre-piloting configuration is analysed in the Table 6 below.

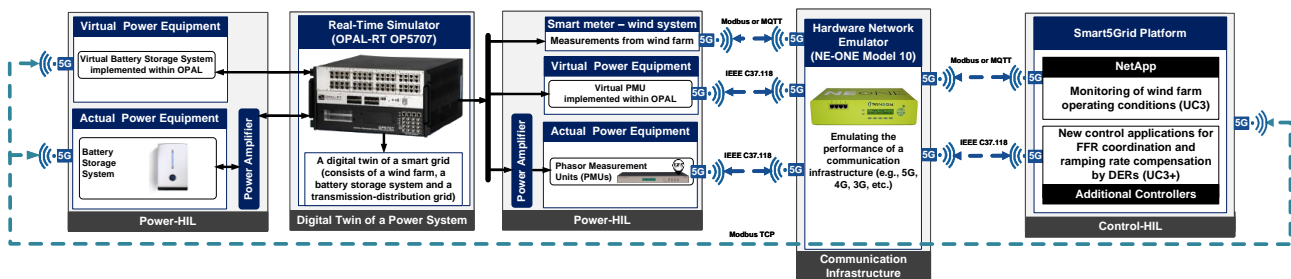


Figure 4: Pre-piloting testbed architecture for the UC3.

Table 6: List of components and their description for the pre-piloting testbed of UC3.

Component Name	Component Description
UC3-C-ID-1: Real Time Simulator (RTS)	<p>The real-time simulator is a key component of the pre-piloting infrastructure since it enables the development of a digital twin of a power system with intense penetration of DERs. The digital twin of the power system is developed as a dynamic, discrete-time MATLAB/Simulink model that runs in a dedicated real-time simulator (OPAL-RT 5707) to enable hard real-time constraints. In this model, the DERs are simulated using full analytical models for renewable sources or energy storage systems, including a grid tied intelligent inverter, where field data from an actual wind farm (e.g., wind speed, wind direction, temperature, power generation, etc.) have been processed to create realistic inputs to the DER model.</p> <p>The operating conditions of the power system or of the DERs are sensed through virtual or actual metering devices (e.g., smart meters, Phasor Measurement Units (PMUs), etc.). On the other hand, controllable actions can be taken within the energy infrastructure through virtual or actual power equipment/actuators (e.g., smart inverters, battery storage system, etc.). In case of virtual metering/actuator devices, these are simulated within the digital twin model that runs in the real-time simulator. The virtual devices exchange information with the Network Application or other related applications using digital communication protocols (e.g., Modbus TCP, IEC 61850, IEEE C37.118) over the local area network and the network emulator. In case</p>

of actual devices, the integration can be achieved through a power amplifier that is able to drive the actual equipment according to the digital-twin operating conditions. In this way, the Power-HIL can be facilitated by exchanging analogue signals between the digital twin and the amplifier. Then, the actual equipment integrated in this configuration (e.g., PMUs, inverters, etc.) communicates with the Network Applications or other related applications.

The real-time simulator is able to emulate the power system operation with a very precise manner with a solver resolution lower than 100 μ s. Accurate, dynamic and discrete-time models are used to replicate the operation of the power system as a digital twin.

The MATLAB/Simulink model to emulate the operation of a power system with intense DERs penetration is presented in Figure 5(a). This model is uploaded and executed in the real-time simulator presented in Figure 5(b) to enable the digital twin of the energy infrastructure.

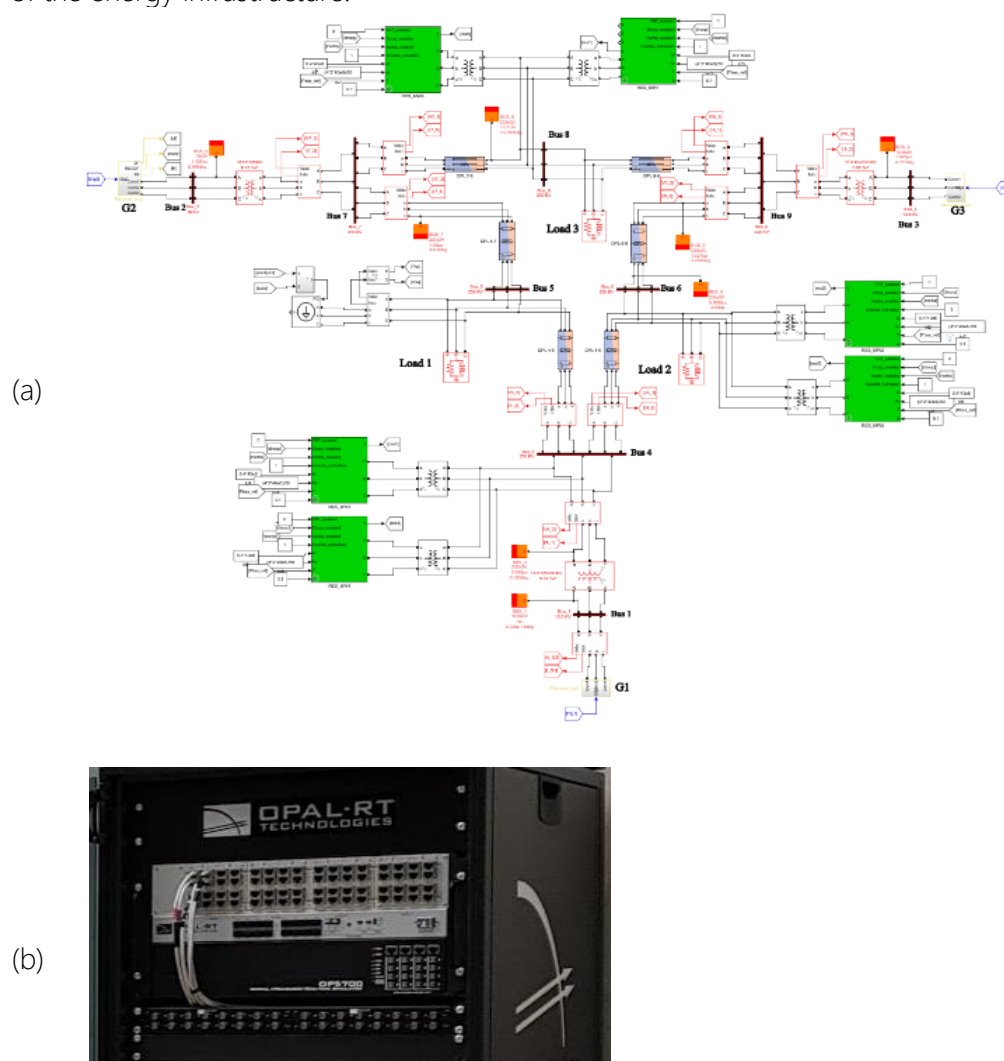


Figure 5: (a) Simulation model and (b) OPAL-RT 5707 real-time simulator that have been used to enable the development of the digital twin.

UC3-C-ID-2:
Power
amplifier

The power amplifier is a key component of the pre-piloting setup that enables the integration of actual power devices, such as meters (e.g., smart meters, PMUs, etc.) or actuators (e.g., inverters, photovoltaic or battery systems, protection relays, etc.), with the power system's digital twin. The power amplifier receives low voltage

analogue signals (e.g., $\pm 10V$) from the real-time simulator regarding the voltage and/or current operation of a selected node/line of the power system's digital twin. Then, it precisely (error lower than 0.2%) amplifies the voltage and/or current into an actual system scale (e.g., 0-400V, 0-32A, etc.) with a transient response of 10 μ s to allow the interconnection of actual power devices. The amplifier is able to exchange bidirectional active and reactive power in four quadrants to drive the operation of power devices by replicating conditions emulated within the real-time simulator. In addition, the amplifier measures the voltage conditions and the current exchanged with the power device in order to provide feedback to the real-time simulator (e.g., every 50 μ s) in order to be considered for the next step of the emulation.

In the particular pre-piloting facilities, two amplifiers have been used. Puissance Plus 3x7000VA (21 kVA) 4Q linear amplifier, shown in Figure 6 (a), is mainly used to interconnect power actuators (e.g., battery or photovoltaic inverter) where mainly the voltage conditions are replicated and enables bidirectional power flow. A second amplifier, Omicron CMS 356, shown in Figure 6 (b), with 4x300V and 3 or 6 x 32A output channels, is mainly used for connecting metering devices (e.g., PMUs, protection relays) where both three-phase voltage and current condition should be independently driven, which is required when short-circuit faults need to be replicated.



(a)



(b)

Figure 6: (a) Puissance plus 21kVA amplifier and (b) Omicron CMS 356 power amplifier.

UC3-C-ID-3:
Phasor
Measurement
Units (PMU)

PMU is a metering device used in power substations to measure and estimate the magnitude and phase angle of an electrical phasor quantity (voltage and current) using a common time source for synchronization. This is achieved by Global Positioning System (GPS) Precision Time Protocol (PTP) which enables the collection of synchronized measurements for wide area monitoring and control purposes. These metering devices are used in power substations and are connected to the secondary side of measurement transformers for voltage (VT) or current (CT) to sample the voltage and current conditions of a selected location in the power system. In the case of a pre-piloting setup, the PMUs are connected to the high voltage/current side of the power amplifier in order to measure the voltage/current conditions of the digital twin that are replicated through the amplifier. The measurements are processed by the PMUs to calculate the voltage phasors every 10 ms or 20 ms, where a GPS timestamp is included to enable the synchronization between measurements taken from different locations. Then, those measurements

are sent to a phasor data concentrator software using the IEEE C37.118 protocol, where the measurements are time aligned and stored to be used in wide area monitoring and control applications.

In this pre-piloting setup, a Sentinel-Arbiter Model 1133A PMU [22] and a Selinc SEL-451 protection relay [23] and PMU are used as shown in Figure 7. In addition, it should be noted that in case multiple PMUs need to be considered in a case study, then virtual PMUs can also be modelled within the real-time simulator, where the measurements are processed, they are GPS synchronized by an external GPS antenna and a synchronization card, and then the measurements are reported to the data concentrator through IEEE C37.118, emulating this way the operation of a physical PMU.



Figure 7: (top) Selenic SEL-451 PMU and protection relay and (bottom) Sentinel-Arbiter PMU 1133A.

UC3-C-ID-4:
Smart meter

Smart meter is also a measuring device that is widely used to measure the electrical quantities related to the operation of a power device. Smart meters provide asynchronized measurements compared to the synchronized measurement by PMUs and can therefore provide voltage and current root mean square (RMS) values and the active and reactive power, but they cannot report the phase angle due to lack of synchronization. Such meters are widely used in power systems, considered as conventional measurement in power substations, smart meters in consumers buildings, or meters connected with the wind turbine or photovoltaic controller in case of DERs. A smart meter measures the voltage through a voltage transformer (VT) and the current through a current transformer (CT) to provide a sort of isolation between the power and the measuring circuit. In the case of a pre-piloting facility, the smart meter is driven through the power amplifier according to the operating conditions of the power system's digital twin. The smart meter processes the measurements and reports the voltage, current, active and reactive power, frequency, power factor and other power quality quantities through a Modbus TCP protocol every 200ms. These measurements can be read by third party devices or software if they are connected as a Modbus server-client application with the smart meter.

In the pre-piloting setup, a Janitza UMG 604 [24] is used as shown in Figure 8. Furthermore, in case multiple smart meters are required in a case study, virtual smart meters can also be modelled within the real-time simulator, where the measurements are processed and reported through a Modbus TCP server to replicate the operational functionalities of an actual smart meter.



Figure 8: A Janitza UMG406 smart meter used to measure the operating conditions and report them to third party software through a Modbus TCP protocol.

UC3-C-ID-5:
Photovoltaic or
battery inverter

A photovoltaic or battery inverter is a power electronics device used to convert the DC power of a Photovoltaic (PV) or Battery Storage System (BSS) into AC power in order to properly inject the power into the grid in a synchronized and controllable manner. The inverter is an intelligent actuator that is able to maximize the PV production and control the charging and discharging procedure of the BSS. In actual systems, the DC side of the inverter is connected to a PV panel string or to an actual battery stack, while in the pre-piloting stage, a DC source with PV or BSS emulation capabilities can be used instead of the PV panel string or the actual BSS stack. The AC side of the inverter is connected to the power grid in actual setups, while in the pre-piloting setup the AC side is connected to the power amplifier (Puissance Plus) to integrate the inverter in a Power-HIL configuration with the digital twin. The embedded controller of the inverter is equipped with IoT functionalities and can be used to report measurements regarding the operating conditions of the inverter, and it can receive coordination signals (set-points) to regulate the operation of the inverter (e.g., reference active or reactive power) according to third party applications (e.g., wide area control application, virtual power plant controller, etc.). The exchange of measurements and coordination signals is performed through the Modbus TCP protocol, where the inverter is the server and other software (clients) can exchange signals with the inverter.

In Figure 9, the inverters used in the pre-piloting setup are presented. A Fronius Symo 5.0-3-M inverter [25] is used for PV system integration and a Soltaro all in one BSS (3x5kVA, 15 kWh) [26] is used as a flexible energy storage. In the pre-piloting stage, in case multiple inverters or scaled-up inverters are required to investigate their impact in the digital twin, then virtual intelligent inverters can be modelled and emulated within the real-time simulator, where the measurements and coordination signals are also exchanged through a Modbus TCP server. In addition, in the virtual inverters, additional functionalities (that may not be currently available in commercial inverters) can be considered to investigate the impact of such advanced functionalities in the operation of a smart grid.

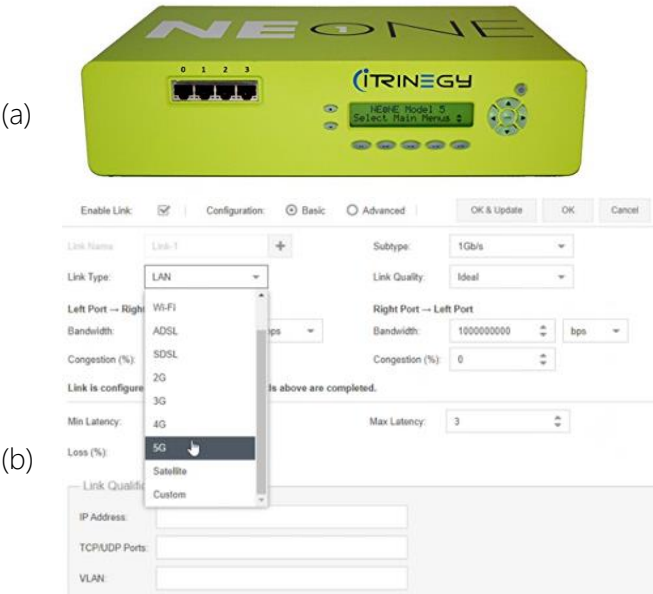


(a)



(b)

Figure 9: (a) Fronius Simo PV inverter, (b) Soltaro battery system.

<p>UC3-C-ID-6: Network Emulator</p>	<p>Network emulator is a hardware device able to emulate in a macroscopic way the operation of a network communication between end-to-end users. In this case, the communication link between two users passes through the network emulator and can be configured (according to IP or ports) to respond according to specific characteristics set by the requirements of the pre-piloting testing. For initiating different kind of investigations, the end-to-end delay response can be configured to achieve different communication performance according to the examined communication infrastructure (e.g., the 5G, 4G, 3G networks) or specific communication delay or loss of package rate can be pre-defined according to probabilistic distributions. In this way, the network emulator can be connected in the loop with all the devices communicating in the pre-piloting setup (e.g., real-time simulator, PMU or smart meter, Network Application or related applications, inverters, etc.) in order to investigate the impact of network performance on the energy domain operation.</p> <p>The iTrinegy NE-ONE Model 10 network emulator [27] is used in the pre-piloting facilities, as shown in Figure 10 (a), where the network performance can be configured through a web interface as shown in Figure 10 (b). Using this network emulator, the 5G communication can be integrated in the pre-piloting case studies to investigate the expected response in case of large-scale deployment of a smart grid application through 5G communication.</p> <div data-bbox="411 981 1066 1572">  <p>Figure 10(a) shows the iTrinegy NE-ONE Model 10 hardware network emulator, a green device with a front panel featuring a display and several buttons. Figure 10(b) shows the web interface for configuring the network emulator. The interface includes tabs for 'Enable Link', 'Configuration', 'Basic', and 'Advanced'. The 'Configuration' tab is active, showing settings for 'Link Name', 'Link Type' (LAN), 'Subtype' (1Gbps), 'Link Quality' (Ideal), 'Left Port -> Right' (Wi-Fi), 'Bandwidth' (ADSL), 'Congestion (%)' (SDSL), 'Link is configured' (2G, 3G, 4G, 5G), 'Min Latency' (4G), 'Loss (%)' (5G), 'Right Port -> Left Port' (Wi-Fi), 'Bandwidth' (1000000000 bps), 'Congestion (%)' (0), 'Max Latency' (3), 'IP Address', 'TCP/UDP Ports', and 'VLAN'. The '5G' option is selected in the 'Link is configured' dropdown.</p> </div> <p>Figure 10: (a) Hardware network emulator iTrinegy NE-ONE Model 10, (b) web-interface to configure the communication response of the network emulator.</p>
<p>UC3-C-ID-7: UC3 Network Application and related Control Applications</p>	<p>This part of the pre-piloting setup focuses on the applications that have been integrated and tested in the case studies. Therefore, in this case the focus is on the Network Application integration in the pre-piloting testing facilities or on the integration of the two additional control applications to showcase potential benefits when incorporating 5G technology within the smart grid.</p> <p>For UC3, the related Network Application has been integrated within the pre-piloting facilities to test and validate its effectiveness to precisely monitor the operation of</p>

	<p>DERs. The digital twin generates the measurements regarding the operation of a wind farm that are collected by the Network Application to monitor the DER operation. In addition, the pre-piloting setup is used to evaluate additional control applications (that was not initially in the DoW/GA), which cannot be tested in a real-life pilot due to either regulations, restrictions or technical limitations, preventing their actual implementation in large-scale systems. The first control application considers the Wide Area Control (WAC) for the coordination of flexible DERs (e.g., energy storage systems) through 5G communication to provide Fast Frequency Response (FRR) in case of intense disturbance to enhance system stability. Since such a control scheme has strict time restrictions, a hardware controller (e.g., Typhoon HIL 402 [28]) is needed to allow hard real-time control applications with a control period in the range of 10ms to 200ms.</p> <p>In addition, a second control application has also been developed to regulate the energy storage system operation to compensate intense variation of Wind or Photovoltaic parks' generation (when the DERs are not locally connected) to ensure strict ramping rate limitation by the DERs, considering MW/sec rates (compared to the MW/min rates considers in nowadays).</p>
UC3-C-ID-8: Hardware Controller	<p>This component is responsible for executing a control application for a smart grid when hard real-time constraints are involved. In the concept of smart grids, there are several cases where a control application should receive information from several devices installed in the grid, process this information and generate corresponding coordination signals for the flexible actuators of the power grid. In some cases, the control period of a smart grid wide area controller (including sampling, communication delay and control processing) should be within few milliseconds (e.g., 20ms, 50ms, etc.); and therefore, a dedicated hardware controller is needed to ensure the hard real-time execution of those applications. The first additional control application related to UC3 for the coordination of DERs involves such hard real-time constraints, since in the case of fast frequency support a control decision needs to be taken within less than 20ms to allow the proactive frequency support.</p> <p>For this reason, a hardware controller is used in the pre-piloting setup to host the additional control application and to ensure the hard real-time constraints. A Typhoon HIL 402 [28] controller is used in the testbed, as presented in Figure 11, and is connected in a hardware in the loop configuration with the digital twin. Besides the several advanced characteristics of this controller, Typhoon supports the digital data exchange through the main communication protocols used by the power industry. The controller receives measurements from the virtual sensors of the digital twin or from the actual measuring devices using different protocols (e.g., Modbus TCP, IEEE C37.118). Then, the measurements are processed accordingly within less than 10ms, considering the objective of the first additional control application, to generate the coordination signals for the flexible DERs. The coordination signals are sent to the virtual flexible DERs of the digital twin or to the actual power devices (e.g., flexible battery storage system) to effectively provide support services to the smart grid.</p>



Figure 11: Typhoon HIL 402 hardware controller.

5.1.1.3. Creation of the realistic operation conditions of the pilot

UC3 (Bulgarian demo) of Smart5Grid focuses on precisely monitoring (and potentially controlling) distributed energy resources. Therefore, a digital twin has been developed to emulate in real-time the operation of a power system with high penetration of DERs. The digital twin has been developed considering a dynamic and discrete-time power system model where field measurements are incorporated to replicate the realistic conditions for the operation of a modern power system. Accurate models for the DERs have been considered taking into account the power electronics converters with their associated controllers and field measurements regarding the renewable energy generation profiles. Then, the entire power system model has been uploaded in a Real Time Simulator (RTS), where it can run considering hard real-time restrictions, to formulate a digital twin able to accurately replicate in real-time the operation of a modern power system with massive penetration of DERs. The digital twin is widely recognized in the power system community¹ as a realistic, relevant and non-invasive environment used in the testing of such use cases.

The digital twin has been connected in a hardware in the loop (HIL) configuration with actual power devices, a network emulator and the UC3 Network Application or other related control applications of the Smart5Grid project. Actual power devices (e.g., smart meters, PMUs, inverters, etc.) are connected through a power amplifier and then measurements or coordination signals can be exchanged with the Network Application or the additional control applications using industrial communication protocols (e.g., Message Queuing Telemetry Transport Protocol (MQTT), Modbus TCP, IEEE C37.118, etc.). The communication perspective has been incorporated in this testing environment through a hardware network emulator able to replicate a pre-defined macroscopic response for the communication infrastructure to investigate how different communication infrastructure can affect the Network Application (e.g., here we refer to the newly designed power controllers) effectiveness or can cause an impact on the energy domain. This HIL configuration for the pre-piloting setup allows very realistic conditions for the specific UC and it enables a flexible environment where the entire system can be tested considering different investigation perspectives.

5.1.2. Phase 2: Network Application integration

5.1.2.1. Integration of the Network Application with the pre-piloting testbed

In this phase the initial objective is to integrate the UC3 Network Application with the pre-piloting testbed. The Network Application developed for UC3 refers to the Real-Time Energy Production Monitoring (RTPM) which aims at facilitating the precise monitoring of DERs operation in real-time over 5G communication. Specifically, Network Application specific for UC3 focuses on two distinct functionalities for the energy vertical. The first functionality as well as the one that has been tested within this HIL demonstration is the

¹ A. Monti *et al.*, "A Global Real-Time Superlab: Enabling High Penetration of Power Electronics in the Electric Grid," in *IEEE Power Electronics Magazine*, vol. 5, no. 3, pp. 35-44, Sept. 2018, doi: 10.1109/MPEL.2018.2850698.

monitoring functionality. This functionality allows the Network Application to receive data for the performance of a renewable energy asset (wind, hydro, solar) and visualise it for monitoring purposes. In the pilot demonstration, 13 wind farm signals will be tested of which 6 (for testing purposes) are already being received and visualised in these early versions of the Network Application. Along with these 13 signals, a series of other signals will be sent and processed for the purposes of the Network Application's second functionality – predictive maintenance enabler. It has to be noted that in the pre-piloting stage the monitoring functionality has been tested due to its relevance for the new control applications developed, while the predictive maintenance service remained out of the scope of the pre-piloting testing.

As presented in the diagram of Figure 12, the signals of the wind farm are being sent through 5G via an MQTT broker. The broker is located on the same virtual machine on which the Network Application has been uploaded (VivaCom Cloud).

The differences between the current version of the Network Application and how it is expected in its finalized version are the following:

- 1) Improved user interface
- 2) Availability of other source's data (hydro, solar)
- 3) Availability of the predictive maintenance enabler
- 4) Access to the Network Application according to roles (RES Owner/TSO)

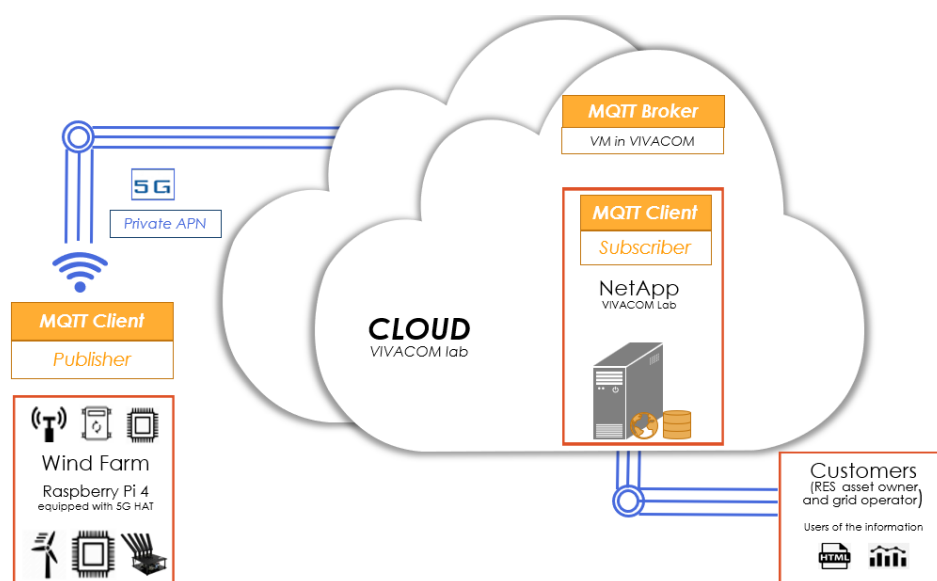


Figure 12: Overall structure of UC3 considering the data exchange from the wind farm to the Network Application using 5G communication.

The integration of the UC3 Network Application (monitoring application) with the pre-piloting facilities is achieved using the following system architecture, presented in Figure 13.

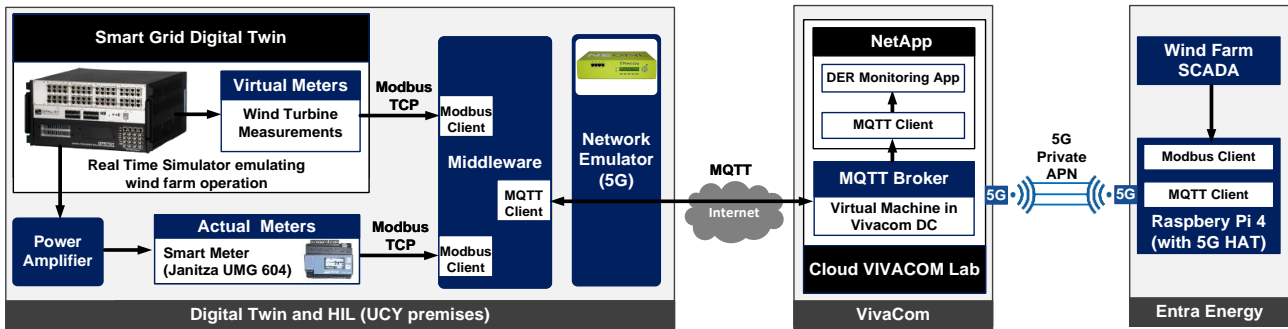


Figure 13: UC3 Network Application integration with the pre-piloting setup.

For the Network Application integration, the University of Cyprus (UCY) has developed a smart grid digital twin (with massive DERs penetration) running in a dedicated real-time simulator. The digital twin communicates measurements regarding the DERs operation through virtual or actual meters integrated with the digital twin. Then, a middleware is developed and utilised to obtain measurements from the meters (as a Modbus TCP client) and send the measurements to the MQTT Broker of VivaCom over the Internet using the MQTT protocol. An important aspect here is that between the developed middleware (MQTT client) and the MQTT broker, a hardware network emulator is integrated to replicate the response of the 5G network that will be used in the actual pilot. Up to this stage, the pre-piloting facilities at the UCY premises are replicating the operation of the actual pilot at the Entra Energy wind farm, where the Supervisory Control and Data Acquisition (SCADA) system of the wind farm measures the operating conditions of each wind turbine and then a Raspberry Pi (with 5G HAT) [29] is used, as a middleware, to obtain SCADA measurements as Modbus TCP client and forward them to the MQTT Broker of VivaCom over 5G communication. Then, the Network Application is developed by considering an MQTT client (subscriber) to receive the wind power system measurements in order to facilitate the monitoring applications for DERs. Key functionalities of the Network Application have been tested considering the capability of receiving a significant amount of data (with minimum loss of data) in a reliable way in order to utilise this data to facilitate a precise monitoring application for DERs.

A summary of the integration of the UC3 Network Application with the pre-piloting testbed is given in the table below.

Table 7: Steps for developing the pre-piloting testbed for enabling UC3 Network Application integration

Step	Step Description
Step 1 – Development of the digital twin	<ul style="list-style-type: none"> A power test system (i.e., IEEE 9 bus system [30]) is modelled in MATLAB/Simulink [31] using discrete-time fixed step solver. Wind turbine systems have been modelled within the power system simulation model using analytical models considering the associated inverters and their controllers. High resolution field measurements from an actual wind farm have been used to drive the wind farm operation in the simulation. Virtual meters have been developed within the simulation model considering Modbus TCP slave approach. All the necessary modifications have been made in order to upload the final simulation model in a real-time simulator to enable the execution of the digital-twin system in real-time.

Step 2 – Middleware development	<ul style="list-style-type: none"> • A middleware is developed, as a replica of the Raspberry PI 4 (with 5G HAT), to interconnect the digital twin running in the UCY laboratory (instead of the actual wind farm) with the MQTT broker (VivaCom cloud) • The middleware operates as a Modbus TCP client to obtain measurements from the virtual meters developed within the digital twin (power system with several wind turbines). The measurements consider at least the active power (P), reactive power (Q), wind speed (V_w), timestamp of the real-time simulator and timestamp of the middleware. • The received measurements are forwarded (published) to the MQTT broker considering a constant reporting rate ΔT (e.g., $\Delta T=500\text{ms}$, $\Delta T=1000\text{ms}$). The data includes the wind farm operation measurements and the timestamps and is published as a JSON data structure. An example of the data structure is presented here: <pre>UCY_HIL = struct with fields: timestamp_opal_sec: 21.450 / simulation time (seconds) timestamp_mw: 27-Oct-2022 12:33:4 / middleware datetime timestamp P: 3560.7 / Active power in kW Q: 120.3000 / Reactive power in kVar Vw: 5.6000 / Wind speed in m/s overrun: 0 / Overrun indication (0/1) to identify loss of data</pre> • The middleware is developed as a Matlab script able to run in a windows computer and as a Python script able to run in a Raspberry PI device.
Step 3 – Network emulator integration	<ul style="list-style-type: none"> • Integrate a network emulator in the communication link between the middleware (UCY premisses) and the MQTT broker (VivaCom cloud) to investigate how different communication infrastructure can affect the operation of smart grid applications. • For the Network Application integration, the network emulator is configured to emulate 5G, 4G and 3G networks with different characteristics (e.g., minimum latency, maximum latency, loss of data, etc.).

5.1.2.2. Integration of the additional control application for UC3 with the pre-piloting testbed

The pre-piloting testbed has also been used to test additional control applications, that have not been initially considered in the DoW/GA and are only investigated in the pre-piloting stage, since technical and regulation restrictions do not allow the large-scale deployment of such control applications in the field. The new control applications aim to demonstrate how 5G technology can beneficially affect the energy infrastructure operation when 5G is incorporated in the smart grid concept to close the loop and control DERs.

5.1.2.2.1. Control application 1 – WAC scheme to coordinate the provision of FFR by DERs

The first additional control application focuses on the Wide Area Control (WAC) of DERs to provide fast frequency support. This application aims to close the loop (move towards the control perspective) and showcase the fast frequency support by DERs coordinated through 5G communication in order to enhance the power system stability. Specifically, this control application considers a wide area control approach where synchronized measurements are taken from several PMUs installed in the grid through 5G

communication in order to timely identify a severe power disturbance that can threaten the stability of the power system. Under such severe disturbances, the control application is able to send coordination signals to flexible DERs (e.g., energy storage systems) to provide a proactive fast frequency support to the power system. In such critical cases, the fast coordination of DERs is needed in order to prevent cascading events. Therefore, this case study examines if the advanced features of the 5G technology are able to facilitate such a coordinated fast frequency support by several DERs. Due to the strict time restrictions of such an application, the new control application needs to be integrated in a hardware controller to ensure hard real-time operation with a control period between 10ms and 200ms.

The analytical description of the new control application can be found in the corresponding publication [21] presented in a special session organized by the Smart5Grid partners in the IEEE International Smart Cities Conference. The control application is developed in 3 main steps and the overall controller structure is presented in Figure 14.

- **Step 1 – Phasor Data Concentrator (PDC):** This step is responsible to receive and time align measurements for Phasor Measurement Units (PMUs) installed in the power system.
- **Step 2 – Wide Area Control (WAC) activation and power imbalance calculation:** In this step, the PMU data are processed to identify a severe power imbalance that can activate the WAC scheme. In case of a severe event, the total power imbalance is estimated.
- **Step 3 – DER coordination:** The estimated power imbalance is proactively compensated by the flexible DERs in order to prevent a severe frequency disturbance. In this step, the estimated power imbalance is allocated to the flexible DERs participating in the WAC scheme according to the real-time upward flexibility of each DER.

It is noted that the new WAC scheme for fast frequency support is developed using wireless communication (e.g., 5G, 4G, 3G) to facilitate the exchange of measurements and the system performance is compared for different cases: (a) when DERs provide frequency support according to the new WAC scheme in addition to the support provided by synchronous generators (according to their local governor controller), (b) when the frequency support is only provided by the conventional synchronous generators and the DERs do not provide any frequency support (baseline scenario), and (c) when the frequency support is provided by the conventional synchronous generators and DERs provide support according to the inverter local controller enhanced with frequency droop and virtual inertia functionalities (state-of-the-art scenario).

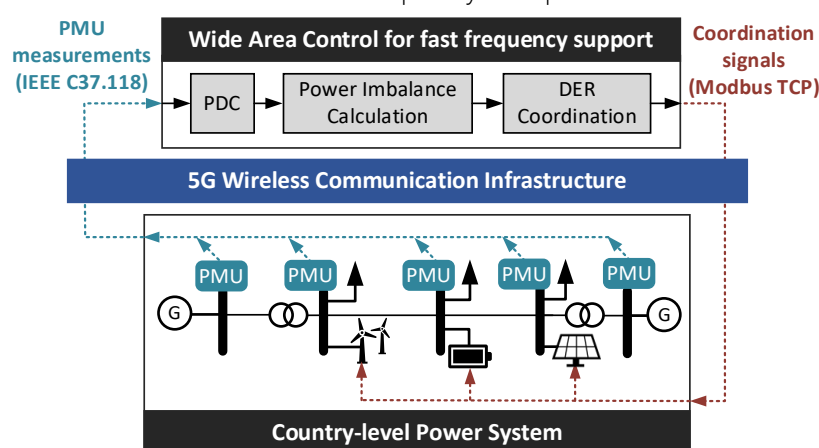


Figure 14: Additional control application 1 based on a wide area control approach to coordinate the provision of fast frequency support services by the flexible DERs.

The additional control application that has been developed to further investigate the potential benefit by the overall concept of UC3 when closing the loop to actively manage the DERs operation also needs to be

integrated within the pre-piloting setup. The integration of this controller is achieved by the following testbed architecture, presented in Figure 15.

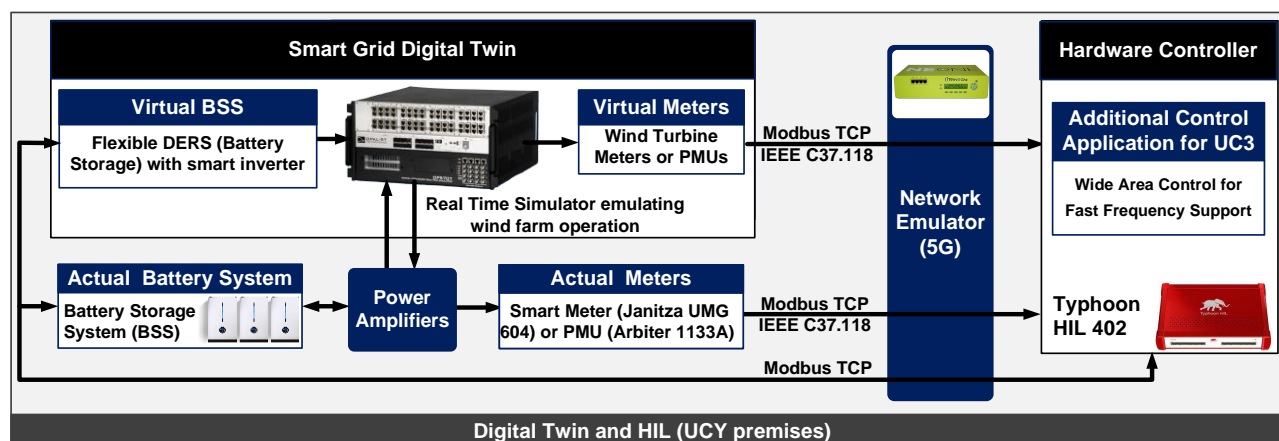


Figure 15: Integration of first additional control application of UC3 in the pre-piloting setup

For the integration of the first additional control application related to UC3 (for the wide area control for fast frequency support by DERs), the University of Cyprus (UCY) has developed a smart grid digital twin (with massive DERs penetration) running in a dedicated real-time simulator. The digital twin communicates measurements regarding the DERs operation through virtual or actual meters integrated with the digital twin, while the flexible DERs to be coordinated in this case study have been similarly integrated, either as virtual battery storage systems or as actual battery systems connected in a power HIL configuration. Then, measurements for the operation of the smart grid and of the non-flexible DERs are sent to a hardware controller (Typhoon HIL 402), where the control application runs due to hard real-time restrictions. The controller processes the measurements and sends coordination signals to the flexible DERs in order to support the power system operation. All the data (measurements and coordination signals) are exchanged through a hardware network emulator (iTrinegy NE-ONE model), which is connected in a HIL configuration (between the digital twin and the controller), in order to emulate the 5G network response. This setup has been used to investigate how the 5G network operation can affect the operation of the energy system and how the new control application can improve the overall power system operation.

5.1.2.2.2. Control application 2 – Ramping rate compensation control scheme for DERs

The second control application focuses on the compensation of unpredicted DERs power deviation by controlling flexible energy storage systems. This control application is facilitated by using UC3 Network Application for real-time monitoring of DERs. The new closed loop control application demonstrates how flexible DERs (e.g., energy storage systems) can be coordinated over 5G communication to compensate intense and unpredicted variation imposed by uncontrollable DERs (e.g., wind turbines, PV systems), ensuring in this way strict ramping rate restrictions that are beneficial for the stable operation of the energy system. Specifically, the second control application enables the virtual power plant concept to compensate the intense power variation of uncontrollable DERs and maintain a strict ramping rate of the combined DERs. To achieve such strict ramping rate limitations, in MW per sec scale instead of the existing MW per minute limit imposed current grid regulations, the power generation of uncontrollable DERs communicates measurements with a virtual plant controller every few msec (e.g., 500ms) over 5G technology and through the UC3 Network Application for real-time monitoring the DERs operation. This measurements exchange

is used by the new controller to coordinate flexible DERs to react immediately to maintain the ramping rate limitations.

The motivation for the development of this controller is the stable operation of the power system with increased penetration of renewable energy resources. Under high penetration levels, the power generation by uncontrollable renewable resources should not present intense power deviations, otherwise the entire system stability is threatened. In the existing grid regulation for interconnecting DERs², a ramping rate limitation is requested by renewable energy based DERs. For example, DERs should ensure that the ramping rate (as the average active power change per minute) should not exceed 15% of the nominal DER power for a 1-minute period. At the same time, a second limit is imposed considering an average power change per minute of 7.5% of the nominal DER, 10 minutes period. The second limit restricts the maximum power change to 75% of the nominal power in 10 minutes. It is worth mentioning that these ramping rate regulations refer to non-flexible DERs (e.g., wind, photovoltaics) and do not consider the extra flexibility that can be provided by flexible DERs (e.g., battery storage). Therefore, with the upcoming massive deployment of energy storage systems, new regulations are expected to further restrict the ramping rate and the allowable power deviation of DERs to ensure the stable operation of the grid when it is dominated by renewable resources. In addition to that and considering the communication technology improvement and the economy of scale, large-scale storage systems are expected to be installed in the system and provide services to DERs located in other locations facilitating the virtual power plant concept. In this case 5G communication can be used to enable the fast and reliable data exchange (measurements, coordination signals) to enable such new services to support the overall operation of the grid. In this framework, strict ramping rate regulations are expected to be applied to ensure the stable operation of the power system with minimum power imbalances. Hence, a strict ramping rate regulation is assumed for this case study, when DERs are virtually combined with energy storage systems. In this case, a 0.5% limit (of the nominal DER power per second) is imposed for the ramping rate for a period of 1 second (RR_{1s}) and an additional limit of 1.5% limit is considered for a ramping period for a period of 10 seconds (RR_{10s}).

For the ramping rate controller design, UC3 NetApp for real-time monitoring of DERs is used, as shown in Figure 16. First, field measurements regarding the operation of renewable energy based DERs (e.g., wind park, photovoltaic park) are obtained by the monitoring Network Application with a reporting period of 500ms through 5G wireless communication. It is noted that the reporting rate should be faster (or at least equal) compared to the ramping rate time scale (1000ms in this case). This measurement data is published to the MQTT broker of the Network Application. Then, the new controller is connected as a MQTT client to the Monitoring Network Application to receive the real-time measurements from the uncontrollable DERs. In this case, the ramping rate controller is assumed to be located at the energy storage site. An alternative way (but still equivalent in terms of communication delay) may be considered, where the ramping rate controller is located at the cloud, but in the same server with the monitoring Network Application in order not to introduce an additional communication hop. Now for the controller design, three main steps have been considered, as shown in Figure 16:

- **Step 1 – Measurement from DERs:** In this step, the measurements of the active power generation of DERs are obtained and analysed in order to identify the per second ramping rate of the active power in a period of 1 second (MW/1s) and in a period of 10 seconds (MW/10s).

² Transmission System Operator of Cyprus, Transmission and distribution grid regulations, Version 5.3.0, April 2022.

- **Step 2 – Ramping rate control:** This step is responsible for ensuring the strict ramping rate limits. If a ramping rate violation occurs, then the coordination signal for the energy storage is calculated, which is able to compensate for the violation of the ramping rate limit. Since two limits are considered in this case, the algorithm sequentially first examines the ramping rate limit in a period of 1 second, and then it examines the limit in a period of 10 seconds.
- **Step 3 – Allocation to energy storage:** The final step is responsible for the allocation of the coordination signal for compensating for a ramping rate violation to the available energy storage participating in this scheme, considering the upward availability of each storage system. The final signals are sent to the energy storage systems via the local area network in order to regulate their charging/discharging power accordingly, and provide the ramping rate service.

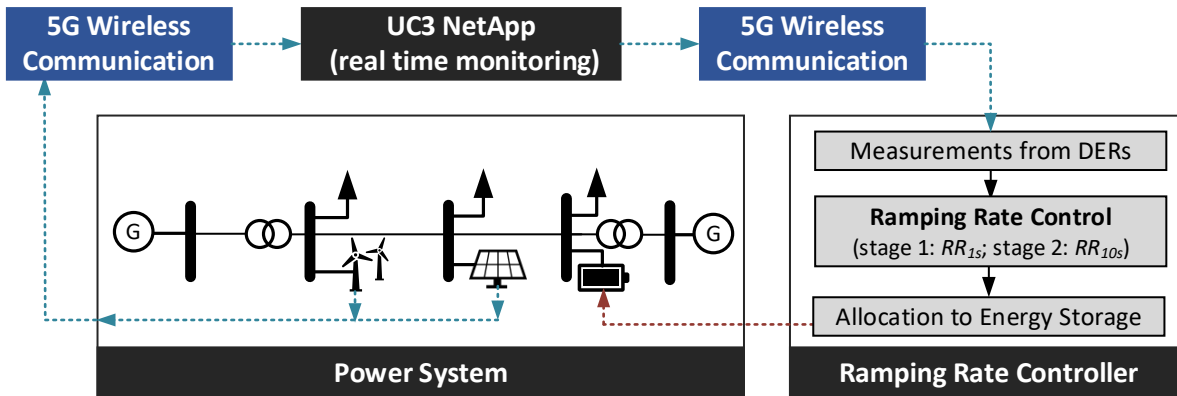


Figure 16: Additional control application 2 based on a strict ramping rate compensation controller for remote DERs based on renewable energy and energy storage systems.

As a result, the combined power of DERs (wind, photovoltaic, energy storage) should ensure the strict ramping rate limits and therefore, minimum power imbalances are expected by the DERs participating in a virtual power plant, with great benefit for the power system stability. This additional control application is related to the overall concept of UC3 and is demonstrating how the monitoring Network Application can be used to actively manage the DERs operation. The ramping rate control application is also integrated within the pre-piloting setup considering the following testbed architecture presented in Figure 17.

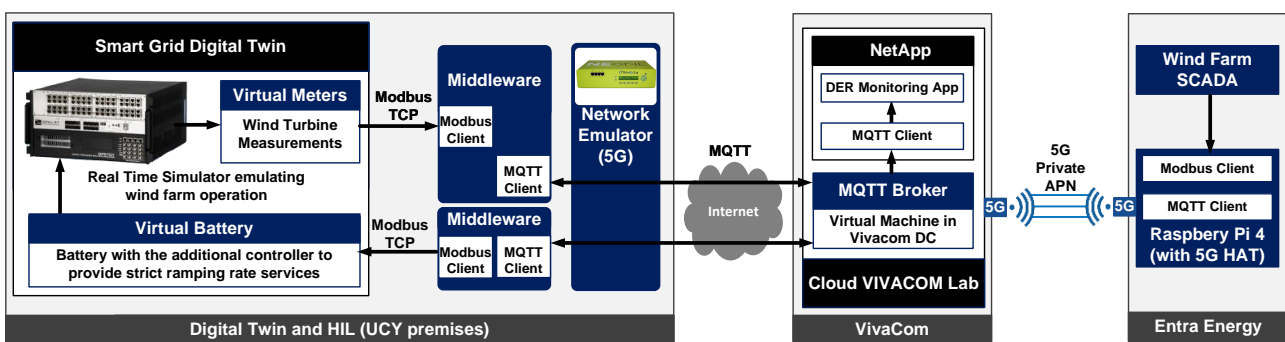


Figure 17: Integration of second additional control application of UC3 in the pre-piloting setup through UC3 Network Application for real-time monitoring.

For the integration of the second control application related to UC3, a similar pre-piloting testbed is developed with the one used for the Network Application integration validation (in Figure 13). The only difference in the new setup, as shown in Figure 17, is the incorporation of a second middleware to enable the communication between the monitoring Network Application of UC3 and the ramping rate controller.

This middleware is connected as an MQTT client with the Network Application MQTT broker (through the network emulator) to read the active power measurements published by DERs. Then, the ramping rate controller and the energy storage system are both emulated within the real-time digital twin. Therefore, this setup allows the control hardware in the loop validation of the new ramping rate controller, since the information exchange between the uncontrollable DERs and the flexible DERs is facilitated through the monitoring Network Application developed within the Smart5Grid project.

5.1.2.3. Main steps for the integration, validation, testing and evaluation of the Network Application and the additional control application

To achieve the successful integration, validation, testing and evaluation of the Network Application and of the additional control applications the testing procedure should be specified, several pre-conditions should be ensured, specific testcase steps should be followed, a common measurement methodology should be determined to properly evaluate the applications performance based on KPIs, and the methodology for the Network Application integration via the NAC should be defined. These main steps are discussed in this subsection.

Testing procedure: With the pre-piloting setups described above three main applications were tested (UC3 Network Application for DERs monitoring, and the two additional control applications for fast frequency support and for ramping rate compensation). For all the applications, a similar power system digital twin has been developed, where a dynamic version of the IEEE 9 bus system is modelled, enhanced with several flexible and non-flexible DERs where real and realistic measurements are employed. Then, the digital twin runs in a real-time simulator replicating the operation of the power infrastructure. The digital twin is able to exchange measurements with the Network Application and the control applications (related to the DERs or to the power system operation) and control set-points (related to the coordination of flexible DERs).

Pre-conditions: To proceed with the pre-piloting testing, there are several pre-conditions that need to be ensured. The digital-twin operation should be first validated to ensure that it is actually replicating a realistic operation of DERs and of a power system under all the scenarios that have been examined. The Network Application and the additional control applications should be integrated with the digital twin over the network emulator or the middleware and ensure the capability to exchange data. A basic validation of the proper operation of the Network Application and of the additional control applications should also be performed before proceeding with the pre-piloting testing. Related measurements from the pre-piloting setup operation should be collected to enable the validation and evaluation phase.

Testcase steps: The following steps have been performed in the pre-piloting stage. For each scenario that has been examined, first, a corresponding digital twin (similar but not the same for each scenario) needs to start running in the real-time simulator. The baseline scenario initially runs (without the use of the Network Application or the additional control applications) to capture the baseline operation of the system. Then, the Network Application or additional control application is integrated in a HIL configuration with the digital twin, and measurements are taken to evaluate the performance of the system when the new applications are employed. Then, the experiments are replicated and for each case considering different network performance (configured by the network emulator) to evaluate how the communication performance can affect the overall operation of a smart grid. Measurements are collected for each scenario (each scenario is based on different power or network conditions) to facilitate the evaluation of the pre-piloting test using key performance indicators.

Expected results/KPIs: For each Network Application or control application different results are expected. For the case of the UC3 Network Application, the goal is to achieve an accurate and real-time monitoring of the DERs operation with minimum loss of data (less than 0.5%). For the first additional control application related to the provision of fast frequency support by DERs, the target is to achieve a significant improvement on the system stability indicated by an improvement on the frequency nadir (minimum frequency) and the Rate Of Change Of Frequency (ROCOF) by at least 60% compared to the baseline scenario where no frequency support is provided by DERs, and by at least 40% compared to the scenario where DERs provide frequency support according to their local controller (considering droop control and virtual inertia concept). For the second control application related to the ramping rate compensation, the target is to reduce the maximum and average ramping rate violation by at least 50% for a 1 second period, and at least 80% for a 10 second period. Related KPIs have been defined to evaluate each case according to some measurements obtained by the pre-piloting investigations.

Measurements methodology: Depending on the pre-piloting experiment and investigations, measurements have been collected either from the power system's digital twin, from the network or from the Network Application/control applications under investigation to calculate the relevant KPIs and evaluate the system operation.

Network Application-NAC integration – Helm Chart: The Network Applications for UC3 (and UC4) use Helm Chart for the installation in Kubernetes. Helm is the package manager for Kubernetes. The Helm Chart contains all the resource definitions necessary to run an application. The following steps described the process of creating Helm Chart package for a Network Application (e.g., UC3 Network Application=der):

1. Creating empty Helm Chart with the following command: `helm create der` – the command creates `der` folder with several files and subfolders.
2. In the created Helm Chart, the following items should be described:
 - The image that should be installed.
 - The service Kubernetes component with the external port to access the application.
 - The startupProbe that is used for detecting the successful starting.
 - The name of the component.
3. In the "values.yaml" file, you can edit the following:
 - The `image` section where the location of the image that will be installed is defined.
 - The name of the chart.
 - The `service` section where the parameters used in service template are defined.
4. Edit "templates\deployment.yaml" file.
5. Edit "templates\service.yaml" file and add the required properties.
6. Create Helm package using the following command: `helm package der`.

Then, a Network Application Descriptor is used to integrate Network Applications for UC3 (and UC4) with NAC. The Network Application Descriptor contains the related fields (e.g., im-version, name, description, provider, version, service-format, services) for successful Network Application onboarding. The main steps for the successful Network Application onboarding are briefly mentioned here:

1. Create Network Application Descriptor file.
2. Add Network Application to "Marketplace" section of "Service Designer" of NBC.
3. Add Network Application as new service in "Designer" section of "Service Designer".

4. Deploy the new created in previous step service in “Deployment” section of “Service Designer”.
5. Check “Services” section and find new service there.

5.1.3. Phase 3: Defining the testing scenarios

In phase 3, the involved partners have defined the main testing scenarios, which have been examined and analysed in the pre-piloting stage of UC3. Four main scenarios have been defined to examine: the integration and validation of UC3 Network Application; the validation and impact evaluation of the first and second additional control applications related to UC3; and the onboarding and deployment of the Network Application via NAC. The details for the testing scenarios related to UC3 are described in the table below.

Table 8: List of testing scenarios for the pre-piloting phase of the UC3

Scenario ID	Scenario Title	Testcase type	Description
PP – UC3 – S1	Monitoring DERs operation	Test and validation of Network Application operation and Service provision	This scenario focuses on the integration of UC3 Network Application for monitoring the DERs operation. The Network Application is integrated with the pre-piloting setup and receives measurements for the DERs operation that are generated by the digital twin. In this way the effectiveness of the Network Application to precisely monitor the operation of DERs has been validated.
PP – UC3 – S2	Provision of fast frequency response by flexible DERs	Test and validation of the system response according to the first additional control application and impact evaluation of the energy system operation under different communication performances.	This scenario focuses on the integration of the additional control application 1 related to UC3, for coordinating the fast frequency support provision by DERs. The control application is integrated with the pre-piloting setup and its effectiveness on supporting the power system operation is evaluated. Furthermore, the impact of the communication network (e.g., 5G, 4G, etc.) used for integrating this control application on the operation of the smart grid is also investigated.
PP – UC3 – S3	Provision of ramping rate compensation by flexible DERs	Test and validation of the second control application response for ramping rate compensation.	This scenario focuses on the integration of the second control application related to UC3, for compensating intense power deviation and maintaining strict ramping rate limits. The control application is integrated with the pre-piloting setup, through the UC3 Network Application for monitoring DERs and its effectiveness on supporting the power system operation has been evaluated.

PP - UC3 – S4	Network Application onboarding and deployment via the NAC	Test and validation of the Network Application onboarding and deployment via the Network Application Controller	This scenario focuses on the integration of the Network Application with the NAC. The user onboards and deploys the Network Application to ensure the correctness of the Network Application and the expected life cycle management of the NAC.
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For each testing scenario, a corresponding functional requirement, and the targeted KPIs have been defined, as presented in the table below.

Table 9: Definition of the target KPIs for the testing scenarios in the pre-piloting phase of UC3

Scenario ID	Functional requirements (FR)	Targeted KPIs
PP – UC3 – S1	FR1: Capability to precisely monitor the DER operation	<ul style="list-style-type: none"> • KPI1: Number of data exchange for monitoring purposes. In this case, a reporting period between 500ms and 1000ms from each DER has been considered and therefore the exchange of 600-1200 sets of data per hour are expected (e.g., one call of the publish command to the MQTT broker is equivalent to one set of data exchange). • KPI2: Loss of data for the Network Application should be less than 0.5% when 5G technology is used. It is noted that any data that is arrived to the MQTT broker with a delay higher than the reporting period is considered as loss of data.
PP – UC3 – S2	FR2: Provision of coordinated fast frequency support by DERs	<ul style="list-style-type: none"> • KPI3: A frequency nadir improvement by at least 60% (compared to the no support case by DER) and by at least 40% (compared to the local support case by DER) is expected when 5G is incorporated for the provision of fast frequency support. • KPI4: A Rate of Change of Frequency (ROCOF) improvement by at least 60% (compared to the no support case by DER) and by at least 40% (compared to the local support case by DER) is expected when 5G is incorporated for the provision of fast frequency support.
PP – UC3 – S3	FR3: Provision of ramping rate compensation by flexible DERs	<ul style="list-style-type: none"> • KPI5: An improvement of the maximum ramping rate violation in a period of 1

		second by at least 50% and in a period of 10 seconds by at least 80%. <ul style="list-style-type: none"> • KPI6: An improvement of the average ramping rate violation in a period of 1 second by at least 50% and in a period of 10 seconds by at least 80%.
PP – UC3 – S4	FR4: The NAC is operative, and the compute nodes onboarded.	A KPI does not apply in this case. This is a pass or fail test.

Each functional requirement that has been tested in the pre-piloting phase for UC3 is described in the table below.

Table 10: Functional requirements definition for the testing scenarios in the pre-piloting phase of UC3

Functional requirement Name	Brief description of each functional requirement
FR1: Capability to precisely monitor the DER operation	This functional requirement is related to the capability of UC3 Network Application for monitoring the operation of DERs. The Network Application should be able to receive information from the digital twin regarding the DERs and should process this information to monitor the DERs operation in real time. A real-time monitoring should be achieved (in millisecond scale, e.g., 500ms, 1000ms) with a minimum loss of data.
FR2: Provision of coordinated fast frequency support by DERs	This functional requirement examines the capability of providing fast frequency support by DERs in a coordinated manner according to a wide area control scheme integrated over 5G communication. The DERs should be coordinated and provide proactive frequency support services to the power system when a critical power disturbance occurs that can threaten the system stability. As a result, the provision of coordinated frequency support is envisioned to enhance the system frequency stability, reducing the ROCOF and the frequency drop (increasing the frequency nadir) under critical events.
FR3: Provision of ramping rate compensation by flexible DERs	This functional requirement focuses on the coordination of flexible DERs to compensate intense variations of uncontrollable DERs. The goal is to maintain a strict active power ramping rate of the combined DERs (e.g., wind and storage system), when operating as a virtual plant.
FR4: The NAC is operative, and the compute nodes onboarded.	This functional requirement focuses on the successful deployment of the Network Application via the Network Application Controller (NAC). The correctness of the deployed Network Application should be ensured.

For each testing scenario, different KPIs have been defined to enable the evaluation of the pre-piloting tests. The definition of each KPI is stated in the following table.

Table 11: Description of the KPIs for the testing scenarios of the UC3

KPI Name	Brief description of each KPI
KPI1: Number of data exchange for monitoring purposes	KPI1 represents the total number of values-data exchange in the entire duration of the experimental testing performed for validating the operation of the monitoring Network Application for DERs.
KPI2: Loss of data	KPI2 indicates a percentage regarding the loss of data related to the monitoring Network Application for the duration of the experimental test. This is calculated by dividing the total number of data lost with the total number of data sent by the digital-twin middleware and is express as a percentage.
KPI3: Frequency nadir	KPI3 represents the minimum (nadir) frequency measured after an intense power disturbance occurs in a power grid. This is a key indicator for the system frequency stability and for a stable system a minimum deviation from the nominal frequency (i.e., 50 Hz) is required.
KPI4: Rate of Change of Frequency	KPI4 represents another key integrator related to the frequency stability of power systems. The Rate Of Change Of Frequency (ROCOF) is calculated as the time derivative of the frequency during a severe event, and for stable systems the ROCOF should be as low as possible. ROCOF is usually calculated as the average rate of change within a certain time window after the event (e.g., 0.2s, 0.5s) indicated as $ROCOF_{0.2s}$ and $ROCOF_{0.5s}$ respectively.
KPI5: Maximum and average ramping rate violation	<p>KPI5 is an indicator related to the capability of an energy resource to maintain controllable power generation. For this case, active power ramping rate is calculated as the power change per second (in MW/s) evaluate for a period of 1 second (RR_{1s}) and for a period of 10 seconds (RR_{10s}). For the calculation of KPI5, the RR_{1s} and RR_{10s} are first calculated in each sample and if the corresponding limit is violated (RRL_{1s} or RRL_{10s}) then the ramping rate violation (RRV_{1s} or RRV_{10s}) is calculated according to the following equations:</p> $RRV_{1s} = \begin{cases} 0 & \text{if } RR_{1s} \leq RRL_{1s} \\ RR_{1s} - RRL_{1s} & \text{if } RR_{1s} > RRL_{1s} \end{cases}$ $RRV_{10s} = \begin{cases} 0 & \text{if } RR_{10s} \leq RRL_{10s} \\ RR_{10s} - RRL_{10s} & \text{if } RR_{10s} > RRL_{10s} \end{cases}$ <p>Then the maximum (RRV_{1s-max} or $RRV_{10s-max}$) and the average ($RRV_{1s-mean}$ or $RRV_{10s-mean}$) value of the ramping rate violation are calculated for the entire period of the experiment to be used for evaluation purposes.</p>

5.1.4. Phase 4: Validation and evaluation

Phase 4 focuses on the validation and evaluation phase of the pre-piloting tests related to UC3. A brief description of the validation results is described below for each testing scenario, while the evaluation is performed using the defined KPIs for each scenario.

5.1.4.1. Validation and evaluation of the Network Application operation for monitoring DERs

The first set of tests focuses on the UC3 Network Application integration and validation. The successful integration of UC3 Network Application is achieved and the Network Application was able to receive measurements regarding the operation of a wind farm that is emulated within the real-time digital twin (pre-piloting setup).

The screenshot presented in Figure 18 demonstrates that the connection is achieved between the UC3 Network Application (monitoring functionality) and the pre-piloting testbed (UCY-HIL), which relies on the HIL setup with the digital twin that is running in the UCY premises in Cyprus. In Figure 19, the Network Application connection status is provided, where the location of the connected device (pre-piloting setup in Cyprus) and the last value of the received signals (e.g., active power, reactive power, wind speed) are presented. The monitoring capability of the Network Application is demonstrated in Figure 20, where a plot of the active and reactive power generated by the emulated wind farm within the pre-piloting setup is demonstrated for a time window between 17:42:33 and 17:42:44 on Nov. 4th, 2022. It is noted that in this experiment a 1000ms reporting rate is considered for the monitoring application.

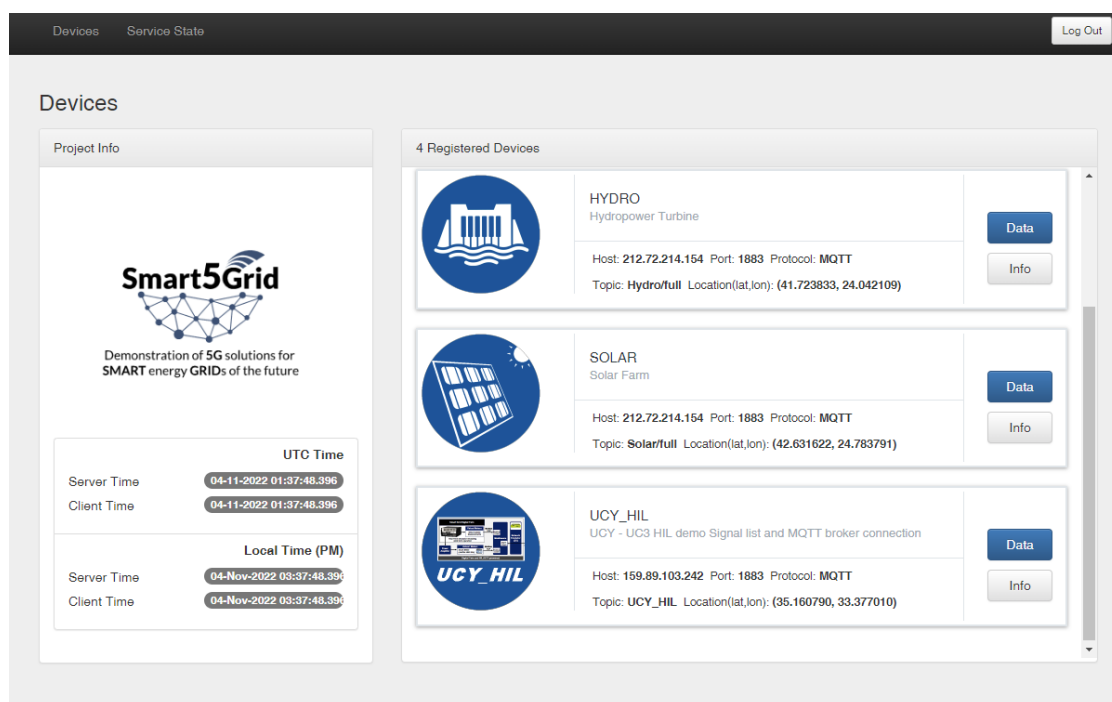


Figure 18: Connectivity status between UC3 Network Application and the UCY-HIL (pre-piloting testbed)

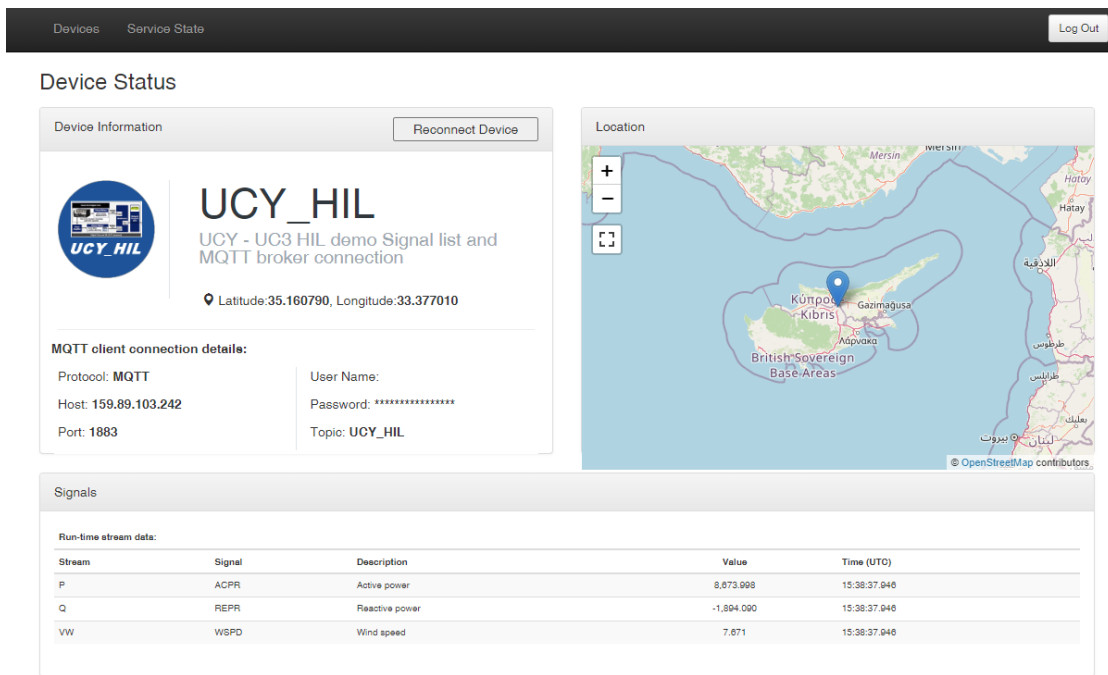


Figure 19: Testbed status for the connectivity tests and signals exchange between the Network Application and the UCY-HIL (pre-piloting testbed).

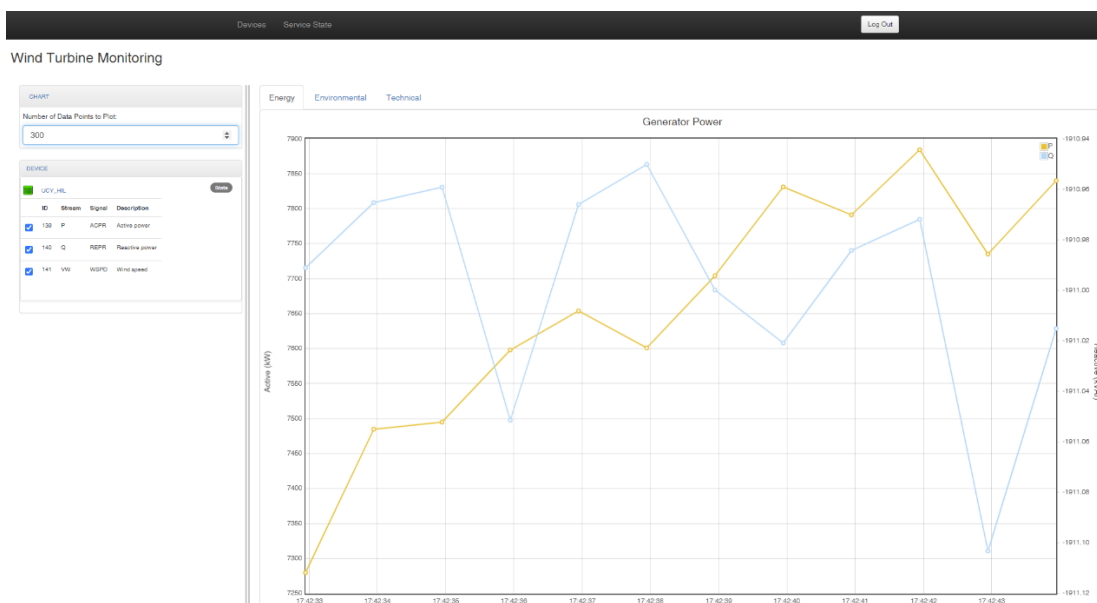


Figure 20: Demonstration of the monitoring functionality for the UC3, where the active and reactive power generated by the wind farm emulated within the digital twin of the pre-piloting testbed is presented considering reporting rate of 1000ms.

The part of UC3 Network Application that focuses on the predictive maintenance functionality is also tested to ensure that it is able to connect and receive measurements from the pre-piloting testbed. It is already clarified that the effectiveness of this functionality will only be validated in the actual pilot demonstration, however, the capability to connect and receive data from the pre-piloting setup is only demonstrated at this stage. Figure 21 demonstrates the capability of the predictive maintenance Network Application to

connect to the pre-piloting setup (UCY_HIL) and select the data (e.g., active power, reactive power, wind speed) to be analysed for enabling the predictive maintenance functionality. The selected data (e.g., active power) can be first visualised considering a selected historical time window (e.g., from 04/11/2022 15:41:32 until 04/11/2022 15:46:32), as shown in Figure 22, and based on the selected time-series data set the predictive maintenance analysis will be performed. The selected data and time window are just indicative examples to demonstrate the capability to collect these measurements to be used for the predictive maintenance purposes.

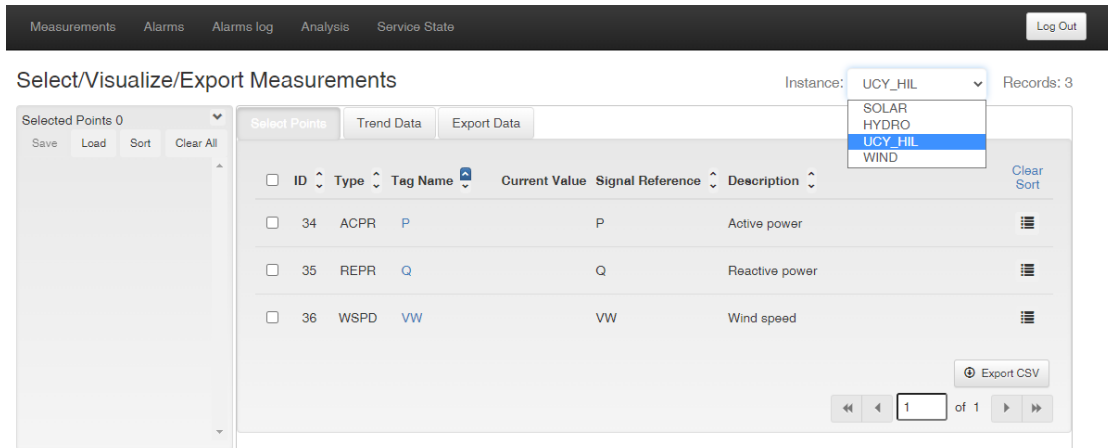


Figure 21: Predictive maintenance Network Application connection with the pre-piloting setup (UCY-HIL).

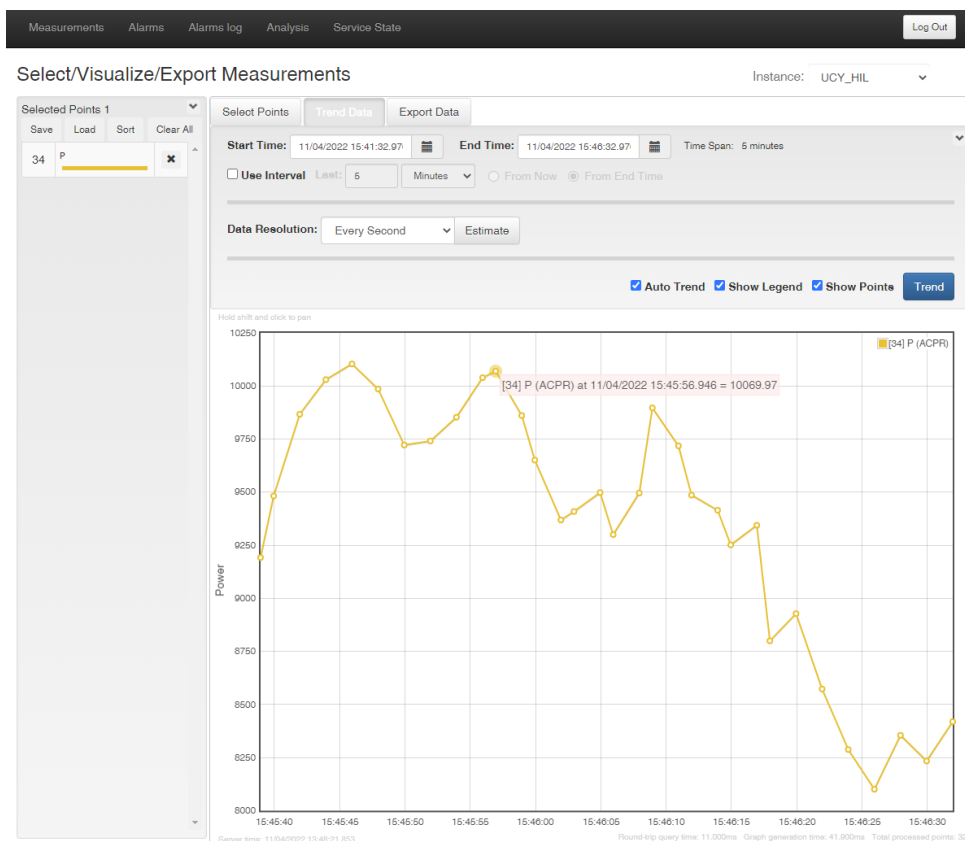


Figure 22: Selection of a signal (e.g., active power) and a historical time window of the data exchanged with the pre-piloting facility that will be used for the predictive maintenance analysis.

In the pre-piloting testing of the Network Application for the precise real-time monitoring of DERs, it is also important to investigate the loss of data that may occur considering different reporting rates and different communication infrastructures (e.g., 5G, 4G, 3G). A real-time monitoring application for DERs can be used to provide data for the real-time management of DERs or for the active management of the power grid. Therefore, it is important to ensure that the real-time constraints are met when the data are going to be used for control purposes. For this reason, any data that delays more than 1 reporting period to arrive to the MQTT broker is considered as loss of data at the application level, since the data is not available to be used for control purposes.

Several investigations have been performed to analyse the reporting rate capability in combination with the wireless communication network that is used for the data exchange between the field and the MQTT broker. The results are presented for an investigation of 1 hour in Table 12 for a reporting rate of 500ms where 1200 data have been exchanged and in Table 13 for a reporting rate of 1000ms where 600 set of data have been exchanged. When the command to publish data to the MQTT broker is called, then a set of data (e.g., values for P, Q, V, I, etc.) is exchanged with the application service. The network characteristics (e.g., minimum latency, maximum latency, and loss of data) used for the communication between the middleware (located in the pre-piloting facilities of UCY) and the MQTT broker (located in cloud VivaCom lab) for each network type are also indicated in those tables. It is noted that the loss of data mentioned for the different network type refers to the loss of a package, while the loss of data in the last column of the tables refers to the loss of data at the application level. When a fast-reporting rate is used (e.g., 500ms), it is observed in Table 12 that an acceptable loss of data of 0.25% is achieved at the application level with 5G technology, while a higher loss of data of 2.08% is observed with 4G and a completely unacceptable loss of data of 86.58% with 3G. On the other hand, in case of a bit slower reporting rate (e.g., 1000ms), it is observed in Table 13 that a zero loss of data is achieved with both 4G and 5G technologies, while a small loss of data of 0.16% is observed when 3G communication is used. It is clear for this investigation, that when a smart grid application requires a fast-reporting rate, in example a reporting period of 500ms or even lower, the necessity of using 5G technology for the data exchange is of high importance, especially when the application considers control functionalities.

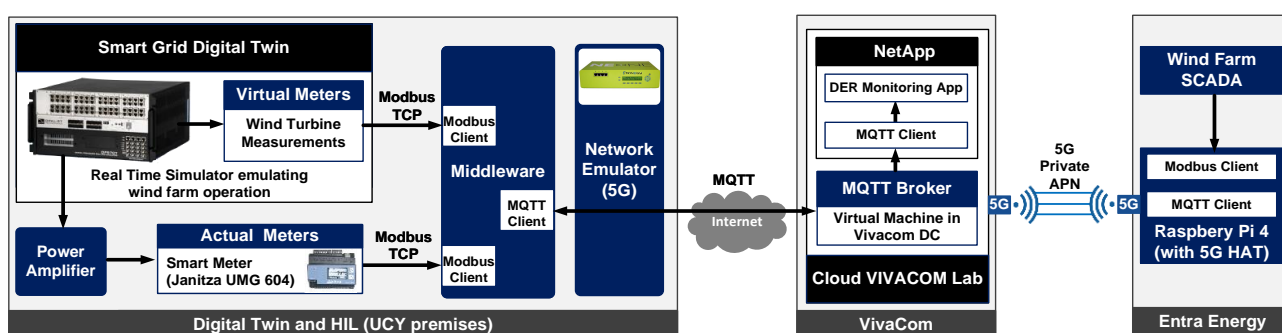


Figure 23: Integration of the Network Application of UC3 with the pre-piloting setup

Table 12: Pre-piloting integration of UC3 Network Application and loss of data investigation for 500ms reporting rate.

Network Type	Network Characteristics	Delayed data/Sent data	Loss of data (%)
--------------	-------------------------	------------------------	------------------

3G Network	<ul style="list-style-type: none"> ▪ Minimum latency: 33ms ▪ Maximum latency: 60ms ▪ Loss of data: 1% 	1039/1200	86.58 %
4G Network	<ul style="list-style-type: none"> ▪ Minimum latency: 17ms ▪ Maximum latency: 27ms ▪ Loss of data: 0.1% 	25/1200	2.08 %
5G Network	<ul style="list-style-type: none"> ▪ Minimum latency: 3ms ▪ Maximum latency: 4ms ▪ Loss of data: 0% 	3/1200	0.25 %

Table 13: Pre-piloting integration of UC3 Network Application and loss of data investigation for 1000 s reporting rate

Network Type	Network Characteristics	Delayed data/Sent data	Loss of data (%)
3G Network	<ul style="list-style-type: none"> ▪ Minimum latency: 33ms ▪ Maximum latency: 60ms ▪ Loss of data: 1% 	1/600	0.16 %
4G Network	<ul style="list-style-type: none"> ▪ Minimum latency: 17ms ▪ Maximum latency: 27ms ▪ Loss of data: 0.1% 	0/600	0 %
5G Network	<ul style="list-style-type: none"> ▪ Minimum latency: 3ms ▪ Maximum latency: 4ms ▪ Loss of data: 0% 	0/600	0 %

5.1.4.2. Validation and impact evaluation of the first controller for frequency support by DERs

In this subsection, the validation and the impact evaluation of the first control application that has been developed related to the UC3 is presented. The new control application considers a Wide Area Control (WAC) approach for coordinating the provision of Fast Frequency Response (FFR) by flexible DERs. The controller response is first validated and then the impact evaluation is performed where frequency stability of the power system is evaluated according to the system frequency under a common intense power imbalance of 200MW (loss of generation) at $t=30s$. The frequency response is demonstrated in Figure 24 under different scenarios, mentioned in Table 14, considering different control approaches and different communication infrastructures used for the data exchange.

Nine different scenarios have been performed within this investigation as listed in Table 14. In all the scenarios, the conventional synchronous generators are always providing frequency support considering their local governor controller. However, in each scenario the provision of fast frequency support by DERs is different. In the baseline scenario (scenario 1), DERs do not provide any frequency support. In scenarios 2 and 3, DERs provide frequency support according to the local inverter's controller considering droop functionality (scenario 2) and droop and virtual inertia functionality (scenario 3). The rest of the scenarios (scenarios 4-9) consider the operation of the new control application based on a WAC for provisioning FFR when different communication infrastructures are used (e.g., 3G, 4G, 5G, ideal). The average communication latency for each scenario is indicated in Table 14. The system frequency response is

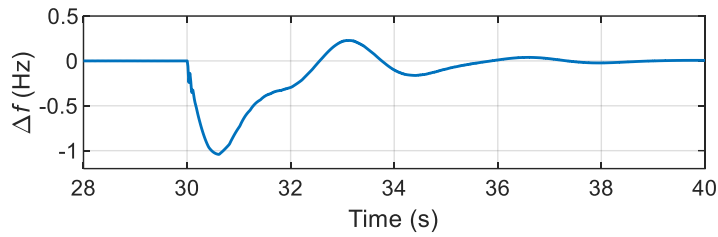
demonstrated in Figure 24 for selected scenarios, while the key frequency stability indicators are summarized in Table 14 for all the scenarios.

It is important here to highlight that when local control functionalities are considered in the inverter of DERs (scenario 3), the frequency stability can improve by up to 30%, considering an improvement on frequency nadir from 48.96 Hz to 49.28 Hz compared to the baseline scenario 1. When the new WAC application is incorporated for the coordinated provision of fast frequency support, then the system response is highly affected by the performance of the communication infrastructure involved during the data exchange. For example, when 3G communication is used (scenario 4), the frequency stability improvement is inadequate, and the minimum frequency (49.22 Hz) is worse compared to the local control approach (scenario 3) approach where no communication is required. However, when 4G communication is used (scenario 5), a stability improvement is observed since the frequency nadir increases to 49.46 Hz.

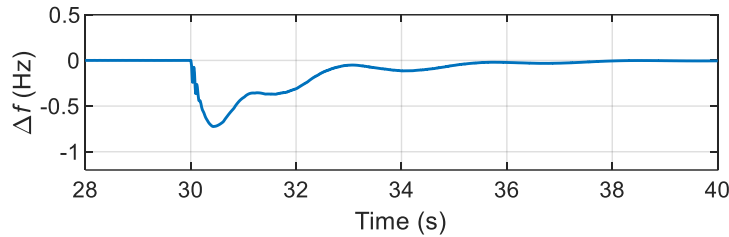
Table 14: Impact evaluation for the frequency stability under different control scenarios and under different communication used for the data exchange.

#	Scenario	Stability performance indicators		
		f_{nadir} (Hz)	$RoCoF_{0.5s}$ (Hz/s)	$RoCoF_{0.2s}$ (Hz/s)
1	No support by DER (baseline)	48.96	-2.01	-2.85
2	DER with droop support	49.22	-1.54	-2.54
3	DER with droop and virtual inertia	49.28	-1.43	-2.46
4	WAC-FFR with 3G (100ms)	49.22	-0.75	-2.86
5	WAC-FFR with 4G (50ms)	49.46	-0.28	-2.09
6	WAC-FFR with 4G (20ms)	49.65	-0.07	-1.03
7	WAC-FFR with 5G (10ms)	49.76	0.03	-0.70
8	WAC-FFR with 5G (3ms)	49.76	0.02	-0.35
9	WAC-FFR with ideal comm.	49.80	0.08	0.04

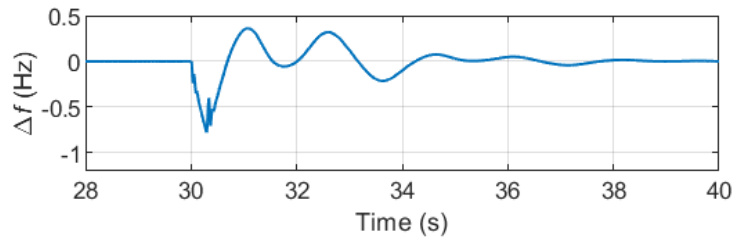
Finally, when 5G communication is used (scenario 7), a significant improvement is achieved regarding the frequency stability, an improvement that is almost equivalent to the case of the ideal communication. When 5G communication is utilised (scenario 7), a frequency nadir improvement of 76.9% and a $ROCOF_{0.5s}$ improvement of 98.5% is achieved compared to the no support case by DERs (scenario 1), while a frequency nadir improvement of 66.6% and $ROCOF_{0.5s}$ improvement of 97.9% is achieved compared to the local support case (scenario 3) with droop and virtual inertia by DERs



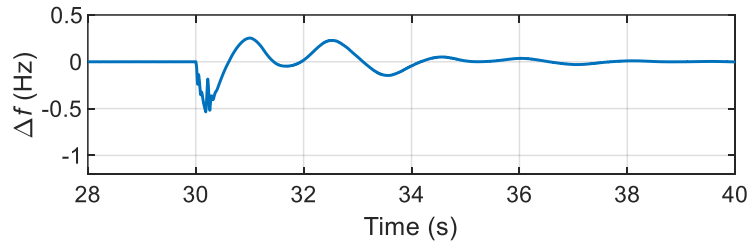
(a) Power system frequency response when DERs do not provide any frequency support (scenario 1-baseline).



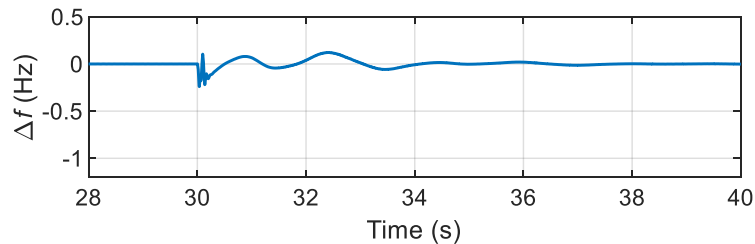
(b) Power system frequency response when DERs provide frequency support according to the inverter's local controller considering frequency droop and virtual inertia functionalities (scenario 3).



(c) Power system frequency response when DERs provide frequency support according to the new WAC application using 3G communication with an average latency of 100ms (scenario 4).



(d) Power system frequency response when DERs provide frequency support according to the new WAC application using 4G communication with an average latency of 50ms (scenario 5).



(e) Power system frequency response when DERs provide frequency support according to the new WAC application using 5G communication with an average latency of 10ms (scenario 7).

Figure 24: Performance evaluation of the new control application related to UC3 for the power system frequency support considering different control approaches and different communication infrastructure.

5.1.4.3. Validation of the second control application for ramping rate compensation by DERs

In this subsection, the validation and evaluation of the second control application is presented. The new control application considers a ramping rate compensation by integrating the monitoring Network Application in order to coordinate the flexible DERs. The controller response is validated considering an uncontrollable DER based on wind energy with a rated power of 200MW (where realistic data have been considered for the power generation) and a flexible DER of 20MW maximum charging/discharging power connected in a different location of the IEEE 9 bus test system. The communication is facilitated through the monitoring Network Application of UC3 between the wind-based DER and the ramping rate controller located at the battery storage system site.

The first scenario (baseline) considers the operation of the wind-based DER (with a blue line), without the ramping rate controller, as presented in Figure 25. In this plot, the power generation along with the ramping rate calculations for a period of 1 second (RR_{1s}) and of 10 seconds (RR_{10s}) are demonstrated (with a blue line). It is obvious that due to the abrupt power variations of DERs, a ramping rate violation occurs in three cases during the experiment (between 110s and 123s; between 200s and 203s; and between 300s and 310s). In these cases, RR_{1s} and/or RR_{10s} violates the limit of 1MW/s and 3MW/s that have been considered for this investigation, while the mean and the maximum ramping rate violations are presented in Table 15 for the entire experiment.

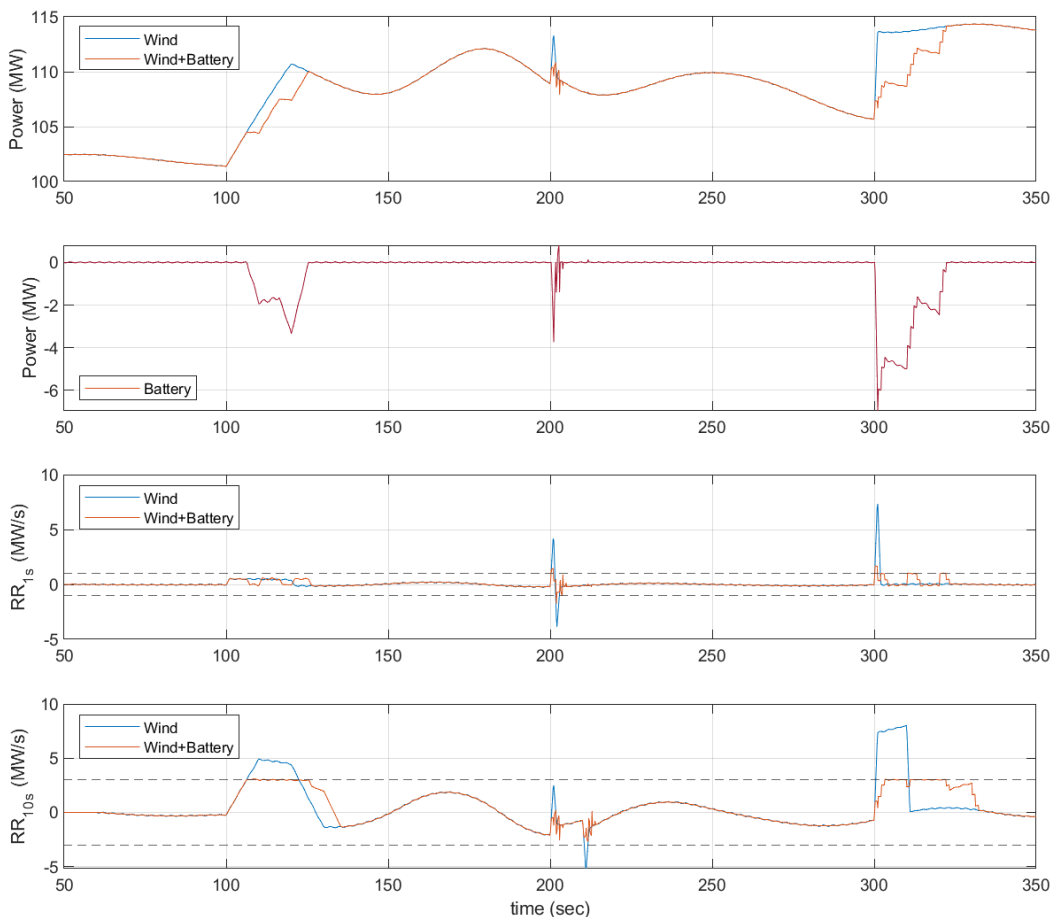


Figure 25: Performance evaluation of the new control application for ramping rate compensation. The blue line corresponds to the baseline scenario (only wind without ramping rate control) and the red line corresponds to the combined DERs response (wind and battery according to the ramping controller).

Table 15: Impact evaluation of the new controller considering the power deviations according to the mean and maximum ramping rate violation (RRV).

#	Scenario	Mean Ramping Rate Violation	Max Ramping Rate Violation
1	Baseline scenario with no ramping rate controller	<ul style="list-style-type: none"> ▪ $RRV_{1s-mean} = 3.1$ MW/s ▪ $RRV_{10s-mean} = 2.7$ MW/s 	<ul style="list-style-type: none"> ▪ $RRV_{1s-max} = 6.3$ MW/s ▪ $RRV_{10s-max} = 8.2$ MW/s
2	Use of the new controller to provide strict ramping rate compensation services	<ul style="list-style-type: none"> ▪ $RRV_{1s-mean} = 0.38$ MW/s ▪ $RRV_{10s-mean} = 0.02$ MW/s 	<ul style="list-style-type: none"> ▪ $RRV_{1s-max} = 2.76$ MW/s ▪ $RRV_{10s-max} = 0.08$ MW/s
Improvement		<ul style="list-style-type: none"> ▪ For 1s period 87.6% ▪ For 10s period 99.2% 	<ul style="list-style-type: none"> ▪ For 1s period 56.5% ▪ For 10s period 98.9%

The second scenario (red line of Figure 25) corresponds to the combined DERs operation (Wind + Battery) according to the new ramping rate controller over 5G communication. It is observed that during the abrupt power changes of the wind farm, the battery system timely reacts in order to ensure the ramping rate power limits for a 1 second and a 10 second window (RRL_{1s} and RRL_{10s} respectively). In the case of a 1 second period of the ramping rate, some violations are still observed since the sampling rate of the controller is in the same scale (0.5s) with the time scale of the ramping rate (1s), however, in the case of a 10 second period the ramping rate violations are almost eliminated. As a result, the combined DERs operation is able to achieve a more controllable operation and avoid intense and abrupt power imbalances that can pose a threat to the stability of the power system. The mean and the maximum ramping rate violations are presented in Table 15 for this scenario as well, indicating a significant improvement of these KPIs that corresponds to a more controllable operation of the combined DERs (VPP approach).

Through the new controller, an improvement of 87.6% and of 56.5% is observed for the mean and maximum ramping rate violation considering a period of 1 second. Similarly, in the case of a 10 second period, an improvement of 99.2% and of 98.9% for the mean and maximum ramping rate violation is achieved. Such new control applications that can be enabled for smart grids by the new 5G communication infrastructure can improve the operational capabilities of the power system under intense penetration of renewable energy sources and can facilitate the green transition of the energy infrastructure.

5.1.4.4. Validation of Network Application onboarding and deployment via NAC

The last part of the validation phase focuses on the validation of the onboarding and deployment procedure for the Network Application via NAC. In this case, by executing a corresponding command (screenshot of Figure 26) the Network Application is added to the *Marketplace* section of *Service Designer* of NBC, as shown in Figure 27.

```

root@kubernetes-worker:/home/vv/Helm Charts# jq -n --arg descriptor "${cat netapp-uc3-helm-1.0.2.yaml}" '${descriptor}' > onboard-request.json
root@kubernetes-worker:/home/vv/Helm Charts# curl -i -H 'Content-Type: application/json' -H 'X-API-key: c94ea546-157f-4907-bd7c-12aelf233fa7' -X POST http
s://smart5grid.nearbycomputing.com/adapters/smart5grid/netapps/ --data-binary "@onboard-request.json"
HTTP/2 200
date: Thu, 01 Dec 2022 10:43:55 GMT
content-type: application/json
content-length: 32
vary: Origin
strict-transport-security: max-age=15724800; includeSubDomains
{"netapp_id":"NetappUC3:1.0.2"}

```

Figure 26: Command execution for adding Network Application to the Marketplace.

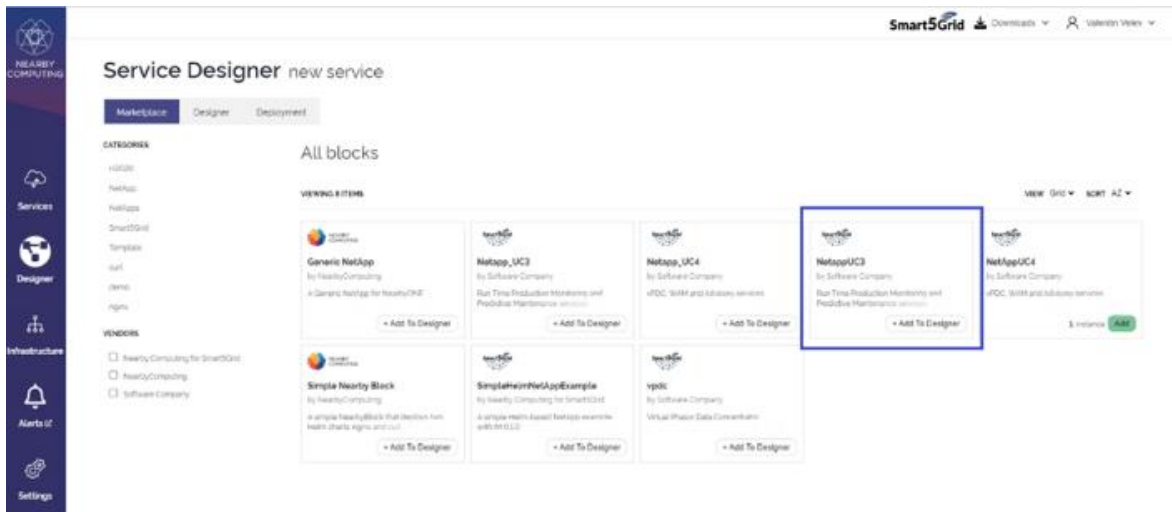


Figure 27: UC3 Network Application appears in the *Marketplace* of *Service Designer*.

Then, in the *Designer* section of the *Service Designer* (of NBC), the Network Application can be configured as a new service, as demonstrated in Figure 28. After that, in the deployment section, a name can be provided for the Network Application and then by pressing the *Deploy* button the Network Application is successfully deployed (Figure 29).

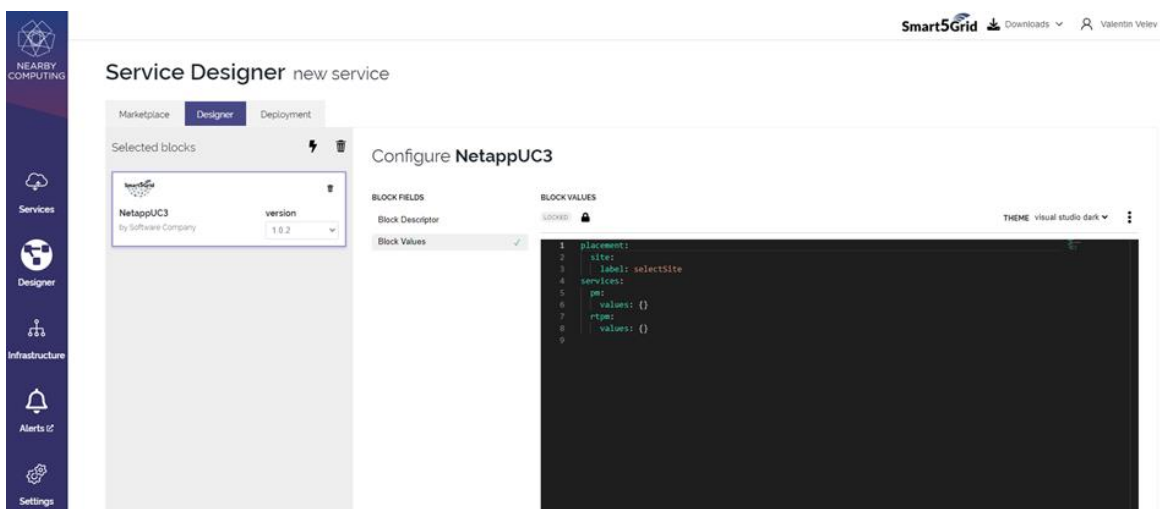


Figure 28: Configuration of the Network Application as a new service in the *Designer* section of *Service Designer*.

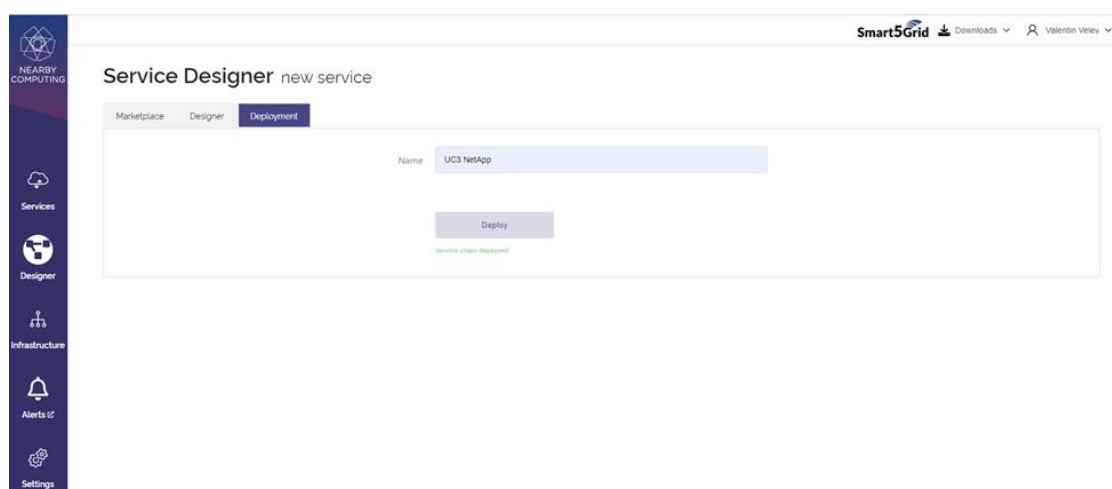


Figure 29: Name and deploy of a new service in the *Service Designer* section.

As a result of the deployment of the Network Application, the deployed Network Application should appear in the *Service* section of the *Service Designer*, as shown in Figure 30. In this section, the status of the Network Application, the deployed date and the user that has deployed the Network Application are presented proving the successful deployment and onboarding of the UC3 Network Application.

NAME	STATUS	DEPLOYED	USER	ACTIONS
NetApp UC1 in Wind3 (service chain)	DEPLOYING	10/20/2022, 11:22:50 AM	ea847d76-a217-4e16-9b51-b4c34a6cf6da	...
UC3 NetApp (service chain)	DEPLOYING	12/1/2022, 1:58:50 PM	9ad75838-d95d-4824-b040-a6f46cfc3551	...
NetappUC3	DEPLOYING	12/1/2022, 1:58:50 PM	9ad75838-d95d-4824-b040-a6f46cfc3551	...
chart-deployment-pm-pm5q6 kind: ChartRelease	PENDING			...
chart-deployment-rlpm-sbjxt kind: ChartRelease	PENDING			...
chart-deployment-pm kind: ChartDeployment	DEPLOYING			...
chart-deployment-rlpm kind: ChartDeployment	DEPLOYING			...
UC4 NetApp (service chain)	DEPLOYING	12/1/2022, 10:56:03 AM	9ad75838-d95d-4824-b040-a6f46cfc3551	...

Figure 30: UC3 Network Application appears in the *Service* section of the *Service Designer*.

5.1.4.5. Summary of validation and evaluation of UC3 pre-piloting tests

In this subsection all the validation and evaluation results have been analysed and the main conclusions are included in Table 16. In this table, the key validation and evaluation results are presented for each testing scenario along with the targeted KPIs and the achieved KPIs during the pre-piloting tests.

It is worth mentioning that all the initial objectives set for the pre-piloting investigation of UC3 have been successfully achieved according to the implementation plan set by the involved partners. The results validate the deployment of UC3 Network Application via NAC and moreover, through the pre-piloting tests the effective operation of UC3 Network Application for precisely monitoring the operation DERs has

been validated and evaluated. In addition to the document of agreement, further investigations have been performed considering two additional control applications in order to highlight the value and the potential of UC3 concept when it is used to close the loop to enable the active management of distributed resources in a smart grid framework.

Table 16: Summary of the testing results of UC3

Scenario ID	Type of test	Targeted KPIs	Real KPIs in tests	Comments
PP – UC3 – S1	Test and validation of Network Application operation and service provision.	<ul style="list-style-type: none"> • Successful Integration of NetAapp with the pre-piloting setup. • Exchange of data with a reporting period between 500ms and 1000ms. • Loss of data less than 0.5%. 	<p>Achieved KPIs:</p> <ul style="list-style-type: none"> • UC3 Network Application has been successfully integrated with the pre-pilot testbed. • Data exchange with reporting rate: <ol style="list-style-type: none"> a. 500ms b. 1000ms • Number of data exchange in 1 hour: <ol style="list-style-type: none"> a. 1200 b. 600 • Data loss with 5G technology: <ol style="list-style-type: none"> a. 0.25% b. 0% • Data loss with 4G technology: <ol style="list-style-type: none"> a. 2.08% b. 0% • Data loss with 3G technology: <ol style="list-style-type: none"> a. 86.58% b. 0.16% 	<p>The first target in this scenario was to integrate the UC3 Network Application with the pre-piloting setup which has been successfully achieved. Furthermore, in this pre-piloting test two different reporting periods have been considered (i.e., 500ms, 1000ms) and the testing has been performed for 1 hour. The loss of data is defined as any data that has delayed by at least 1 reporting period to arrive in the MQTT broker, which will eventually violate the real-time characteristics of the application. For the case of a 500ms reporting period, the loss of data with 3G communication was 86.58%, with 4G 2.08%, and with 5G only 0.25%. For the case of a 1000ms reporting period, the loss of data with 3G communication was 0.16%, while with 4G and 5G there was not any loss of data.</p>
PP – UC3 - S2	Test and validation of control application response, for coordinating the fast frequency	<ul style="list-style-type: none"> • A frequency nadir and ROCOF improvement when 5G is incorporated on the 	<p>Achieved KPIs with 5G:</p> <ol style="list-style-type: none"> a. Frequency nadir improvement of 76.9% and ROCOF 	<p>In this pre-piloting test, several scenarios have been demonstrated to validate the proper operation of the new control application for coordinating the fast frequency support by DERs. The scenarios examine the</p>

	support by DERs and of the impact of the network response on the energy system operation.	<p>provision of fast frequency support:</p> <p>a. by at least 60% compared to the no support case by DER.</p> <p>b. by at least 40% compared to the local support case (droop and virtual inertia) by DER.</p>	<p>improvement of 98.5% compared to the no support case by DER.</p> <p>b. Frequency nadir improvement of 66.6% and ROCOF improvement of 97.9% compared to the local support case (droop and virtual inertia) by DER.</p> <p><u>Achieved KPIs with 4G or 3G:</u></p> <p>3G: The system response is comparable to the local support by DERs case.</p> <p>4G: There is a slight (but inadequate) improvement on the stability (frequency nadir improvement of 48% compared to the no support case and 25% compared to the local support case).</p>	<p>no support case by DERs (baseline) and the support by DERs according to local inverter controller with droop and virtual inertia functionalities for comparison purposes. Further scenarios have been investigated based on the additional control application that relies on WAC approach for coordinating DERs, when different communication infrastructure is used. It is demonstrated that when 5G is used, a significant improvement on the frequency stability is observed (76.9% on frequency nadir and 98.5% on <i>ROCOF</i>) compared to the baseline scenario. On the other hand, using 4G or 3G communication cannot provide any significant improvements compared to local control scenarios, since the communication latency of those communication technologies does not allow a preventing frequency support by the new control application.</p>
PP – UC3 – S3	Test and validation of control application response, for coordinating the fast frequency support by	<p>Improvement of the mean and maximum ramping rate violation:</p> <ul style="list-style-type: none"> • $RRV_{1s-mean}$ and RRV_{1s-max} by at least 50%. 	<p><u>Achieved KPIs:</u></p> <p>The control application of UC3 for ramping rate compensation over 5G has been successfully validated and significant</p>	<p>In this pre-piloting test, the performance of the new control application for ramping rate compensation by DERs through 5G is validated and demonstrated. This control application is enabled through the utilisation of</p>

	DERs and of the impact of the network response on the energy system operation.	<ul style="list-style-type: none"> • $RRV_{10s-mean}$ and $RRV_{10s-max}$ by at least 50%. 	<p>improvement has been achieved:</p> <ul style="list-style-type: none"> • $RRV_{1s-mean}$ is improved by 87.6% and RRV_{1s-max} is improved by 56.5%. • $RRV_{10s-mean}$ is improved by 99.2% and $RRV_{10s-max}$ is improved by 98.9%. 	the monitoring Network Application UC3 to close the loop and enable the provision of ramping rate compensation for DERs (e.g., wind) by energy storage system that are installed in a different of the power system, facilitating the virtual power plant concept. A significant improvement is demonstrated regarding the controllability of the combined DERs, and the ramping rate violation have been almost eliminated.
PP – UC3 – S4	Test and validate the deployment and onboarding of UC3 Network Application.	The target is the successful Network Application deployment.	The procedure for the deployment and onboarding of UC3 Network Application is demonstrated, proving the successful Network Application deployment capability.	Through this validation procedure, the successful deployment and onboarding of UC3 Network Application has been verified.

5.2. UC4- Real-time Wide Area Monitoring

5.2.1. Phase 1: Pre-piloting testbed description and realistic conditions to replicate the UC operational environment

5.2.1.1. Introduction

The scope of this pre-pilot testing is to create the operational environment having a system under test (IEEE 9-bus system) and test the virtual Phasor Data Concentrator (vPDC) service of the Network Application that will be applied to the UC4 demonstration site. In particular, the scope of this pre-piloting is to have a tie transmission line in realistic conditions (emulating the case of UC4 with the tie transmission line that connects the Bulgarian and the Greek system) from which measurements are captured by the two PMUs that are installed in the UCY lab. In the pre-piloting phase and for the scope of T3.4, the vPDC service is connected to the pre-piloting setup to receive PMU measurements from the two PMUs that monitor the operating condition of the emulated tie-line (in the IEEE 9-bus system). In addition, the pre-piloting testing considers the system under test for investigating the impact of the 5G network on the wide area protection scheme. This is an

aspect that cannot be tested in a real-life environment due to the criticality of the protection scheme in the tie transmission line. In general, this pre-piloting testing alleviates any restrictions that are imposed in the testing of the energy part that may cause power interruptions during the testing procedure.

For UC4, *“a vertical-service pre-piloting testing”* is adopted where digital twin and hardware in the loop setups are used to validate the related Network Application and to further investigate the impact of new potential applications in the operation of the energy domain. Specifically, the UC4 vPDC service of the Network Application is tested in this pre-piloting stage. In particular, the hardware in the loop setup that includes two actual PMUs is used to report real-time PMU measurements to the vPDC service that was developed for the purposes of UC4. The connection of the vPDC and the pre-piloting setup (PMUs) is facilitated through the IEEE C37.118 protocol. It should be noted that only the energy-related services (high-level functional requirements) of the Network Applications are tested as part of the pre-piloting phase.

5.2.1.2. Description of the pre-piloting testbed

The pre-piloting architecture for UC4 creates a realistic framework with real-time conditions related to the specific UC in order to test and validate the developed Network Application that facilitates the real-time wide area monitoring of a tie transmission line in the Greece-Bulgaria borders. In addition, the same pre-piloting framework is used to examine some additional protection functionalities (beyond the initial purpose of the project), demonstrating how the advanced features of 5G technology can benefit a wide area protection scheme of the tie transmission line. It is noted that the wide area protection application is only demonstrated in the pre-piloting stage, since several technical and regulatory restrictions are preventing the interference with the actual protection of the line. Therefore, the pre-piloting phase of UC4 includes:

- *Test and validate the operation and real-time responsiveness of UC4 Network Application for wide area monitoring (WAM) applications.*
- *Investigate the impact of the 5G network on the real-time responsiveness of a wide area protection scheme.*

The UC4 of the Smart5Grid project is related to the monitoring (and protection) of the interconnected Bulgarian and Greek transmission systems. Therefore, a digital twin was developed to emulate, in real-time, the operation of a cross-border power system which integrates two national power systems (Greek and Bulgarian transmission power systems). The digital twin of the power systems is connected in a Power Hardware In the Loop (Power-HIL) configuration with actual PMU devices (or virtual PMUs is emulated within the digital twin) in order to enable the interaction with the Network Application or the wide area protection scheme. Therefore, the digital twin with actual or virtual PMUs is connected in a Control Hardware In the Loop (Control-HIL) framework with the UC4 Network Application (or additional protection applications) through a network emulator. In this context, the network emulator can be configured with different settings to emulate the performance of the 5G, 4G, or 3G communication infrastructures, allowing an

interesting investigation where the Network Application performance or the impact on the power system operation can be evaluated under different communication infrastructures. A diagram of the pre-piloting testbed for the UC4 is demonstrated in Figure 31, while detailed descriptions about each key component of the pre-piloting configuration are presented in the table below.

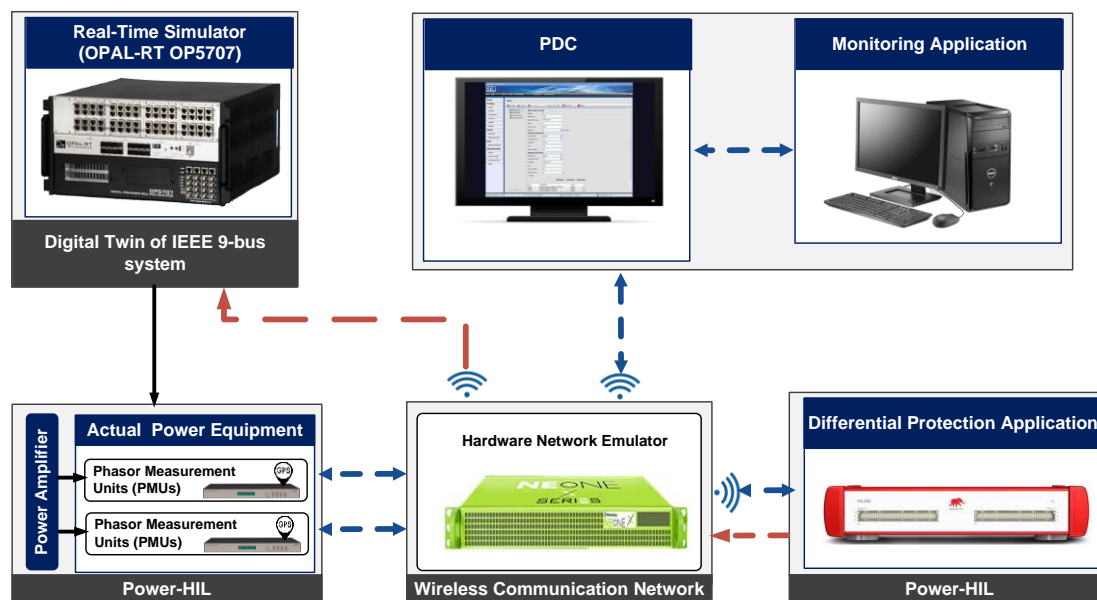


Figure 31: Pre-piloting configuration for the UC4 of the Smart5Grid project

Table 17: List of components and their description for the pre-piloting testbed of UC4

Component Name	Component Description
UC4-C-ID-1: Real Time Simulator (RTS)	<p>The real-time simulator is a key component of the pre-piloting infrastructure since it enables the development of a digital twin of an interconnected power system with a tie line in order to emulate the UC4 (connection of Bulgarian and Greek systems). The digital twin of the power system is developed as a dynamic, discrete-time MATLAB/Simulink model that runs in a dedicated real-time simulator (OPAL-RT 5707) to enable hard real-time constraints.</p> <p>The operating conditions of the power system and especially the real-time operating status of the tie line can be sensed/measured through actual PMUs. On the other hand, protection actions can be taken within the energy infrastructure through a controller that acts as a wide area protection actuator. The PMUs situated at the two ends of the line exchange information with the vPDC service or other related applications using digital communication protocols (IEEE C37.118) over the local area network and the network emulator. The integration of the PMUs is achieved through a power amplifier that is able to drive the actual equipment according to the digital twin operating conditions. In this way, the Power-HIL is facilitated by exchanging analogue signals between the digital twin and the amplifier. Then, the PMUs integrated in</p>

this configuration communicates with the Network Applications or other related applications.

The real-time simulator is able to emulate the power system operation in a very precise manner with a solver resolution lower than 100us. Accurate, dynamic and discrete-time models are used to replicate the operation of the power system as a digital twin.

The MATLAB/Simulink model to emulate the operation of a power system is presented in Figure 32(a). This model is uploaded and executed in the real-time simulator presented in Figure 32(b) to enable the digital twin of the energy infrastructure.

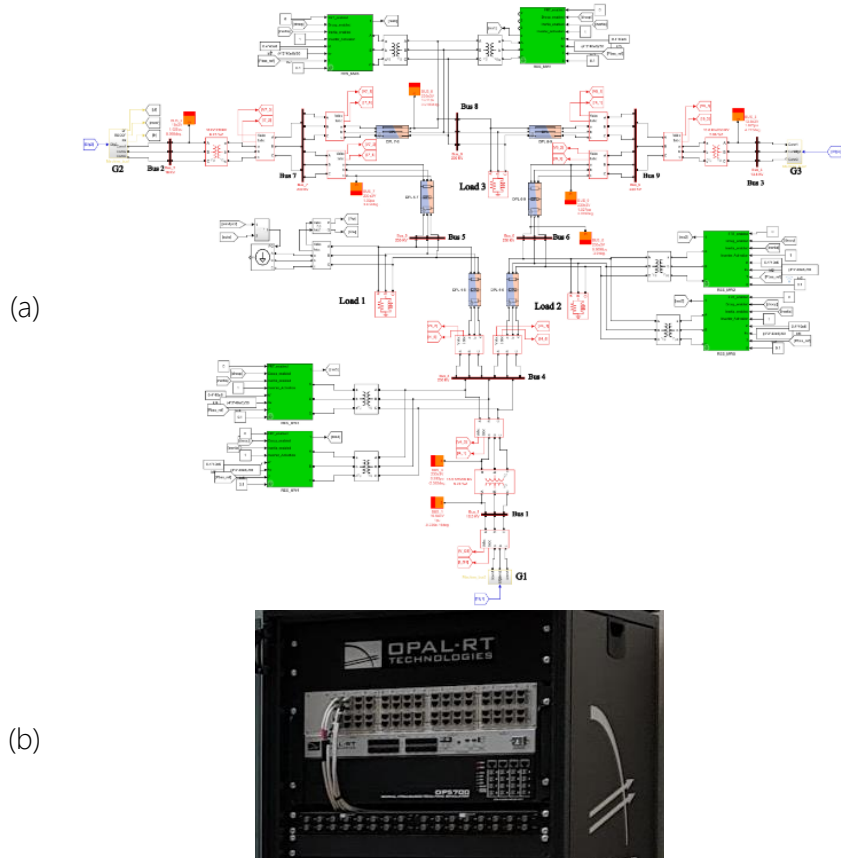


Figure 32: (a) Simulation model and (b) OPAL-RT 5707 real-time simulator that have been used to enable the development of the digital twin

UC4-C-ID-2: Power amplifier

The power amplifier is a key component of the pre-piloting setup that enables the integration of actual PMUs with the power system's digital twin. The power amplifier receives low voltage analogue signals (e.g., $\pm 10V$) from the real-time simulator regarding the voltage and/or current operation of a selected node/line of the power system's digital twin. Then, it precisely (error lower than 0.2%) amplifies the voltage and/or current into an actual system scale (e.g., 0-400V, 0-32A, etc.) with a transient response of 10 μ s to allow the interconnection of actual power devices. The amplifier is able to exchange bidirectional active and reactive power in four quadrants to drive the operation of power devices by replicating conditions emulated within the real-time simulator. In addition, the amplifier measures the voltage conditions and the current

UC4-C-ID-3: Phasor
Measurement Units (PMU)

exchanged with the power device in order to provide feedback to the real time simulator (e.g., every 50 μ s) in order to be considered for the next step of the emulation.

In the particular pre-piloting facility an amplifier, Omicron CMS 356, shown in Figure 33(a), with 4x300V and 3 or 6 x 32A output channels, is used mainly for connecting the PMUs where both three-phase voltage and current condition should be independently driven, which is required when short-circuit faults need to be replicated.

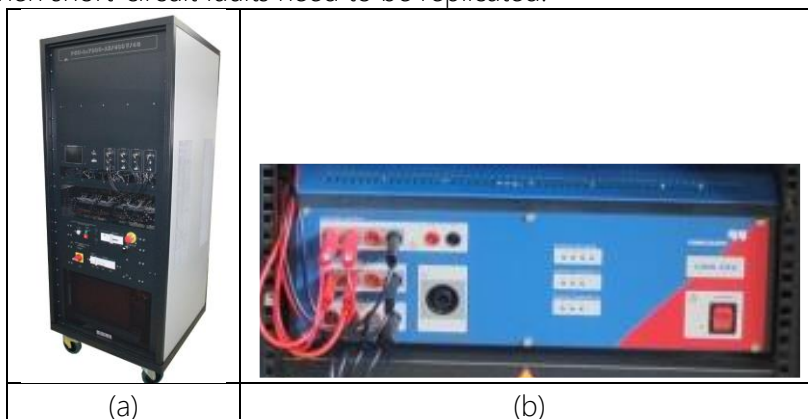


Figure 33: (a) Puissance plus 21kVA [32] and (b) Omicron CMS 356 power amplifier [33].

PMU is a metering device used in power substations to measure and estimate the magnitude and phase angle of an electrical phasor quantity (voltage and current) using a common time source for synchronization. This is achieved by GPS Precision Time Protocol which enables the collection of synchronized measurements for wide area monitoring and control purposes. These metering devices are used in power substations and are connected to the secondary side of measurement VT or CT transformers to sample the voltage and current condition of a selected location in the power system. In the case of a pre-piloting setup, the PMUs are connected to the high voltage/current side of the power amplifier in order to measure the voltage/current conditions of the digital twin that are replicated through the amplifier. The measurements are processed by the PMUs to calculate the voltage phasors every 10ms or 20ms, where a GPS timestamp is included to enable the synchronization between measurements taken from different locations. Then, those measurements are sent to a phasor data concentrator software using the IEEE C37.118 protocol, where the measurements are time aligned and stored to be used in wide area monitoring and control applications.

In this pre-piloting setup, two Sentinel-Arbiter Model 1133A PMUs [34] are used as shown in Figure 34.

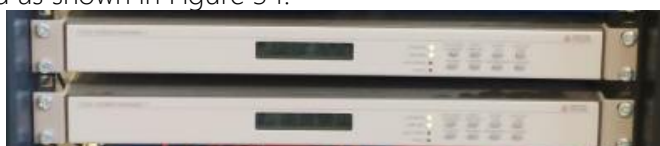


Figure 34: Sentinel-Arbiter PMU 1133A.

UC4-C-ID-4: Network Emulator

The network emulator is a hardware device able to emulate in a macroscopic way the operation of a network communication between end-to-end users. In this case, the communication link between two users passes through the network emulator and can be configured (according to IP or ports) to respond according to specific characteristics set by the requirements of the pre-piloting testing. For initiating different kind of investigations, the end-to-end delay response can be configured to achieve different communication performance according to the examined communication infrastructure (e.g., 5G, 4G, 3G, etc.) or specific communication delay or loss of package rate can be pre-defined according to probabilistic distributions. This way, the network emulator can be connected in the loop with all the devices communicating in the pre-piloting setup (e.g., real-time simulator, PMU or smart meter, Network Application or related applications, inverters, etc.) in order to investigate the impact of network performance on the energy domain operation.

The iTrinegy NE-ONE Model 10 network emulator is used in the pre-piloting facilities, as shown in Figure 35a, where the network performance can be configured through a web interface (Figure 35b). Using this network emulator, the 5G communication is integrated in the pre-piloting case studies to investigate the expected response in case of large-scale deployment of smart grid application through 5G communication.

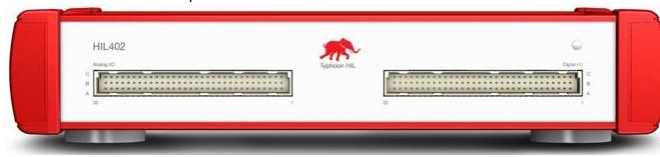


Figure 35: (a) Hardware network emulator iTrinegy NE-ONE Model 10, (b) web-interface to configure the communication response of the network emulator

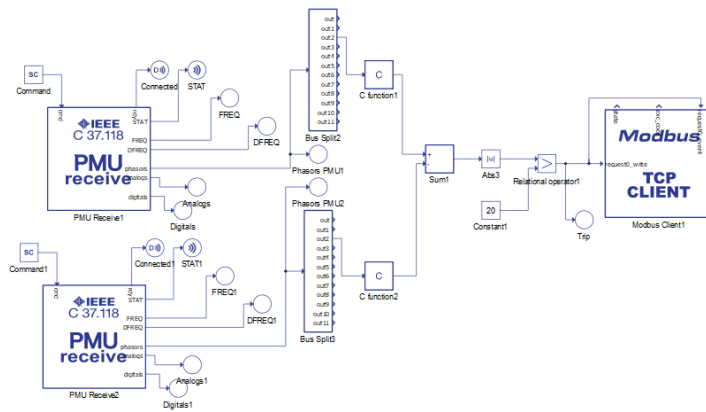
UC4-C-ID-5: Typhoon HIL 402

Typhoon HIL 402 Figure 36 (a), provides all the tools you need to implement a Hardware in the Loop controller that interfere in real time

with the OPAL-RT simulator (the power system). It has 16 analogues inputs and 16 analogues outputs, as well as 32 digital inputs and outputs. The Typhoon HIL 402, can be connected through Ethernet to the Real Time Simulator. In UC4, Typhoon HIL is used to implement the wide area protection scheme of the tie line. More specifically, the Typhoon HIL 402 receives measurements from the two PMUs that report voltage and current phasor measurements from the two ends of the line. The communication between the PMUs and the Typhoon HIL 402 is established with the IEEE C37.118 protocol. Then a differential protection logic is implemented in the Typhoon HIL 402 (Figure 36 (b)) to detect any faults within the transmission line. If any faults are detected within the transmission line range, then the Typhoon sends a trip command to the breakers of the transmission line (implemented to the OPAL RT simulator) in order to open the transmission line.



(a)



(b):

Figure 36: (a) Typhoon HIL 402 (b) Typhoon HIL 402 interface

5.2.1.3. Creation of the realistic operation conditions of the pilot

The pre-piloting facilities include all the components that enable the realistic conditions to replicate the operational environment of UC4. Since UC4 focuses on the real-time monitoring of the tie transmission line that connects Bulgarian and Greek transmission systems, the real-time information for the transmission line is provided by two PMUs installed at the ends of the tie line. The measurements of the two PMUs are collected through the vPDC service of the Network Application of UC4. In this context, for the pre-piloting testbed, an IEEE test system was created in OPAL-RT simulator to emulate the realistic conditions of an actual system including the system high and slow dynamics. Within this system a particular line was selected for emulating the tie transmission line of the real use case. Two actual PMUs (Sentinel Model 1133A) are used to provide voltage and current phasor measurements from the two ends of the transmission line. The PMUs are connected in a Hardware-In the Loop framework with the OPAL-RT simulator through the Omicron Amplifier. In addition, in order to create realistic conditions regarding the

communication infrastructure, the PMU measurements are transferred to the Phasor Data Concentrator through the NE-ONE network emulator, which emulates the 5G network characteristics (delay, data dropouts). In this pre-piloting setup, the implemented vPDC service is easily integrated to test its functional characteristics and verify that all the functional requirements are fulfilled for this Network Application. As a step further the Wide Area Monitoring service for the tie line is also tested with this pre-pilot setup using measurements provided by the two PMUs that were collected by the vPDC service.

Moreover, the pre-piloting testbed provides the opportunity to investigate use cases that cannot be investigated in a real system due to the possibility of affecting the actual operation of the system. In particular, through the UC4 pre-piloting setup, the impact of wireless networks on wide area protection schemes is investigated. In such case, the wide area protection scheme implemented to the Typhoon HIL receives measurements from the two actual PMUs integrated to the OPAL-RT after the measurements pass from the network emulator (to create realistic conditions for the wireless communication network).

5.2.2. Phase 2: Network Application integration

As it is aforementioned, the Network Application of UC4, which includes the vPDC, the WAM and the Advisory services, is tested in this pre-piloting setup while the impact of the wireless network on the wide area differential protection is investigated. This section describes the integration of the vPDC to the pre-piloting setup.

5.2.2.1. UC4 - Network Application

The service components of the Network Application developed for the Greek-Bulgarian demo includes the following services:

- **vPDC service:** The vPDC receives phasor data from multiple PMUs and produces a real-time, time-aligned output data stream for each time stamp.
- **Wide Area Monitoring (WAM) service:** WAM service connects to the output stream of vPDC and visualises the data of the PMUs. WAM service can be used in the control center for visualising in real time the operating condition of the tie transmission line.
- **Advisory service:** Advisory service connects to the output stream of vPDC and provides analytics for the collected PMU data. The analytics can be used for taking decisions regarding the energy exchange between the two transmission systems.

The UC4: vPDC & WAM & Advisory services Net App are installed on a single server with installed Docker or on cluster of servers managed by Kubernetes. The Docker images of the services are located in Docker Hub repository. After installation, the WAM service is accessible in a web browser on a dedicated port (e.g., port 30580, thus <http://localhost:30580/>), using the predefined credentials such as Username and password. Thus, following the previous example, the Advisory service is accessible in a web browser on another port, (e.g., 30581, thus <http://localhost:30581/>) using the same username and password as the WAM service.

According to the logical schema of Figure 37, the vPDC service receives phasor data from PMUs and produces a data stream (a set) with time aligned and time stamped PMUs that forwarded to WAM and Advisory service. In order to visualise the real-time condition of the tie line, the WAM service receives a data stream with PMU data from the vPDC and produces graphs for grid operators. Through the WAM application the user can obtain the current phasor that flows through the line and the voltage phasors of the two ends from the two ends of the line. In the case of the Advisory service, the time aligned

measurements that are received from vPDC, are stored in a database and are used for producing statistical analysis for the grid operators.

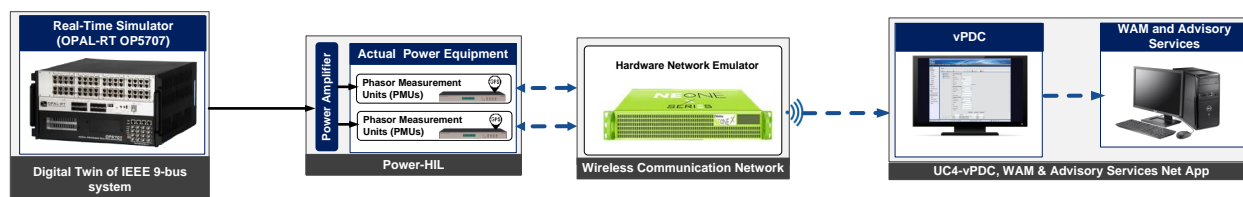


Figure 37: Logical schema for the data flow for UC4 pre-piloting

It should be noted that for the sake of pre-piloting activities, the initial versions of the user interface of the WAM and Advisory services are used. For both services the final version will be shown in the demonstration site.

5.2.2.2. Wide area differential protection application

For the pre-piloting phase only, the impact of the 5G communication on the wide area differential protection is also investigated. Although this additional application is not mentioned in the DoW/GA, the investigation of the impact of 5G on the wide area differential protection application is crucial for indicating the importance of 5G wireless network compared with the previous wireless communication technologies, such as 4G and 3G wireless networks. In this UC, the wide area differential protection is the application that is affected by the characteristics of the wireless communication network. The service that is provided by the wide area differential protection is based on the detection and isolation of faults that happen within the transmission line utilising the current phasor measurements from both ends. The logical schema for the data flow of the wide area differential protection is shown in Figure 38. In particular, in this case study, the PMU measurements are received directly by the Typhoon HIL after passing through the network emulator that emulates the characteristics of the wireless communication network. The differential protection application processes the current phasor measurements from the two ends and in case of a fault in the tie transmission line it sends a trip command to the circuit breakers of the lines. In the pre-pilot setup, the trip command is passed again through the hardware network emulator before arriving to the OPAL RT simulator and trip the line.

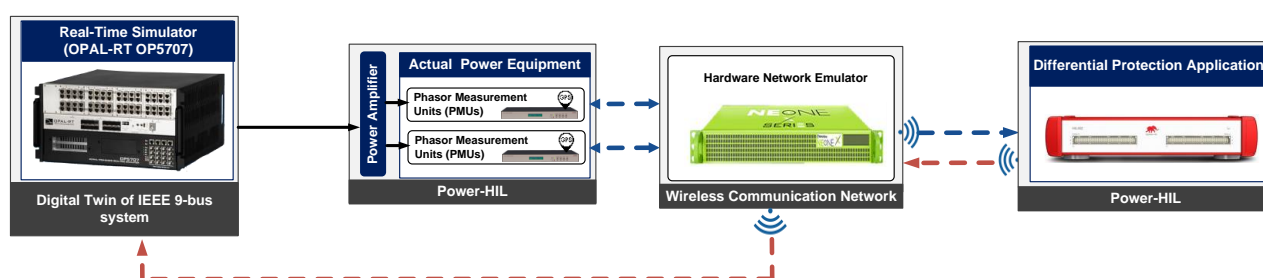


Figure 38: Logical schema for the data flow for wide area differential protection application

5.2.2.3. Methodology for the integration of the Network Application with the pre-piloting testbed

5.2.2.3.1. UC4: vPDC & WAM & Advisory services Network Application

According to the logical schema shown in Figure 37, the integration of the vPDC & WAM & Advisory services Net App is done through the hardware network emulator. In particular, the real-time simulator that emulates the real-time operation of the power system is physically (wired) connected with the power

amplifier which amplifies the voltage and current analogue signals (from the two ends of the tie line) in a proper level to be measured by the two PMUs. The PMUs, which are again physically (wired) connected to the power amplifier calculate the voltage and current phasor measurements of the two-line ends, as well as the frequency of the power system in real time. The PMU measurements are transferred to the vPDC through the network emulator that emulates the characteristics of a wireless network (3G, 4G, and 5G). The PMUs and the hardware network emulator are connected through Ethernet while the communication protocol that is used to transfer the measurements is the IEEE C37.118. The Network Application is at the same communication network as the pre-piloting setup, for being integrated successfully to the pre-pilot testbed. The vPDC receives measurements through the IEEE C37.118 protocol.

5.2.2.3.2. Wide area differential protection application

The integration of the wide area differential protection application is facilitated at the same pre-pilot setup architecture used in the vPDC & WAM & Advisory services Net App. As it is shown in Figure 38, the real-time simulator, the PMUs and the network emulator are connected in the same manner as in the case of the vPDC & WAM & Advisory services Net App pre-pilot architecture. The wide area protection application is implemented in the Typhoon HIL which directly receives measurements from the two PMUs. The communication between the Typhoon HIL and the PMUs is done through Ethernet, using the IEEE C37.118 protocol. The intermediate network emulator is again used to emulate the wireless network characteristics (in this use case 3G, 4G, and 5G). The wide area differential protection application provides a feedback signal to the OPAL-RT through again the network emulator. The signal is a trip command for the breakers of the tie line in case of a fault in the transmission line range and is actually communicated through a TCP protocol.

The pre-pilot setup that is described above provides a controlled environment where the Network Applications that are related to UC4, namely the vPDC & WAM & Advisory services Net App and Wide Area Differential Protection can be tested extensively.

5.2.3. Phase 3: Defining the testing scenarios

The procedure that was followed to test the two applications is separated in different testing scenarios. In the first stage the proper operation of the testbed is verified by following different testing approaches that are described below including results for these testing scenarios. In the second phase the functionality of the Network Application and the wide area differential application are tested.

Table 18: Summary of testing scenarios for the pre-piloting stage of UC4

Scenario ID	Scenario Title	Testcase type	Description
PP-UC4-S1	Testing of the pre-piloting setup	Measurement Devices	Test the connectivity of the PMU installed at the pre-pilot setup with the emulated power system in the OPAL-RT simulator through the Omicron amplifier as well as with the communication network emulator.
PP - UC4 - S2	Testing the connectivity of the vPDC,	Network Application	Test the connectivity of the Network Application with (vPDC) as well as WAM & Advisory Services.

	WAM & Advisory service Net with the PMUs		
PP - UC4 - S3	Testing vPDC	Network Application	Test vPDC capabilities vs Network Application description to demonstrate how the Edge Cloud/MEC-based vPDC service operates to gather, synchronize and process signal inputs coming from the PMUs installed at the pre-pilot setup.
PP – UC4-S4	Testing WAM & Advisory Service	Network Application	Test WAM capabilities vs Network Application description to demonstrate cross-border (CB) monitoring of voltage, current, and voltage phase angle in the UC4 setup on the emulated transmission line in the testbed power system developed in OPAL-RT. The scenario is to showcase, inter alia, the WAM Net App potential for URLLC detection of transmission (energy balance) abnormalities such as power swings, etc., before they escalate. Further to that the accurate visualisation of actual operating conditions of the line are evaluated as well as the alarm triggering and visualisation functionalities of the Network Application, in case of voltage deviation, frequency deviation, line thermal limit violation and ROCOF violation.
PP – UC4 – S5	Wide area differential protection application	Control in the loop Application	This scenario aims to test the real-time responsiveness of the wide area differential protection in clearing faults that occur within the transmission line range.
PP – UC4 – S6	Network Application onboarding and deployment via the NAC	Test and validation of the Network Application onboarding and deployment via the Network Application Controller	This scenario is focused on the integration of the Network Application with the NAC. The user onboards and deploys the Network Application to ensure the correctness of the Network Application and the expected life cycle management of the NAC.

Table 19: Testing scenarios and targeted KPIs for UC4

Scenario ID	Functional requirements	Targeted KPIs
PP – UC4 - S1	Proper operation of the pre-piloting testbed	The targeted KPI is to pass all the test for proper functioning of the pre-piloting testbed: The KPI is denoted as "Test passed"
PP – UC4 - S2	Successful integration of vPDC Net app to the pre-piloting setup	The targeted KPI is to integrate the vPDC to the pre-piloting testbed: The KPI is denoted as "Test passed"
PP – UC4 – S3	Proper gathering and time alignment PMU measurements through the vPDC	The targeted KPI is the loss of data which should be less than 1% in case of 5G wireless network
PP-UC4-S4	Timely track of real-time operating condition by the WAM and Advisory Service	The targeted KPI in this scenario is the data latency which should be smaller than 20ms when 5G is used.
PP – UC4 – S5	Real time fault clearing within the tie transmission line	The targeted KPI in this scenario is the fault clearing time which should be less than 0.2 seconds in case of 5G.
PP – UC4 – S6	The NAC is operative, and the compute nodes onboarded.	The targeted KPI in this scenario is the successful integration of the vPDC Network Application to the NAC. The KPI is denoted as "Test passed"

Table 20: Definition of the functional requirements to be tested

Functional requirement Name	Brief description of each functional requirement
Proper operation of the pre-piloting testbed	This functional requirement corresponds to the proper operation of the testbed. In order to ensure this, several testing stages were followed such as, the testing of the emulated power system, and the testing of the PMU connectivity to the emulated power system (e.g., to ensure that the system is working correctly following the power system operational rules).
Successful integration of vPDC service	This functional requirement is related to the integration of the vPDC service to the pre-piloting setup.
Proper gathering and time alignment of PMU measurements	The developed vPDC service should be able to gather all the measurements from the PMUs that are connected to it without causing loss of data. Furthermore, the data sets should be time aligned according to the PMU measurements time stamp.
Timely track of real-time operating condition by the	This functional requirement is related to the WAM and the Advisory service of the Net App. Since the WAM is based on PMU measurements with a real-time reporting rate, it is required to detect timely any abnormalities that occur in the system, with minimum latency.

WAM and Advisory Services	
Real time fault clearing that occurs within the tie transmission line	The fault that occurs within the transmission line should be cleared as fast as possible to prevent any system instability when the fault is propagated to the system. This functional requirement is related to the wide area differential protection application.

Table 21: Definition of the KPIs for pre-piloting testing of UC4

KPI Name	Brief description of each KPI
KPI 1: Proper operation of the test bed	This KPI is related to the operation of the testbed before the Network Application integration. This KPI is quantified after several test related to the testbed operation and in case of successful testbed operation the KPI took a "Test passed" value, an in case of failure a "Test failed" value.
KPI 2: Successful integration of the Network Application	This KPI is related to the integration of the Network Application to the testbed. This KPI is quantified after several test related to the Network Application integration and in case of successful Network Application integration the KPI took a "Test passed" value, an in case of failure a "Test failed" value.
KPI 3: Loss of data	Amount of the PMU measurements that are lost by the PDC when the PDC gathers the PMU measurements.
KPI 4: Latency to detect abnormality	Time that the Advisory service takes to detect any abnormalities in the system.
KPI 5: Fault clearing time	Time that the wide area differential protection takes to clear the detected fault in the transmission line.
KPI 6: Integration of the Network Application in NAC	This KPI is related to the integration of the Network Application to the NAC. This KPI is quantified after several test related to the Network Application integration and in case of successful Network Application integration to the NAC the KPI took a "Test passed" value, an in case of failure a "Test failed" value.

5.2.4. Phase 4: Validation and evaluation

The validation and evaluation of the UC4 Network Application was carried out in this Phase by following the scenarios outlined in Table 19. Based on the validation and evaluation results, the Network Application that was developed in UC4 successfully performs, while through this validation procedure it is pointed out that the characteristics of the wireless communication network impact the performance of the Network Application. In this section the testing scenarios are analysed in detail providing some key results from the validation and evaluation of the UC4 Network Application.

5.2.4.1. PP – UC4 - S1: Testing of the pre-piloting testbed operation

Stage 1: Test the operation of the emulated power system

After the implementation of the testbed power system in the real time simulator, several case studies were conducted in order to verify the proper operation of the power system, evaluating the response of the

system in normal and transient conditions (where fault or other contingencies can occur). Since the UC4 is related to the tie line between the borders of the Greek and Bulgarian transmission systems, special attention is provided to the chosen tie line of the simulated power system, where different loading scenarios and faults were applied to verify the proper operation of the simulation. The testing of the emulated power system operation was successful as the simulation provided the expected results. For instance, as indicated in Figure 39, after a sudden increase in the load of the interconnected systems, the frequency drops as expected, while in the case of a 3-phase fault in the line the fault current increases.

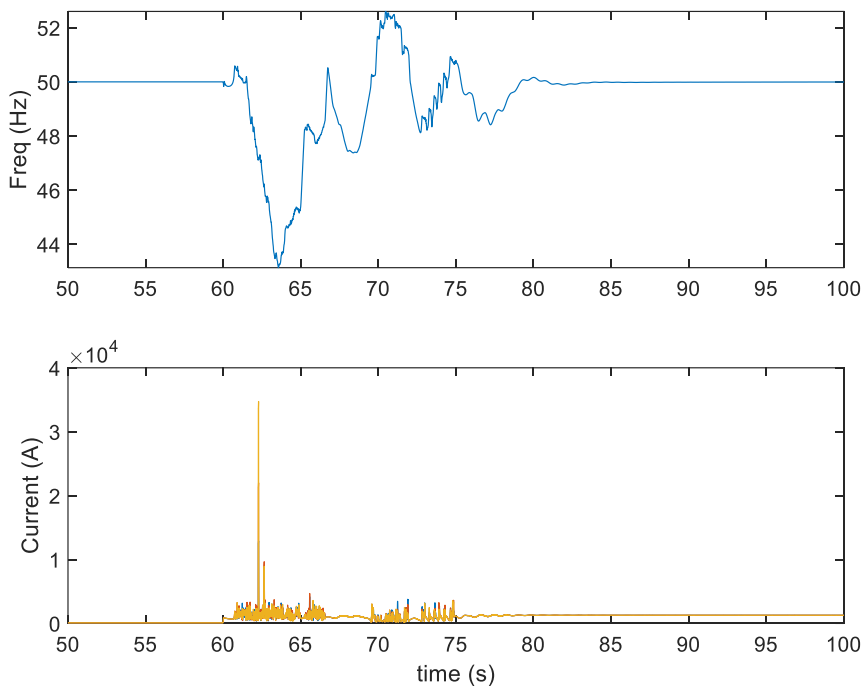


Figure 39: Simulation results from the IEEE 9 bus system.

Furthermore, in this scenario the proper connection of the two PMUs that monitor the two ends of the emulated tie line was tested. As it is aforementioned, the two PMUs are connected with the Omicron amplifier to the real-time simulator. The proper electrical connection of the two PMUs with the real-time simulator were verified through the build-in screen of the PMUs, where voltage current and frequency measurements are illustrated.

Stage 2: Test the connectivity of the two PMUs with the network emulator and the Typhoon HIL 402 controller

This is the final stage of the testing scenario 1 (PP – UC4 - S1) and is related to the testing of the communication of the PMUs with any client application through the network emulator. At this stage, a commercial phasor data concentrator is used (SEL 5073) to collect the measurements from the two PMUs, time align them and quantify the latency imposed to the measurements by the communication network. In this sense, both the integrity of the PMU data, as well as the proper functionality of the network emulator, are validated. Regarding the network emulator, different latencies and data dropouts were inserted in its settings for verifying with the help of the commercial PDC (which provides the capability to measure the latency of the PMU measurements) that correctly emulates the input settings by the user. A screenshot of the average and maximum latency that was imposed by the network emulator to the PMU measurements

is shown in Figure 40. The connectivity of the two PMUs with the network emulator and the Typhoon HIL 402 was successful, and the realistic conditions were created for integrating the Network Application of UC4.

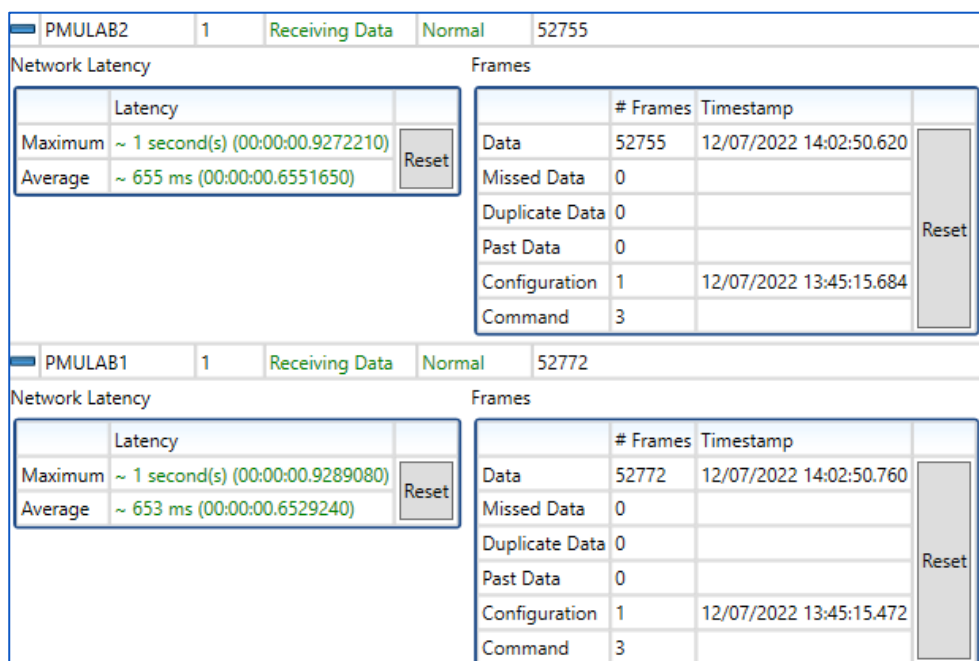


Figure 40: Screenshot from the commercial PDC showing the delay of the PMU measurements

In the case of the wide area differential protection application, the communication of the Typhoon HIL 402 with the PMUs was verified by employing the interface of the Typhoon HIL, which provides the capability to visualise the measurements received at the Typhoon HIL through the IEEE C37.118 protocol. The accuracy of the measurements was verified through the comparison of the received PMU measurements to the OPAL-RT simulation results.

PP – UC4 - S2: Testing of the Network Application integration to the pre-piloting testbed

The vPDC & WAM & Advisory services of the Network Application are installed via Docker at the VivaCom premises. Through VPN access provided by the University of Cyprus, the two PMUs that are installed at the UCY pre-pilot setup can be remotely connected to the vPDC service. As it is shown in Figure 41, the two PMUs (PMULAB1 and PMULAB2) were connected to the vPDC service and subsequently to the WAM and Advisory services, indicating that the Network Application integration in the pre-piloting setup was successful.

PP – UC4 – S3: Testing of data integrity with different types of wireless communication network characteristics

After establishing a successful connection with the vPDC, the functional requirements of the vPDC were tested and validated in a controlled environment. One of the most important tests for the UC4 Network Application was the data integrity of the measurements using different wireless communication networks. In this testing scenario the power system (emulated in the OPAL-RT) was operated in normal operating conditions and the PMUs reported to the vPDC the voltage and current phasor measurements from the two ends of the line as well as the frequency of the system. In this stage, different communication network

latencies were imposed by the network emulator to examine how the vPDC service is affected by the wireless communication networks and how the waiting time can affect the data integrity. In particular, three types of wireless networks were considered in the pre-piloting testing, namely 3G, 4G, and 5G and their characteristics were emulated in the network emulator. The delays that were imposed by the wireless network to the PMU measurements before arriving to the PDC are shown in Table 22. The waiting time of the vPDC, which is actually the time that the PDC waits for the PMU measurements before time aligning them and storing them to its database is set to 60ms. This waiting time accounts for the end-to-end delay of the PMU measurements (including the hardware delays and the process of measurements by the Network Application) and not only for the network latency. However, in this case hardware and Network Application process time are considered constant and therefore the only factor that can affect the data integrity is the data latency due to the network characteristics.

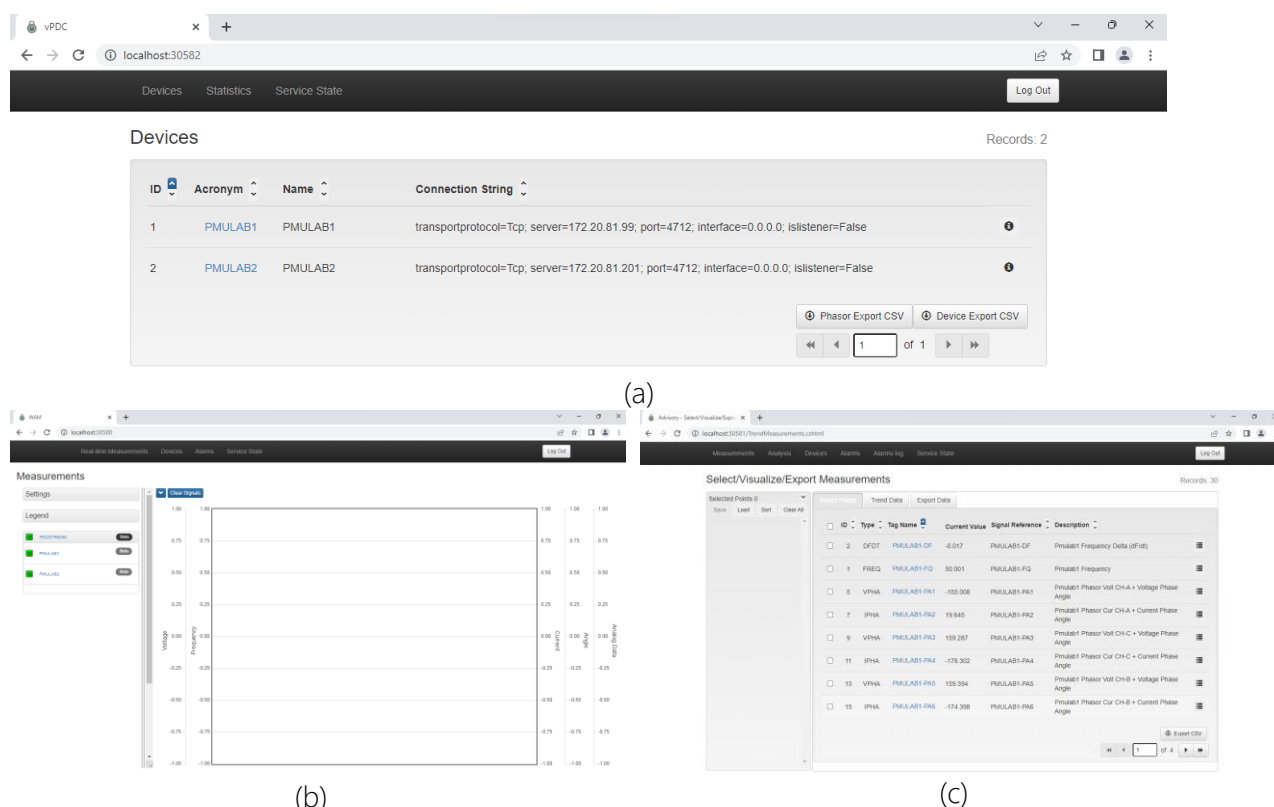


Figure 41: Connection of the two PMUs in the pre-piloting setup (a) with the vPDC, (b) with the WAM service and (c) with the Advisory service

Table 22: Delays for the wireless communication networks

Communication Network	Uniform distribution limits	
	Minimum (ms)	Maximum (ms)
3G	33	60
4G	17	27
5G	3	4

In Figure 42(a), the frequency measurements that are reported by the two PMUs when the emulated power system runs in normal operating condition are received and time aligned by the vPDC. The PMU measurements are transferred to the vPDC through 3G, 4G, and 5G, while in case that the end-to-end delay is larger than 60ms (larger than the waiting time of the PDC), the measurements are discarded by the vPDC and a NaN value is reported instead. It should be noted here that although the maximum delays imposed by the 4G wireless network is smaller than the waiting time of the PDC, the additional computational time needed for the hardware (where the Network Application is integrated) to receive the PMU measurements as well as the additional time needed for the Network Application to process the PMU measurements increases the end-to-end delay over the 60 ms and therefore some of the measurements are discarded. As indicated in the figure, the transfer of measurements through 3G and 4G affects the data integrity of the PMU measurements that are concentrated in the vPDC. This is because the end-to-end delay is larger than 60ms, therefore several PMU measurements are discarded. It should be noted that although in Figure 42(b) the frequency provided by the PMUs is shown, all the type of PMU measurements (current, voltage, and ROCOF) are discarded since they arrive as a packet with a common timestamp. On the other hand, in the case of the 5G wireless network, the PMU measurements arrive before the elapse of the waiting time and therefore no PMU measurements are discarded, as indicated in Figure 42(c).

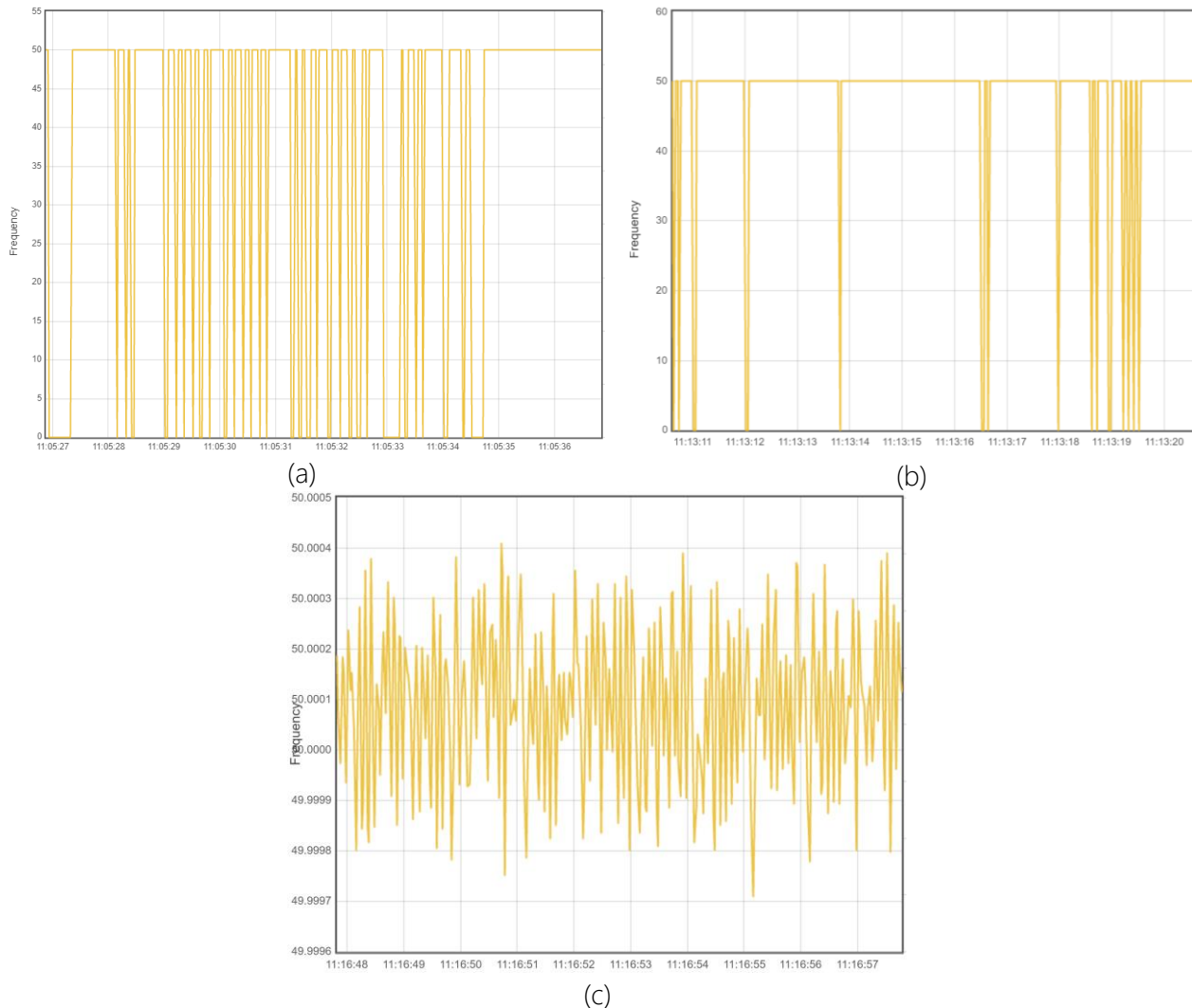


Figure 42: Frequency measurements demonstrated in the vPDC Network Application with (a) 3G network, (b) 4G network and (c) 5G network

Further to that in this testing scenario the data loss from the vPDC service for the three wireless networks was calculated over a 3-minute interval and tabulated in Table 23. As expected, over this interval there was 0% data loss for 5G, indicating the importance of having a 5G network in wide area monitoring and control applications. In the case of 4G, the data loss was around 1.9% and in the case of 3G the data loss was even higher reaching 12%. Such a percentage of 3G and 4G compromises the data integrity of the PMU measurements that are concentrated to the vPDC service and affects the situational awareness of the power system operators.

Table 23: Data loss in the vPDC for 3G, 4G, and 5G wireless network.

Communication Network	Data loss (%)
5G	0
4G	1.9
3G	12

PP – UC4 – S4: Testing of the real-time responsiveness of the WAM and Advisory Services

This testing stage is related to the WAM and Advisory service of the Network Application. Since this service is related to the monitoring of the operating situation of the tie transmission line, two relative case studies were conducted for verifying that all the operating conditions were captured and monitored properly by the Network Application. In this context, the WAM service was tested in increased loading conditions and transient conditions (occurrence of a fault). The responsiveness of the Advisory service of the Network Application to trigger alarms when the operating condition of the system deviates from the nominal limits was tested in those pre-piloting case studies.

In order to verify that the Network Application can capture the dynamics of the power system in case of a fault, a three-phase fault was imposed in the middle of the emulated tie-line in the IEEE 9-bus system and the WAM service of the Network Application was activated in order to verify that it can timely provide the operating condition of the system. In Figure 43, the current of tie line in pre-fault conditions is shown in the WAM service of the Network Application. As it is illustrated the current is around 83A and fluctuates according to the load change of the two systems. In the case of the fault in the tie-line, the fault increases rapidly and reaches around 200A as shown in Figure 44. This is well-captured by the WAM service since the transient condition during the fault is visualised in detail. Further to that, in the case of a sudden increase of the loading condition, the WAM service is able to provide the frequency disturbance as it was captured by the two PMUs that are installed in the ends of the tie-line as it is illustrated in Figure 45. It should be noted that the PMU measurements in the pre-piloting setup were sent through the 5G wireless network, since in the case of the 3G and 4G communication networks there was a high data loss percentage.

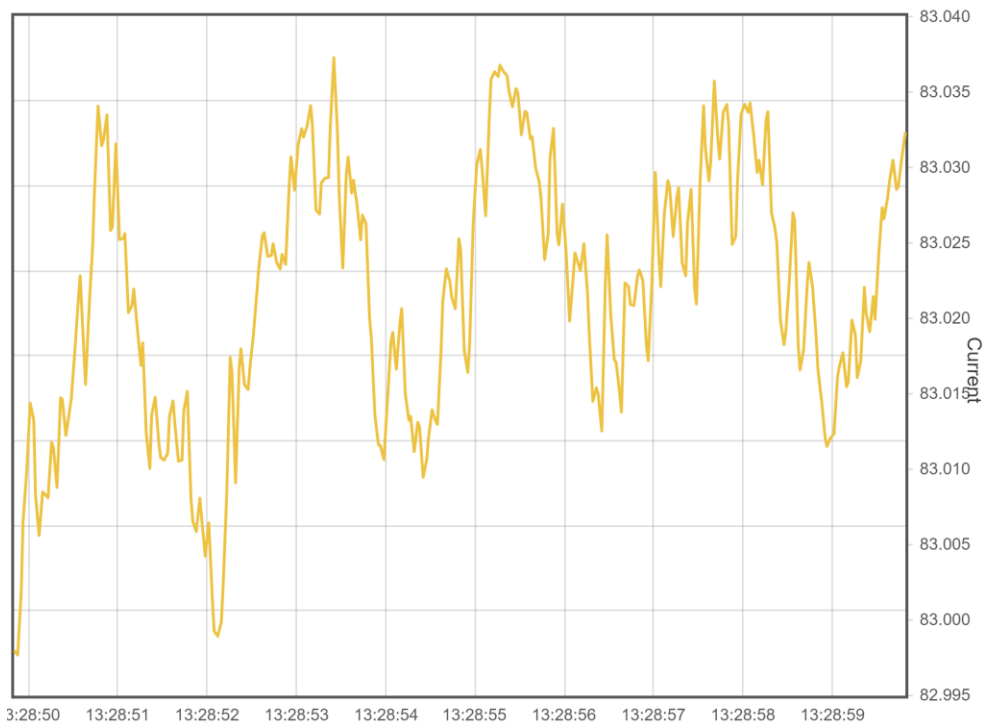


Figure 43: Current of the tie line in pre-fault conditions

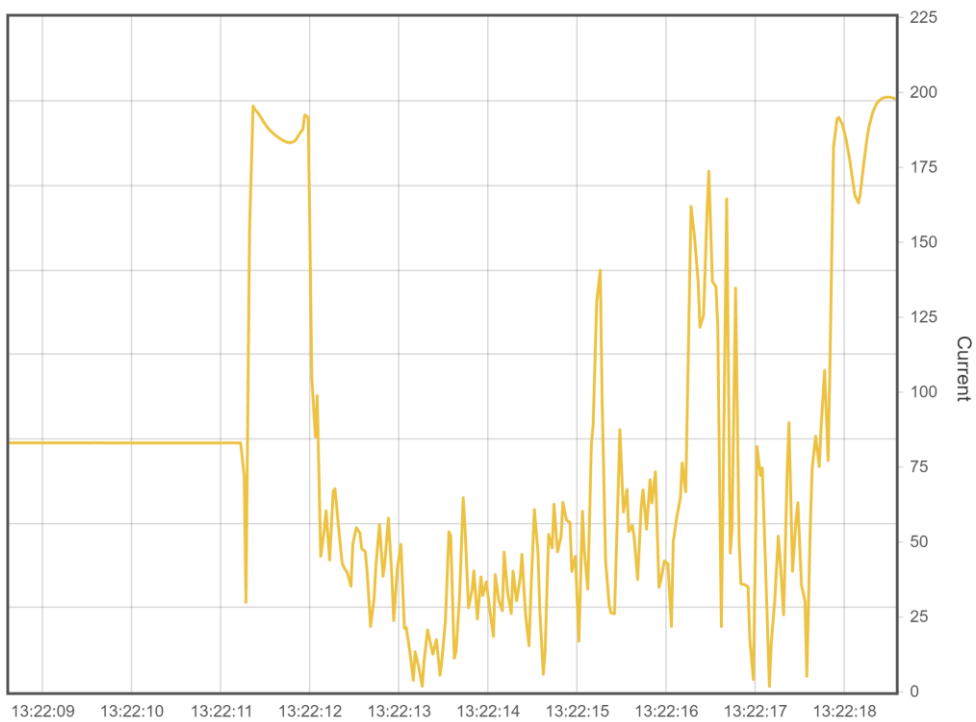


Figure 44: Current in the tie line-during fault conditions

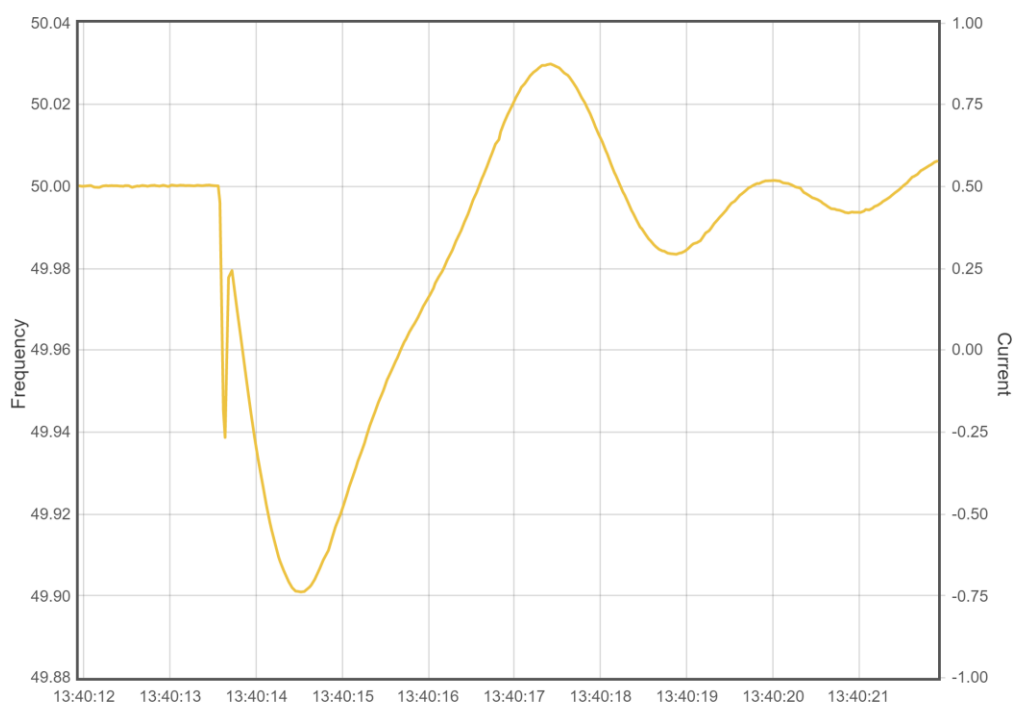


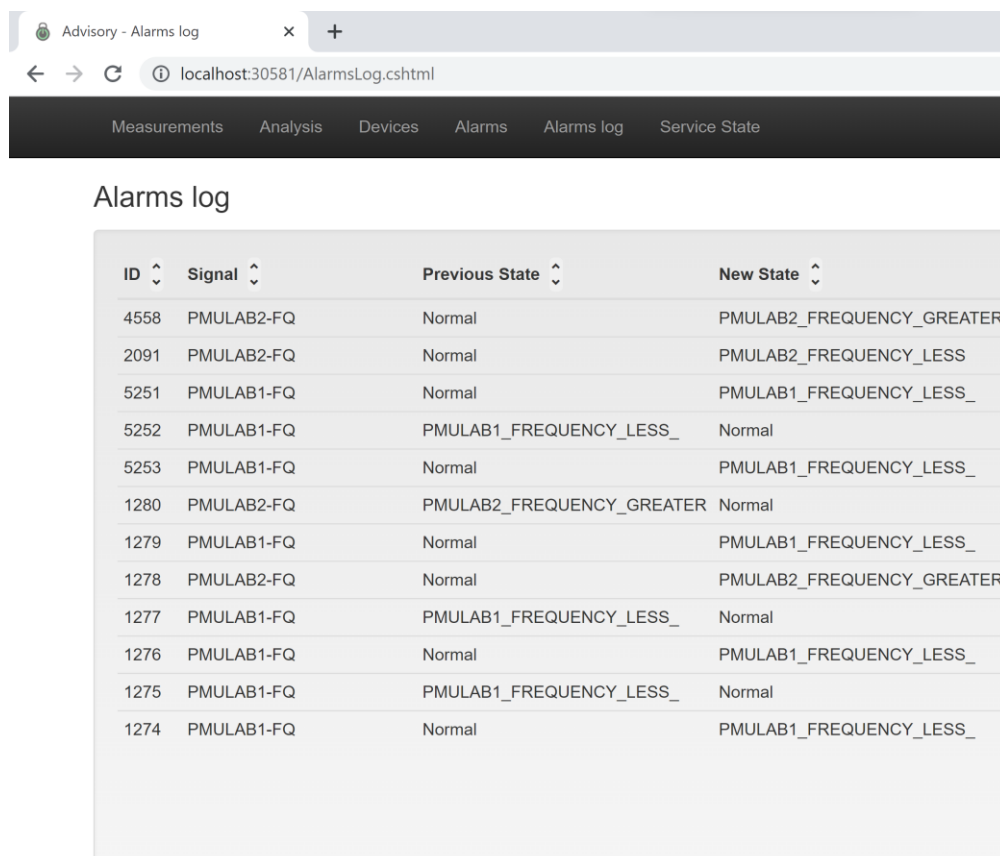
Figure 45: Frequency for a change in the tie-line loading condition

Further to that, the actual mean latency that the WAM service experiences (including the computational latency due to the hardware equipment) for detecting timely a transient event in the system in the case of 3G, 4G, and 5G wireless network is quantified. As shown in Table 24, the WAM service provides the operating condition with only 7 ms latency in case of the 5G wireless networks, however this latency increases significantly in case of the 4G and 3G wireless networks, something that compromises the real-time responsiveness of the Network Application. It should be noted that the latency affects the real-time responsiveness of the Network Application, since the faster the measurements arrive to the Network Application the more promptly any disturbances can be visualised (this is the case for the 5G).

Table 24: Latency in of the WAM and Advisory Services for the 3G, 4G, and 5G wireless networks.

Communication Network	Latency (ms)
5G	7
4G	47
3G	94

In Figure 46, the interface of the Advisory service is shown, when several events were created in the system for affecting the system frequency. The service is able to inform the operator about an event based on the PMU measurements. It should be noted that the time that the alarm is triggered is based on the latency shown in Table 24.



ID	Signal	Previous State	New State
4558	PMULAB2-FQ	Normal	PMULAB2_FREQUENCY_GREATER
2091	PMULAB2-FQ	Normal	PMULAB2_FREQUENCY_LESS
5251	PMULAB1-FQ	Normal	PMULAB1_FREQUENCY_LESS_
5252	PMULAB1-FQ	PMULAB1_FREQUENCY_LESS_	Normal
5253	PMULAB1-FQ	Normal	PMULAB1_FREQUENCY_LESS_
1280	PMULAB2-FQ	PMULAB2_FREQUENCY_GREATER	Normal
1279	PMULAB1-FQ	Normal	PMULAB1_FREQUENCY_LESS_
1278	PMULAB2-FQ	Normal	PMULAB2_FREQUENCY_GREATER
1277	PMULAB1-FQ	PMULAB1_FREQUENCY_LESS_	Normal
1276	PMULAB1-FQ	Normal	PMULAB1_FREQUENCY_LESS_
1275	PMULAB1-FQ	PMULAB1_FREQUENCY_LESS_	Normal
1274	PMULAB1-FQ	Normal	PMULAB1_FREQUENCY_LESS_

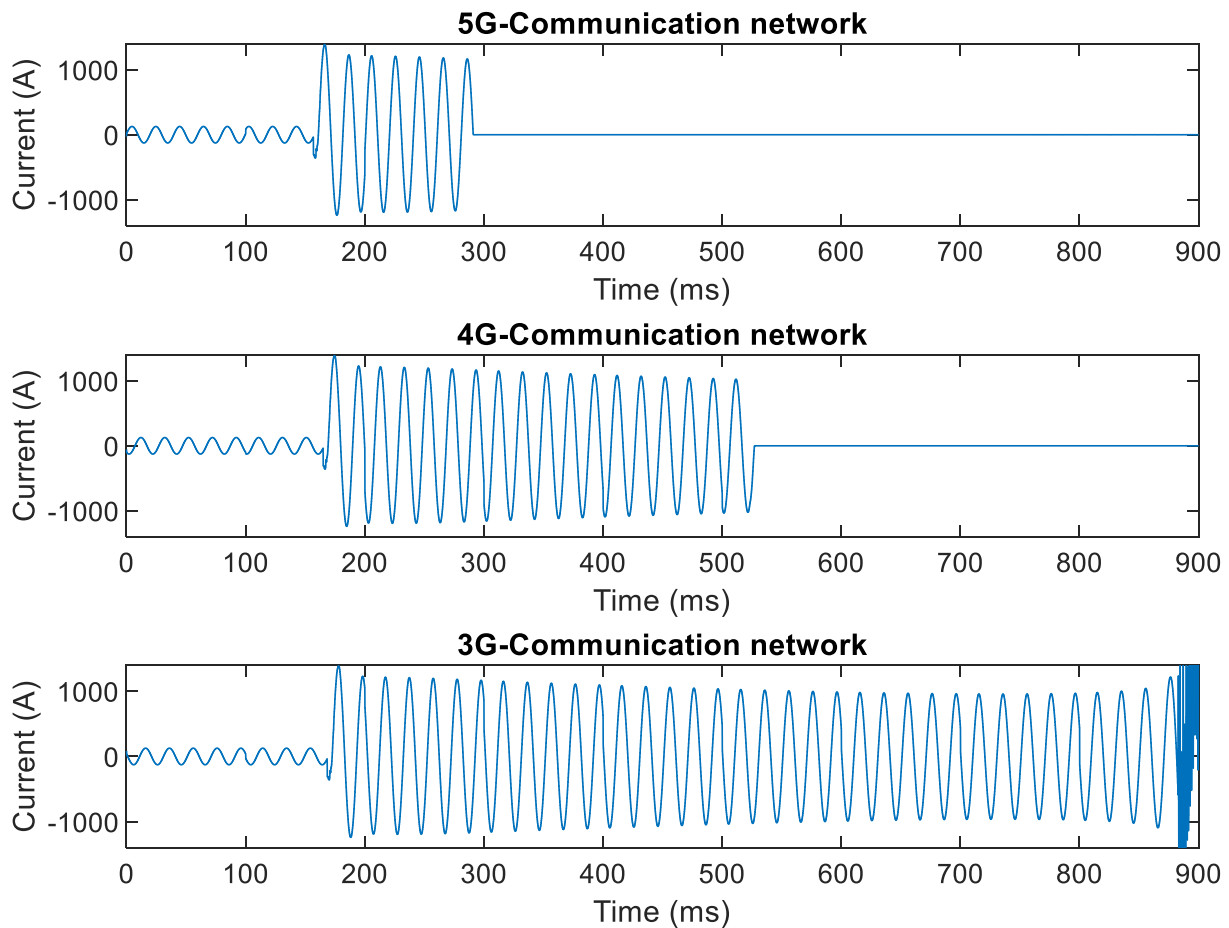
Figure 46: Interface of the advisory service for alarms

PP – UC4 – S5: Testing of the Wide Area Differential Protection Application

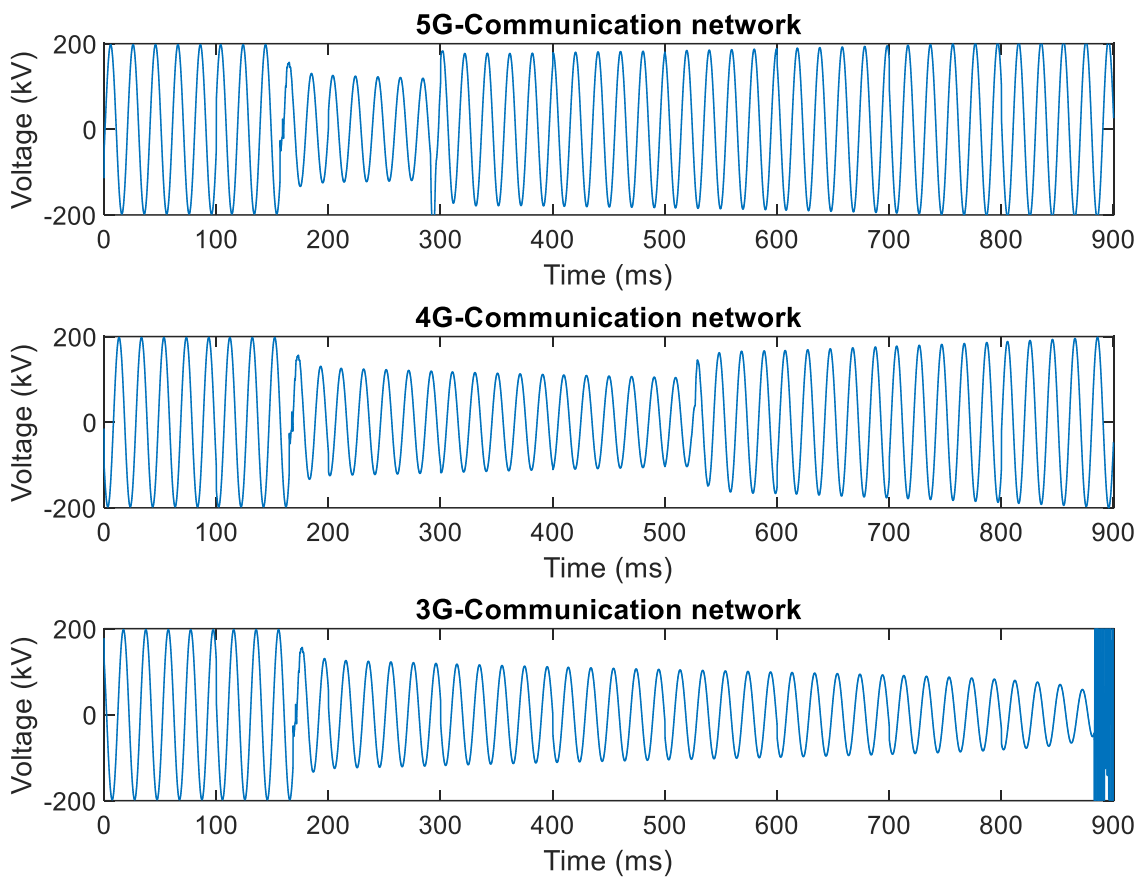
The Wide Area Differential Protection Application was implemented in the Typhoon HIL 402 and was operated locally at the pre-piloting testing setup. The aim of this scenario is to test the real-time responsiveness of the wide area differential protection in fault within the range of the tie transmission line measuring the time needed for the fault to get cleared. In particular, for this case study a three-phase fault was applied to the middle of the emulated tie-transmission line in the IEEE 9-bus system. Based on the Wide Area Differential Protection Application that was developed for this testing scenario, if the magnitude of the current phasor measurements with the same time stamp that are captured by the two PMUs (at the end of the transmission line) have a deviation larger than a certain threshold (in this case 20A), then the protection application sent a trip command to the breakers of the tie line to open. This is because the line currents from the two ends of the line in normal operating conditions do not expect to deviate more than 20A. However, in case of a fault within the transmission line, the line currents from the two ends have a difference larger than 100A. Obviously, this protection application should act as fast as possible to isolate the faults in the transmission line. However, this response time relies on the (transfer) time it takes for of the PMU measurements with the same time stamp to arrive to the application.

In this testing scenario, the wide area differential application receives measurements that are transferred from 3G, 4G, and 5G wireless communication networks. Figure 47 shows the pre fault, during fault, and after fault behaviour of the current and voltage from one of the two buses of the system when the three

types of networks are used. As it is illustrated in the figure, when the 5G network is used for transferring the PMU measurements to the application the fault is cleared timely and the system gets back to stability. In the case of the 4G communication network the fault remains longer on the system. However, using the 3G network affects the stability of the system. In particular, due to the transfer delay that is imposed to the PMU measurements the fault is not cleared on time and the system goes to instability. Further to that, the fault clearing time for the three types of networks is shown in Table 25, which clearly indicates that with the 5G communication network the fault is cleared faster than with the 3G and 4G networks, while 3G network delays the fault significantly. It should be noted that the diagrams of Figure 47 show the end-to-end delay including the computational latency of the wide area protection application, so the fault clearing time includes the computational time of the application and the network delay. As in the loss of data case the 5G network enhances the transmission of measurements and therefore the fault is cleared faster than in the case of the 3G and 4G networks.



(a)



(b)

Figure 47: Pre fault and post fault current end voltage in one of the two ends of the tie transmission line

Table 25: Fault clearing time of the Wide Area Differential Application using 3G, 4G, and 5G network

Communication Network	Fault clearing time (s)
5G	0.14
4G	0.37
3G	0.72

PP – UC4 – S6: Deployment of UC4 Network Application in Network Application Controller

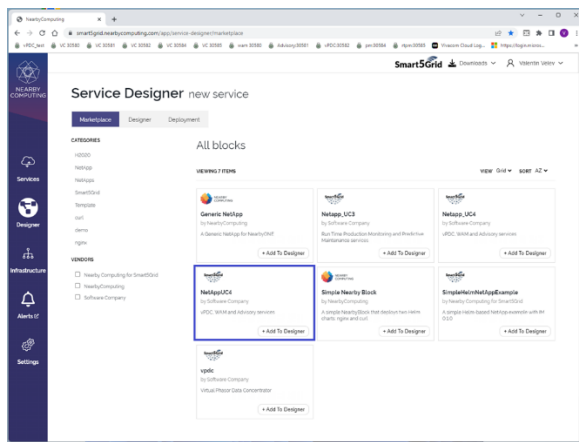
The procedure of deploying the Network Application of UC4 in the Network Application Controller (NAC) that was also conducted in the framework of Task 3.4 (pre-piloting testing) of the Smart5Grid project is described below.

In the first step the Network Application is added to the “Marketplace”, designed at the “Service Designer” of NBC by executing the command in Kubernetes as shown in Figure 48. The result from the command execution is shown in Figure 49 in which the Network Application is added as a new service in the “Designer” section of the “Service Designer” of NBC. Then the service is added to the deployment section

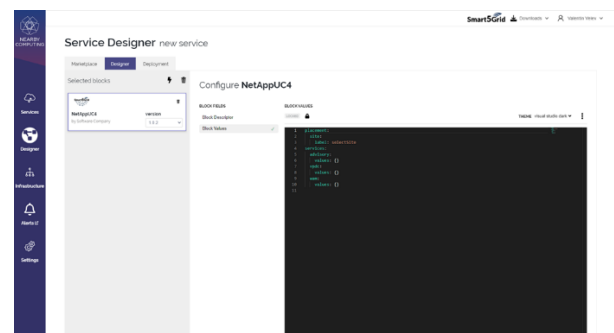
of the Service Designer (Figure 50) and after that the Network Application of UC4 is in the service designer of NBC.

```
root@kubernetes-worker:/home/vv/Helm Charts# jq -n --arg descriptor "$(cat netapp-uc4-helm-1.0.2.yaml)" '${descriptor}' > onboard-request.json
root@kubernetes-worker:/home/vv/Helm Charts# curl -i -H 'Content-Type: application/json' -H 'X-API-key: c94ea546-157f-4907-bd7c-12ae1f233fa7' -X POST http://ps://smart5grid.nearbycomputing.com/adapters/smart5grid/netapps/ --data-binary "@onboard-request.json"
HTTP/2 200
date: Thu, 01 Dec 2022 08:54:25 GMT
content-type: application/json
content-length: 32
vary: Origin
strict-transport-security: max-age=15724800; includeSubDomains
{"netapp_id":"NetAppUC4:1.0.2"}
```

Figure 48: Adding Network Application to “Marketplace” section of “Service Designer” of NBC



(a)



(b)

Figure 49: Integration of UC4 Network Application to the service designer as a new service

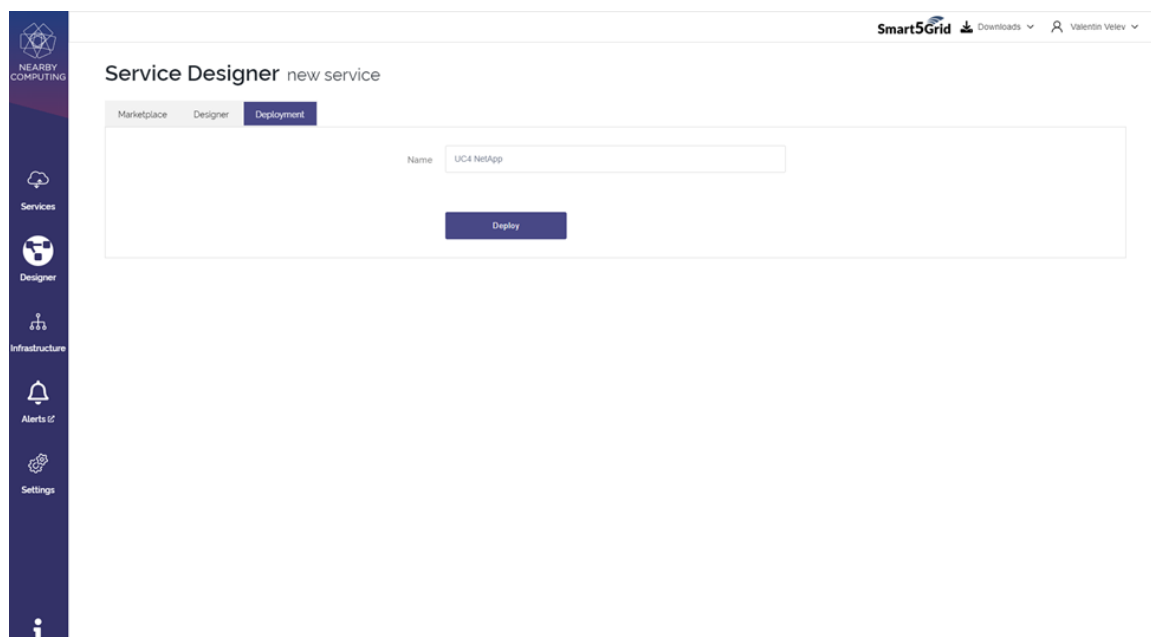
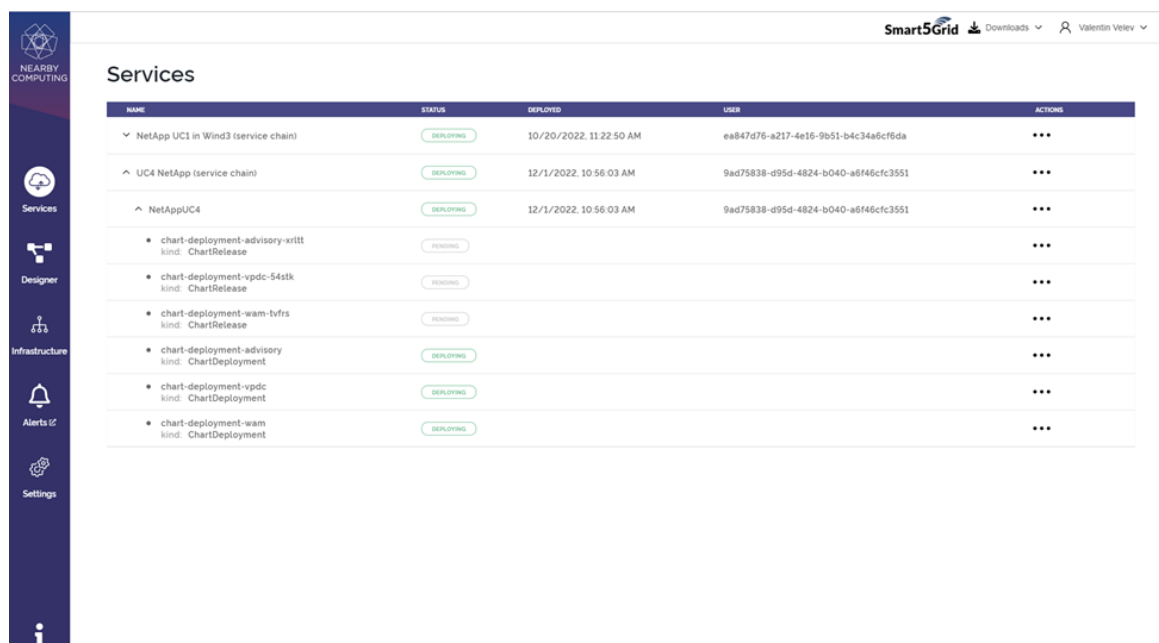


Figure 50: Deploying the service in the “Deployment” section of the “Service Designer” of NBC



NAME	STATUS	DEPLOYED	USER	ACTIONS
NetApp UC1 in Wind3 (service chain)	DEPLOYING	10/20/2022, 11:22:50 AM	ea847d76-a217-4e16-9b51-b4c34a6cf6da	...
UC4 NetApp (service chain)	DEPLOYING	12/1/2022, 10:56:03 AM	9ed75838-d95d-4824-b040-a6f46cfc3551	...
NetAppUC4	DEPLOYING	12/1/2022, 10:56:03 AM	9ed75838-d95d-4824-b040-a6f46cfc3551	...
chart-deployment-advisory-wrttt kind: ChartRelease	PENDING			...
chart-deployment-vpdc-54stk kind: ChartRelease	PENDING			...
chart-deployment-wam-bvfrs kind: ChartRelease	PENDING			...
chart-deployment-advisory kind: ChartDeployment	DEPLOYING			...
chart-deployment-vpdc kind: ChartDeployment	DEPLOYING			...
chart-deployment-wam kind: ChartDeployment	DEPLOYING			...

Figure 51: Service displayed in the “Services” section of the “Service Designer” of NBC

5.2.4.2. Summary of the results

A summary for the testing and evaluation results is shown in Table 26 for all the testing scenarios. In particular, both the operation of the pre-piloting setup and the Network Application integration to the setup were successful, which ensures the testing of the Network Application under different realistic scenarios and wireless communication networks. As illustrated in Table 26, by comparing the targeted KPIs and the Real KPIs that were obtained in tests, it can be concluded that the 5G wireless communication network is very crucial for the operation of the vPDC Network Application according to the design requirements. In the case of 3G and 4G wireless communication networks the Network Application services are affected significantly and the real-time responsiveness of the Network Application as well as the integrity of data are compromised. This has a direct negative impact to the situational awareness of the power system operators.

Table 26: Summary of the evaluation results for UC4 pre-piloting testing

Scenario ID	Type of test	Targeted KPIs	Real KPIs in tests	Comments
PP – UC4 - S1	Proper operation of the pre-piloting testbed.	Test passed	Test passed	The operation of the pre-piloting testbed was according to the requirements.
PP – UC4 - S2	Successful integration of vPDC Net app to the pre-piloting setup.	Test passed	Test passed	The integration of the UC4 Network Application was successful to the pre-piloting setup.

PP – UC4 – S3	Proper gathering and time alignment PMU measurements through the vPDC.	Less than 1% loss of data	3G: 12% 4G: 1.9% 5G: 0%	The 5G wireless network is the only wireless network that fulfills the targeted KPIs
PP-UC4-S4	Timely track of real-time operating condition by the WAM and Advisory Service.	Data latency smaller than 20ms	3G: 94ms 4G: 47ms 5G: 7ms	The 5G wireless network is the only wireless network that fulfills the targeted KPIs.
PP – UC4 – S5	Real time fault clearing within the tie transmission line.	The fault clearing time should be less than 0.2s	3G: 0.72s 4G: 0.37s 5G: 0.14s	The 5G wireless network is the only wireless network that fulfills the targeted KPIs.
PP – UC4 – S6	The NAC is operative, and the compute nodes onboarded.	Test Passed	Test Passed	The UC4 Network Application was successfully deployed to the NAC.

6. Pre-piloting for the use-cases that use 5G connectivity architecture

6.1. UC1 (Italian demo): Automatic Power Distribution Grid Fault Detection

In a nutshell, the Italian demo (UC1: *Automatic power distribution grid fault detection*) aims to test the viability of potential use of 5G technology for remote connectivity of grid elements for an advanced automation and real-time monitoring system, enabled with grid fault automation and self-healing features for energy distribution grids. A 5G network deployed at the pilot site is in charge of offering high levels of network availability and reliability for the communication layer of this grid automation system. The final business-related goal is to reduce the effort and time spent for troubleshooting communication problems between the central hub (supervisory control room of the grid operator, E-Distribuzione in this case) and the field devices (e.g., grid remote terminal units in charge for grid reconfiguration). Thus, as part of the Italian demo, a use-case specific Network Application was developed to perform continuous monitoring of the communication service level of the automation system, providing the Distribution System Operator (DSO). Some services of this Network Application calculate relevant statistical information of the Radio Access Network (RAN) service levels in terms of bandwidth and latency. In case of passing specific thresholds related to the required QoS by the communication layer of the grid automation system, then an alarm service of the Network Application is also activated.

6.1.1. Phase 1: Pre-piloting testbed description and realistic conditions to replicate the UC operational environment

6.1.1.1. Introduction

The aim of the pre-piloting setup for the Italian demo (UC1: *Automatic power distribution grid fault detection*) is:

- to provide a safe operation and testing environment similar to the secondary power substation where the Italian pilot will be demonstrated (Olbia, Italy).
- to create a realistic operational testing environment that encompasses all the necessary features of the real pilot to validate the functional requirements for the use-case specific Network Application.

Specifically, the pre-piloting testbed was used to evaluate the performance of the same or similar hardware (HW) and software (SW) components of the advanced power system automation system which is present in the actual setup of the pilot. Furthermore, during the pre-piloting testing phase several testing scenarios addressed the compliance of the HW and SW setup with the cyber security guidelines requested by E-Distribuzione, the owner of the UC1 pilot.

In this specific use case, a Cisco IR1101 communication router [35], equipped with a 5G ready module, is used for the first time within an advanced power automation system owned by E-Distribuzione. This

communication router is capable of simultaneously using two different Access Point Names (APNs) with a single Subscriber Identity Module (SIM) to connect to the 5G mobile network. In order to ensure complete segregation of the communication traffic, business-critical traffic is sent toward E-Distribuzione's central communication infrastructure through one APN, while the monitoring traffic exchanged with the Network Application hosted on the multi-access edge computing (MEC) server is sent through a different APN.

A very important activity in pre-piloting phase is represented by the verification of compliance with ENEL's cyber security guidelines. Specifically for this use-case, a segregation functionality between the business-critical traffic (coming from the power equipment on the field) and the network traffic related to the Network Application monitoring application is strictly needed. This is because there is an interaction between an external element, represented by the use-case specific Network Application, and the operational elements of the power grid infrastructure of ENEL (E-Distribuzione), such as the Remote Terminal Units (RTU). At the same time, it is desirable to verify that this new mode of deployment does not impair the performance of the communication router (the key element of the communication layer of the grid automation system).

6.1.1.2. Description of the pre-piloting testbed

The pre-piloting testbed of the Italian demo shares most of the configurations and the 5G equipment involved in the actual pilot. Specifically, the pre-piloting testbed is hosted in Gridspertise laboratory (a company of Enel group specialized in the digitalization of power systems) in Rubattino-Millan, Italy. The pre-piloting testbed architecture is presented in Figure 52. It is composed of indoor components, related to parts relevant to the grid automation system (the elements inside the blue dashed rectangle of Figure 52, such as the industrial Cisco IR1101 router [35] and its connections to the remote terminal units (RTU), the MV protection and control device (RGDM) from the MV substation) and all the outdoor equipment (all devices related to the 5G communication infrastructure located outside the laboratory) which are common with the actual pilot (e.g., 5G antennas, the Wind3 5G RAN, the edge site hosting the multi-access edge computing (MEC) server, the Wind3 public IP network and so forth).

Given that there are both software (SW) components and HW components which are planned to be integrated for the first time within the advanced grid automation system of Enel (in the pilot stage) it is important that SW and HW components are tested during the pre-piloting phase. Thus, the scope of the pre-piloting phase of the UC1 is to provide suitable testbed(s) in which both newly developed SW components (e.g., early versions of the use-case specific Network Application) and HW components, like industrial communication router equipped with a 5G module are to be tested, accordingly. Specifically, for UC1 two types of pre-piloting testbeds were used: (1) one which mimics to the most accurate extent the actual pilot, which integrates both grid-related infrastructure and 5G-related infrastructure, but where the early versions of the Network Application were not possible to be integrated (no end-to-end tests are performed); and (2) a local testbed facility (see Figure 55) for functional testing of the Network Application, provided by STAM (the partner in the Smart5Grid project, in charge with the development of the use-case specific Network Application for UC1). Specifically, in this latter testbed setup a docker application with the same functionalities as the actual Network Application of the UC1 is used. However, this docker application is not fully integrated with the NearbyONE Network Application Controller (NAC), the enabler of the onboarding and deployment of the Network Application at the Edge Site (see the upper part of Figure 52).

It is worth mentioning that while most of the 5G infrastructure elements were deployed and installed at the telco provider of UC1, and integration between the pre-piloting testbed related to grid infrastructure and 5G infrastructure took place (as it is depicted in the integrated pre-piloting testbed in Figure 52), the integration process between the 5G infrastructure layer and the some of the critical elements of the Smart5Grid platform, such as the Network Application controller, is still ongoing. Thus, in this stage of pre-piloting testing it was not possible to test direct communication between the Cisco router of the automation system and the Network Application. These tests are going to be performed in the pilot.

Secondary Substation Logical layout

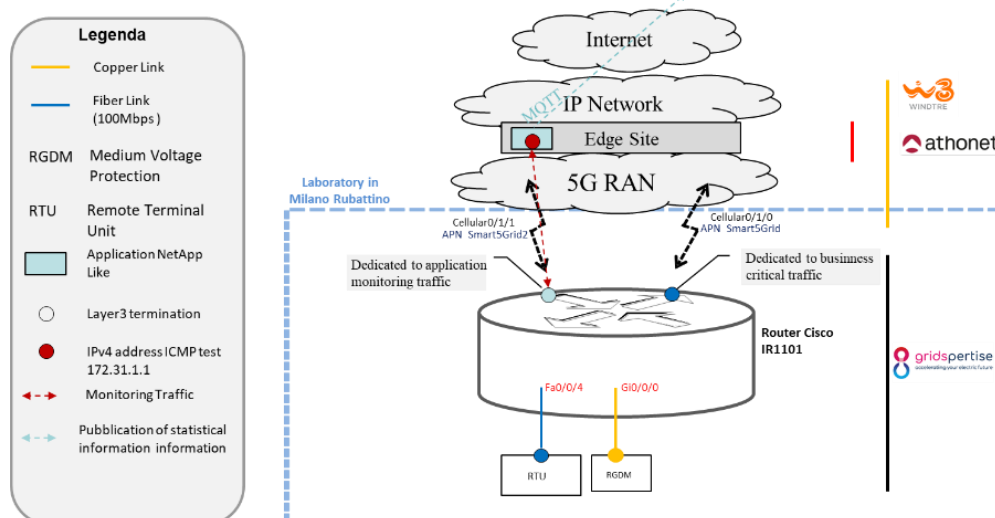


Figure 52: The integrated pre-piloting testbed for the Italian demo (UC1)

Physical layout

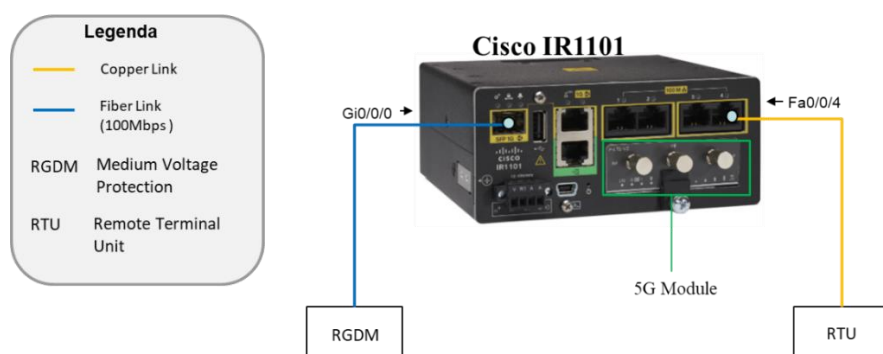


Figure 53: CISCO IR1101 as key component of the communication layer of the advanced automation system of UC1

A key aspect for the pre-piloting phase is to maximize the similarity of the pre-piloting lab deployment (that is hosted at Gridsptertise laboratory of E-Distribuzione) with the final deployment in the power substation in Olbia region, Italy (where the actual pilot of the UC1 will be executed). To achieve this, the 5G network, including the radio devices, the edge site, 5G core and the application servers, are connected to Gridsptertise laboratory, using the same 5G HW and configurations as in the power substation of the actual

pilot. Furthermore, the industrial Cisco IR1101 communication router enabled with 5G communication module [35] is identical with the one to be deployed on the pilot site, and fully integrated with the rest of the power automation subcomponents that are deployed on the field at the power substations in Olbia, where the Italian demo site is located. Thus, a first set of tests was to check the stability of the new router firmware and the compatibility between the router and the new 5G module. Furthermore, all the traffic generated by the protections installed downstream of the communication router (for the purpose of fault detection or remote control of power grid), as well as the monitoring traffic to the Network Application passes through the same router. Thus, it is important to verify that the new firmware in use on this equipment to take advantage of the 5G capabilities is working properly and it remains stable in order to not create problems for the automation and remote-control traffic.

During the pre-piloting tests at the laboratory of Gridspertise we aim to verify whether all the monitoring traffic generated by the Network Application to be deployed on the edge site (red colour dashed double arrow in Figure 52) interferes in any way with the traffic exchanged on the other interfaces of the router (black colour dashed arrows in Figure 52). It is to be noted that through the output originating from the commands entered directly on the router command line, we can monitor the workload of the device and verify that the above-mentioned segregation of the traffic is indeed operational.

The integrated pre-piloting testbed of UC1 is shown in Figure 52. The identification of each component evaluated and tested in the pre-piloting phase related to this testbed, their corresponding description, and their role in the pre-piloting tests are detailed in the table below.

Table 27: Description of each component of the integrated pre-piloting testbed of UC1

Component Name	Component Description
UC1-C-ID-1: Cisco IR1101 router	This is the same communication device to be used for the advanced automation system for grid fault detection in the secondary power substation of the Italian demo. Its role is to ensure secure and reliable communication between the field power equipment (e.g., remote terminal unit (RTU), protection, etc.) and the central control room (e.g., central hub of the Supervisory Control and Data Acquisition (SCADA) System) of the distribution System Operator (DSO) using 5G technology communication network.
UC1-C-ID-2: 5G RAN (Radio Access Network)	This network consists of the main components of a wireless telecommunications system that connects individual customers premises equipment (CPEs) to the telco network.
UC1-C-ID-2: 5G edge node	Athonet's "edge node," hosting the 5G Non-Standalone (NSA) user-plane functionalities (S/P-Gateway) that allow 5G traffic to be steered directly towards the MEC server.
UC1-C-ID-4: MEC Server	Common off-the-shelf piece of hardware (a Dell R640 server ³) deployed to perform edge computing. It receives data from the 5G network via its interconnection with the edge node and it is the host of the instantiated Network Application. It is remotely

³ <https://www.dell.com/ae/business/p/poweredge-r640/pd>

	accessible by the Network Application Controller (NearbyONE of NBC).
UC1-C-ID-5: IP Network	Commercial Wind3 IP Network guarantees connection between RAN and Core Network and it also guarantees connection to CO of Enel; IP Network is used as transport network.
UC1-C-ID-6: Dashboard	It graphically represents the traffic statistics collected from the router queries in the lab highlighting any critical issues, similar to what will be done in the pilot. The traffic statistics are collected by querying the SIMs installed in the pilot's secondary substations. Through the dashboard, E-Distribuzione operators are able to detect any communication problems before they can impair the proper operation of the real-time self-healing functionality of the power grid automation system.

6.1.1.3. Creation of the realistic operation conditions of the pilot

To create the realistic operation conditions of the pilot, the 5G network HW is deployed and integrated with the lab, which allows us to test most of the network-related functionalities of the new HW and SW components of the industrial Cisco router IR1101 (the communication layer of the grid automation) of the UC1. It is worth mentioning once again that in the pre-piloting testing phase, we used the identical industrial network router that will be installed in each power substation of the pilot, and this router uses a 5G SIM which was configured based on the profile provided by Wind3, and which is again similar to the one that will be used in Sardinia.

It is worth mentioning that the functional testing of the Network Application of UC1 involves the monitoring of the power distribution grid fault detection system equipped with a 5G communication module. Thus, the scope of the pre-piloting tests reported in this document is focused on what concerns changes in the SW and HW of the communication layer of this automation system (e.g., from wired type communication module to the 5G communication module).

As was previously explained, for testing functional requirements related to the UC1-specific Network Application we have used a separate setup, hosted at a laboratory of STAM (Network Application developer for UC1). Figure 55 shows the schema (a) and the picture taken from the lab(b) which encompasses the HW components used for this testbed.

In order to better understand how the realistic operation conditions were created to test the functional requirements of the Network Application, let us briefly review the logical composition of the Network Application for UC1, as it was detailed in D2.2 (*Overall Architecture Design, Technical Specifications and Technology Enablers*) [2].

The Network Application of UC1 consists of three separate subcomponents, as it is shown in Figure 54:

- receiver subcomponent
- fault detection subcomponent
- monitoring subcomponent

The Network Application receives the network flow (which in the pilot setup will come from the IR1101 router) via the receiver SW subcomponent of the Network Application and generates a normalized traffic flow which is forwarded to both monitoring and fault detection SW subcomponents of the Network Application. The fault detection subcomponent detects any anomalies (e.g., overpassing of a pre-defined threshold for a set of specific quality of service parameters such as latency or loss of packets) and informs the SW monitoring subcomponent of the Network Application. On top of that, the monitoring subcomponent performs basic flow analysis, logs the related information and informs the TeLeCommunication (TLC) team on the network status (both regular and irregular network traffic), via 5G communication with the central Hub of E-distribuzione. In other words, the information for the status of the network is collected in the deployed sensors via a passive network to the edge in the deployed Network Application using the 5G infrastructure, and eventually the TLC team is informed.

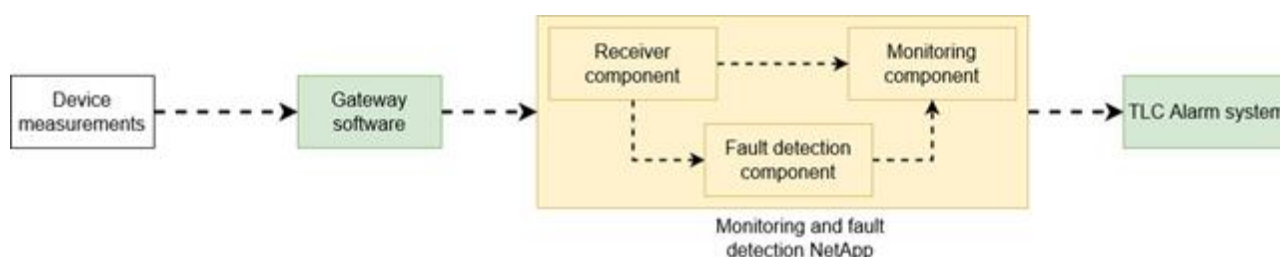
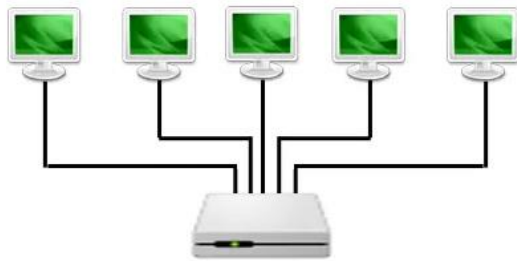


Figure 54: Software Component Architecture of the Network Application of UC1

For the functional testing phase of the Network Application of UC1, we have used the laboratory setup presented in Figure 55 hosted at STAM lab. Because there is no 5G network integration in this setup, the docker image of the actual Network Application was used. This docker image contains all three components – microservices of the Network Application, which was built in a personal computer (PC).

For the generation of realistic input data for the Network Application, which could emulate possible status of the 5G network traffic passing the communication router of the automation system, we used a set of 20 different personal computers (PCs) connected to a common router. Note that this common router is intended to mimic only the Network Application related traffic section of the IR1101 router (the red dashed line with double arrows in Figure 52).

Different data streams were generated using the connected set of 20 PCs. The classical operation case and the stressed operation case were simulated, so as to understand what the behaviour of the system will be in both modes of operation and to understand what the responses generated by the system might be. Specifically, all the PCs in this configuration were running live video streaming aiming at creating different networks loading conditions, including the scenario needed to emulate conditions which raise the alarm triggering functionality of the second component of the Network Application (detection of network QoS deterioration). For the latter scenario, the high flow of data was generated overloading the network by simultaneous downloading of 4K video from all 20 PCs.



(a) Schema of the lab setup for Network Application functional testing



(b) Photo of the actual lab depicting the router (bottom) and the wired connections of the router with the traffic generating computers

Figure 55: Schema (a) and photo (b) of the pre-piloting setup for functional testing of the UC1's Network Application

6.1.2. Phase 2: Network Application integration

In the pre-piloting phase, a docker application with the same functionalities as the actual Network Application of the UC1 is used. However, as it was previously explained this docker image of the Network Application was not fully integrated with the NearbyONE Network Application Controller (NAC) for actual deployment of the Network Application in a 5G infrastructure testing environment. This will happen at the pilot site.

The Network Application used in the pre-piloting phase was however integrated in a lab deployment setup using a docker image of the actual Network Application and an emulated network and gateway using several PCs and a common network router, which provided a reasonable development and integration playground for the functional testing of each of the Network Application components.

Furthermore, the Network Application was also prepared for the deployment in the 5G infrastructure, which is expected to take place when the integration between the NearbyONE's NAC and the edge site of the Wind3 5G network infrastructure is finalized.

In this respect, it is worth highlighting what are the pre-conditions needed for the Network Application deployment in the 5G network:

- The network needs to be operational, and the NAC fully integrated in the network operation, such that the Network Application can be deployed in the network.
- Package the Network Application Helm Charts for NAC (preparatory step for Network Application integration with the NAC).
- Deploy the Network Application as a set of Helm Charts.

- Access Network Application Administration Panel from the NAC user interface.

6.1.3. Phase 3: Defining the testing scenarios

This section defines the scenarios that are to be validated as part of the pre-piloting testing activities of UC1. It is to be noted that within the pre-piloting phase only a subset of testing scenarios of the pilot were performed in relation to the readiness level of the 5G infrastructure and the level of integration between the Smart5Grid platform and the 5G infrastructure. Furthermore, this is due to several other reasons, such as: the pre-piloting testbed does not include the full list of components of the pilot, the pre-piloting testing environment reflects only the parts that could have the greatest impact on the operation of the Network Application in the actual pilot testing environment, among others. It is to be noted that this is valid for all the UCs, and not only for UC1.

The testing scenarios of UC1 could be clustered by type in three categories, given below:

- Testing the interconnection between the components of the pre-piloting testbed.
- Testing the integration of the Network Applications (early versions) within the pre-piloting testbed for functional tests of the Network Application.
- Testing the functional requirements of the Network Applications (early versions).

The list of the testing scenarios ran and validated during the pre-piloting phase of UC1 is given in the table below.

Table 28: List of testing scenarios for the pre-piloting testing of UC1

Scenario ID	Scenario Title	Testcase type	Description
PP – UC1 – S1	Configuration test of user equipment (IR1101)	Configuration test of network component	Configuration test for assignment of Wind3 APN to Cellular interfaces of the router.
PP – UC1 – S2	Connectivity and quality service test (latency)	Network component (IR1101 router)	Check communication by ping test between the router and the MEC Server by latency evaluation.
PP – UC1 – S3	Quality communication service between router and MAC server (packet loss)	Network component (IR1101 router)	Check communication by ping test between the router and the MEC Server by counting loss of packets.
PP – UC1 – S4	Configuration and verification a simultaneous connectivity on a second- cellular interface	Network component (IR1101 router)	Check that we have received two different IPs from two different APNs on different cellular interfaces.
PP – UC1 – S5	Connectivity between user equipment(router) and Network Application	Network Application Functional Test	Check communication by ping test between docker image host and router.

	(Early version) – Receiver component		
PP – UC1 – S6	Count number of lost packets (Monitoring component of the Network Application)	Network Application Test	Service that counts the number of lost packets.
PP – UC1 – S7	Measurement of Latency (Monitoring component of the Network Application)	Network Application Test	Service that can measure the latency 90 and the latency 99.
PP – UC1 – S8	Measurement of jitter (Monitoring component of the Network Application)	Network Application Test	Service that can measure the jitter.
PP – UC1 – S9	Alarm generator for the Fault Detection component of the Network Application)	Network Application Test	Generate an alarm when a threshold is overpassed.

Table 29: Targeted KPIs for each scenario of UC1 to be tested in the pre-piloting phase

Scenario ID	Functional requirements	Targeted KPIs
PP - UC1- S1	To receive two different IPs addresses corresponding to each cellular interface of the router.	Obtain two different Ips.
PP – UC1 - S2	To receive acknowledgement from Internet Communication Message Protocol (ICMP) – latency related.	Successful response in less than 30ms.
PP – UC1 – S3	To receive acknowledgement from Internet Communication Message Protocol (ICMP) – loss of packet related.	Successful response and packet loss less than 0.1%.
PP - UC - S4	Check that we have received two different IPs from two different APNs on different cellular interfaces.	Two different IP addresses.
PP - UC1- S5	Test communication.	Receive acknowledgement from ping between router and Network Application

PP - UC1 - S6	Count packet loss.	Successful count of number of lost packets.
PP - UC - S7	Latency evaluation.	Successful measurement of latency.
PP - UC1 - S8	Jitter evaluation.	Successful measurement of jitter.
PP – UC1 – S9	Alarm generation.	Successful generation of alarm.

Table 30: Description of the functional requirements

Functional requirement Name	Brief description of each functional requirement
To receive two different IP addresses corresponding to each cellular interface of the router.	In the pre-piloting scenario S1, related to configuration tests, we verify that we indeed receive 2 different IP addresses linked with 2 different alias names for the cellular interfaces of the router as the APN names allocated in the SIM card profile. For example, in the snippets of the router logs, presented in Figure 57, the cellular 0/1/0 is the interface of the router that matches with the alias name "SMART5GRID" which corresponds to an IP address, while the second cellular 0/1/1 interface of the router matches with the alias name "SMART5GRID2" which corresponds to a different IP address.
To receive acknowledgement from Internet Communication Message Protocol (ICMP) – latency and loss of packet related.	Verify if the connection between the MEC Server and the router is established successfully using a typical ping tool available from the vendor MEC server, the KPI represents the average.
Test communication.	Verify if the connection between router and Network Application is established.
Count packet loss.	Packet loss test help is needed to verify the effective operation of the service.
Latency evaluation.	The P90 and P99 latency tests are needed to verify the effective operation of the service.
Jitter evaluation.	The jitter test is needed to verify the effective operation of the service.
Alarm generation.	An alarm is generated when a threshold is overpassed.

6.1.4. Phase 4: Validation and evaluation

Table 31: Summary of testing results for the pre-piloting phase of UC1

Scenario ID	Type of test	Targeted KPIs	Real KPIs in tests	Comments
PP – UC1 – S1	Configuration test of user equipment (IR1101)	Obtain two different IPs.	We receive on cellular 0/1/0 the IP address 10.62.62.1 and on cellular 0/1/1 the IP address 10.2.1.2.	Test passed successfully.
PP – UC1 – S2	Test communication Network component (IR1101 router)	Receive response in less than 30ms.	Response received within the specified threshold	Test passed successfully.
PP – UC1 – S3	Count the loss of packets	Packet loss under 0,01%.	Packet loss under 0,01%.	Test passed successfully.
PP – UC1 – S4	Latency evaluation	Latency under 25ms.	Latency average under 25ms.	Test passed successfully.
PP – UC1 – S5	Network Application Functional Test	Received acknowledgement from ping between router and Network Application.	Received acknowledgement from ping between router and Network Application .	The functional test was successful.
PP – UC1 – S6	Network Application Functional Test	Count lost packets	Successful count of number of lost packets	The functional test was successful.
PP – UC1 – S7	Network Application Functional Test	Latency evaluation	Successful measurement	The functional

			ent of latency.	test was successful.
PP – UC1 – S8	Network Application Functional Test	Jitter evaluation.	Successful measurement of jitter.	The functional test was successful.
PP – UC1 – S9	Network Application Functional Test	Alarm generation.	Successful generation of alarm.	The alarm was generated when a threshold is overpassed.

The following figures show the logs from the connectivity type of tests for the IR1101 Cisco router, as well as the results for the functional tests of the early version of the Network Application of UC1. The titles of the figures are self-explanatory in terms of the testing scenario they refer to.

```
cellular 0/1/0 lte profile create 1 SMART5GRID none
cellular 0/1/1 lte profile create 2 SMART5GRID2 none
```

Figure 56: Cisco IR1101 Router configuration logs for assignment of the APNs (from Wind3 profile) to the cellular interfaces of the UC1 communication router (PP-UC1-S1)

```
SMART5Grid#sh ip int brief
Interface      IP-Address    OK? Method Status    Protocol
GigabitEthernet0/0/0 unassigned    YES NVRAM  down      down
FastEthernet0/0/1  unassigned    YES unset  up         up
FastEthernet0/0/2  unassigned    YES unset  down       down
FastEthernet0/0/3  unassigned    YES unset  down       down
FastEthernet0/0/4  unassigned    YES unset  down       down
Cellular0/1/0     10.62.62.1    YES IPCP  up         up
Cellular0/1/1     10.2.1.2      YES IPCP  up         up
Async0/2/0        unassigned    YES unset  up         down
Vlan1             unassigned    YES unset  up         down
Vlan50            192.168.50.1  YES NVRAM  up         down
Vlan215           192.168.115.121 YES NVRAM  up         up
Vlan500           192.168.130.0 YES NVRAM  up         down
```

Figure 57: Router logs for the verification of the correct IP allocation for the two APNs (ensures segregation of the traffic)

```

PING 172.31.1.2 (172.31.1.2) 56(84) bytes of data.
64 bytes from 172.31.1.2: icmp_seq=1 ttl=255 time=43.2 ms
64 bytes from 172.31.1.2: icmp_seq=2 ttl=255 time=57.6 ms
64 bytes from 172.31.1.2: icmp_seq=3 ttl=255 time=32.6 ms
64 bytes from 172.31.1.2: icmp_seq=4 ttl=255 time=21.5 ms
64 bytes from 172.31.1.2: icmp_seq=5 ttl=255 time=22.5 ms
64 bytes from 172.31.1.2: icmp_seq=6 ttl=255 time=22.4 ms
64 bytes from 172.31.1.2: icmp_seq=7 ttl=255 time=21.4 ms
64 bytes from 172.31.1.2: icmp_seq=8 ttl=255 time=29.4 ms
64 bytes from 172.31.1.2: icmp_seq=9 ttl=255 time=28.4 ms
64 bytes from 172.31.1.2: icmp_seq=10 ttl=255 time=21.3 ms
64 bytes from 172.31.1.2: icmp_seq=11 ttl=255 time=21.3 ms
64 bytes from 172.31.1.2: icmp_seq=12 ttl=255 time=21.3 ms
64 bytes from 172.31.1.2: icmp_seq=13 ttl=255 time=39.3 ms
64 bytes from 172.31.1.2: icmp_seq=14 ttl=255 time=24.2 ms
64 bytes from 172.31.1.2: icmp_seq=15 ttl=255 time=22.2 ms
64 bytes from 172.31.1.2: icmp_seq=16 ttl=255 time=21.2 ms
64 bytes from 172.31.1.2: icmp_seq=17 ttl=255 time=21.2 ms
64 bytes from 172.31.1.2: icmp_seq=18 ttl=255 time=21.1 ms
64 bytes from 172.31.1.2: icmp_seq=19 ttl=255 time=21.1 ms
64 bytes from 172.31.1.2: icmp_seq=20 ttl=255 time=29.1 ms
^C
--- 172.31.1.2 ping statistics ---
20 packets transmitted, 20 received, 0% packet loss, time 19055ms
rtt min/avg/max/mdev = 21.165/27.170/57.601/9.377 ms

```

Figure 58: PP-UC1-S2 Logs for ping tests results for latency

```

FGVM1VTM22004933 # execute ping 10.2.1.2
PING 10.2.1.2 (10.2.1.2): 56 data bytes
64 bytes from 10.2.1.2: icmp_seq=0 ttl=254 time=28.3 ms
64 bytes from 10.2.1.2: icmp_seq=1 ttl=254 time=31.2 ms
64 bytes from 10.2.1.2: icmp_seq=2 ttl=254 time=31.9 ms
^C
--- 10.2.1.2 ping statistics ---
200 packets transmitted, 200 received, 0% packet loss, time 199295ms
rtt min/avg/max/mdev = 31.295/47.244/248.683/28.129 ms

```

Figure 59: PP-UC1-S3 Logs for ping tests results for packet loss

In the following figures the Network Application functional testing results are presented as follows: Figure 60 reports on the latency P90 (for the probability that 90% of the traffic is within the value indicated); similarly, Figure 61 presents the functional testing results for the Network Application component in charge to calculate the latency using the P99 probability metric. Figure 62 shows the functional testing results for the jitter component of the Network Application of UC1, while in Figure 63 the results of the functional test related to the Network Application component in charge with the number of lost packets calculation are presented.

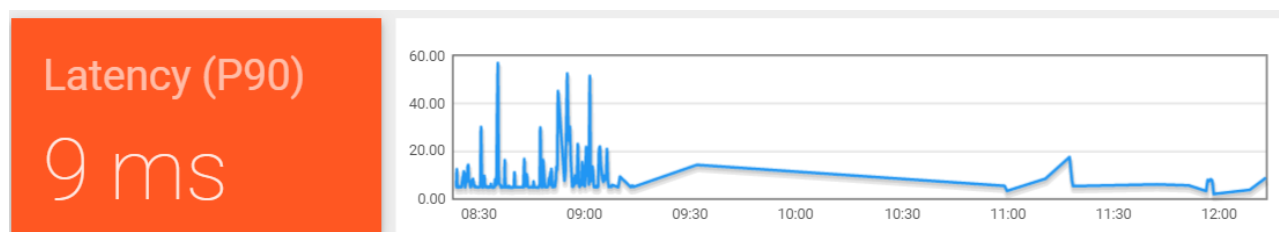


Figure 60 Results for the functional Network Application test for the Network Application component in charge for counting the Historical data of latency P90 (PP-UC1-S7)

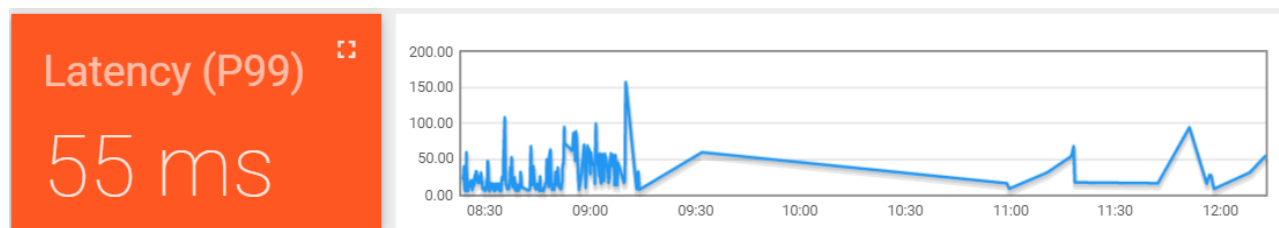


Figure 61 Results for the functional Network Application test for the Network Application component in charge for counting the Historical data of latency P99 (PP-UC1-S7)

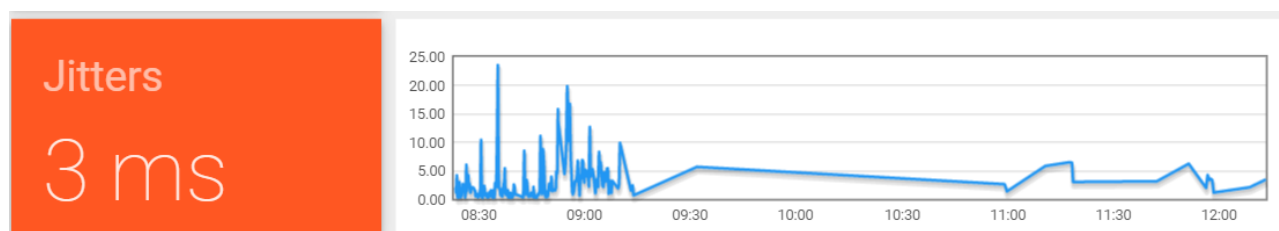


Figure 62 Results for the functional Network Application test for the Network Application component in charge for calculating historical data jitter (PP-UC1-S8)

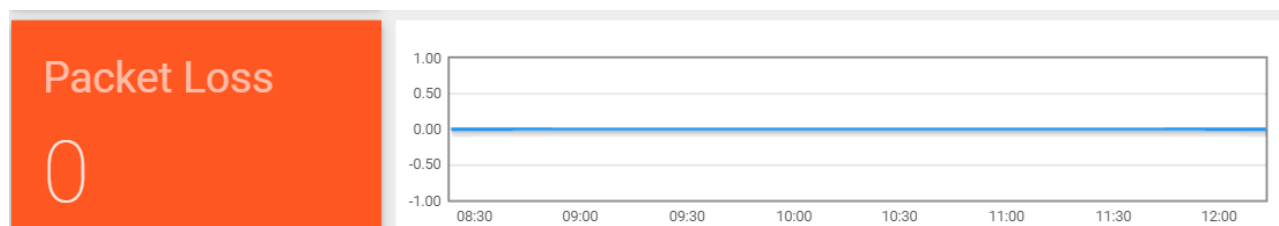


Figure 63: Results for the functional Network Application test for the Network Application component in charge for counting the historical packet loss (PP-UC1-S6)

From the Figure 60 - Figure 63 one can observe in the first phase the network was subjected to high data traffic which is also reflected on the analysis of jitter and latency, while there is no effect on the number of lost packets. While in classical operating conditions the values of these parameters for monitoring the QoS of the 5G network might, in some cases, not meet all the energy service requested KPIs, it is expected that generally they will remain below the required thresholds.

Nevertheless, in order to show these low probability cases, another Network Application component was created, which raises an alarm, when one or more of the QoS network parameters exceed the indicated thresholds. Thus, the implementation of functional test for the Alarm generation component of the Network Application involved the generation of traffic which overpass the pre-set threshold level. In the following figure, we present the logs of the Network Application output when this crossing of the threshold takes place.

2022-12-13 10:24:42	alarms	{'latencyP90':false,'latencyP99':true,'jitters':true,'packet_loss':true}
2022-12-13 10:24:42	jitters	4.864
2022-12-13 10:24:42	latencyP90	17.16
2022-12-13 10:24:42	latencyP99	61.58
2022-12-13 10:24:42	packet_loss	4.0

Figure 64: System logs for the functional test output related to the Alarm component of the Network Application of UC1 (PP-UC1-S9)

6.1.4.1. Analysis of the pre-piloting testing results for UC1

Pre-piloting tests have confirmed that the IR1101 provided in all the pilot's secondary substations is able to keep segregated the different types of traffic passing over its interfaces and there is also no evidence of excessive use of resources in terms of CPU and memory to respond to queries from the MEC server.

Brief conclusions are that the preliminary goals to be achieved during the pre-piloting tests, before we go to the actual pilots (readiness of the Network Application to be deployed in the actual pilot) were achieved.

6.2. UC2: Remote Inspection of Automatically Delimited Working Areas at Distribution Level

In a nutshell, the Spanish Demo (UC2: *Remote inspection of automatically delimited working areas at distribution level*), aims at developing an automated process to detect workers and their tools when accessing a primary power substation. This detection is carried out by ultra-wideband (UWB) cameras and sensors, which need fast and low latency processing capabilities. As the delimitation of the zones must be in real-time, a private 5G network with edge computing capabilities was used in the pre-piloting testbed. The Real-Time Location System (RTLS), developed as a use-case specific Network Application for the Spanish Demo is intended to monitor activity and create a 3D volumetric security zone, as well as to trigger audio-visual, electronic and physical warnings when required. The Network Application receives the information collected by the sensors and process it, verifying the data and evaluating them, to activate a danger alert signal in case the workers or their tools are in the danger zone. Part of the pre-piloting activities several preparatory steps, related to communication tests between sensors, relevant 5G network components, and functional tests of the Network Application were performed. The details of those activities are summarized in the sections that follow.

6.2.1. Phase 1: Pre-piloting testbed description and realistic conditions to replicate the UC operational environment

6.2.1.1. Introduction

For UC2, the pre-piloting phase has two major objectives:

- to provide a testing environment that is as similar as possible to the final pilot deployment in terms of HW setup and 5G network capacities.
- to create a testing environment that features the necessary elements to be able to deploy and validate functional blocks of UC2.

In this sense, the pre-piloting phase covered functional tests of parts of the UC pilot (e.g., validating that user equipment detect people and tools, validating that the Network Application can process data from the sensors, validating end-to-end connectivity of the 5G network, etc.). Also, the pre-piloting phase includes the execution of scenarios that cover sub-parts of the final pilot scenarios and their associated KPIs enabling the validation of those scenarios and the evaluation of the performance of the HW and SW setup.

6.2.1.2. Description of the pre-piloting testbed

The following figure shows the final setup that was replicated in different labs to execute the pre-piloting phase. It consists of the future indoor equipment including the servers and networking equipment, and the outdoor radio equipment including the remote radio unit (RRU). The Smart5Grid platform and the Network Application are deployed in the indoor equipment (MEC), whereas the sensors, cameras and alarms are connected to the Network Application over the CPEs connected to the 5G network. This traffic flow works in both directions, from the end devices (sensors, cameras) to the Network Application and vice-versa. The 5G-based pre-piloting testbed of UC2 is shown in Figure 65. In addition, a custom-built Wi-Fi node (user equipment) and access points are used for the evaluation of concurrent use of radio technology, i.e., when connection over 5G NR and Wi-Fi 6 is established by a user equipment in parallel. The details of this evaluation, including its specifics are shown in Section 6.2.4.

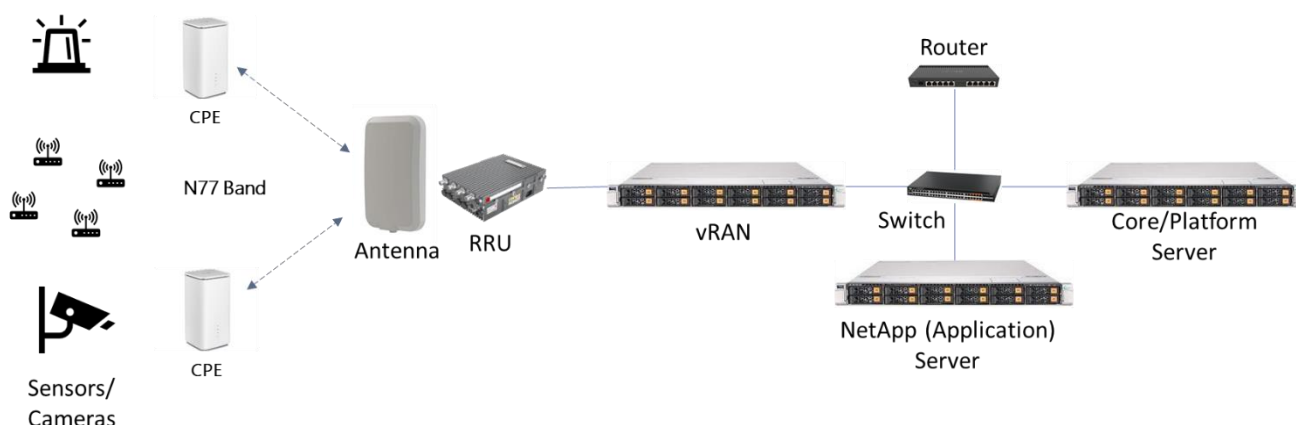


Figure 65: Pre-piloting testbed of UC2

Given all SW components to be deployed in UC2 are under development and need to be tested during the pre-piloting phase, the scope of the pre-pilot is to provide a suitable testbed in which the SW components can be deployed and integrated with the rest of the hardware, like sensors, servers and 5G radio. The development of said components is handled in different internal testbeds of participating partners, aligning with each other, and performing the first integration tests in the framework of the pre-pilot.

A key aspect for the pre-piloting phase is to maximize the similarity of the different pre-piloting labs deployment with the final deployment in the ECOGARRAF power substation (where the actual pilot of the UC2 will be executed). To achieve this, the 5G network, including the radio devices, the 5G core and the application servers, is deployed at i2CAT's lab, using the same HW as in the power substation.

The pre-piloting testbed of UC2 is shown in Figure 65. The identification of each component evaluated and tested in the pre-piloting phase, their corresponding description, and their role in the pre-piloting tests are detailed in Table 32.

Table 32: Description of each component of the pre-piloting testbed of UC2

Component Name	Component Description
UC2-C-ID-1: 5G Network	<p>The 5G network provides the 5G NR connectivity to the user equipment deployed in UC2. It also provides the computing resources at the edge, where the early version of the Network Application was deployed. Data between sensors and cameras and the Network Application was transferred over the 5G network. For the UC2, a share (slice) of the radio and computing resources was allocated so that the Network Application can be deployed and UEs obtain connectivity. In order to integrate with the Smart5Grid platform, an integration with the NAC is necessary.</p> <p>The 5G network has several physical components: RRUs, BBU, MEC, Network Switch and Server to host the 5G network management platform. We also connect a Wi-Fi node to the network, to be able to do concurrency tests with 5G NR in the pre-piloting phase.</p>
UC2-C-ID-2: Ultra-wide-band (UWB) Sensor (Anchor and tag)	<p>The anchors/sensors consist of UWB real-time positioning base stations (RTLS) within a defined secure area. The exact location is determined from the UWB signal exchange between the anchors and personal tags (which represent the current location of the worker inside the secure area) using the Time Difference of Arrival (TDOA) principle. The real-time position evaluation is collected with switch and further processed in the industrial PC.</p>
UC2-C-ID-3: Camera	<p>Camera modules Intel RealSense D455 are used to capture the environment of a defined protected area in real time. The acquired data is then evaluated by System on Module (SOM) processors with character detection and sent to the server for further processing.</p>

UC2-C-ID-4: Industrial PC	Data from anchors/sensors (wrist tags position) are collected via a switch and sent to an industrial personal computer (PC), where they are pre-synchronized and sent through a 5G modem to the server to evaluate. Based on evaluated data (inside the Network Application, according to the predefined safety zones) the information about turning the alarm and the vibration on/off is sent back from the server by the API to the industrial PC to proceed at the substation.
UC2-C-ID-5: Switch	Active element in the UWB RTLS network that collects and connects information from individual anchors/sensors (network ports, Ethernet communication) and sends it to the industrial PC for processing.
UC2-C-ID-6: Camera Sensor worker (SW)	The Network Application includes several camera sensor worker components, based on the amount of deployed camera sensors. The core functionality camera worker component is common for all cameras and specifically configured for each one. Each worker receives the coordinates of each detection from the corresponding camera and it manages to transform the 3D detection into 2D in order to pass the result to the Synchronization component.
UC2-C-ID-7: UWB Tag Sensor worker (SW)	Similarly, to the Camera worker, the UWB Tag Sensor worker is responsible for receiving the provided accumulated detections of the deployed UWB tags and passing them to Synchronization component.
UC2-C-ID-8: Synchronization component (SW)	The Synchronization is the main component of the UC2 Network Application. The component's role is that it can retrieve data from the Data Streaming component every 50 milliseconds and gather all the available sensor's information as it was stored by the worker components. The time interval is configurable based on the corresponding requirements and available resources of each Network Application. Based on the provided information it determines the position of the worker(s) and/or tools by correlating the normalized detections by the sensors. Once a spatial violation is detected, the Alarm component is triggered accordingly. Also, the results of the Synchronization component is transmitted, via the Data streaming, towards the KPI component for further KPI evaluation.
UC2-C-ID-9: Configuration component (SW)	The Configuration component exposes a simple web app for the administrators to be able to define basic configuration for the Network Application, such as active maintenance areas.
UC2-C-ID-10: Data Streaming component (SW)	The Data Streaming component acts as an intermediary data exchange layer for all the components to be able to communicate with each other.

6.2.1.3. Creation of the realistic operation conditions of the pilot

As mentioned before, the lab deployment at i2CAT intends to mimic the power substation as much as possible. As such, the 5G network HW is deployed, which allows us to test most of the functionalities of the UC2. The physical space is, however, not similar to the outdoor environment of the substation, which can impact the performance of the radio part of the 5G infrastructure. Further, in the substation tens of devices (sensors and cameras) will be deployed to enable the location of workers and objects. In the lab, no such deployment is done. In order to test the Network Application functionality, traces of real sensor and camera captures gathered in NOSIA's lab are fed to the Network Application, emulating information gathered in a real test environment. Further, a Wi-Fi node is connected to the 5G network to test whether the 5G and Wi-Fi connectivity can be used in parallel to achieve better performance.

6.2.2. Phase 2: Network Application integration

6.2.2.1. Network Application pre-piloting testbed integration

During the pre-piloting stage, UC2 aims to test a version of the application with as many features as possible. The version deployed and tested during pre-piloting is capable of receiving information from the sensors (real traffic or simulated) and calculating the results about the identified workers and/or tools. The KPI evaluation and alarm service, however, are to be tested in the actual electrical substation, with the real deployment.

The Network Application used in the pre-piloting phase includes the following services:

Network Application UC2 – Worker Detection and Tracking Service

Network Application UC2 – Worker Tools Detection and Tracking Service

Network Application UC2 – Administrative Network Application Configuration Service

Using traces of recordings and tracking done by the cameras and sensors, respectively, the overarching goal of this version of the Network Application is to validate the worker detection and the tracking that is featured in the use case. The key services listed above have been defined, that in an iterative manner start from the pure tracking and location service for workers and tools, to the administrative Network Application. The following diagram (Figure 66) shows the data flows of the UC and how the Network Application processes them.

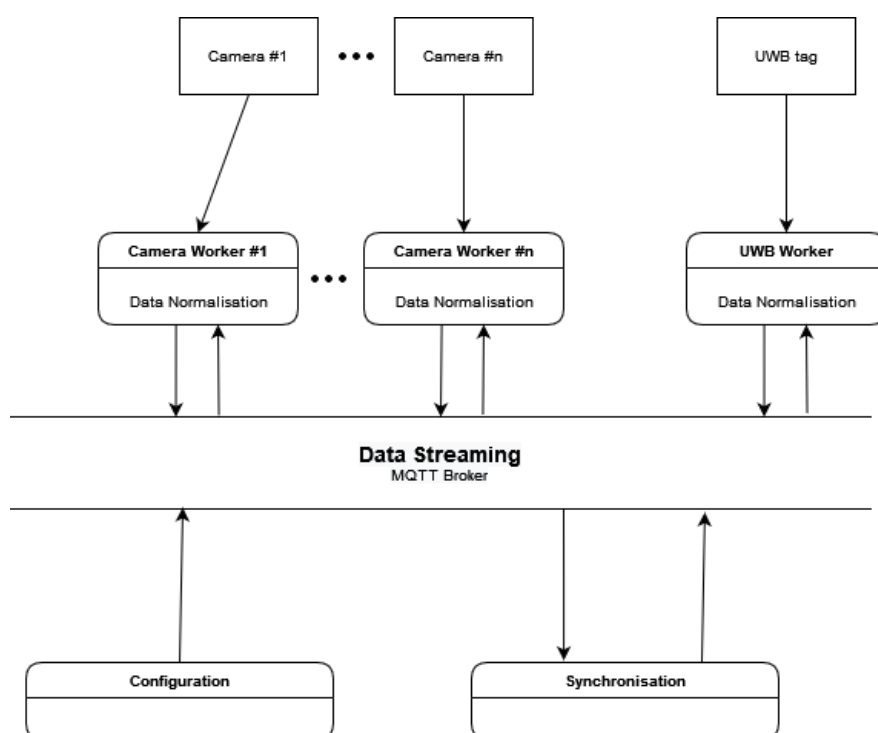


Figure 66: Diagram of the data flow in the UC2 specific Network Application

The Network Application in this first version is deployed in the Kubernetes cluster deployed in the MEC of the pre-piloting testbed, using Helm Charts.

From the perspective of the Network Application, a key functionality that was tested is the connectivity with the sensors. More specifically, we verified that the sensor API's is reachable from within the deployed Network Application components.

Several pre-conditions apply for the Network Application final integration, which is not part of the pre-pilot scope, and they are summarized as follows: (1) the 5G network needs to be operational, (2) the Network Application can be deployed in the 5G network, and (3) there is a simulated sensor feed to validate the Network Application functionality.

Other pre-conditions are:

1. Package the Network Application Helm Charts for NAC.
2. Access Network Application Administration Panel, via 5G.
3. Validate (emulated) sensor traffic over 5G and towards the Network Application.
4. The tests are done to validate the Network Application service functionality and the integration between sensors and Network Application and to extract some functional KPIs.

Any validation and functional checking need to be possible locally, but also remotely. As such, remote access to the deployment for the different developers of the Network Application and UC partners is provided. Over this remote access, trusted users can access the different software components (e.g., application pods) over ssh and is able to collect information generated by the services by accessing any available log files. As such, measurements taken by the services/Network Application have to be locally stored by the software for a latter evaluation. During live-testing or demos, the logs can also be shown as they are written to by the services, allowing for a live capture of outputs and events.

6.2.2.2. Network Application-NAC integration

The brief description of the Network Application flow is depicted in this section. First, the coordinates of the safe zones must be set in the configuration web app to begin the process and calculate alarm responses based on these values. Then, those values are published in a MQTT broker which is responsible for sending the coordinates to the synchronisation app. After that, the camera and UWB workers have the capability to establish socket connections to exchange messages and calculate the exact position of workers in the substation area. After calculations, data is sent to the synchronisation app which decides, based on the safe zones, if it must send an alarm activation/deactivation to the camera or UWB. Finally, with our simulation apps, the observation of the alarm responses to open/close the alarm can be observed, to complete the flow from the data received to the alarm activation.

Encapsulate Kubernetes files in Helm-chart

The Network Application deployment on Kubernetes consists of two Helm Charts. A successful Helm Chart installation occurs when all of the necessary resources specified in the chart are properly deployed and configured in the target Kubernetes cluster. The two main Helm Charts are:

1. uc2-main-components-helm-chart
2. uc2-sensors-helm-chart

```
$ helm install main uc2-main-components-helm-chart
NAME: main
LAST DEPLOYED: Fri Dec 9 16:00:19 2022
NAMESPACE: default
STATUS: deployed
REVISION: 1
NOTES:
1. Get the application URL by running these commands:
  export POD_NAME=$(kubectl get pods --namespace default -l "app.kubernetes.io/name=uc2
-main-components-helm-chart,app.kubernetes.io/instance=main" -o jsonpath="{.items[0].me
tadata.name}")
  export CONTAINER_PORT=$(kubectl get pod --namespace default $POD_NAME -o jsonpath="{.
spec.containers[0].ports[0].containerPort}")
  echo "Visit http://127.0.0.1:8080 to use your application"
  kubectl --namespace default port-forward $POD_NAME 8080:$CONTAINER_PORT

$ helm install sensors uc2-sensors-helm-chart
NAME: sensors
LAST DEPLOYED: Tue Dec 20 11:16:28 2022
NAMESPACE: default
STATUS: deployed
REVISION: 1
NOTES:
1. Get the application URL by running these commands:
  export POD_NAME=$(kubectl get pods --namespace default -l "app.kubernetes.io/name=uc2-sensors-helm-chart,app.kubernetes.io/instance=uc2-sensors-helm-chart" -o jsonpath="{.items[0].metadata.name}")
  export CONTAINER_PORT=$(kubectl get pod --namespace default $POD_NAME -o jsonpath="{.spec.containers[0].ports[0].containerPort}")
  echo "Visit http://127.0.0.1:8080 to use your application"
  kubectl --namespace default port-forward $POD_NAME 8080:$CONTAINER_PORT
```

Figure 67: Installation of main and sensors Helm Chart to Kubernetes cluster (top). Kubernetes resources created from the yaml manifests that are applied (bottom)

Kubernetes deployment

In the locally deployed Kubernetes, each containerized application is represented by a Docker image. This image includes all of the code, libraries, and dependencies that are needed to run the application. All the images are stored in a repository that is accessible to the cluster.

In the **main Helm Chart**, we deploy 3 containerized applications:

- Configuration → Set safe zones coordinates.

- Synchronisation → Decides if the worker is in danger.
- MQTT Broker → Data streaming

The core of the Network Application is the central component that provides the core functionality of the application and takes all the important decisions for alarm activation and data streaming.

Deployments				
Name	Images	Labels	Pods	Created ↑
configuration	uc2_netapp/configuration	app: configuration app.kubernetes.io/managed-by: Helm	1 / 1	3 minutes ago
mqttbroker-depl	hivemq/hivemq-ce	app: mqttbroker app.kubernetes.io/managed-by: Helm	1 / 1	3 minutes ago
synchronisation	uc2_netapp/synchronisation	app: synchronisation app.kubernetes.io/managed-by: Helm	1 / 1	3 minutes ago

Figure 68: Deployments of the main Helm Chart

In the **sensors Helm Chart**, we deploy the workers who are responsible for socket connection and the communication between the cluster, camera, and UWB tags. For the purpose of the simulation, we have created sockets for the camera and UWB data respectively.

worker1	uc2_netapp/cameraworker	app: worker1 app.kubernetes.io/managed-by: Helm	1 / 1	a minute ago
worker2	uc2_netapp/cameraworker	app: worker2 app.kubernetes.io/managed-by: Helm	1 / 1	a minute ago
worker3	uc2_netapp/cameraworker	app: worker3 app.kubernetes.io/managed-by: Helm	1 / 1	a minute ago
worker4	uc2_netapp/cameraworker	app: worker4 app.kubernetes.io/managed-by: Helm	1 / 1	a minute ago
worker5	uc2_netapp/cameraworker	app: worker5 app.kubernetes.io/managed-by: Helm	1 / 1	a minute ago
worker6	uc2_netapp/cameraworker	app: worker6 app.kubernetes.io/managed-by: Helm	1 / 1	a minute ago

Figure 69: Deployments of sensors Helm Chart- camera workers

camerawebsocket1	uc2_netapp/websocket-echo-server	app.kubernetes.io/managed-by: Helm	1 / 1	4 minutes ago
camerawebsocket2	uc2_netapp/websocket-echo-server	app.kubernetes.io/managed-by: Helm	1 / 1	4 minutes ago
camerawebsocket3	uc2_netapp/websocket-echo-server	app.kubernetes.io/managed-by: Helm	1 / 1	4 minutes ago
camerawebsocket4	uc2_netapp/websocket-echo-server	app.kubernetes.io/managed-by: Helm	1 / 1	4 minutes ago
camerawebsocket5	uc2_netapp/websocket-echo-server	app.kubernetes.io/managed-by: Helm	1 / 1	4 minutes ago
camerawebsocket6	uc2_netapp/websocket-echo-server	app.kubernetes.io/managed-by: Helm	1 / 1	4 minutes ago

Figure 70: Deployments of sensors Helm Chart - simulation camera sockets

uwbtagserver9010	uc2_netapp/tag-server	app: uwbtagserver9010 app.kubernetes.io/managed-by: Helm	1 / 1	2 minutes ago	⋮
uwbtalarm9011	uc2_netapp/tag-alarm-activation	app: uwbtalarm9011 app.kubernetes.io/managed-by: Helm	1 / 1	2 minutes ago	⋮
uwbsocket1	uc2_netapp/uwb-tag-worker	app: uwbsocket1 app.kubernetes.io/managed-by: Helm	1 / 1	2 minutes ago	⋮

Figure 71: Deployments of sensors Helm Chart - UWB deployments

We also have our Kubernetes services to achieve communication between our pods. Also, with services, we can expose our application and receive traffic based on the application needs. We have used two types of services to cover our needs and all of them can be observed at the figure below:

- **ClusterIP Type:** Service only reachable from within the cluster.
- **NodePort Type:** Exposes the service on each Node's IP at a static port.

Name	Labels	Type	Cluster IP	Internal Endpoints	External Endpoints	Created ↑
configuration	app.kubernetes.io/managed-by: Helm	NodePort	10.102.220.66	configuration:8020 TCP configuration:30079 TCP	-	8 minutes ago ⋮
mqttbroker-svc	app.kubernetes.io/managed-by: Helm	ClusterIP	10.106.207.76	mqttbroker-svc:1883 TCP mqttbroker-svc:0 TCP	-	8 minutes ago ⋮
camerawebsocket2	app.kubernetes.io/managed-by: Helm	NodePort	10.108.84.163	camerawebsocket2:80 TCP camerawebsocket2:32081 TCP	-	9 minutes ago ⋮
camerawebsocket4	app.kubernetes.io/managed-by: Helm	NodePort	10.98.8.168	camerawebsocket4:80 TCP camerawebsocket4:32083 TCP	-	9 minutes ago ⋮
camerawebsocket5	app.kubernetes.io/managed-by: Helm	NodePort	10.109.187.100	camerawebsocket5:80 TCP camerawebsocket5:32084 TCP	-	9 minutes ago ⋮
camerawebsocket6	app.kubernetes.io/managed-by: Helm	NodePort	10.105.237.192	camerawebsocket6:80 TCP camerawebsocket6:32085 TCP	-	9 minutes ago ⋮
camerawebsocket1	app.kubernetes.io/managed-by: Helm	NodePort	10.106.188.13	camerawebsocket1:80 TCP camerawebsocket1:32080 TCP	-	9 minutes ago ⋮
camerawebsocket3	app.kubernetes.io/managed-by: Helm	NodePort	10.101.130.100	camerawebsocket3:80 TCP camerawebsocket3:32082 TCP	-	9 minutes ago ⋮
uwbsocket1	app.kubernetes.io/managed-by: Helm	NodePort	10.108.253.196	uwbsocket1:9015 UDP uwbsocket1:31258 UDP	-	9 minutes ago ⋮
uwbtalarm9011	app.kubernetes.io/managed-by: Helm	ClusterIP	10.96.93.35	uwbtalarm9011:9011 UDP uwbtalarm9011:0 UDP	-	9 minutes ago ⋮

Figure 72: Kubernetes services of our app

6.2.3. Phase 3: Defining the testing scenarios

The pre-piloting testing scenarios of UC2 can be clustered in 3 categories:

- **Physical setup/connectivity:** The baseline to be able to deploy a Network Application and to execute the pilot is to have an operational 5G network on top of which Network Applications can be deployed. To assure this baseline the 5G network connection between user equipment and the core, but also any end-user devices (e.g., laptops) connected to the 5G network are tested and validated, as specified below.
- **Communications:** UC2 features a series of physical devices that rely on 5G customer premises equipment (CPEs) to reach the Network Application deployed in the MEC. Information flows in both directions: sensor data is reported to the Network Application and notifications/alerts are sent from the Network Application to physical devices. Testing the different communication flows and

assuring that connectivity between all components is guaranteed, is key before moving to the actual pilot.

- **Network Application functionality:** The Network Application developed in UC2 implements a series of features to assure safety for workers in the substation. The process of detecting workers and tools, determining their positions and detecting when they are exposed to danger are all functionalities that need to be tested and validated.

Having identified these 3 main categories, testing scenarios have been designed for the pre-piloting phase to validate the key functionalities that will be demonstrated in UC2 during the pilot. Table 33 lists these testing scenarios. Note that Scenario ID PP-UC2-S4 and below were all tested using simulated or captured traces from the sensors and cameras, rather than real live streams.

Table 33: Definition of the testing scenarios for the pre-piloting of UC2

Scenario ID	Scenario Title	Testcase type	Description
PP - UC2 - S1	End-to-end connectivity	Network component	We set up the entire 5G network, and test that the end user equipment has connectivity.
PP – UC2 - S2	Testing zone	S/W testing environment	Preparation of the testing zone (physical environment) for UC2 Network Application testing.
PP – UC2 – S3	Sensor tracking validation	Network Application functionality	Validate that the Network Application can receive and process sensor readings.
PP – UC2 - S4	No worker present	Camera/sensors functionality	Nobody is present in the detection area, which means that no data is sent to the Network Application. As such, no further action is taken.
PP - UC2 – S5	Present in the detection area, inside the safety zone	Camera/sensors functionality, communication with Network Application	A worker (wearing the wrist tag) is present in the detection area, moving inside the safety zone. At this moment, the device is continuously sending the worker's position to the Network Application, instructing it to not take any further action as the worker is inside the safety area.
PP – UC2 – S6	Present in the detection area, outside the safety zone	Camera/sensors functionality, communication with Network Application	A worker is present in the detection area, moving outside the safety zone. At this point the system is continuously sending the worker's position to the Network Application that detects

			the worker is outside the safety zone.
PP – UC2 – S7	Present in the detection area, from outside to inside the safety zone	Camera/sensors functionality, communication with Network Application	A worker is present in the detection area, returned from warning to safety zone and moving. The system is continuously sending the worker's position to the Network Application. The return to the safety area is detected by the Network Application.
PP – UC2 – S8	Present in the detection area, not moving	Camera/sensors functionality, communication with Network Application	A worker is present in the detection area, but not moving. The Network Application detects this situation and is=f the immobilization is preceded by the worker's fall (rapid change in the vertical position of the wrist tag), then the sensors send information to the Network Application as well.
PP – UC2 – S9	Present in the detection area, pressing SOS button	Wrist tag functionality, communication with Network Application	A worker is present in the detection area and presses the SOS button on his wrist tag. This information (together with his coordinates) is sent to Network Application to take an action.
PP – UC2 – S10	Simultaneous use of 5G and Wi-Fi	Validating achievable performance with multi-path TCP (MPTCP)	While not to be used in the pilot, the validation of MPTCP over a combination of 5G and Wi-Fi is performed to evaluate possible performance gains.

To validate functional aspects, the following set of scenarios along with the targeted KPIs have been defined (Table 34).

Table 34: KPIs related to the testing scenarios of the UC2

Scenario ID	Functional requirements	Targeted KPIs
PP – UC2 – S1	The 5G base station is radiating and user equipment, such as CPEs can connect to the 5G network. Devices attached to the CPEs have connectivity with the edge.	KPI 1: Key functions of 5G network fully operational.
PP – UC2 – S2	The 5G HW and the physical space need to be set up so that the subsequent scenarios can be validated.	KPI 2: Testing environment configured, set up and ready for testing.

PP – UC2 – S3	We can send data over the 5G network from user equipment to the server.	KPI 3: end-to-end connectivity.
PP – UC2 – S4	The detection area is active (cameras + sensors). No worker is present inside the detection area.	KPI 4: Sensors are connected, but no data about coordinates or detection is forwarded.
PP – UC2 – S5	The detection area is active (cameras + sensors). A worker is present inside the detection area. The worker is moving inside the safety area. The worker is wearing his personal wrist tag.	KPI 5: Cameras – coordinates and detection data are sent to server and received by Network Application. KPI 6: Sensors – coordinates and detection data are sent to server and received by Network Application.
PP – UC2 – S6	A worker present in the detection area is active (cameras + sensors). A worker is present inside the detection area. The worker is moving outside the safety area. The worker is wearing his personal wrist tag.	KPI 5: Cameras – coordinates and detection data are sent to server and received by Network Application. KPI 6: Sensors – coordinates and detection data are sent to server and received by Network Application. KPI 7: Network Application sends back the order to take the warning action (turn on the alarm beacon).
PP – UC2 – S7	The detection area is active (cameras + sensors). A worker is present inside the detection area. The worker is moving from outside to inside the safety area. The worker is wearing his personal wrist tag.	KPI 5: Cameras – coordinates and detection data are sent to server and received by Network Application. KPI 6: Sensors – coordinates and detection data are sent to server and received by Network Application. KPI 8: Network Application sends back the order to cancel the warning action (stop buzzing the wrist tag and turn off the alarm beacon).
PP – UC2 – S8	The detection area is active (cameras + sensors). A worker is present inside the detection area.	KPI 5: Cameras – coordinates and detection data are sent to server and

	<p>The worker is not moving.</p> <p>The worker is wearing his personal wrist tag.</p>	<p>received by Network Application.</p> <p>KPI 6: Sensors – coordinates and detection data are sent to server and received by Network Application.</p> <p>KPI 7: Network Application sends back the order to take the warning action (turn on the alarm beacon).</p> <p>KPI 9: Sensors – sending additional signals to server (and received by Network Application) when worker's immobilization is preceded by the worker's fall.</p>
PP – UC2 - S9	<p>The detection area is active (cameras + sensors).</p> <p>A worker is present inside the detection area.</p> <p>The worker is wearing his personal wrist tag.</p> <p>The worker presses the SOS button on his personal wrist tag.</p>	<p>KPI 5: Cameras – coordinates and detection data are sent to server and received by Network Application.</p> <p>KPI 6: Sensors – coordinates and detection data are sent to server and received by Network Application.</p> <p>KPI 8: Network Application sends back the order to take the warning action (turn on the alarm beacon).</p> <p>KPI 10: Sensors (wrist tag) – sending additional signal to server (and received by Network Application) when pressing the SOS button.</p>
PP – UC2 – S10	<p>When both 5G and Wi-Fi form part of a slice and MPTCP is enabled, both technologies are used in parallel, leading to a variety of benefits, such as a higher aggregate throughput, traffic redundancy, etc.</p>	<p>KPI 11: MPTCP allows to use 5G and Wi-Fi in a combined form to connect UEs with the services in the MEC.</p>

Table 35: Description of the pre-piloting testing KPIs for UC2

KPI Name	Brief description of each KPI
S1 KPI 1: 5G network fully operational	The 5G network and all of its components is fully operational, UEs can see the network radiating and connect to it.

S2 KPI 2: Physical testbed setup operational	The testbed environment is operational, with HW in place.
S3 KPI 3: end-to-end connectivity.	Connectivity between UEs, as well as devices behind the UEs, and the 5G core and the applications is feasible, and data can be exchanged between the two endpoints.
S5-S9 KPI 4: Cameras' function	Data about worker detection are kept receiving to Network Application.
S5-S9 KPI 5: Sensors' function	Data about worker coordinates are kept receiving to Network Application.
S6+S8+S9 KPI 6: Warning feedback	Network Application receives signal to take a warning action.
S7 KPI 7: Cancel warning feedback	Network Application receives signal to cancel a warning action.
S8 KPI 8: Detect Fall	Check the detection of a fall (worker).
S9 KPI 9: end-to-end delay	Network Application receives an additional signal when a worker presses the SOS button.
S10 KPI 10: Dual connectivity	End-to-end connection between UEs and applications can go over 5G NR and Wi-Fi in parallel.

6.2.4. Phase 4: Validation and evaluation

This section summarizes the outcomes of the tests done during the pre-piloting phase of UC2. Table 37 lists the KPIs measured and any relevant comments for each experiment. Note that for UC2, all KPIs as per definition are functional validations, i.e., the scenarios are used to validate whether a sub-function of the overall use case scenario is operational or not. In addition to the outcomes shown in the table, a few screenshots, pictures and extracted logs for some of the tests are shown in the following paragraphs.

For the validation of the 5G network (PP-UC2-S1) and the physical space preparation (PP-UC2-S2), end-to-end connectivity tests were done, and some pictures of the deployed hardware were taken. The physical setup in which the end-to-end connectivity tests were done is shown in Figure 73 (picture taken on the first day of testing).

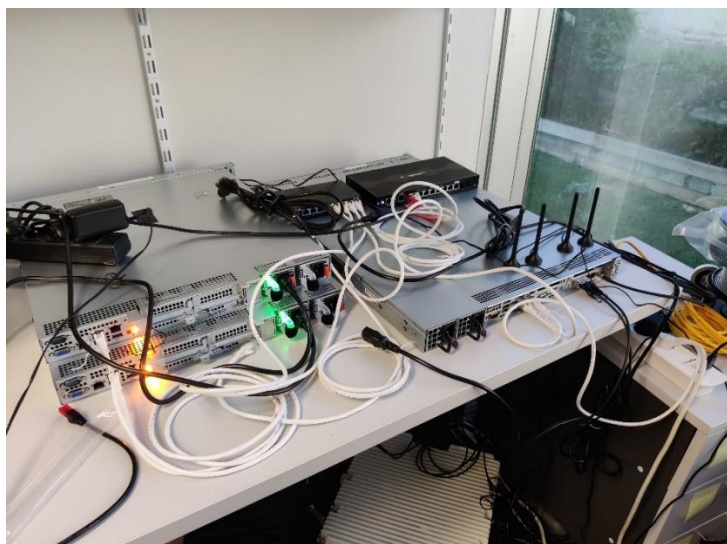


Figure 73: UC2 Pre-piloting 5G network setup with network equipment (very top), servers (on top of the table) and RRU (white element below table).

A set of outdoor and indoor CPEs from Mulesight were tested with the 5G network with a laptop connected to them, but also using a Smartphone, as such allowing for the end-to-end communication tests. The upload and download speed for TCP with different devices was tested, as well as the average round-trip time (RTT) towards the 5G core. To measure these values, the iperf and ping tools were used. The following tables gather the outcomes of these evaluations, taking the average over the course of at least 60 seconds of performance tests and with 3 or more repetitions.

Table 36: Results for TCP upload and download speed for different user-equipment of UC2

Device	Upload (Mbps)	Download (Mbps)	RTT (ms)
Cell phone (2x2 MIMO)	33.9	136	23.11
CPE (4x4 MIMO)	27.3	286	26.86

Note that in this setup, basic indoor antennas have been used that will be replaced by a large directional outdoor antenna with better specifications and better coverage in the pilot setup. The measured throughput showed that the required throughput to transmit the data generated by sensors and cameras can be delivered and that the RTT is below 30ms. Higher upload throughput than the one listed in the table could be achieved when re-distributing the antennas and the CPE/cell phone when compared to the reference setup shown above (peak of 44.9Mbps). Even though the expected carried upload traffic is only expected to be around 10Mbps, knowing that there is some margin between the required and delivered throughput is important to prepare for cases where the throughput could be lower due to meteorological conditions on the field.

In order to test the correct detection of workers, a dedicated setup with cameras and sensors was done. The detection system uses the positioning implemented by UWB and also the image processing and person detection from the cameras. The implementation of both detection systems was tested thoroughly

and evaluated by validating the outputs generated of the system once items or persons are detected by the system. In the following, a sample of the logs obtained by the system is shown, in particular, the detections of the anchors and also of the cameras:

```

RTLS (anchors): {"type":"location","tag":"00D010","timestamp":"2022-11-29
08:40:54.891","x":2.6431612662099364,"y":4.6268488695215435,"z":0.7384317686266219}

Cameras: {"action": "detection", "timestamp": 1669729256248, "data": {"camera": {"name": "Camera
c86314713c8b", "fps": 5, "width": 640, "height": 480, "rotation": {"x": -2.08, "y": 179.95, "z": -29.74}}, "detections":
[{"label": "person", "confidence": 0.9995604157447815, "position": {"x": 0.3240959346294403, "y": -
0.07330204546451569, "z": 2.820000171661377}, "width": 0.3978138715028763, "height": 0.9883922934532166,
"depth": 0.5990000284509733, "rect": {"left": 327, "top": 159, "width": 78, "height": 137}}, {"label": "person",
"confidence": 0.4367839992046356, "position": {"x": 0.7077818512916565, "y": 0.015469003468751907, "z":
1.1510000228881836}, "width": 0.23059839010238647, "height": 1.470870554447174, "depth":
0.9060000430326909, "rect": {"left": 484, "top": 0, "width": 145, "height": 485}}]}

```

Figure 74: Sample of logs for detection of workers using anchors and cameras in UC2

These logs outputs validate the detection of the worker, in order to validate that the location detected is correct, the produced values of x, y and z axis were compared to the actual physical location of the worker, showing that the position is correctly calculated. Furthermore, a testing procedure was implemented to correctly detect whenever a worker presses the SOS button. This is a functionality implemented by the UWB system and when a button press is detected, it registers, the tag ID, the timestamp and the coordinates of the incident, as shown in the following snippet taken from the logs:

```

RTLS (anchors): {"type":"sos","tag":"00D010","timestamp":"2022-11-29
08:41:57.991","x":2.76,"y":2.30,"z":1.43}

```

Figure 75: Sample of logs for detection when a worker presses the SOS button

Similarly, the sensors can detect when a person falls, which looks as follows in the logs that were captured in the validation process:

```

RTLS (anchors): {"type":"location","tag":"00D010","timestamp":"2022-11-29
08:41:51.091","x":2.667851567429219,"y":2.4499014210784877,"z":-0.787962337598668}

```

Figure 76: Sample of logs for sensors to detect when a person falls

A collection of log entries could be as shown in the following two figures. Figure 77 shows a log snippet of the RTLS detection system, whereas Figure 78 shows a log snippet of the camera detection system.

```

{"type":"location","tag":"00D010","timestamp":"2022-11-29 08:40:54.891","x":2.6431612662099364,"y":4.6268488695215435,"z":0.7384317686266219}
{"type":"location","tag":"00D010","timestamp":"2022-11-29 08:40:54.991","x":2.642272343727989,"y":4.624923022822999,"z":0.7276250662217976}
{"type":"location","tag":"00D010","timestamp":"2022-11-29 08:40:55.090","x":2.6416333790561204,"y":4.620726789540182,"z":0.7114213638169624}
{"type":"location","tag":"00D010","timestamp":"2022-11-29 08:40:55.191","x":2.641174086080425,"y":4.61208666491718,"z":0.6772786586735704}
{"type":"location","tag":"00D010","timestamp":"2022-11-29 08:40:55.291","x":2.638032023478773,"y":4.605876073435066,"z":0.6527366059842711}
{"type":"location","tag":"00D010","timestamp":"2022-11-29 08:40:55.391","x":2.6357734834597863,"y":4.601411850030811,"z":0.6350955799532416}
{"type":"location","tag":"00D010","timestamp":"2022-11-29 08:40:55.491","x":2.634150026621376,"y":4.598202930129944,"z":0.6224150677170688}
{"type":"location","tag":"00D010","timestamp":"2022-11-29 08:40:55.590","x":2.6329830727113173,"y":4.579024817974555,"z":0.6076763747401678}
{"type":"location","tag":"00D010","timestamp":"2022-11-29 08:40:55.690","x":2.6321442567995033,"y":4.556803678511958,"z":0.5970820829846852}
{"type":"location","tag":"00D010","timestamp":"2022-11-29 08:40:55.791","x":2.6315413091356348,"y":4.521147510022057,"z":0.5894668203575181}

```

Figure 77: UWB worker detection logs: structure of the RTLS data file

```
{
  "action": "detection",
  "timestamp": 1669729304662,
  "data": {
    "camera": {
      "name": "Camera c86314724d7d",
      "fps": 10,
      "width": 640,
      "height": 480,
      "rotation": {
        "x": -1.46,
        "y": 180.0,
        "z": -23.
      }
    }
  }
},
{
  "action": "detection",
  "timestamp": 1669729304663,
  "data": {
    "camera": {
      "name": "Camera c86314725319",
      "fps": 11,
      "width": 640,
      "height": 480,
      "rotation": {
        "x": -1.63,
        "y": 180.01,
        "z": -31
      }
    }
  }
},
{
  "action": "detection",
  "timestamp": 1669729304692,
  "data": {
    "camera": {
      "name": "Camera c86314724d5b",
      "fps": 8,
      "width": 640,
      "height": 480,
      "rotation": {
        "x": 5.34,
        "y": 180.0,
        "z": -23.2:
      }
    }
  }
},
{
  "action": "detection",
  "timestamp": 1669729304764,
  "data": {
    "camera": {
      "name": "Camera c86314725319",
      "fps": 10,
      "width": 640,
      "height": 480,
      "rotation": {
        "x": -1.77,
        "y": 180.0,
        "z": -31.
      }
    }
  }
},
{
  "action": "detection",
  "timestamp": 1669729304766,
  "data": {
    "camera": {
      "name": "Camera c86314724d21",
      "fps": 6,
      "width": 640,
      "height": 480,
      "rotation": {
        "x": -7.98,
        "y": 180.0,
        "z": -35.8
      }
    }
  }
},
{
  "action": "detection",
  "timestamp": 1669729304772,
  "data": {
    "camera": {
      "name": "Camera c86314724d7d",
      "fps": 10,
      "width": 640,
      "height": 480,
      "rotation": {
        "x": -1.38,
        "y": 179.97,
        "z": -2:
      }
    }
  }
},
{
  "action": "detection",
  "timestamp": 1669729304805,
  "data": {
    "camera": {
      "name": "Camera c86314724d5b",
      "fps": 9,
      "width": 640,
      "height": 480,
      "rotation": {
        "x": 5.3,
        "y": 179.96,
        "z": -23.11
      }
    }
  }
}
```

Figure 78: Camera-based worker detection logs.

For the validation of the MPTCP feature (PP-UC2-S10), a dedicated setup was created, based on the same 5G network to be used in the pilot, along with an Atheros 11k chipset (Wi-Fi6) mounted on a Gateworks Venice single-board computer, to which also a 5G modem (Quectel) was connected. A non-mainstream version of the MPTCP kernel module was used (out-of-tree), as it allows for automatic MPTCP stream creation, without the additional need of the traffic originating applications to specifically request for a MPTCP session. This specific configuration of the radio node to enable the MPTCP connection over the two technologies was implemented in the 5G CLARITY project and brought to the Smart5Grid deployment to be validated.

The radio node was placed close (<3m) to assure good connectivity both with Wi-Fi6 and 5G NR. With this setup it was tested whether the radio node equipped with both the Wi-Fi transceiver and a 5G transceiver can simultaneously send data up to saturation of the radio channel to a virtual machine instantiated in the application server where the Network Applications run. This connection was successfully tested, and the throughput results were obtained, as shown in Figure 79, a series of data captured over the course of 60s.

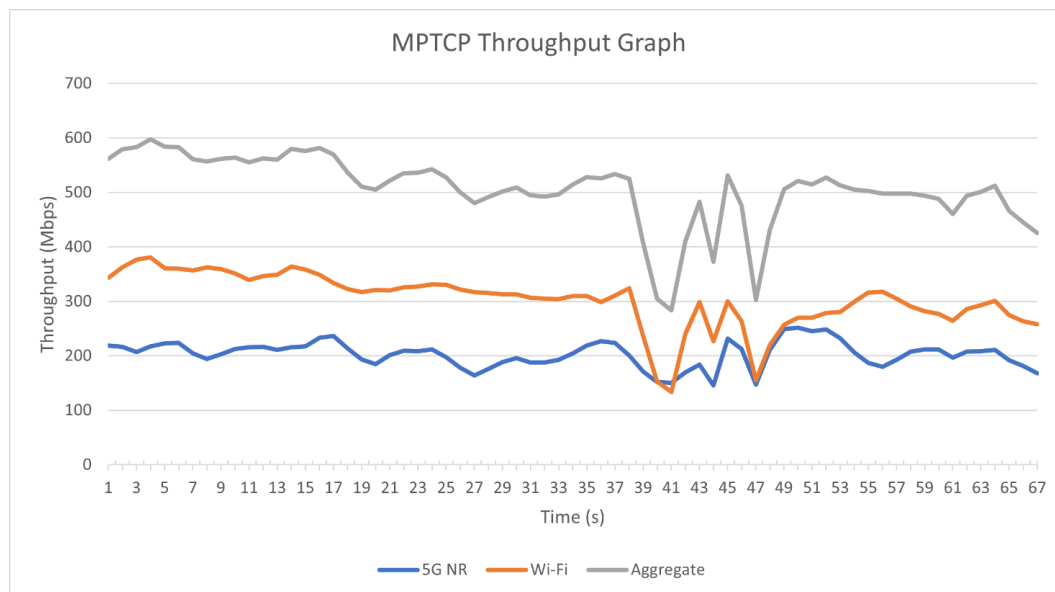


Figure 79: Throughput results for MPTCP evaluations

Overall aggregate throughput of up to 600Mbps is observed. It should be noted that in good link conditions, the Wi-Fi 6 transceiver can outperform the 5G NR. This, however, can change quickly when the link quality deteriorates (can happen for example by simply moving away from the Wi-Fi access point a few meters) or when there are many users, since in Wi-Fi the users compete for channel access.

Independently from the throughput observed, the overall outcome is that MPTCP is supported in the pre-piloting testbed.

Network Application Simulation Tests:

The testing that was performed consists of traces of data from the cameras and the UWB that simulate the real scenario that will be performed in the substation. The results of those tests have shown that the NetApp is ready and can alert properly.

Camera Simulation:

We simulated the socket connection between the worker and the camera to send JSON data with 1 sec delay in order to observe the behaviour of the application. As shown in the figures below, worker1 received the data, calculated the exact position in the substation and published the results to the synchronisation app.

```
$ k logs worker1-85685f75fd-rf9rh
defaulted container "worker1" out of: worker1, wait-mqttbroker-svc (init)
{"action": "init", "data": {"confidence": 0, "model": "people", "device": "Camera d53b65871ee0", "frame_width": 640, "frame_height": 480, "readonl
y": True}}
{"action": "detection", "data": {"camera": {"name": "Camera d53b65871ee0", "fps": 11, "width": 640, "height": 480, "rotation": {"x": -1.39, "y": 1
80.0, "z": -35.79}}, "detections": []}}
{"action": "detection", "data": {"camera": {"name": "Camera d53b65871ee0", "fps": 11, "width": 640, "height": 480, "rotation": {"x": -1.51, "y": 1
81.93, "z": -31.54}}, "detections": [{"label": "person", "confidence": 0.39750421047210693, "position": {"x": 0.0, "y": 0.0, "z": 0.0}, "width": 0
0.0, "height": 0.0, "depth": 0.0, "rect": {"left": 455, "top": 166, "width": 104, "height": 238}}]}}
{"action": "detection", "data": {"camera": {"name": "Camera d53b65871ee0", "fps": 11, "width": 640, "height": 480, "rotation": {"x": 8.05, "y": 18
0.0, "z": -37.15}}, "detections": [{"label": "person", "confidence": 0.7234624028205872, "position": {"x": 0.0, "y": 0.0, "z": 0.0}, "width": 0.0,
"height": 0.0, "depth": 0.0, "rect": {"left": 456, "top": 166, "width": 104, "height": 238}}]}}
{"action": "detection", "data": {"camera": {"name": "Camera d53b65871ee0", "fps": 11, "width": 640, "height": 480, "rotation": {"x": -1.39, "y": 1
82.25, "z": -31.48}}, "detections": [{"label": "person", "confidence": 0.8387044072151184, "position": {"x": 0.0, "y": 0.0, "z": 0.0}, "width": 0
0.0, "height": 0.0, "depth": 0.0, "rect": {"left": 457, "top": 166, "width": 104, "height": 238}}]}}
```

Figure 80: Data received in worker pod

After that, the Synchronisation app with the input data from the worker component and based on the safe zones, can decide whether to send an alarm activation/deactivation (1,0). The alarm message was sent because the state changed.

```
camera/d53b65871ee0
{"action": "alarm", "data": {"state": 1}}
camera/d53b65871ee0
Status changed and published: 0
{"action": "alarm", "data": {"state": 0}}
camera/d53b65871ee0
Status changed and published: 1
{"action": "alarm", "data": {"state": 1}}
camera/d53b65871ee0
{"action": "alarm", "data": {"state": 1}}
camera/d53b65871ee0
{"action": "alarm", "data": {"state": 1}}
camera/d53b65871ee0
{"action": "alarm", "data": {"state": 1}}
```

Figure 81: Data received in Synchronisation pod - camera

Eventually, the final results that the camera received from our simulation app can be observed in the figure below.

```
$ k logs camerawebsocket3-75685f75fd-1wb7p
Received message from client: {"action": "alarm", "data": {"state": 1}}
Received message from client: {"action": "alarm", "data": {"state": 0}}
Received message from client: {"action": "alarm", "data": {"state": 1}}
```

Figure 82: Data received from the camera socket pod - alarm activation/deactivation

UWB Simulation:

The exact same simulation was held for the UWB with the difference that the exact position was known, and the data can be sent directly to the synchronisation app.

```
$ k logs uwbtagserver9010-85b6f58667-7t9d1
0/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:34.721", "x": 3.7890574331023665, "y": 0.7014481938536942, "z": 0.7014481938536942}
1/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:34.821", "x": 3.7836986370985195, "y": 0.7038528925534792, "z": 0.7038528925534792}
2/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:34.922", "x": 3.7798466911755093, "y": 0.702769490339344, "z": 0.702769490339344}
3/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:35.021", "x": 3.7517706094285797, "y": 0.7019907320625366, "z": 0.7019907320625366}
4/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:35.122", "x": 3.731589294718794, "y": 0.6789356015541855, "z": 0.6789356015541855}
5/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:35.221", "x": 3.717082802428075, "y": 0.6342441962687664, "z": 0.6342441962687664}
6/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:35.321", "x": 3.7066554184044445, "y": 0.5880600570988973, "z": 0.5880600570988973}
7/2272
{"type": "location", "tag": "00D003", "timestamp": "2022-11-21 08:06:34.421", "x": 2.724044228145081, "y": 3.509300160575734, "z": 3.509300160575734}
8/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:35.421", "x": 3.699160130405303, "y": 0.5548625242099069, "z": 0.5548625242099069}
9/2272
{"type": "location", "tag": "00D003", "timestamp": "2022-11-21 08:06:35.520", "x": 2.736966619384606, "y": 3.534804221612999, "z": 3.534804221612999}
10/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:35.520", "x": 3.693772456750745, "y": 0.5309998689840063, "z": 0.5309998689840063}
11/2272
{"type": "location", "tag": "00D003", "timestamp": "2022-11-21 08:06:35.621", "x": 2.757503015135649, "y": 3.558760585217299, "z": 3.558760585217299}
12/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:35.621", "x": 3.675840157864754, "y": 0.5138471993463464, "z": 0.5138471993463464}
13/2272
{"type": "location", "tag": "00D003", "timestamp": "2022-11-21 08:06:35.721", "x": 2.7722647425516134, "y": 3.575980613195502, "z": 3.575980613195502}
14/2272
{"type": "location", "tag": "00D010", "timestamp": "2022-11-21 08:06:35.721", "x": 3.6601383572490835, "y": 0.5015177216367845, "z": 0.5015177216367845}
```

Figure 83: Data received in UWB socket

```
UWB/00D010
{"type": "zone", "tag": "00D010", "timestamp": "12/20/2022 10:38:07.710027", "status": "danger"}
UWB/00D003
Status changed and published: danger
{"type": "zone", "tag": "00D003", "timestamp": "12/20/2022 10:38:10.713742", "status": "danger"}
UWB/00D010
{"type": "zone", "tag": "00D010", "timestamp": "12/20/2022 10:38:13.718967", "status": "danger"}
UWB/00D003
{"type": "zone", "tag": "00D003", "timestamp": "12/20/2022 10:38:16.717963", "status": "danger"}
UWB/00D010
{"type": "zone", "tag": "00D010", "timestamp": "12/20/2022 10:38:19.720354", "status": "danger"}
UWB/00D003
{"type": "zone", "tag": "00D003", "timestamp": "12/20/2022 10:38:22.721644", "status": "danger"}
UWB/00D010
{"type": "zone", "tag": "00D010", "timestamp": "12/20/2022 10:38:25.724180", "status": "danger"}
UWB/00D003
{"type": "zone", "tag": "00D003", "timestamp": "12/20/2022 10:38:28.727668", "status": "danger"}
```

Figure 84: Data received in Synchronisation pod - UWB

The final results for UWB alarm activation are shown below.

```
$ k logs uwbtalarm9011-6bbbd68cbf-kt7zv
b'{"type": "zone", "tag": "00D010", "timestamp": "12/20/2022 10:37:49.701447", "status": "danger"}'
b'{"type": "zone", "tag": "00D003", "timestamp": "12/20/2022 10:38:10.713742", "status": "danger"}'
```

Figure 85: Data received in UWB alarm pod - alarm activation/deactivation

The final step is to add the Helm-chart(s) in the Network Application descriptor, of which a preliminary version is ready, and it was tested in the lab. The final Network Application will be created by the two Helm-chart packages that were described above and will be integrated into that Network Application descriptor for later integration with the NAC of UC2 in the actual pilot.

With all these test scenarios executed, the basic requirement for moving the 5G network deployment to the substation is satisfied.

Table 37: Summary of testing results for the pre-piloting phase of UC2

Scenario ID	Type of test	Targeted KPIs	Real KPIs in tests	Comments
PP – UC2 - S1	5G Network validation.	1	1	UEs can connect and reach core and the application server (MEC) where the Network Application is deployed.
PP – UC2 - S2	Validate setup for on-site and remote tests.	2	2	Physical space is prepared, tests can be performed as well as trusted users can connect to the lab.
PP – UC2 - S3	Send and receive data from and to a device connected to the 5G network and the core.	3	3	Not only the 5G-enabled UEs per se (5G CPE or 5G modem), but also devices attached to it can communicate with the core and the application server and exchange data.
PP – UC2 - S4	No worker present.	4,5	4,5	Systems communicate with a server, but do not send any data about coordinates (no detection information in cam/rtls txt testing data set).
PP – UC2 – S5	Inside safety zone data.	4,5	4,5	Both systems send data to the server about the coordinates of a worker present (detection information in cam/rtls txt testing data set).
PP – UC2 – S6	Outside safety zone data.	4,6	4,6	Both systems send data to the server about the coordinates of a worker present (detection information in cam/rtls txt testing data set). Test of safe area.
PP – UC2 – S7	Outside to inside zone data.	4,5,7	4,5,7	Both systems send data to the server about the coordinates of a worker present (detection information in cam/rtls txt testing data set). Test of safe area.
PP – UC2 – S8	Not moving data.	4,5,6,8	4,5,6,8	Both systems send data to the server about the coordinates of a worker present (detection information in cam/rtls txt testing data set). The anchor system sends data about workers immobility (fall) (detection information with sudden drop of Z axis position in rtls.txt testing data set).
PP – UC2 – S9	SOS button data.	4,5,6, 7,9	4,5,6, 7,9	Both systems send data to the server about the coordinates of a worker

				<p>present (detection information in cam/rtls.txt testing data set).</p> <p>The anchor system sends data about pressing SOS button (detection information with SOS button pressed in rtls.txt testing data set).</p>
PP – UC2 – S10	MPTCP validation.	10	10	<p>End-to-end connectivity over 5G NR and Wi-Fi 6 was successfully validated. An overall high aggregate throughput could be achieved.</p>

7. Analysis of the pre-piloting results

7.1. HIL related tests

The scope of the pre-piloting testing using RT-HIL technology reflected the needs of the Bulgarian pilot (UC3) and the Greek-Bulgarian pilot (UC4) respectively in terms of “vertical-service pre-piloting testing” which could impact the safe and reliable operation of the grid. Specifically, for both of these two use-cases the pre-piloting testing involved a thorough investigation on the impact of 5G communication technology for providing real-time measurements for newly developed time-critical control-in-the loop applications, as extensions of the scope of the UC3 and UC4, as it was defined in the DoW (Grant Agreement).

Besides these new control applications all the necessary physical equipment connectivity tests and the Network Application functional tests were also investigated and successfully passed the defined testing scenarios KPIs. More specifically, each of the testing scenarios and results are once more summarized and highlighted below:

7.1.1. UC3 (Bulgarian demo: Millisecond precise level monitoring and control of DER)

Pre-pilot tests for the UC3: *Millisecond precise level monitoring and control of DER*, involved four type of testing scenarios: Network Application integration tests with the pre-piloting RT-HIL setup, Network Application onboarding and deployment tests using the Smart5Grid platform’s Network Application controller (NAC), functional testing of the Network Application services, and testing and validation of the new control applications in the RT-HIL pre-piloting environment.

Specifically, the following testing scenarios and KPIs were validated during the pre-piloting tests of the UC3:

- The first target scenario was to integrate UC3 Network Application with the pre-piloting setup which has been successfully achieved. Two different reporting periods have been considered (i.e., 500ms, 1000ms) and the testing has been performed for 1 hour. The loss of data is defined as any data that has delayed by at least 1 reporting period to arrive in the MQTT broker, which might eventually violate the real-time characteristics of the application. Thus, a comparison in quality performance of the application was investigated, as follows: for the case of 500ms reporting period, the loss of data with 3G communication was 86.58%, with 4G 2.08%, and with 5G only 0.25%. For the case of the 1000ms reporting period, the loss of data with 3G communication was 0.16%, while with 4G and 5G there was not any loss of data.
- The second targeted scenario tested the impact of a wide area control (WAC) application response for coordinating the fast frequency support by DERs using 5G communication and of the impact of the network response on the energy system operation. The scenarios examined the no support case by DERs (baseline) and the support by DERs according to local inverter controller with droop and virtual inertia functionalities for comparison purposes. Further scenarios have been investigated based on the additional control application that relies on WAC approach for coordinating DERs, when different communication infrastructure is used. It was demonstrated that when 5G is used, a significant improvement on the frequency stability is observed (76.9% on frequency nadir and 98.5% on ROCOF) compared to the baseline scenario. On the other hand, using 4G or 3G communication cannot provide any significant improvement compared to local

control scenarios, since the communication latency of those communication technologies does not allow a preventing frequency support by the new control application.

- The third pre-piloting testing validated another control application response for coordinating the fast frequency support by DERs using ramping rate compensation by DERs and of the impact of the network response on the energy system operation. This control application was enabled through the utilisation of the monitoring Network Application UC3 to close the loop and enable the provision of ramping rate compensation for DERs (e.g., wind) by an energy storage system that is installed in a different location of the power system, facilitating the virtual power plant concept. A significant improvement is demonstrated regarding the controllability of the combined DERs and the ramping rate violations that have almost been eliminated. Specifically, it was shown that parameters such as RRV1s-mean is improved by 87.6% and RRV1s-max is improved by 56.5%, while RRV10s-mean is improved by 99.2% and RRV10s-max is improved by 98.9%.

7.1.2. UC4 (Greek-Bulgarian demo: Real time Wide Area Monitoring of cross border power flow)

Pre-pilot tests for the UC4: *Real-time Wide Area Monitoring (WAM)* of cross-border power flow involved five type of testing scenarios: physical connectivity tests for the power measurement devices with the pre-piloting setup, Network Application integration tests with the pre-piloting RT-HIL setup, Network Application onboarding and deployment tests using the Smart5Grid platform's Network Application controller (NAC), functional testing of the Network Application services, and testing and validation of a new wide area protection applications in the RT-HIL pre-piloting environment.

Specifically, the following testing scenarios and KPIs were validated during the pre-piloting tests of the UC4:

- The first testing scenario related to the physical connection between commercial PMUs and the RT-HIL setup for the UC4. Since this UC is related to the tie line between the borders of the Greek and Bulgarian transmission systems, special attention was provided to the chosen tie line of the simulated power system, where different loading scenarios and faults were applied to verify the proper operation of the simulation. The testing of the emulated power system operation was successful, for instance after a sudden increase in the load of the interconnected systems, the frequency drops as expected, while in the case of a 3-phase fault in the line the fault current increases. Furthermore, in this scenario the proper connection of the two commercial PMUs (similar to those to be installed in the pilot) that monitors the two ends of the emulated tie line was successfully tested and verified through the build-in screen of the PMUs where voltage, current and frequency measurements are illustrated. Furthermore, within the same testing scenario it was validated that the connectivity between the two commercial PMUs and the hardware network emulator (macroscopic model of the 5G infrastructure in the pre-piloting setup) passed successfully. This test is a pre-requisite for testing any type of functional requirements of the UC4 Network Application.
- The next passing test refers to the actual Network Applications of UC4 integration with the pre-piloting RT-HIL testbed. The Network Application of UC4 was installed in the docker at the VivaCom premises (Bulgaria), while the RT-HIL testing environment is hosted at the University of

Cyprus (UCY). Thus, through VPN access provided by the UCY, the vPDC service of the UC4 Network Application was successfully connected remotely to the two commercial PMUs that are installed at the UCY pre-pilot setup.

- Following were the successful tests of the Network Application functionalities, such as the vPDC function which validated that for the 5G data integrity and synchronization were achieved (all the PMU measurements arrived at the vPDC before the elapse of the waiting time therefore, no PMU measurements were discarded). In comparison, by emulating 3G or 4G via the Network emulator in the pre-piloting RT-HIL of UCY, it was demonstrated that these latter networks compromise the data integrity of the PMU measurements that are concentrated to the vPDC Network Application and thus affect the situational awareness of the power system operators (4G with a 1.9% data loss, while 3G with an unacceptable 12% data loss).
- Another testing scenario successfully passed the WAM service and the Advisory service of the UC4 Network Application for its functional requirements. Specifically, it was verified that the WAM service of the Network Application is able to accurately capture the dynamics of the power system in case of a three-phase fault imposed in the middle of the emulated tie-line in the IEEE 9-bus system. More specifically, it was proved that the WAM service tracked the transient condition of the system during the fault in detail (through the visualisation function of this Network Application service). Furthermore, it was demonstrated that the WAM service is able to provide the operation conditions of the power grid with as low as 7ms latency, compared to 47ms latency for the 4G, and 97ms latency for the 3G. For the Advisory service it was shown that when several events were created which affect the system frequency (all these events were emulated in the digital-twin model of the power system in the RT-HIL setup), the Network Application service component was able to inform the operator (send the message to a specific server) about the specific event based on the timely received PMU measurements and the WAM service triggering.
- As an add-on to the initial scope of the UC4, a new control application considering a differential wide area protection scheme was also investigated in a control HIL setup. This scenario considered the case where if the magnitude of the current phasor measurements with the same time stamp that are captured by the two PMUs (at the end of the transmission line) have a deviation larger than a certain threshold (in this case 20A) then the protection application needs to send a trip command to the breakers of the tie line to open. It was demonstrated that with the use of the 5G communication (via the network emulator) in the loop with the RT-HIL and WAP controller (hardware implementation) the fault clearing time was as low as 0.14s, while for the 4G network it was 0.37s (more than 2 times higher).

7.2. 5G- connectivity related tests

The 5G-connectivity pre-piloting architecture was successfully customized for the needs of UC1 (Italian demo) and UC2 (Spanish demo). Specifically,

7.2.1. UC1 (Italian demo: Automatic power distribution grid fault detection)

Pre-pilot tests have confirmed that the IR1101 provided in all the pilot's secondary substations is able to keep segregated the different types of traffic passing over its interfaces, and there is also no evidence of excessive use of resources in terms of CPU and memory to respond to queries from the MEC server.

Brief conclusions are that the preliminary goals to be achieved during the pre-piloting tests, before we go to the actual pilots (readiness of the Network Application to be deployed in the actual pilot) were achieved.

- 9 testing scenarios (4 related to configuration and 5G connectivity/communication tests and 5 related to functional tests of the early versions of the Network Application, using emulated realistic traffic signal).
- The configuration and connectivity tests involved the same hardware that will be deployed in the pilot site of the UC1, e.g., advanced industrial communication router cisco IR1101 equipped with a 5G communication module. Specifically, it was successfully tested that this hardware is able to communicate and receive distinct IPs for each of its cellular interfaces, and thus to ensure the full segregation between the business-critical traffic (grid automation function related) and the Network Application monitoring traffic (related to the continuous monitoring of the QoS of the 5G network). Further, communication-related QoS tests using ping tools were also successfully passed within the targeted QoS KPIs such as latency less than 30ms, and loss of packets less than 0.1%.
- The functional tests for the early versions of the Network Applications first involved a ping acknowledgement test to confirm that the Network Application (early version) is able to communicate with the pre-piloting hardware testbed. This is a pre-requisite test in order to be able to test the other functionalities of the Network Application (counting of loss of packets, latency and jitter evaluation, as well as the ability to successfully send an alarm message when pre-defined thresholds for these parameters are exceeded). All those service functional tests for each of the components of the Network Application of UC1 also passed successfully.

7.2.2. UC2 (Spanish demo: Remote inspection of automatically delimited working areas)

Pre-pilot tests of UC2 covered physical setup connectivity, communication tests for the Network Application deployment in the 5G MEC server and Network Application functional tests. Thus, in the pre-piloting setup of UC2 parts of the UC pilot have been tested (e.g., validating that user equipment can connect to the 5G network, validating the Network Application passes the functional tests of each of its promised services, etc.).

Specifically, UC2 involved:

- 10 testing scenarios (4 related to physical connectivity tests for relevant components of the pilot such as static or wearable sensors, cameras, etc. and 6 scenarios dedicated to Network Application deployment and functional tests.). All tests were passed successfully.
- The physical connectivity/communication tests involved scenarios such as end-to-end connectivity (set up the entire 5G network, deploy the Network Application and test that the sensors/cameras can communicate with the Network Application) and camera/sensor functionality for worker tracking.
- The deployment tests for the Network Application (early versions) validated that the Network Application successfully created the Helm Charts for the docker chain applications of the Network Application, then it also validated the installation of main and sensors Helm Chart to Kubernetes cluster took place successfully.
- The functional tests validated that the detection area of the sensors and cameras is active and that operation scenarios pass successfully (e.g., no worker or a worker is present inside the detection

area, worker moving inside or outside the the safety area, etc.). Alarm functionality was also successfully tested for the case when the worker presses the SOS button on his personal wrist tag or the worker cross-passes the safety working area (e.g., sensors – coordinates and detection data are sent to server and received by Network Application, Network Application sends back the order to take the warning action).

- Furthermore, MPTCP validation for end-to-end connectivity over 5G NR and Wi-Fi 6 was successfully validated, and an overall high aggregate throughput was achieved.

In summary, all four use-cases have successfully passed the required functional tests for the early versions of the Network Applications. In the majority of the scenarios used for the tests, the input data came from the actual hardware sensors, measurment units similar or identical with those to be deployed in the actual pilots. Because the Network Applications for UC3 and UC4 were already successfully deployed in the actual 5G infrastructure of VivaCom premises using the NAC controller of the Smart5Grid platform, it was possible to perform more advanced pre-piloting tests in connection with the RT-HIL pre-piloting environment of the UCY.

8. Conclusions and next steps

The main outcome of this document is the demonstration of the early version of the use-case specific Network Applications using advanced pre-piloting-controlled testing environments tailored to the needs of each of the four Smart5Grid pilots. This report elaborated on the type of HW and SW components integrated in these pre-piloting testbeds in order to replicate as accurately as possible the real operation conditions of the pilots. In this respect, two types of pre-piloting architectures were proposed, and they were further adapted and tailored to the needs of each of the pilots.

The first pre-piloting architectures aimed to serve the needs for testing and validation of energy services, with a strong focus on the possible impact they might have on the real-time (dynamic behaviour) operation of the power grid. This type of architecture proved to be relevant especially for the Bulgarian demo (UC3: *Millisecond precise level monitoring and control of DER*) and for the Cross-border Greek-Bulgarian demo (UC4: *Real-time Wide Area Monitoring of cross-border power flow*). The second type of pre-piloting architecture aimed to serve the needs for testing and validation of 5G-related services offered to the energy vertical, with a strong focus on the network QoS monitoring perspective. This type of architecture was used for early-stage testing and validation of physical connectivity between the new 5G enabled equipment (from the energy infrastructure) and the 5G network, the ability of the pre-piloting testbed to deploy the Network Applications and to validate the functionality of each of the use-case specific Network Application services. This architecture proved relevant for the Italian demo (UC1: *Automatic power distribution grid fault detection*) and for the Spanish demo (UC2: *Remote inspection of automatically delimited working areas*).

Specifically, for the purpose of the UC3 and UC4, an advanced RT-HIL technology, power-HIL and control-hardware in the loop pre-piloting environments have been used. Thus, digital twins based on dynamic models of power grids or of DER and ESS plants were developed using high-fidelity models and field measurements. Moreover, additional innovative control applications have been developed, for facilitating fast frequency response and power balance services and wide area protection schemes and were integrated with the power system digital twins using control hardware in the loop approach to realistically investigate the behaviour of the grid response according to different control actions. This pre-piloting architecture enabled full functional testing and integration of early versions of the respective use-case specific Network Application. The Network Applications of UC3 and UC4 were successfully onboarded and deployed in the actual 5G infrastructure of VivaCom (the Bulgarian telco provider) using the NearbyONE NAC. Then, all the functional tests of the Network Applications were successfully carried out via the integration between the RT-HIL testing environments from the University of Cyprus and the VivaCom hosting server of the Network Applications. The tests involved the use of actual commercial PMUs (UC4) and IoT sensor data sent via an MQTT broker to the pre-piloting setup (UC3). It is also worth mentioning that the development and testing of the extra control applications for these two use-cases proved that 5G communication technology could indeed lead to a significant improvement in the accuracy of the WAM service (UC4) and it is suitable for future WAC implementation schemes for DER (UC3), as well as for WAP schemes for large-interconnected power grids (UC4).

The pre-piloting validation tests of the UC1 and UC2 prepare the grounds for the deployment of the use-case specific Network Applications for the 5G infrastructure of the pilots. Several HW and SW components

of the real pilot have been successfully integrated with the actual 5G infrastructure setup in a lab environment or in actual field environments. The functionalities of each of the Network Application services were also successfully tested. Due to different stages of Smart5Grid components deployment in the actual 5G infrastructure of the pilots some functionalities related to onboarding and deployment of the Network Applications were not tested (e.g., NAC deployed and operational at the edge sites of the 5G infrastructure for UC1). This is expected to take place during the pilot testing campaign.

In summary, this report elaborated on the pre-piloting testing facilities (testbeds) tailored to the needs of each of the four use-cases. A deep dive into each of the major blocks for the pre-piloting testbeds (i.e., Smart5Grid platform side, 5G telco side, HIL, control-HIL, and energy infrastructure side) was also provided, describing its components, their functionality and the interactions among them including any interfaces needed to replicate the real operation conditions of the actual demo pilot. This report also revised the formal specification of each of the use-case specific Network Application that offers the flexibility required to fulfil the requirements outlined by the UCs in previous deliverable D2.1. Furthermore, this document includes the relevant testing scenarios (with measurable KPIs) along with the testing methodology used to validate each of these scenarios which will serve as the basis for the final pilot tests. It also collected in a structured and homogeneous manner the testing results and compared them with the pre-defined targeted KPIs for each of the defined testing scenarios. Finally, it integrates all necessary proofs (logs, screenshots, Network Application visualisation tools, etc) for the obtained testing results.

The work presented in this deliverable provided the necessary input for the upcoming tasks and enables the project to take its next steps. Within WP4, the developers can take the required actions in order to fine tune the final version of the Network Applications and to set the path for their V&V framework further testing and validation. Finally, within WP5 and WP6, the results obtained during this pre-piloting testing stage will form the comparison basis for the final Network Application deployment and testing.

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