



## Deliverable 5.2

### Solution Integration and Validation

April 2025

|                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
|--------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Contractual Date of Delivery:</b> | <b>February 28, 2025</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| <b>Actual Date of Delivery</b>       | <b>April 1, 2025</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| <b>Editor(s):</b>                    | Simon Pryor, German Castellanos (ACC)<br>Jesús Gutiérrez (IHP)                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| <b>Author(s)/Contributor(s):</b>     | German Castellanos, Simon Pryor (ACC)<br>Vladica Sark, Mert Özates, Navaneetha C Manjappa, Ramya Vasist,<br>Jesús Gutiérrez (IHP)<br>Josep Xavier Salvat, Jose A. Ayala (NEC)<br>Pablo Suarez Reyero (TSA)<br>Miguel Catalan-Cid, David Reiss, Esteban Municio (i2CAT)<br>Joss Armstrong, Jimmy O'Meara, Joseph McNamara (LMI)<br>Israel Koffman, Baruch Globen (RunEL)<br>Richard Mackenzie, Keith Briggs (BT)<br>Ory Eger (PW)<br>Anna Umbert, Juan Sanchez (UPC)<br>Mir Ghoraishi (GIGASYS) |
| <b>Work Package</b>                  | <b>WP5</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| <b>Target Dissemination Level</b>    | <b>Final Version: Public</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |

*This work is supported by the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101097083, BeGREEN project. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or SNS-JU. Neither the European Union nor the granting authority can be held responsible for them.*

## Revision History

| Revision | Date       | Editor / Commentator                                                                                                                                               | Description of Edits                                            |
|----------|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|
| 0.1      | 10.10.2024 | Simon Pryor (ACC)                                                                                                                                                  | Document creation & initial ToC made ready                      |
| 0.2      | 23.10.2024 | Germán Castellanos (ACC),<br>Jesús Gutiérrez (IHP)                                                                                                                 | Revised version and revision of the ToC                         |
| 0.3      | 29.10.2024 | Ory Eger (PW),<br>Vladica Sark, Jesús Gutiérrez (IHP),<br>Anna Umbert, Juan Sanchez (UPC),<br>Josep Xavier Salvat, Jose A. Ayala (NEC),<br>Esteban Municio (I2CAT) | Updated PoC4, Updated PoC2                                      |
| 0.35     | 30.10.2024 | ALL                                                                                                                                                                | Testbed descriptions, Chapter 2                                 |
| 0.4      | 01.11.2024 | German Castellanos (ACC)                                                                                                                                           | Revised and updated PoC1 and PoC3                               |
| 0.5      | 01.11.2024 | Miguel Catalán (I2CAT)                                                                                                                                             | Revised and updated PoC1                                        |
| 0.6      | 06.11.2024 | Vladica Sark, Jesús Gutiérrez (IHP)                                                                                                                                | Revised and updated PoC2                                        |
| 0.7      | 07.11.2024 | Israel Koffman, Baruch Globen (REL),<br>Germán Castellanos (ACC)                                                                                                   | Revised and updated PoC5                                        |
| 0.8      | 09.11.2024 | Jesús Gutiérrez (IHP),<br>Mir Ghoraishi (GIGASYS),<br>Simon Pryor (ACC)                                                                                            | Final review for interim report.                                |
| 0.9      | 10.02.2025 | All                                                                                                                                                                | Update to final plans                                           |
| 0.99     | 20.03.2025 | Jesús Gutiérrez (IHP)<br>Mir Ghoraishi (GIGASYS)                                                                                                                   | Final review and proof reading                                  |
| 1.00     | 28.03.2025 | Simon Pryor (ACC)                                                                                                                                                  | Editorial inputs, complete section 5.1.<br>Submission to the EC |

## Table of contents

|                                                                               |    |
|-------------------------------------------------------------------------------|----|
| List of Figures .....                                                         | 5  |
| List of Tables.....                                                           | 6  |
| List of Acronyms .....                                                        | 7  |
| Executive Summary .....                                                       | 9  |
| 1 Introduction.....                                                           | 10 |
| 2 Testbeds .....                                                              | 13 |
| 2.1 5G Accelleran SNPN integration laboratory .....                           | 13 |
| 2.2 Integrated sensing and communication (ISAC) testbed .....                 | 14 |
| 2.2.1 ISAC Sub-6 GHz testbed.....                                             | 14 |
| 2.2.2 NEC Reconfigurable Intelligent Surface.....                             | 16 |
| 2.3 DU acceleration testbed .....                                             | 16 |
| 2.4 BT laboratories testbed in Adastral Park .....                            | 18 |
| 3 BeGREEN Proof-of-Concepts .....                                             | 19 |
| 3.1 PoC1: BeGREEN Intelligence Plane .....                                    | 20 |
| 3.1.1 PoC1 updated description .....                                          | 20 |
| 3.1.2 PoC1 updated planning .....                                             | 22 |
| 3.2 PoC2: Sensing-assisted communications using RIS .....                     | 23 |
| 3.2.1 PoC2 updated description .....                                          | 24 |
| 3.2.2 RIS assisted ISAC.....                                                  | 26 |
| 3.2.3 PoC2 updated planning .....                                             | 29 |
| 3.3 PoC3: Energy efficient CU and O-RAN RIC .....                             | 29 |
| 3.3.1 CU Hardware Acceleration and ARM Porting.....                           | 30 |
| 3.3.2 RIC Porting into ARM.....                                               | 30 |
| 3.3.3 Full demo testing workflow and procedures .....                         | 32 |
| 3.3.4 KPI description for PoC3 testing Workflow .....                         | 33 |
| 3.3.5 PoC3 updated planning .....                                             | 33 |
| 3.4 PoC4: Energy-efficient DU implementation using hardware acceleration..... | 34 |
| 3.4.1 PoC4 updated description .....                                          | 34 |
| 3.4.2 PoC4 updated planning .....                                             | 36 |
| 3.5 PoC5: RU power amplifier blanking .....                                   | 36 |
| 3.5.1 PoC5 – purpose and use cases .....                                      | 37 |
| 3.5.2 PoC5 use case 3 updated planning.....                                   | 38 |
| 3.6 Final demonstrations .....                                                | 38 |
| 4 BeGREEN PoC mapping to BeGREEN KPIs .....                                   | 40 |
| 5 Updated Risks and Mitigation Plans.....                                     | 43 |
| 5.1 Risks associated with the final demo and the mitigation plan .....        | 44 |
| 6 Summary and conclusions.....                                                | 45 |

## List of Figures

|                                                                                                                |    |
|----------------------------------------------------------------------------------------------------------------|----|
| Figure 1-1 BeGREEN architecture, Source: D4.2 [5] .....                                                        | 11 |
| Figure 2-1 Accelleran Laboratory, left: general view, right: Supermicro server used for PoC1 .....             | 13 |
| Figure 2-2 PoC3 Setup with ARM and x86 servers .....                                                           | 14 |
| Figure 2-3 Sub-6 GHz system used in PoC2 .....                                                                 | 15 |
| Figure 2-4 Example of the tests that can be carried out at IHP's Anechoic chamber with corner reflectors ..... | 15 |
| Figure 2-5 NEC RIS board.....                                                                                  | 16 |
| Figure 2-6 DU HW accelerator PoC setup [1] .....                                                               | 17 |
| Figure 2-7 Waveform generator – Keysight EXM .....                                                             | 17 |
| Figure 2-8 Channel emulator – Keysight PropSim .....                                                           | 17 |
| Figure 2-9 DU under test – Intel Icelake Server.....                                                           | 17 |
| Figure 3-1 Mapping of each of the PoCs to BeGREEN's architectural framework .....                              | 19 |
| Figure 3-2 Distributed PoC1 implementation detailed set up.....                                                | 20 |
| Figure 3-3 PoC 1 - main architecture.....                                                                      | 21 |
| Figure 3-4 Sub-6 ISAC testbed @ EuCNC 2024 BeGREEN booth .....                                                 | 25 |
| Figure 3-5 Sensing assisted communications demo - use case 2 .....                                             | 25 |
| Figure 3-6 Sensing assisted communications demo - use case 3 .....                                             | 26 |
| Figure 3-7 Anechoic chamber configuration .....                                                                | 27 |
| Figure 3-8 Anechoic chamber setup, view from the ISAC system towards RIS .....                                 | 27 |
| Figure 3-9 Anechoic chamber setup, view from RIS towards ISAC system and corner reflector .....                | 28 |
| Figure 3-10 Heat maps for a) 80, b) 85, c) 90, d) 95 degrees reflection angled on the RIS.....                 | 28 |
| Figure 3-11 CU-RIC HW acceleration proposal, left: CU energy evaluation, right: RIC energy evaluation.....     | 30 |
| Figure 3-12 RIC on ARM evaluation set up.....                                                                  | 31 |
| Figure 3-13 PoC4 DU HW accelerator setup .....                                                                 | 35 |
| Figure 3-14 RU PA power blanking demo.....                                                                     | 37 |
| Figure 3-15 PA blanking tests carried out in Sept. 2024 .....                                                  | 37 |
| Figure 3-16 Powering-off the PA during more symbols with the PA blanking module .....                          | 37 |

## List of Tables

|                                                                                               |    |
|-----------------------------------------------------------------------------------------------|----|
| Table 2-1 Accelleran Server Configurations for PoC3.....                                      | 13 |
| Table 3-1 Updated Planning of PoC1.....                                                       | 23 |
| Table 3-2 Updated Planning of PoC2.....                                                       | 29 |
| Table 3-3 Updated Planning of PoC3.....                                                       | 34 |
| Table 3-4 PoC4 Scenarios for LDPC Decoder .....                                               | 35 |
| Table 3-5 PoC4 Scenarios for Sphere Decoder .....                                             | 35 |
| Table 3-6 Updated Planning of PoC4.....                                                       | 36 |
| Table 3-7 Updated Planning of PoC5.....                                                       | 38 |
| Table 4-1 BeGREEN KPI Evaluation (based on that initially included in BeGREEN D2.2 [7]) ..... | 40 |
| Table 5-1 Unforeseen Risks per PoC.....                                                       | 43 |

## List of Acronyms

|         |                                      |
|---------|--------------------------------------|
| 3GPP    | 3rd Generation Partnership Project   |
| 5GC     | 5G Core                              |
| 5G NR   | 5G New Radio                         |
| A/D     | Analogue to Digital                  |
| AI      | Artificial Intelligence              |
| AIA     | AI Engine Assisted                   |
| AoA     | Angle-of-Arrival                     |
| API     | Application Programming Interface    |
| B5G     | Beyond 5G                            |
| BLER    | Block Error rate                     |
| BPF     | Berkeley Packet Filter               |
| CP      | Control Plane                        |
| CU      | Central Unit                         |
| CW      | Cell Wrapper                         |
| DoW     | Description of Work                  |
| D/A     | Digital to Analogue                  |
| DU      | Distributed Unit                     |
| E2E     | End-to-End                           |
| EE      | Energy Efficiency                    |
| ES      | Energy Saving                        |
| FPGA    | Field Programmable Gate Array        |
| gNB     | Next Generation Node B               |
| GPU     | Graphics Processing Unit             |
| GTP     | GPRS Tunnelling Protocol             |
| HW      | Hardware                             |
| IDFT    | Inverse discrete Fourier transform   |
| IP      | Internet Protocol                    |
| IQ      | In-phase and Quadrature              |
| ISAC    | Integrated Sensing and Communication |
| ISM     | Industrial Scientific and Medical    |
| KPI     | Key Performance Indicator            |
| KPM     | Key Performance Metric               |
| L2      | Layer 2                              |
| LDPC    | Low Density Parity Check             |
| LNS     | Linux Network Stack                  |
| LO      | Local Oscillator                     |
| LoS     | Line-of-Sight                        |
| LTE     | Long Term Evolution                  |
| MAC     | Medium Access Control                |
| MIMO    | Multiple-Input Multiple-Output       |
| ML      | Machine Learning                     |
| MMSE    | Minimum Mean Square Error            |
| MNO     | Mobile Network Operator              |
| MU-MIMO | Multiuser MIMO                       |
| near-RT | near Real-Time                       |



|         |                                               |
|---------|-----------------------------------------------|
| NFV     | Network Function Virtualisation               |
| NIC     | Network Interface Card                        |
| NLoS    | Non-Line-of-Sight                             |
| non-RT  | Non-Real-Time                                 |
| OFDMA   | Orthogonal Frequency-Division Multiple Access |
| O-RAN   | Open RAN                                      |
| PA      | Power Amplifier                               |
| PDCCP   | Packet Data Convergence Protocol              |
| PDU     | Power Distribution Unit                       |
| PHY     | Physical layer                                |
| PC      | Personal Computer                             |
| PoC     | Proof-of-Concept                              |
| RAN     | Radio Access Network                          |
| RCS     | Radar Cross Section                           |
| RF      | Radio Frequency                               |
| RIC     | Radio Intelligent Controller                  |
| RIS     | Reconfigurable Intelligent Surface            |
| RMS     | Root Mean Square                              |
| RRC     | Radio Resource Control                        |
| RRM     | Radio Resource Management                     |
| RU      | Radio Unit                                    |
| SDR     | Software Defined Radio                        |
| SHO     | Smart Handover                                |
| SLA     | Service Level Assurance                       |
| SMO     | Service Management Orchestrator               |
| SNR     | Signal-to-Noise Ratio                         |
| SU-MIMO | Single User MIMO                              |
| TGW     | Telemetry Gateway                             |
| UE      | User Equipment                                |
| UPF     | User Plane Function                           |
| UPS     | User Plane Service                            |
| WiP     | Work in Progress                              |
| WP      | Work Package                                  |
| XDP     | eXpress Data Path                             |



## Executive Summary

BeGREEN D5.2 takes the definitions and plans in BeGREEN D5.1 [1] and reports the design and implementation of the testbeds to deliver the proof-of-concepts (PoCs) and associated measurements. An integration plan is defined, including timescales and agreed interfaces, and the use cases and their integration onto the testbeds in readiness for final demonstration and testing.

The document initially provides details of the testbeds that will be used for the PoCs, and the description of the final BeGREEN demonstration.

This deliverable provides additional details of the PoCs, including descriptions, associated use cases (reference to use cases defined in BeGREEN D2.1 [6] and BeGREEN D2.2 [7]), and a high-level plan for each PoC implementation and a description of the BeGREEN final demonstration is provided, identifying PoCs that are going to be presented. BeGREEN PoCs described in this document are the following:

- PoC1: BeGREEN Intelligence Plane; that is one of the main components of the BeGREEN architecture. Its main functionality is to expose Artificial Intelligence (AI)/Machine Learning (ML) functions to rApps and xApps, enabling the creation of intelligent closed-loop automation empowered by AI/ML, aiming at improving energy efficiency (EE). Its features will be tested by including it in different PoCs, and at least one AI/ML-based rApp/xApp targeting EE at the RAN will be showcased.
- PoC2: Sensing assisted communications using a Reconfigurable Intelligent Surface (RIS); The sensing-assisted communications PoC aims to demonstrate how user positioning data coming from sensing services can be used for energy savings in future mobile networks. The main idea of the demo is to dynamically change the reflection properties of a RIS depending on the potential user location. Additionally, this data can be fed into the network and used for optimization of network resource allocation.
- PoC3: Energy efficient CU and O-RAN RIC; This PoC will provide an alternative implementation (acceleration) of CU and O-RAN RIC based on ARM architecture to demonstrate enhanced performance and reduce energy consumption in these components.
- PoC4: Energy-efficient DU implementation using hardware (HW) acceleration; This PoC is on implementation of DU high-PHY algorithms, using HW acceleration techniques, to reduce power consumption compared to legacy implementation. Specific targets are Low Density Parity Check (LDPC) decoder and sphere decoder.
- PoC5: RU power amplifier (PA) blanking; This PoC is on a RU power consumption optimisation technique called "PA blanking". The PA blanking algorithm reduces the RU power consumption by turning off (blanking) the RF PA, which is the highest power-hungry component in the RU (especially in high power RUs > 1 Watt) at times when there is no data to be transmitted by the RU.

The outline of the Key Performance Indicators (KPIs) that each PoC will cover, which is based on the KPIs defined in the Description of Work (DoW) and augmented in BeGREEN D2.2. The initial set of measurement results stemming from the PoCs are provided as well. Finally, the risks associated to the implementation and deployment of the PoCs infrastructure are updated and justified appropriately.

# 1 Introduction

This document, BeGREEN D5.2 follows the work presented in BeGREEN D5.1 [1] (which reported the work of T5.1), continuing the efforts in T5.2 and reporting the activities of the relevant Work Packages (WPs). The primary focus of this document is to define and update the plans for the development, integration, and testing of the proof of concepts (PoCs) in the various partner testbeds. These plans include a detailed integration strategy, the provisioning of components by partners, and the deployment of PoCs across different testbed environments. BeGREEN D5.2 serves as an introduction to the integration and validation processes that will be carried out, outlining the collaborative efforts between partners and their respective roles in ensuring successful implementation.

The main objectives of BeGREEN D5.2 are:

- (1) to update the architecture and descriptions of the testbeds,
- (2) to refine the details of the integration plans, and,
- (3) to identify any potential risk that could impact the successful implementation of the PoCs. These risks, such as timeline delays, resource limitations, or technical compatibility issues, are critical to ensure smooth progression towards the final demonstration and testing phases.

This deliverable also merges the work from BeGREEN WP3 and WP4, where the energy-saving enablers were developed and reported in BeGREEN D3.1 [2], BeGREEN D3.2 [3], BeGREEN D4.1 [4] and BeGREEN D4.2 [5]. These PoCs have been designed and implemented with precise alignment to the BeGREEN architecture defined in WP2 and its BeGREEN D2.1 [6] and then evolved in BeGREEN D2.2 [7] and BeGREEN D4.2 [5], ensuring unified integration into the project's testbeds. The evolved BeGREEN architecture of BeGREEN D4.2 [5], depicted in Figure 1-1, combines findings from WP2, WP3, and WP4, and it is the baseline for WP5.

Each PoC is built upon the testbed descriptions provided in Chapter 2, ensuring a robust foundation for validation and demonstration. The detailed implementation and testing timeline for each PoC ensures that all necessary developments, responsibilities, and interfaces are well-defined, paving the way for the successful demonstration of BeGREEN innovative energy-saving solutions. As part of the ongoing work, these plans remain subject to updates based on the received feedback and project progression. An updated timeline for the implementation of each PoC has been outlined, showing the expected milestones and readiness for demonstration phases.

The main PoCs, described in detail in Chapter 3 of this deliverable, are designed to showcase the integration of BeGREEN's energy-saving innovations into real-world scenarios. These include

- PoC1: BeGREEN Intelligence Plane, which focuses on AI/ML-powered automation for EE;
- PoC2: Sensing-assisted communications using an Reconfigurable Intelligent Surface (RIS), which leverages user location data for energy optimization;
- PoC3: Energy-efficient Central Unit (CU) and O-RAN Radio Intelligent Controller (RIC), demonstrating HW acceleration to improve EE;
- PoC4: Energy-efficient Distributed Unit (DU) implementation using HW acceleration, focusing on power reduction through advanced algorithms; and
- PoC5: Radio Unit (RU) power amplifier (PA) blanking, which aims to reduce RU power consumption through efficient resource management.

Finally, this document will form the basis for the T5.3 final demonstrations that will deploy of some of the PoCs developed onto the final testbed demonstration, plus providing additional PoCs deployed in other partners' premises.

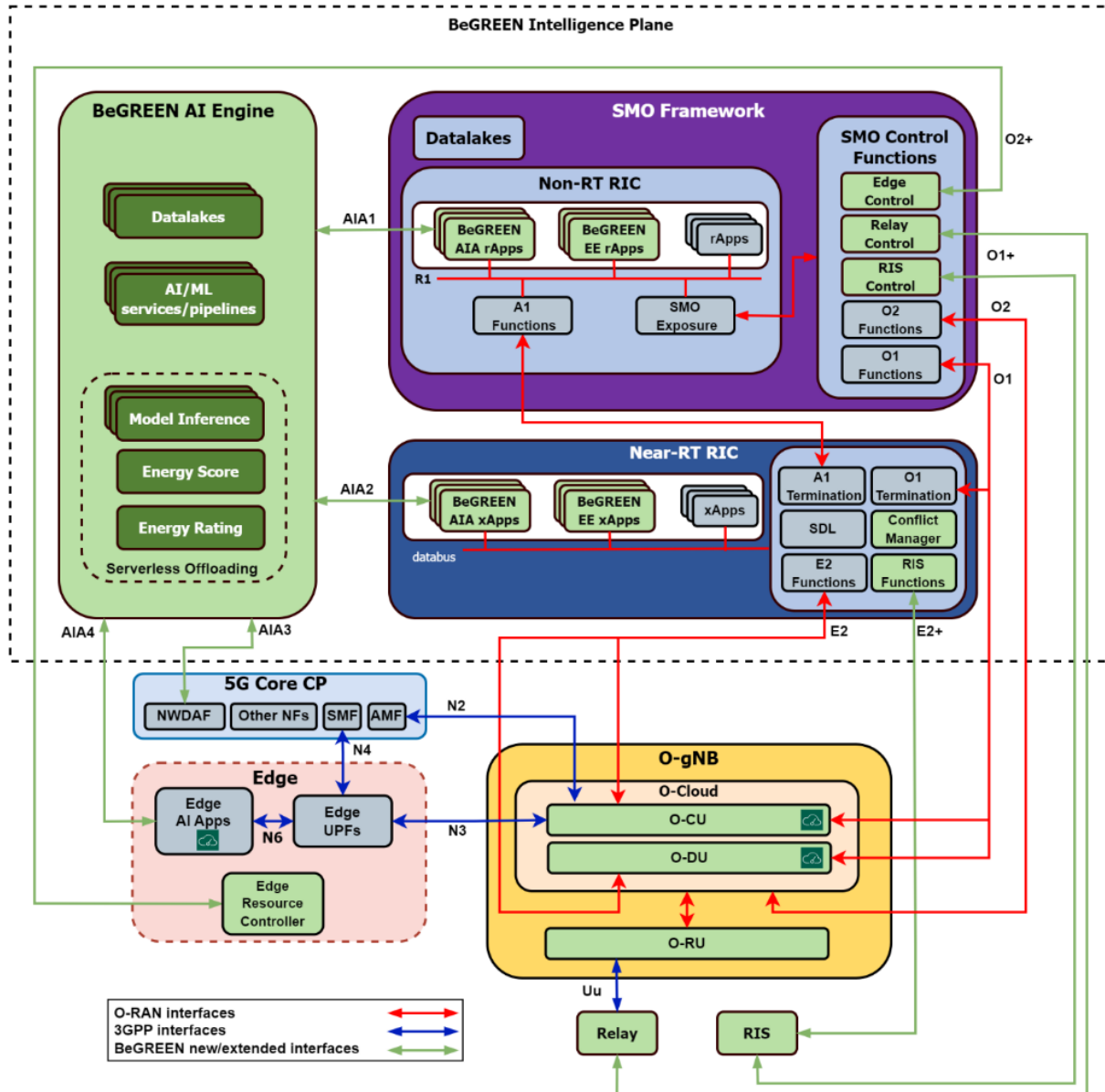


Figure 1-1 BeGREEN architecture, Source: D4.2 [5]

The BeGREEN architecture shown below in Figure 1-1, as evolved in BeGREEN D2.2 [7] and BeGREEN D4.2 [5], extends the O-RAN baseline architecture by integrating advanced components such as the AI Engine, RIS, and relays.

These components, alongside future enhancements like distributed Multiple-Input Multiple-Output (MIMO) and Integrated Sensing and Communication (ISAC), are part of the BeGREEN Intelligence Plane, which provides a framework for AI/ML-driven optimizations. The Intelligence Plane, consisting of both non-RT and near-RT RICs and the AI Engine, is central to implementing EE improvements through intelligent closed-loop control. The AI/ML services hosted by the AI Engine offer serverless execution environments for training and inference, making them accessible to various rApps/xApps. The architecture also emphasizes modularity and scalability, enabling efficient control and monitoring of energy consumption. Key features include control-loop decoupling, model reuse across different rApps/xApps, and integration with AI/ML workflows independent of the underlying RIC implementation. This modular design allows BeGREEN to evolve while incorporating future enhancements for energy-saving capabilities across both the RAN and Edge infrastructures as discussed in diverse PoCs.

BeGREEN D4.2 [5] expands the architecture of BeGREEN Intelligence Plane, focusing on its role in energy-

efficient RAN and Edge optimizations. The Intelligence Plane integrates cross-domain control functions, covering both RAN and Edge components, and facilitates energy-saving strategies via advanced ML models. These models are hosted in the AI Engine and exposed to rApps/xApps through BeGREEN-specific interfaces, allowing seamless integration and control. The Intelligence Plane also introduces new interfaces, e.g. O1+, E2+, and O2+, extending standard O-RAN interfaces to support additional elements like RIS and relays.

The BeGREEN Intelligence Plane plays a pivotal role in enabling the PoCs outlined in this deliverable. Each PoC leverages different components of the architecture to demonstrate energy-saving innovations in a real-world setup. For instance, *PoC1: BeGREEN Intelligence Plane* directly integrates the AI Engine, non-RT RIC, and near-RT RIC to implement intelligent closed-loop automation. This PoC tests the ability of the Intelligence Plane to optimize RAN operations through AI/ML-driven rApps/xApps that adjust network parameters, such as RU on/off switching, based on real-time and historical data. The architecture's flexible AI/ML model management allows PoC1 to serve models and make decisions dynamically, ensuring efficient RAN operations while minimizing energy consumption. Similarly, *PoC2: Sensing-Assisted Communications using RIS* integrates the extensions developed for RIS control into the BeGREEN architecture. The near-RT RIC and non-RT RIC facilitate control and monitoring through the O1+ and E2+ interfaces, enabling dynamic adjustments to RIS elements in real-time. The Intelligence Plane's AI Engine further enhances this PoC by analysing sensing data and optimizing RIS configurations, making it possible to steer signals and extend coverage with minimal energy consumption. The architectural components ensure that RIS configurations are dynamically adjusted based on user locations, demonstrating how the architecture supports both advanced sensing and EE.

*PoC3: Energy-Efficient CU and O-RAN RIC* and *PoC4: Energy-Efficient DU Implementation* leverage the HW acceleration capabilities embedded in the BeGREEN architecture. The modular design of the Intelligence Plane enables the placing of energy-efficient AI/ML models on specialized HW, such as ARM servers, to optimize the performance of CU and DU components. These PoCs highlight how BeGREEN's architecture supports real-time optimization and energy reduction through the Intelligence Plane's control over resource allocation and processing tasks, which are essential for improving the efficiency of RAN components. In PoC4, the deployment of energy-efficient DUs using high-PHY algorithms, combined with HW acceleration, showed promising results in reducing power consumption while maintaining satisfactory system performance. This PoC highlighted the efficiency gains achieved through high-PHY algorithms with HW acceleration, leading to significant power reductions without compromising performance. The focus on optimizing the physical layer through advanced algorithms allowed PoC4 to achieve substantial energy savings, demonstrating the value of these techniques for future mobile networks. Finally, for *PoC5: RU Power Amplifier Blanking*, the PA blanking approach for RUs demonstrated the effectiveness of selectively powering down high-consumption components during idle periods, leading to significant power savings. This PoC showed that energy usage in RUs can be effectively reduced by turning off power-consuming components when not in use. The PA blanking technique provided a practical means of reducing the energy footprint of RUs, particularly during times of low activity, thus contributing directly to the goal of minimizing unnecessary energy expenditure in mobile networks.

This document, BeGREEN D5.2, starts giving an updated overview of the BeGREEN architecture and main changes from the previous version in Chapter 1. Chapter 2 presents an updated version of the testbeds used for PoC implementation and summarizes the main technologies available on each testbed. Chapter 3 dives into the details of each PoC, presenting a general description, and an update plan with some initial and expected results, and its relationship with other results in WP3 and WP4. Chapter 4 discusses the mapping of the project PoC with and the actual status of the Key Performance Indicators (KPIs) defined in the project scope and their use cases. The deviations from the initial planning, with an updated plan, also raise several risks that are discussed in Chapter 5, together with a mitigation plans for those risks, to achieve the goals of the BeGREEN project. Finally, Chapter 6 concludes the document.



## 2 Testbeds

This chapter provides an updated version of the BeGREEN testbeds being put together to host the BeGREEN PoCs. These testbeds initially served as the research playground to assess WP3 and WP4 developments, to then become the ones hosting the necessary components that build up the PoCs. Some of the PoCs are only attached to one testbed, while other PoCs are (or can be) implemented across different testbeds.

### 2.1 5G Accelleran SNPN integration laboratory

In BeGREEN D5.1 [1] we outlined the capabilities of the Accelleran 5G Integration Laboratory (see Figure 2-1). The laboratory focuses on two main capabilities. The first is an integration server for the development of PoC3 (Figure 2-2), which will later be described in detail. The second capability involves integrating with BT Laboratories and I2CAT Laboratories needed for PoC1. To facilitate this, we have established VPN access to both infrastructures and implemented the necessary port mapping. This ensures seamless connectivity and functionality of the dRAX infrastructure with other interfaces and laboratories, providing a distributed integration test facility.

The Accelleran 5G Integration Laboratory also involves specific system configurations for testing, as shown in Table 2-1. These configurations include both x86 and ARM setups, detailing HW settings, operating systems, memory, and processor capabilities. The CU is configured for 64 connected users and is deployed with 6 User Plane Service (UPS) eXpress Data Path (XDP) pods. These UPS XDP pods are single-thread applications designed to handle user-plane traffic, optimizing the processing capabilities and ensuring efficient data throughput.

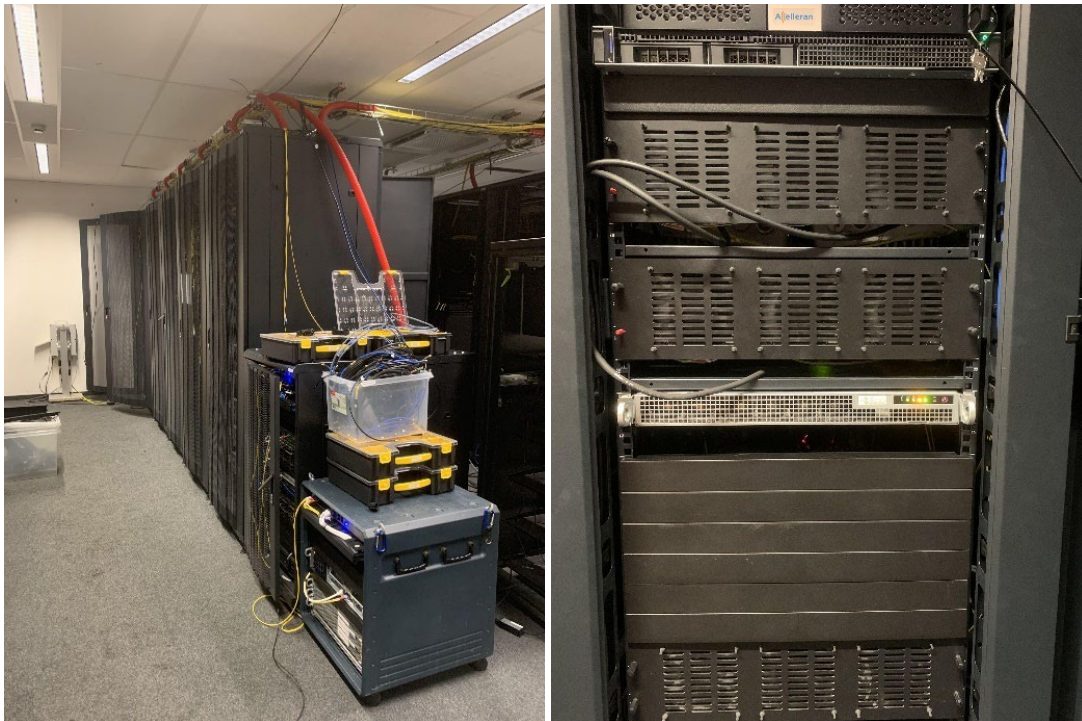


Figure 2-1 Accelleran Laboratory, left: general view, right: Supermicro server used for PoC1

Table 2-1 Accelleran Server Configurations for PoC3

| Configuration Aspect | x86 AMD Details                   | ARM Details                                                                        |
|----------------------|-----------------------------------|------------------------------------------------------------------------------------|
| Server Type          | DELL R630, 2x E5-2667 V4 CPU      | 80 cores configuration reduced to 32 cores/32 threads (rest of the cores disabled) |
| Operating System     | Ubuntu 22.04, no special settings | Ubuntu 22.04, customized kernel settings                                           |

| Configuration Aspect           | x86 AMD Details                                                                                                                           | ARM Details                                                                                                                                         |
|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Kernel Version</b>          | Generic kernel (5.15.0-100-generic #110-Ubuntu SMP Wed Feb 7 13:27:48 UTC 2024 x86_64 x86_64 x86_64 GNU/Linux)                            | Customized kernel version with parameters for huge pages and specific optimizations                                                                 |
| <b>Memory</b>                  | 128GB RAM Memory                                                                                                                          | 512GB RAM reduced to 256GB (lower reduction was not possible)                                                                                       |
| <b>Processor Cores</b>         | Hyper-threading enabled (16 cores/32 threads)                                                                                             | 32 cores/32 threads                                                                                                                                 |
| <b>Special Configurations</b>  | None                                                                                                                                      | Huge pages configured (default_hugepagesz=1G hugepagesz=1G hugepages=64 tsc=rffinity=0 rcu_nocbs=1-69 rcu_nocb_poll nosoftlockup cma=256m kpti=off) |
| <b>CPU Frequency</b>           | Dynamic up to 2.75 GHz                                                                                                                    | Fixed to maximum 3 GHz for some tests                                                                                                               |
| <b>Software specifications</b> | dRAX ver 12.0.1, VIAVI AI RSG ver 2.3, influxdb2 ver 2.1.2, influxdb ver 1.8.10, TGW Ver 2.0, Grafana version 8.6, CU Release 4.3.4_leffe | dRAX ver 12.0.1, VIAVI AI RSG ver 2.3, influxdb2 ver 2.1.2, influxdb ver 1.8.10, TGW Ver 2.0, Grafana version 8.6, CU Release 4.3.4_leffe           |

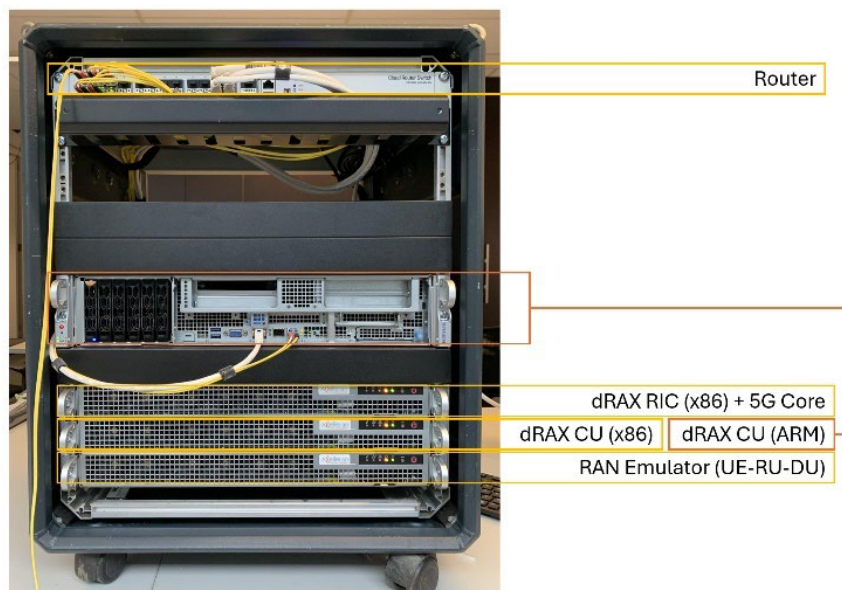


Figure 2-2 PoC3 Setup with ARM and x86 servers

## 2.2 Integrated sensing and communication (ISAC) testbed

The ISAC testbed has been built up to assess the sensing functionality of the **Sub-6 ISAC system**, using the transmitted data communication frames for sensing purposes, together with the **RIS board** provided by NEC. This ISAC system is used in the context of PoC2 and was initially introduced in BeGREEN D5.1 [1]. Additional details of this system and an initial set of results were provided in BeGREEN D3.2 (cf. Section 4.1.5) [3]. The results obtained therein have proven the suitability of the testbed for sensing purposes, despite the HW constraints.

The RIS board characteristics, theory behind and an initial set of measurements were provided in BeGREEN D3.2 (section 4.2).

### 2.2.1 ISAC Sub-6 GHz testbed

The Sub-6 GHz testbed comprises multiple software-defined radios (SDR) from Ettus Research. A total of four BeGREEN [SNS-JU-101097083]

Ettus N321 units are used in BeGREEN as depicted in Figure 2-3. As presented in BeGREEN D3.2 [3], this system practically transmits a waveform that represents a data frame, but it only performs sensing and not data transmission, since the transmitted waveform is not received by another device. Even if there is no communication with another device, data transmission and sensing are performed simultaneously. There is no loss of generality, since data frames are being transmitted by the system and the sensing is performed.

The **Sub-6 GHz testbed** has been initially deployed in an anechoic chamber available at IHP premises. A photo of the anechoic chamber is given in Figure 2-4. The anechoic chamber has substantial dimensions of  $7 \times 4 \times 2.5$  meters, allowing for different objects to be placed in it, e.g. corner reflectors (see Figure 2-4). These objects are the obstacles to be used for testing of the sensing system. The KPIs measured in PoC2 have been initially evaluated in such controlled environment prior to the deployment of the ISAC system in a lab environment. Furthermore, tests with the RIS provided by the BeGREEN partner NEC will be performed using the Sub-6 system in both the anechoic chamber and in a laboratory environment, which is currently Work in Progress (WiP).

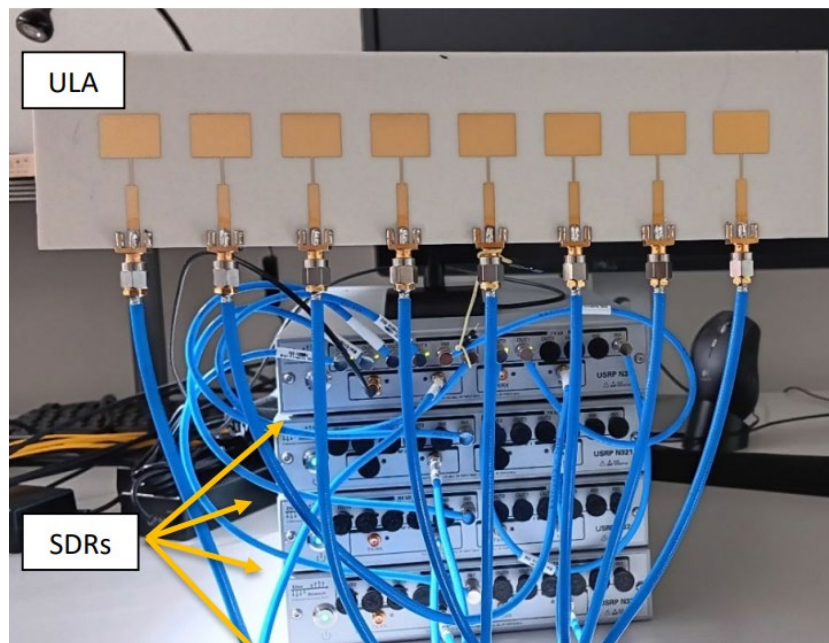


Figure 2-3 Sub-6 GHz system used in PoC2

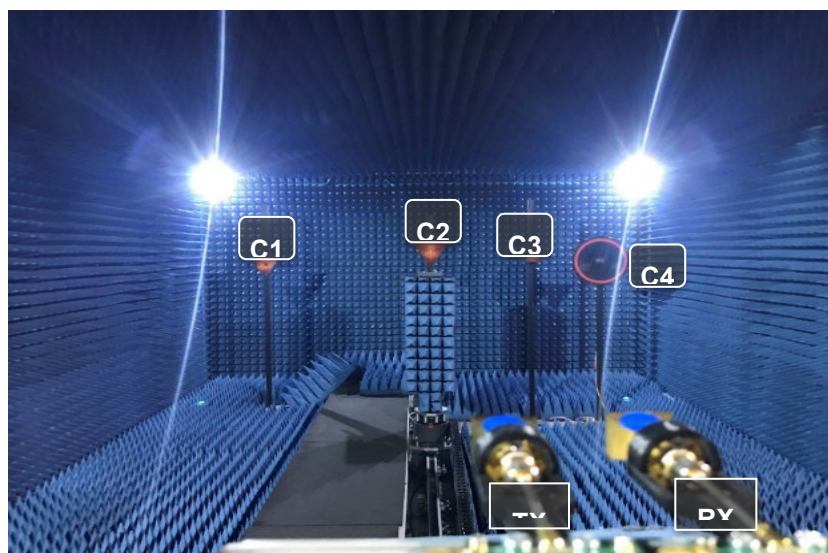


Figure 2-4 Example of the tests that can be carried out at IHP's Anechoic chamber with corner reflectors



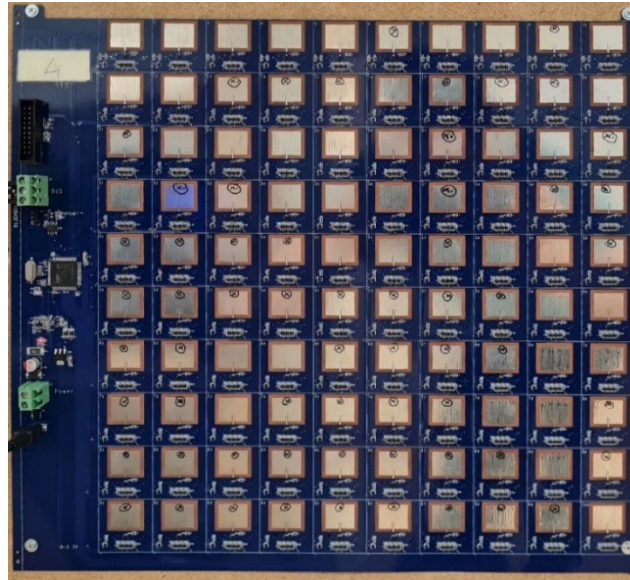


Figure 2-5 NEC RIS board

### 2.2.2 NEC Reconfigurable Intelligent Surface

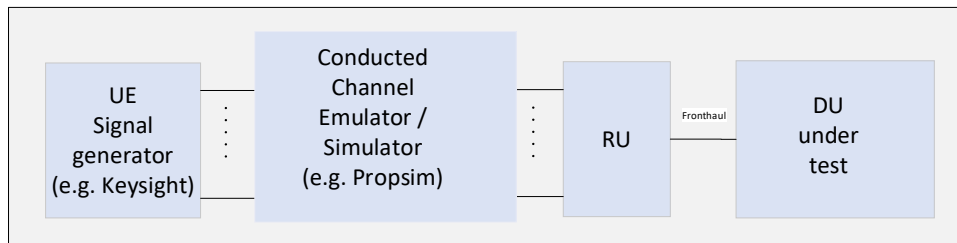
NEC RIS board consists of 100 patch antennas in a  $10 \times 10$  grid of unit cells (each with one antenna), implemented with printed circuit board (PCB) technology on a board with a thickness of 0.6 mm. The board is depicted in Figure 2-5.

The antennas are separated by a distance equal to  $\lambda/2$ , both horizontally and vertically, with  $\lambda$  being the wavelength of the supported carrier signals. The operating frequency of the RIS is 5.3 GHz and, thanks to 3-bits delay lines-based phase shifter, 7 different phase shifts equally spaced between  $0^\circ$  and  $360^\circ$  can be chosen for every unit cell. The 8<sup>th</sup> state is dedicated to the absorption mode which each redirects the incoming signal through a  $50 \, \Omega$  resistor that will dissipate the incoming signal. The RIS is designed to be a modular device. This means that multiple RIS boards can be connected together, thus creating a larger RIS, while still respecting the  $\lambda/2$  inter-element distance even between cross-board elements. For more details the reader can refer to [9].

## 2.3 DU acceleration testbed

Figure 2-6 shows the block diagram of the DU accelerator testbed at Parallel Wireless (PW). The testbed consists of a DU, a RU, a channel simulator/emulator, and different User Equipment (UEs). Any DUs under test can be deployed either in an x86-based platform, an ARM-based platform and a platform containing a Graphics Processing Unit (GPU), e.g., the NVIDIA Jetson AGX Orin. Second, the carrier frequency ranges supported are below sub-6 GHz. The channel emulator can be used to create the relevant propagation channels (rural or urban) by filtering the signal using a multipath channel impulse response. For example, a PropSim<sup>1</sup> channel emulator can be used to map all UE Tx antenna to all UE Rx antennas. The way this emulator implements the multipath coefficient is by generating several taps, each with a different mean power level. Then, the value of the tap changes as a function of time, for emulating different channel realisations. The delay spread is defined as the Root Mean Square (RMS) delay of the channel.

<sup>1</sup> <https://www.keysight.com/us/en/products/channel-emulators/propsim-platforms.html>



**Figure 2-6 DU HW accelerator PoC setup [1]**

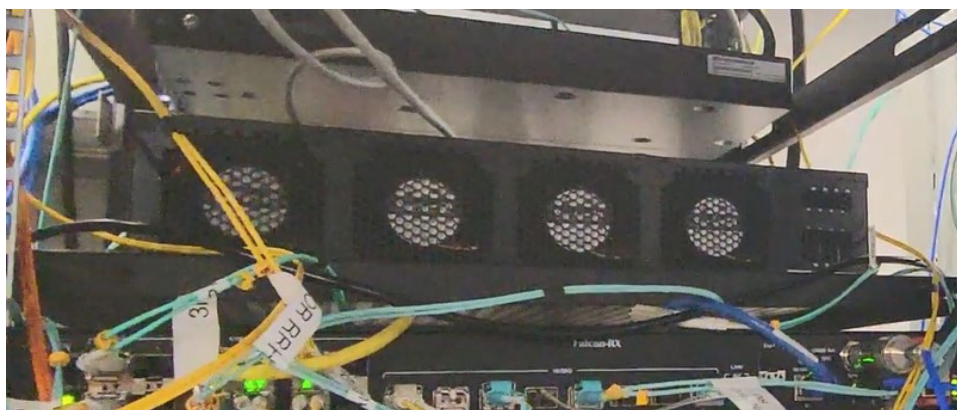
This testbed allows us to test different MIMO scenarios and to emulate correlations between the different Tx antennas and the different Rx antennas. Thus, this testbed is well suited to test different levels of spatial diversity and challenge the DU under test. The components of this demo are presented in Figure 2-7, Figure 2-8 and Figure 2-9. In addition to the testbed featuring the possibility of emulating the channel, PW is able to provide a simulated signal demo by running pre-recorded signals on the DUs under test.



**Figure 2-7 Waveform generator – Keysight EXM**



**Figure 2-8 Channel emulator – Keysight Prosim**



**Figure 2-9 DU under test – Intel Icelake Server**

## 2.4 BT laboratories testbed in Adastral Park

The BT's research and development campus at Adastral Park, located in Martlesham Heath near Ipswich, UK, serves as a premier hub for deploying and testing O-RAN radio access technologies. This state-of-the-art facility, detailed in BeGREEN D5.1 [1], plays a role supporting BeGREEN PoC implementations described in this deliverable. Specifically, it hosts both Accelleran and i2CAT's O-RAN solutions, and RunEL's solution for PoC1 and PoC5 use cases, respectively, facilitating a robust environment for experimenting with and validating new RAN technologies. The Adastral Park laboratory is equipped with essential interfaces to deploy Accelleran's dRAX and i2CAT's Non-Real-Time RIC, backed by VPN connectivity for smooth integration with their respective laboratories, which also houses additional testing equipment, such as the TeraVM AI RSG, enabling automated RIC and xApps/rApps validation. This connectivity enables collaborative development work and thus streamlines testing across facilities, strengthening interoperability between systems.

### 3 BeGREEN Proof-of-Concepts

The purpose of this chapter is to first make the mapping of the PoCs and the current BeGREEN architectural blueprint. The architectural work proposed in BeGREEN D2.2 and the evolution included in BeGREEN D4.2 has accommodated the added features being promoted in BeGREEN. WP5 takes the BeGREEN architecture as the reference model and attempts to implement various of its artifacts in different PoCs (see Figure 3-1). Needless to say, the demonstration activities that revolve around the PoCs do not represent the full implementation of the reference architecture but are able to provide representative results that confirm the gains achieved by BeGREEN's offering. The experimental validation will confirm the fundamental elements and discoveries of the project.

Then, this chapter describes BeGREEN PoCs that will be deployed and demonstrates the use cases that are associated to each. Full level of details on how to build the PoC will be provided in the following sections.

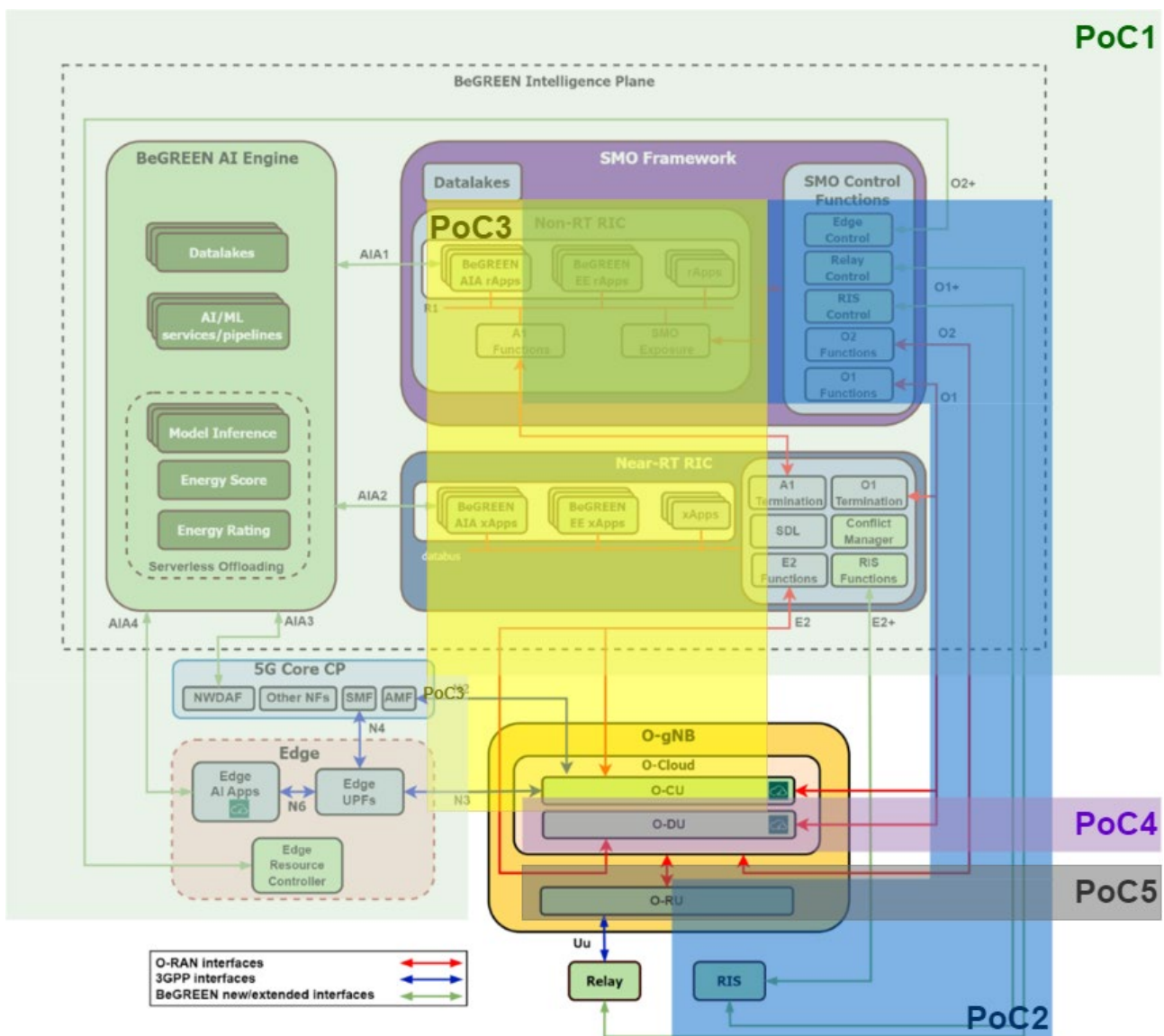


Figure 3-1 Mapping of each of the PoCs to BeGREEN's architectural framework

### 3.1 PoC1: BeGREEN Intelligence Plane

A key component of the BeGREEN architecture is the Intelligence Plane, designed to enable AI/ML-powered functions for rApps and xApps, facilitating intelligent closed-loop automation aimed at improving EE. This PoC will test the Intelligence Plane's capabilities, including AI/ML-enhanced rApps/xApps aimed at enhancing the EE of the RAN. The setup will emulate a RAN environment using Viavi's TeraVM provided by BT, offering the flexibility and scalability needed to test various scenarios involving multiple cells, users, and traffic patterns.

#### 3.1.1 PoC1 updated description

The PoC1 integrates the main Intelligence Plane components. First, the non-RT RIC developed by i2CAT, which hosts rApps for RAN optimization using AI/ML models trained on data collected from emulated E2 nodes. These models are hosted in the AI Engine, which exposes model inference in a serverless way through AI Engine Assisted (AIA) rApps. Additionally, the AI Engine also implements Energy Score and Rating functions, which are used to determine the areas or cells requiring of energy saving policies. The control rApps will determine the energy saving policies to be applied, notifying them to the near-RT RIC through the A1 interface. Control and AIA rApps are fed with data from RAN nodes, which is exposed through a KPI producer rApp connected to the Near-RT RIC through O1.

Secondly, the Near-RT RIC developed by Accelleran will handle fast telemetry and control operations for the RAN, utilizing xApps for controlling RU configurations and supporting energy-saving operations based on non-RT policies. The Near-RT RIC is part of the dRAX product, that provides the telemetry, via the Telemetry Gateway (TGW), that collects information from O-RAN and non-O-RAN compliant interfaces and merged into 3GPP data messages to be distributed in the dRAX data bus that also sends information through the O1 interface. Conversely, the TGW allows sending control messages to the RAN based on control decisions made by the xApps. Additionally, the Near RT- RIC, has direct interface with the dashboard that present the metrics and results from the system and its performance. Finally, the near-RT RIC communicates with TeraVM environment in order to apply the RAN control and monitor the RAN KPIs. Figure 3-2 depicts the distributed implementation of PoC1 by the three partners involved.

Based on feedback from reviewers, it has also been identified a new use case, PoC1 use case 3, which is devoted to Conflict Management. This additional use case will address potential conflicts between Energy Saving (ES) xApps and other RAN control applications like Smart Handover (SHO) xApps. The detailed description of this new use case will be provided in the subsequent sections.

Figure 3-3 illustrates the main components involved in PoC1. For a more detailed description of these components, the reader is referred to BeGREEN D4.2 [5].

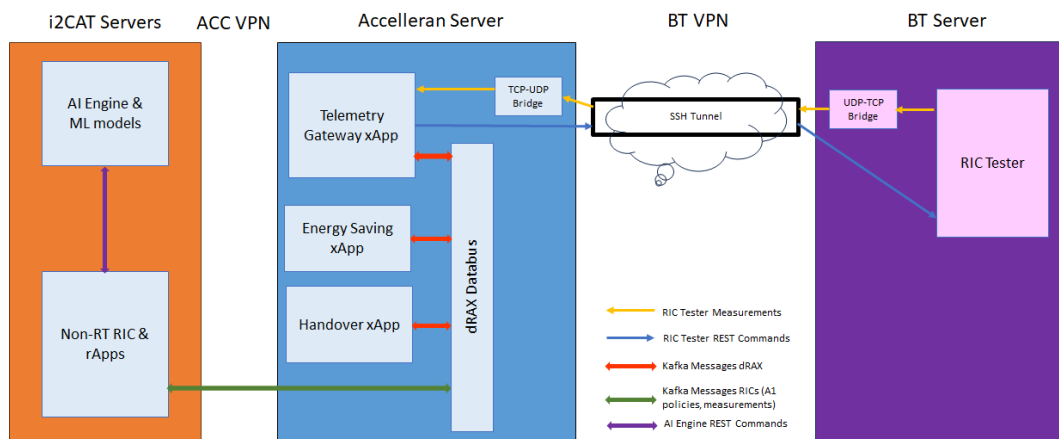


Figure 3-2 Distributed PoC1 implementation detailed set up



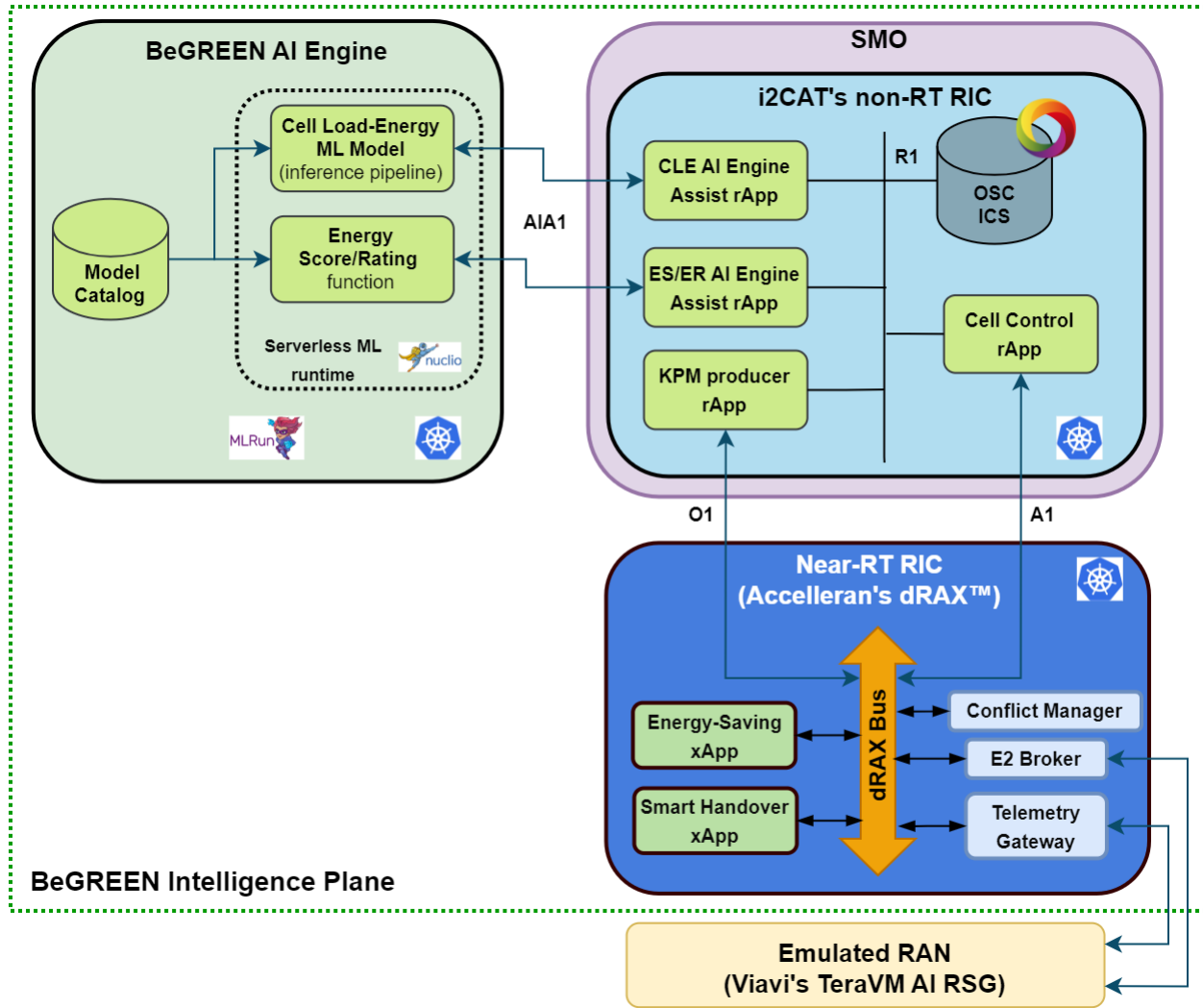


Figure 3-3 PoC 1 - main architecture

The following use cases are described to evaluate the implementation of the Intelligence Plane:

- PoC1 – Use Case 1 – Intelligence Plane baseline:** This first use case will entail the validation of the Intelligence Plane baseline architecture comprehending the AI Engine, the RICs and the RAN emulator. First, the basic O-RAN operation will be evaluated, such as supporting the different required interfaces enabling RAN node control and monitoring (e.g., E2, O1, A1...). Then, we will consider the integration of the AI Engine by implementing and evaluating the serverless environment. Finally, we will demonstrate the support of AI/ML workflows including model training and inference, and its exposure to rApps and/or xApps.
- PoC1 – Use Case 2 – RU energy-saving control through the Intelligence Plane:** This use case will validate the utilization of the Intelligence Plane to empower rApps/xApps targeting EE. The focus will be RU on/off control and Tx power control through an xApp according to the monitored status of the network (e.g., user location and traffic demands). In addition, the xApp operations will allow configuration through A1 policies, via rApp AI/ML-based predictions. The A1 policy specific for energy saving was defined in BeGREEN D4.2 and has been adopted in this use case, ensuring that both RICs are able to generate and process it. The use case scenario will be based on the cell deployment in Adastral Park, where some cells serve as coverage cells while others function as capacity cells.
- PoC1 – Use Case 3 – Conflict Management:** In this PoC, we aim to evaluate potential conflicts arising from the interaction of different xApp applications within the RAN. Specifically, we will focus on two key

applications: an ES xApp and a SHO xApp. Each xApp offers distinct actions and solutions for optimizing RAN operations. However, conflicts may emerge when, for example, the ES xApp necessitates switching off a cell, while the SHO xApp requires handing over users to that very cell. Through the BeGREEN project, we have identified this scenario as an ideal opportunity to demonstrate conflict management within an intelligent RIC. We will develop a Conflict Manager, integrated with A1 policies, to resolve such conflicts. This Conflict Manager will send policy guidelines to orchestrate xApp actions, ensuring harmonious performance. For instance, the ES xApp will send A1 policy messages to the SHO xApp, advising which cells are available for action, thereby preventing conflicts.

These three use cases will be evaluated by means of different KPIs and functional validations. On one hand, the proper execution of both use cases will validate the implementation of the Intelligence Plane framework, including the RICs, the datalakes, the AI Engine and related functions. Additionally, in the case of the evaluated ML models, we will consider model performance indicators such as accuracy or precision. On the other hand, use case 2 will be evaluated measuring the energy consumption and the achieved throughput, characterising the performance of the developed xApps/rApps in terms of EE and QoS. Finally, use case 3 will validate the correctness of conflict management procedures.

### 3.1.2 PoC1 updated planning

Table 3-1 details the updated planning of PoC1, describing the different milestones associated to each of the use cases. The envisioned planification reported in BeGREEN D5.1 has been updated according to the development status and the planned demonstrations. Note that use case 1 finalized in M23 (second review<sup>2</sup>), although some initial developments were already demonstrated at the 2024 EuCNC & 6G Summit<sup>3</sup>, as was reported in BeGREEN D4.2 [5]. Use case 2 will be demonstrated at INFOCOM 2025 [12] and at next EuCNC & 6G Summit. Outputs of these two use cases have been published in a joint paper with VIAVI [13].

---

<sup>2</sup> BeGREEN dRAX Intelligence plane integration DEMO: [https://www.youtube.com/watch?v=lauc\\_ffb8E](https://www.youtube.com/watch?v=lauc_ffb8E)

<sup>3</sup> BeGREEN Intelligence Plane EUCNC'24 Demo: <https://www.youtube.com/watch?v=N0JY0Sepgc>

Table 3-1 Updated Planning of PoC1

| PoC 1 UCs | Objective                      | Tasks                                                              | Description                                                                                                                                | Month       |
|-----------|--------------------------------|--------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| UC1       | Intelligence Plane development | AI Engine development                                              | Implement the baseline version of AI Engine, enabling serverless inference of ML models.                                                   | DONE<br>M18 |
|           |                                | Non-RT RIC developments                                            | Implement AIA rApps for hosted models and consumer rApps to demonstrate this feature. Integrate with near-RT RIC through A1/O1 interfaces. | DONE<br>M22 |
|           |                                | Near-RT RIC developments                                           | Integrate with non-RT RIC through A1/O1 interfaces. Exposure of RAN telemetry including Energy-related KPIs.                               | DONE<br>M22 |
|           | Integration with TeraVM        | TeraVM deployment and preparation                                  | Deploy TeraVM and make it accessible to RICs. Enable targeted UCs and scenarios.                                                           | DONE<br>M20 |
|           |                                | Intelligence Plane integration with TeraVM                         | Integrate near-RT RIC with TeraVM, allowing collection of KPIs and RAN control.                                                            | DONE<br>M22 |
|           | Demonstration                  | AI Engine Demonstration                                            | Demonstrate integration of AI Engine and RIC.                                                                                              | DONE<br>M18 |
|           |                                | RAN Control Demonstration                                          | Demonstrate integration of Intelligence Plane and TeraVM.                                                                                  | DONE<br>M25 |
| UC2       | Energy-Saving RAN Control      | Control rApp development                                           | Develop a control rApp managing energy-saving policies according to UC logic.                                                              | DONE<br>M25 |
|           |                                | Control xApp development                                           | Develop control xApps devoted to energy-saving use cases and implement control policies to manage them.                                    | DONE<br>M25 |
|           |                                | Integration with TeraVM                                            | Integrate rApps and xApps with TeraVM to test developed control-loop.                                                                      | DONE<br>M26 |
|           | AI-driven RAN Control          | ML-driven Control-loop development                                 | Integrate ML model outputs with the control-loop, for instance load predictors.                                                            | M28         |
|           |                                | ML models development                                              | Develop the required ML models.                                                                                                            | M28         |
|           | Demonstration                  | ES control-loop validation                                         | Validate developed energy-saving strategy.                                                                                                 | M28         |
|           |                                | AI-driven ES control-loop validation                               | Validate developed ML-based energy-saving strategy.                                                                                        | M29/M30     |
| UC3       | Definition of CM               | Definition of the Conflict management process                      | Define the mechanism to implement the conflict management guidance based on A1 policies and the entities needed inside the RIC.            | DONE<br>M20 |
|           | Development work               | Update of xApps to support Conflict Management                     | Implementation of functionalities inside the xApps and the Conflict Manager to account and avoid conflicts.                                | DONE<br>M22 |
|           | Initial testing                | Definition of testing scenarios and integration of functionalities | Integrate initial conflicts and functionalities in the system.                                                                             | DONE<br>M23 |
|           | Demonstration                  | Conflict management validation                                     | Validate developed Conflict management strategy.                                                                                           | DONE<br>M26 |

### 3.2 PoC2: Sensing-assisted communications using RIS

This PoC aims to demonstrate how user positioning data coming from sensing services can be used for energy

savings in future mobile networks. There are two main entities that play a role PoC2: the Sub-6 sensing system and the RIS board.

### 3.2.1 PoC2 updated description

The scenarios considered for PoC2 are an anechoic chamber (cf. Figure 3-4 in BeGREEN D5.1) and a laboratory room.

**PoC2 – Use Case 1** – as included in BeGREEN D5.1, we test standalone sensing by setting up a sensing demo including only the Sub-6 sensing system (without the RIS). This use case has been initially showcased at EuCNC'24 conference (see Figure 3-4), and the results associated to it have been already captured in BeGREEN D3.2 [3].

So far these demonstration activities have been used to verify the initial functionality, to demonstrate the capabilities of the sensing system and to provide a tentative KPI (included in Chapter 4). The initial tests have shown valuable results and the work from now on will be to refine the measurement setup and obtain the final KPIs (sensing accuracy and EE).

**IPoC2 – Use Case 2** – NEC's RIS board serves as the reflective surface in a scenario where an obstacle separates two adjacent RUs that cover different areas. We consider both Sub-6 RUs having ISAC support that can provide sensing metrics related to the position/density of the users in the scenario. The RIS board is placed aside the RUs and permits control over its reflection properties.

This use case is still under preparation, once the Sub-6 sensing system and the RIS have been assessed separately. For the final version of this deliverable, the use of the RIS can allow turning off one of the RUs offloading the users in a specific area and use the RIS and RU 2 to extend the coverage. In this way, we could cover the active users with one RU using a lower energy footprint. Figure 3-5 shows use case 2, where the users of RU 2 are located in an area that the RIS can cover. Thus, we can turn off RU 2 and use the RIS to extend the coverage to that area. However, in this use case, while the RU will not transmit any data, it still has its sensing capabilities.

**PoC2 - Use Case 3 - beam steering/tracking:** In use case 3, we extend use case 2, adding mobility to the UE that we offloaded from RU 2 to RU 1. We show how users' position/spatial density sensing data can be used to reconfigure the reflection properties of the RIS. Moving users can still be covered, and the RU can maintain its sleeping state, leading to substantial energy savings. Figure 3-6 shows use case 3 where we extend use case 2 and add mobility to the users of RU 2 that are offloaded to RU 1.

The use cases previously described will be evaluated by means of different KPIs. Meanwhile, use case 2 will be evaluated by estimating the energy consumption of the setup scenario as the main contribution is to seek opportunities to turn on and off one of the deployed RUs. On the other hand, use case 3 will be evaluated from the point of view of the sensing accuracy showing how accurately we can estimate the spatial density of the moving UE and reconfigure the RIS so that the users are still covered.



Figure 3-4 Sub-6 ISAC testbed @ EuCNC 2024 BeGREEN booth

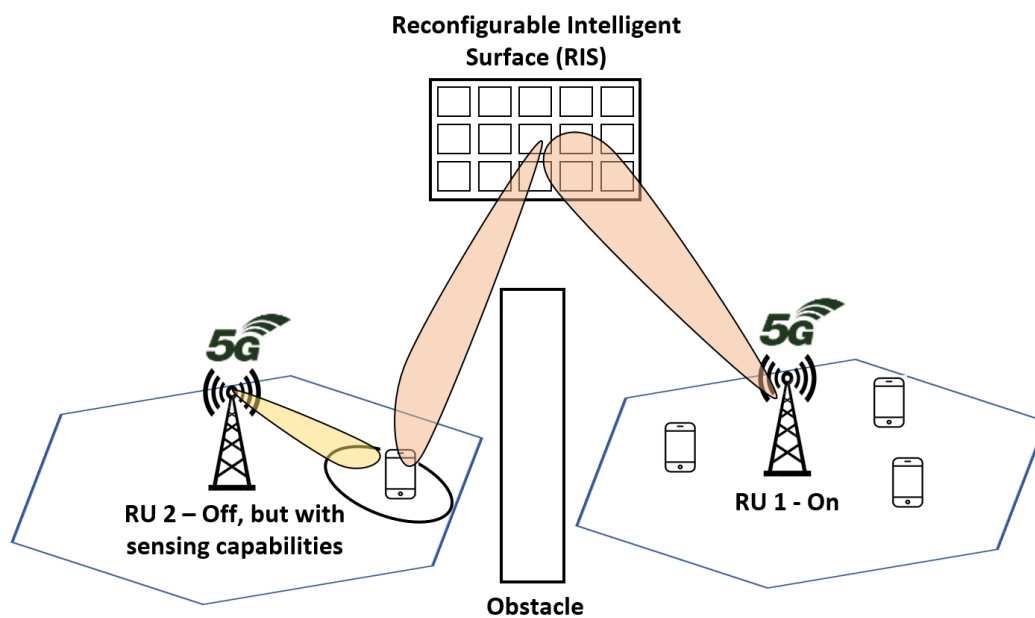


Figure 3-5 Sensing assisted communications demo - use case 2



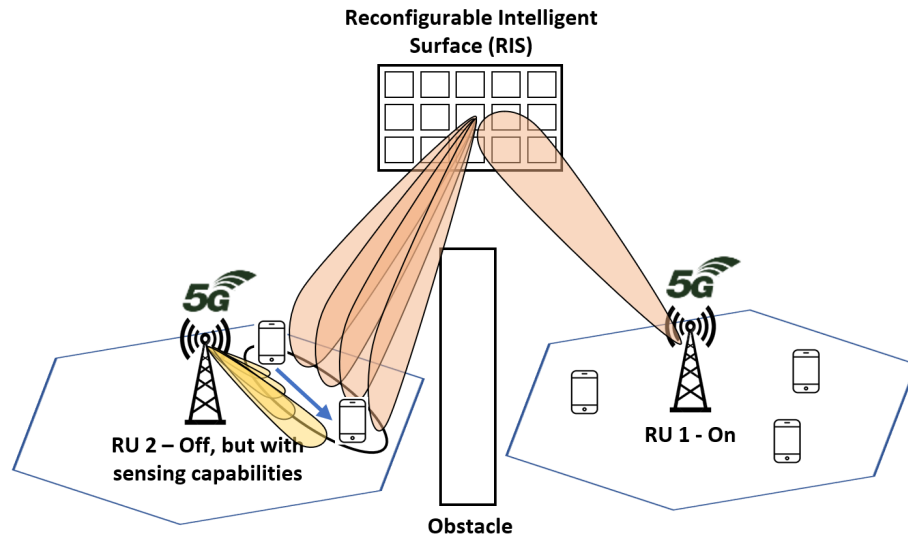


Figure 3-6 Sensing assisted communications demo - use case 3

### 3.2.2 RIS assisted ISAC

In order to showcase PoC2 use cases, the technologies developed in WP3 are being integrated in WP5 and evaluated. During this evaluation different KPIs and other parameters will be measured. In this WP, for the sake of PoC2, the developed RIS and the ISAC systems are being integrated in a single system.

To be able to perform sensing behind an obstacle, the sensing system is configured to perform sensing over the RIS. The main idea is to transmit a signal through the RIS and to receive a reflection from an object, again through the RIS. To be able to sense a wider area, the RIS is commanded to change the angle between the transmitter and the receiver.

The system was integrated and tested initially in a controlled environment, such as an anechoic chamber. This was necessary, since the developed system works in the 5 GHz ISM band, and strong multipath is expected in indoor environment.

The setup for testing the integrated RIS/ISAC system is shown in Figure 3-7. The blue triangles represent the absorbers in the anechoic chamber. The “SDR sensing node” in the figure is the developed sensing system using SDRs. The RIS is placed in front of the ISAC sensing system at a distance of 3.4 meters. Additionally, a corner reflector is placed a bit offside, hidden behind a wall made of absorbing material and completely undetectable by the sensing system. A photo of the setup is shown in Figure 3-8 and Figure 3-9.

With the current setup, the sensing system was monitoring the environment in the direction of the RIS, while the RIS was changing the angle of reflection. The 90-degree angle of reflection in the azimuth plane means that the received energy is reflected towards the transmitter. The sensing is performed by instructing the RIS to change the reflecting angle and to scan the environment. For each different angle a snapshot of the reflected signal is made and, later, a heat map of the reflected signals is created. The heat map shows from which direction and distance the reflections are coming.

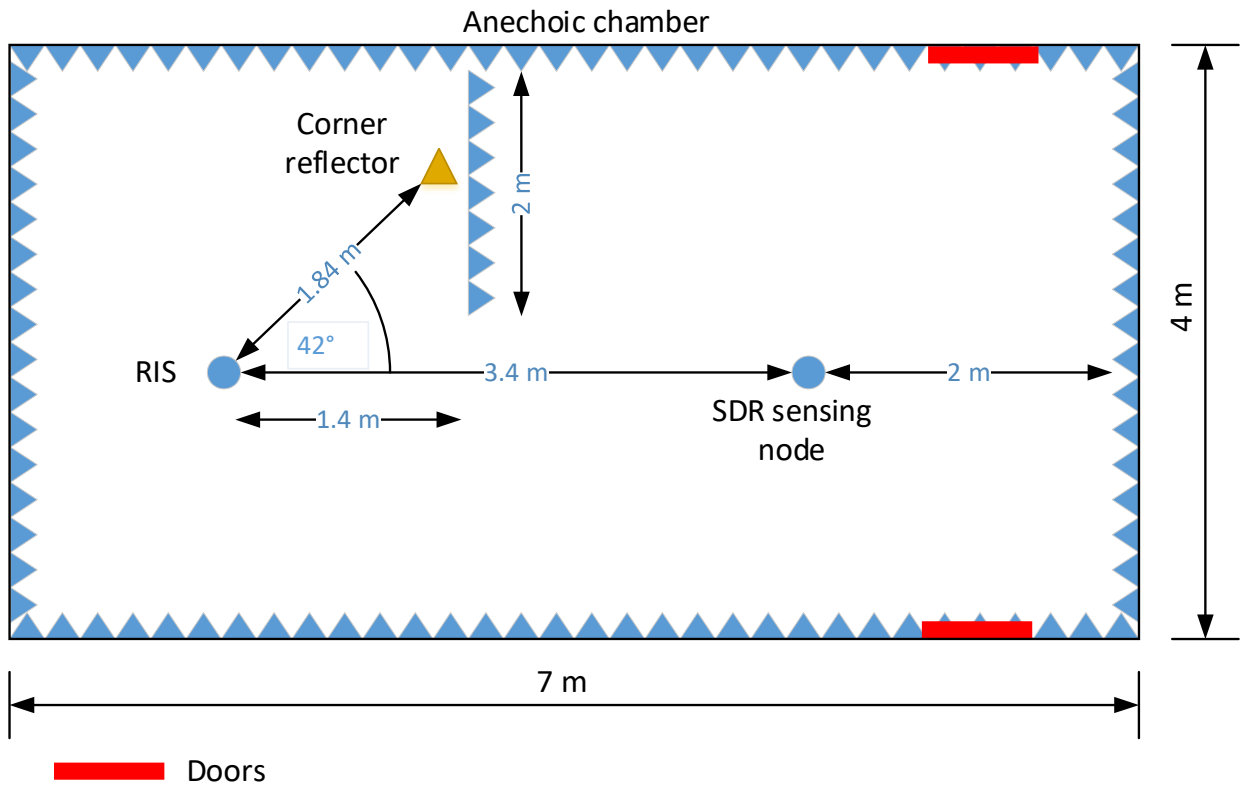


Figure 3-7 Anechoic chamber configuration

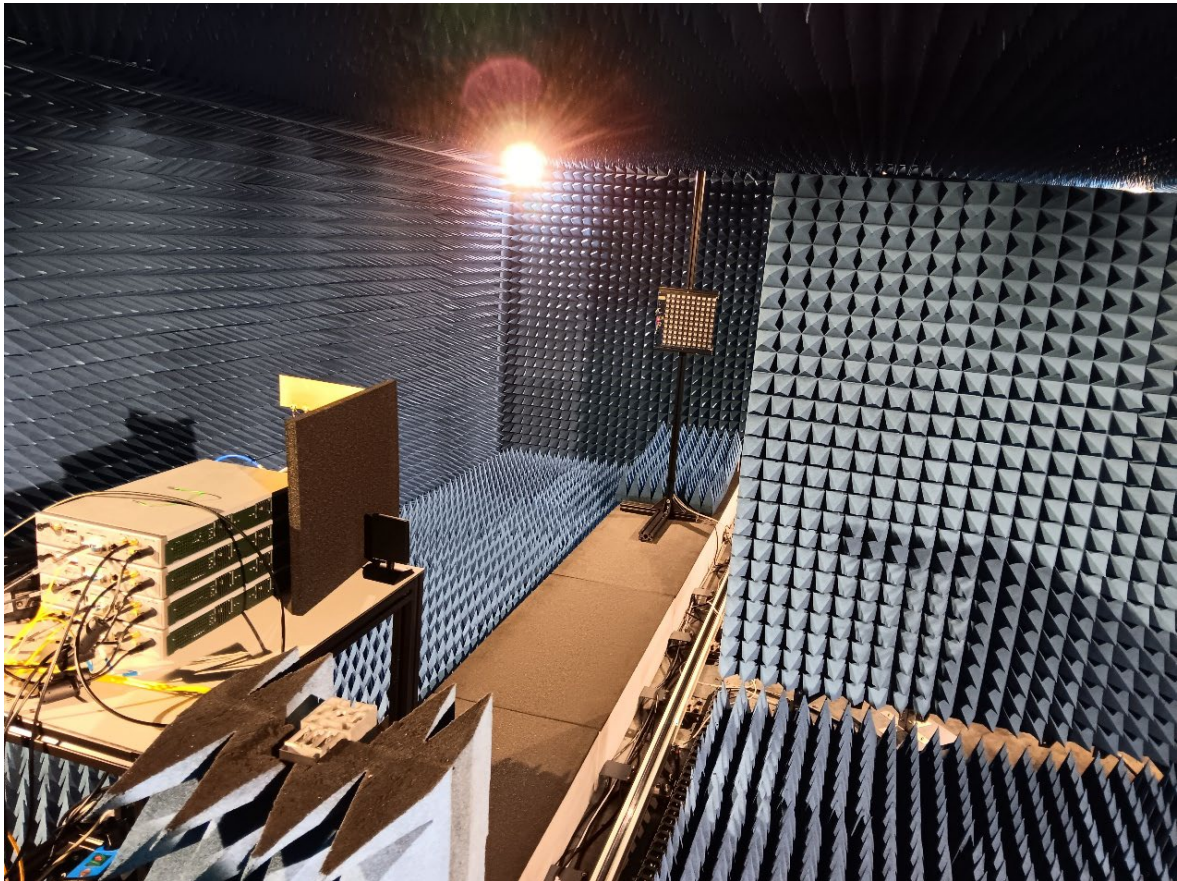


Figure 3-8 Anechoic chamber setup, view from the ISAC system towards RIS

The initial results are shown in Figure 3-10. It can be noticed that, for angles of around 90 degrees, a reflection from the RIS can be seen in the heat maps. This reflection gets lower as the azimuth reflection angle is made larger or smaller than 90 degrees. Unfortunately, during this experiment, it was not possible to detect the corner reflectors behind the wall. It is suspected that the main reason is the relatively low output power of the used SDRs. Namely, the SDR has an output power of less than 15 dBm, which is further reduced by the 1-meter cable used to connect the antenna. Additionally, the used transmit antenna has a relatively low antenna gain of 5-7 dBi, which does not improve the situation much. Since the signal has to travel through the RIS twice and the corner reflectors reflect back only a part of the power, relatively little power is received at the receiver. Furthermore, the RIS itself always reflects back a small amount of power back. This is due to the imperfections of the RIS itself.

To solve these issues, additional experiments with increased output transmit power will be performed. Namely, a PA will be used to increase the output power. The result of this experiment will be presented in BeGREEN D5.3.

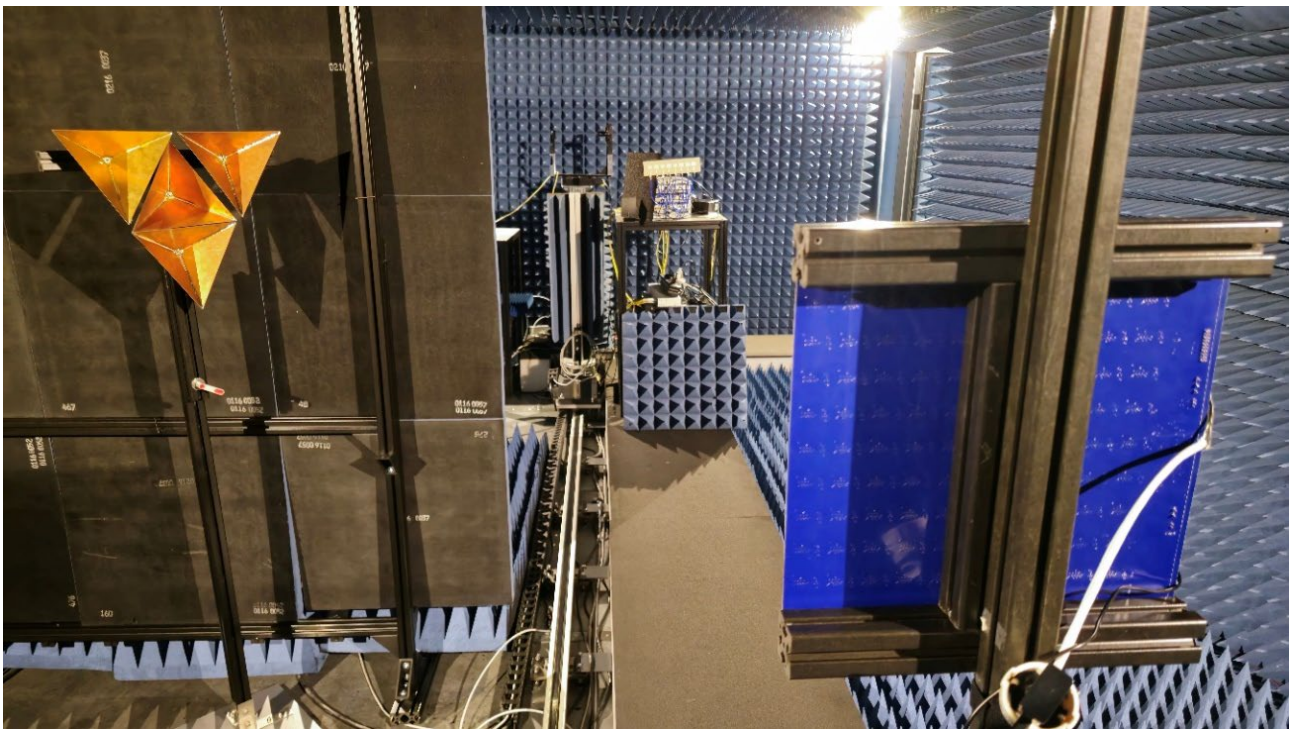


Figure 3-9 Anechoic chamber setup, view from RIS towards ISAC system and corner reflector

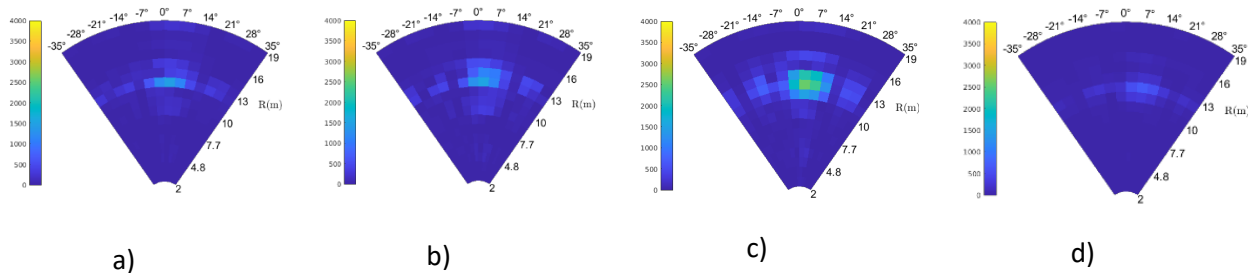


Figure 3-10 Heat maps for a) 80, b) 85, c) 90, d) 95 degrees reflection angled on the RIS



### 3.2.3 PoC2 updated planning

Table 3-2 shows the planning of the sensing assisted communications PoC.

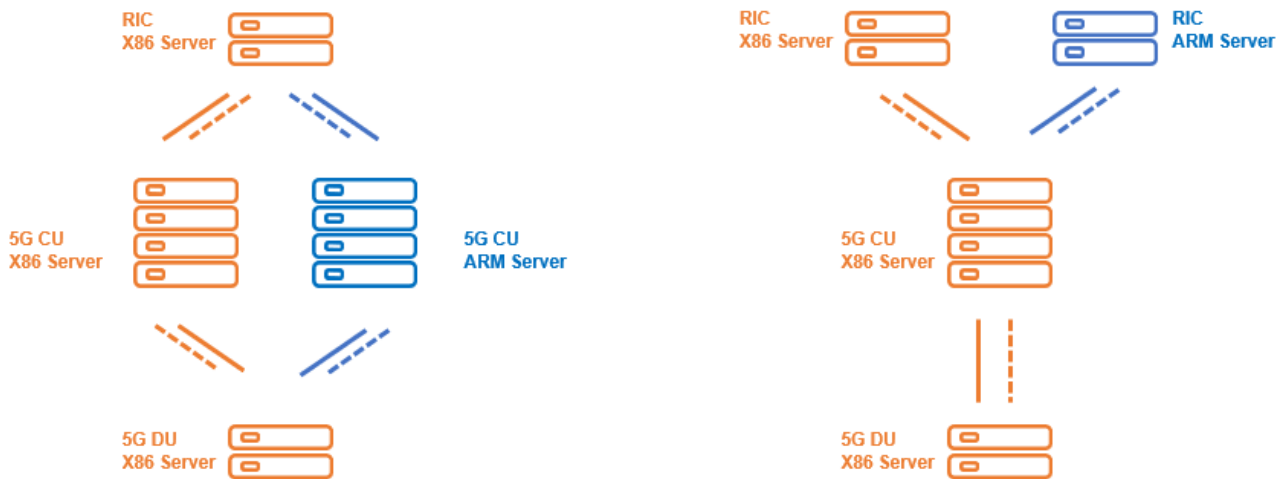
**Table 3-2 Updated Planning of PoC2**

| PoC 2 UC        | Objective                                                           | Tasks                                                                                                            | Description                                                                                                                                                   | Month     |
|-----------------|---------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| <b>UC1 (v1)</b> | Sub-6 ISAC system development                                       | Development of Sub-6 Hardware                                                                                    | Sensing demo with the sub-6 GHz ISAC system. To be used as a prerequisite for the sensing assisted communications demo with RIS                               | DONE M16  |
|                 |                                                                     | Development of Sub-6 Hardware                                                                                    |                                                                                                                                                               | DONE M17  |
|                 |                                                                     | Initial test of Sub-6 system in the lab                                                                          |                                                                                                                                                               | DONE M18  |
| <b>UC2 (v2)</b> | Sensing-assisted demo using the RIS board for coverage extension    | Setting up the necessary demo equipment for RAN functionality and sensing (Sub-6 ISAC system and RIS)            | The sensing metrics from RU 1 and 2 are pushed to an accessible database. It is possible to retrieve the position of potential users from the sensing metrics | M25 - M27 |
|                 |                                                                     | Ensure that the sensing metrics can be retrieved                                                                 |                                                                                                                                                               |           |
|                 |                                                                     | Calibrate the RIS and reconfigure it to work in the area of the scenario                                         | An rApp reconfigures the reflection properties of a RIS to offload a UE in the coverage area of RU 2 and puts it to sleep mode to save energy.                | M27 - M30 |
|                 |                                                                     | Implementation of the rApp                                                                                       |                                                                                                                                                               |           |
| <b>UC3 (v3)</b> | Beam tracking by reconfiguring the reflection properties of the RIS | The rApp periodically retrieves the sensed position of potential users and reconfigures the RIS beam accordingly | Extending the rApp to periodically reconfigure the RIS reflection properties.                                                                                 | M28 - M30 |

### 3.3 PoC3: Energy efficient CU and O-RAN RIC

The initial phase of PoC3 involves the migration of CU to an ARM server, followed by a performance evaluation compared to the x86 implementation. This evaluation covers detailed metrics such as energy consumption, power usage, and throughput, while also accounting for environmental factors that may influence these measurements. The testing includes assessing system stability, scalability, and responsiveness across varied workloads. Performance metrics will be evaluated under low, medium, and high traffic conditions, thereby ensuring an exhaustive analysis. The main scenarios include: (i) deploying both CU and RIC on independent x86 servers, (ii) deploying the CU on an ARM machine and the RIC on an x86 server, and (iii) deploying the CU on an x86 server and the RIC on an ARM server. These configurations are fundamental for establishing a baseline for system performance. Additionally, mechanisms such as the eXpress Data Path (XDP) are leveraged to enhance data processing efficiency. XDP integrates directly with the Network Interface Card (NIC) and utilizes the Berkeley Packet Filter (BPF) to manage GPRS Tunneling Protocol (GTP) messages, thereby reducing processing latency and enhancing CU performance. The main goal of PoC3 is to compare the performance of the O-RAN CU and RIC components implemented on a x86 platform and on an ARM server. Thus, PoC3 will port the x86 CU and RIC implementations into ARM servers and test whether the ARM implementation improves the energy consumption.

To delve further, XDP technology facilitates efficient packet processing by bypassing multiple layers of the network stack. This approach not only reduces latency but also significantly decreases CPU load, promoting more efficient use of system resources. In scenarios requiring high throughput — particularly in data-intensive applications or when supporting a significant number of user devices — XDP can offer substantial performance enhancements.



**Figure 3-11 CU-RIC HW acceleration proposal, left: CU energy evaluation, right: RIC energy evaluation**

By integrating these advanced methodologies, PoC3 aims to extend the potential of ARM-based servers, demonstrating their capability to match or even surpass traditional x86 platforms in specific contexts.

### 3.3.1 CU Hardware Acceleration and ARM Porting

In high-traffic environments, such as those with considerable telemetry or data-intensive operations like the BeGREEN architecture, porting the CU to an ARM platform aims to deliver both performance improvements and EE. Another significant aspect of migrating the CU to ARM is ensuring compatibility with existing network elements and protocols. This requires extensive testing for interoperability with other network entities, such as DUs and Radio Units RUs. The CU must maintain seamless communication with these components while running on ARM, which demands rigorous validation. These validations include monitoring interactions between the CU and both upstream and downstream network components, allowing engineers to identify and address potential bottlenecks or incompatibilities.

A comprehensive explanation of CU on ARM can be found in BeGREEN D5.1 [1], where specific optimizations tailored for ARM’s architecture—such as efficient utilization of its multi-core processors for parallel processing—are described in detail.

### 3.3.2 RIC Porting into ARM

The RAN RIC is another pivotal component that is subject to EE assessment in PoC3. By porting the RIC to an ARM server, we aim to determine if the ARM implementation delivers power savings while sustaining or exceeding the performance of its x86 counterpart. An extended analysis of the dRAX RIC ARM support has been done to identify local and third-party components that are vital for the performance of the RIC. The testing environment includes a Kubernetes setup comprising both ARM and x86 nodes, providing a flexible and dynamic deployment model. Kubernetes manages the workload distribution based on node resources, maximizing the efficiency of ARM and x86 architectures.

The ARM testing environment includes a two-node Kubernetes cluster—one ARM and one x86 node—where components compatible with ARM are executed on the ARM node, while the remaining components run on the x86 node. This setup provides a realistic basis to evaluate performance discrepancies between ARM and x86 architectures across various operational conditions. The laboratory infrastructure replicates that used for prior CU testing on ARM, incorporating the Amarisoft UE emulator, which emulates diverse UE traffic patterns to stress-test the RIC effectively.

The ARM machine, provided as part of the BeGREEN project, is incorporated into the Kubernetes cluster through appropriate cluster join commands. This ensures that the ARM server operates seamlessly within



the existing infrastructure. Kubernetes nodes are labelled to differentiate between ARM and x86, simplifying resource allocation and improving efficiency. Moreover, the *NodeAffinity* feature is used to route workloads to appropriate nodes, ensuring that ARM nodes prioritize tasks that benefit most from their power efficiency, while other tasks are allocated to x86 nodes.

### 3.3.2.1 Lab Setup and Amarisoft

The laboratory setup for testing the RIC on ARM includes the use of Amarisoft, which simulates up to 128 UEs. These UEs are configured to perform Radio Resource Control (RRC) measurements, ensuring detailed granularity in the reporting of metrics. The Amarisoft emulator is employed to generate traffic from the UEs, which is then reported to the RIC. Specific data flows include:

- **From DU - E2 KPM:** Key Performance Measurements (KPM) are reported from the DU using the E2 interface, facilitating performance testing of the dRAX E2 Broker. Questions arise regarding where to obtain the UE IDs, especially for per-UE KPM subscriptions.
- **From CU - dRAX Databus:** Data flows from the CU via the dRAX Databus. A critical part of this process is comparing the timestamps from the dRAX Databus to the timestamps when messages are received in the x/rApp, providing insights into system latency and data flow consistency.

### 3.3.2.2 Differentiating ARM & x86 Nodes in Kubernetes

To manage workloads efficiently in a mixed ARM and x86 environment, Kubernetes nodes are differentiated using two primary methods:

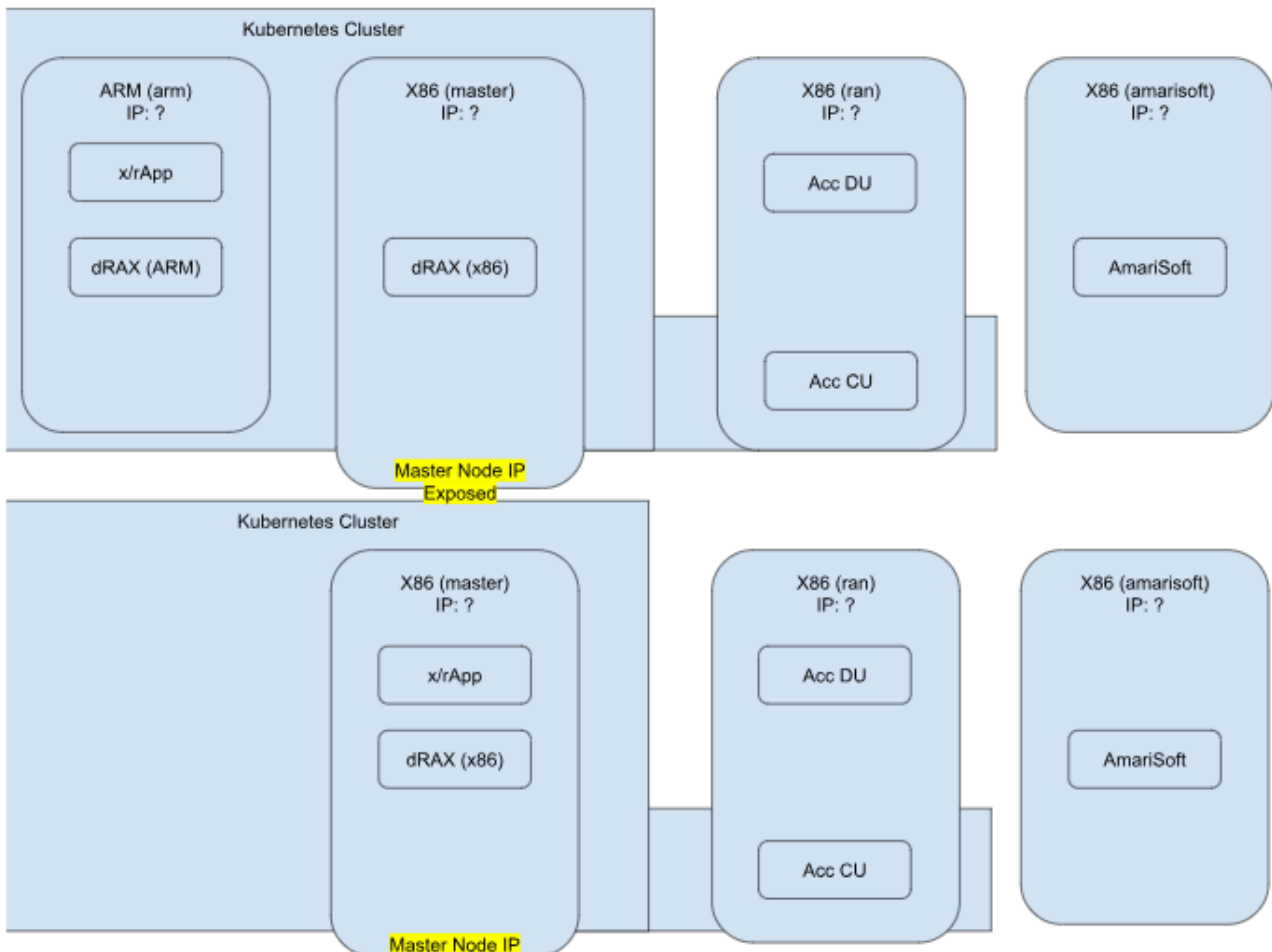


Figure 3-12 RIC on ARM evaluation set up

- **Option 1: Label Kubernetes Nodes:** Kubernetes nodes are labelled to distinguish between ARM and x86 architectures. This labelling simplifies resource allocation and allows for straightforward identification of nodes, ensuring that appropriate workloads are directed to suitable hardware.

```
Unset
kubect1 label nodes master-node my_label=arm
```

- **Option 2: NodeAffinity:** *NodeAffinity* rules are configured in Kubernetes to ensure that specific workloads are scheduled on either ARM or x86 nodes, based on their resource requirements and compatibility. This mechanism helps prioritize ARM nodes for energy-efficient tasks while allocating other workloads to x86 nodes as needed.

```
Unset
$ kubect1 describe no myarmnode
Name:          myarmnode
Roles:         control-plane,etcd,master
Labels:        kubernetes.io/arch=arm64
               kubernetes.io/hostname=myarmnode
               kubernetes.io/os=linux
```

The Grafana monitoring system captures a wide array of performance metrics—including CPU and memory usage, as well as network throughput—for both ARM and x86 nodes. These metrics are visualized in real-time, allowing engineers to make informed decisions about potential adjustments needed during testing. The goal is to assess the effectiveness of the ARM-based RIC, particularly in minimizing energy consumption without compromising RIC's essential management and control functions. The collected performance data, visualized through Grafana, facilitates a comprehensive comparison between architectures.

### 3.3.3 Full demo testing workflow and procedures

The testing workflow for PoC3 is structured into multiple phases:

1. **Setup and Deployment:** The initial phase utilizes the same testing setup used for previous CU testing on ARM. This includes the development work necessary for successful deployment:
  1. **CU Porting into ARM (v1):** The dRAX CU implementation was successfully ported to work on ARM servers, ensuring compatibility and enhanced efficiency.
  2. **RIC Porting into ARM (v2):** The dRAX RIC implementation was also migrated to ARM servers, facilitating improved performance and EE.
  3. **XDP Implementation (v3):** The eXpress Data Path (XDP) function is developed for both x86 and ARM servers, enhancing the CU's ability to handle data packets more efficiently. The XDP implementation is key to improving the overall performance of the system.

Incorporating the ARM machine into the Kubernetes cluster involves labelling nodes, deploying components, and configuring network settings to ensure optimal data transmission. Additionally, Kubernetes is fine-tuned to balance workloads effectively across both ARM and x86 nodes.

2. **Traffic Generation (v4):** The Amarisoft emulator generates traffic by simulating UE interactions through the Accelleran CU, making the data accessible via the dRAX Databus. The emulator reproduces a variety of traffic scenarios—including bursty, constant bit rate, and variable bit rate conditions—to simulate real-world environments. This diversity in traffic generation allows for an in-depth assessment of system performance under different load conditions.
3. **Testing Algorithm Deployment (v5):** A resource-intensive Testing Algorithm is deployed to evaluate

system load on both ARM and x86 setups. The Testing xApp consumes data from the dRAX Databus, providing metrics related to CPU and RAM utilisation. This algorithm is designed to be computationally demanding, stressing the system to provide a comprehensive understanding of how ARM and x86 systems cope with extreme workloads. Multiple runs of the algorithm are conducted to ensure consistency and reliability in the results.

4. **Performance Monitoring (v5):** Performance metrics are collected via Grafana dashboards, both on a system-wide level and for individual components such as the Testing xApp. The dashboards provide insights into not only CPU and memory usage but also critical network metrics such as latency and packet loss, which significantly impact overall system performance.
5. **Experiment Execution (v6):** The experimental phase starts with the x86-only configuration, followed by the integration of ARM into the setup. Each configuration undergoes multiple iterations to mitigate environmental variability and gather substantial data for statistical analysis. This enables meaningful comparisons between ARM and x86 nodes.
6. **Result Analysis and Reporting:** The comparative analysis between ARM and x86 setups assesses the EE and throughput of each architecture. These results are documented, with particular emphasis on energy savings achieved by the ARM implementation. Visualizations—such as graphs and charts—are used to clearly present performance differences, thus supporting data-driven recommendations for future development efforts.

This structured testing approach thoroughly evaluates the transition of both the CU and RIC to ARM platforms. It provides valuable insights into performance gains and EE, including quantitative metrics and qualitative observations that inform the overall impact of ARM deployment on system performance. This holistic assessment underscores both the benefits and the limitations of ARM architecture in practical RAN environments, serving as a basis for future improvements.

### 3.3.4 KPI description for PoC3 testing Workflow

The KPIs for RIC hardware acceleration with an Intelligence Plane are outlined in PoC3. The first KPI targets a power consumption reduction exceeding 20% when operating the CU on ARM architecture while utilizing hardware acceleration for the Packet Data Convergence Protocol (PDCP) of CU-UP. The second KPI considered aims for a power consumption reduction surpassing 20% when running the Near-RT RIC on ARM, combined with hardware acceleration for xApp operations.

### 3.3.5 PoC3 updated planning

As described in Section 3.3.3, the updated PoC3 planning is reported here. In this PoC the porting of both CU and RIC into the ARM architecture, and then, the creation of the XDP functionality for both architectures and finally the testing is arranged. The overall performance tests will be organised in single or multiple UEs scenarios. Detailed planning of PoC3 is found in Table 3-3.

**Table 3-3 Updated Planning of PoC3**

| PoC3 Version | Description                   | Functionalities                                                                                                             | Required Developments                                                   | Month       |
|--------------|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|-------------|
| V1           | CU porting into ARM           | dRAX CU implementation working on ARM servers.                                                                              | Extend Accelleran CU into ARM.                                          | DONE<br>M18 |
| V2           | RIC porting into ARM          | dRAX CU implementation working on ARM servers.                                                                              | Extend Accelleran RIC into ARM.                                         | DONE<br>M22 |
| V3           | XDP implementation            | XDP function ability either for x86 and ARM servers.                                                                        | Develop the XDP CU enhancement for the performance of the system.       | DONE<br>M19 |
| V4           | CU in ARM Testing             | Single test to probe the capabilities of the CU based on a creation of a traffic generation with diverse traffic scenarios. | V1 ready                                                                | DONE<br>M20 |
| V5           | RIC in ARM Testing            | Testing algorithm development and deployment for RIC testing.                                                               | Grafana web page for data visualisation. V2 ready                       | DONE<br>M23 |
| V6           | Full demo testing             | Full capabilities for HW acceleration                                                                                       | Integration of the enhanced capabilities with single UE and multiple UE | DONE<br>M25 |
|              | Result analysis and reporting | All                                                                                                                         |                                                                         | M28         |

### 3.4 PoC4: Energy-efficient DU implementation using hardware acceleration

This PoC is on implementation of DU high-PHY algorithms, using hardware acceleration techniques, to reduce power consumption compared to legacy implementation. Specific targets are the LDPC decoder and the sphere decoder, as described in [8]. These methods will be demonstrated running over operational platforms.

#### 3.4.1 PoC4 updated description

PoC4 will be implemented at the laboratories of PW in PW's acceleration testbed, which is described in section 2.2.2. Actual HW will be used, which features standard test equipment in conducted mode. The setup is shown in Figure 3-13. PoC4 will show how well different DUs under test perform relative to the power consumption KPIs and receiver performance KPIs. Specifically, PoC4 aims to assess how much power reduction can be achieved using any of the suggested BeGREEN DU architectures (i.e., ARM and ARM+GPU) and compare them to legacy architectures (i.e., x86). The associated use cases are as listed as follows.

##### 3.4.1.1 PoC4 - Use case 1 – testing of DU algorithms in simulation mode

As a preliminary stage of any DU development and related PoC, before running the DU under test in real-time, a stage of running the platform in simulation mode is performed. This enables better debuggability and helps with algorithms development and tuning. A Matlab simulation is used for generating the UE signals, and for simulating the fading and channel impairments. The UE signal, after undergoing the fading channel and impairments, is then injected as a baseband In-phase and Quadrature (IQ) file into the DU under test memory, and from there on the DU will run the code as it would run in a real deployment. Another advantage of this stage is that we can simulate any channel and any impairment, which is sometimes very hard to achieve in a real-time PoC. In this use case, the power consumption of the DU under test can be derived by tools such as the “Jetson Stats Package” [11] and utilisation counters. The receiver performance can be measured using the receiver outputs, e.g. by counting how many blocks were decoded successfully, how many blocks failed, and derive the block error rate (BLER).

##### 3.4.1.2 PoC4 - Use case 2 – testing of DU algorithms in emulation mode

As a second stage the demo will be performed in real-time, after fronthaul integration with an RU. There, a signal generator (such as Keysight) will be used to generate the UE signal in RF frequency and a channel

emulator will be used to generate the channel between the UE transmit antennas and the gNB receive antennas. The advantage of the emulation mode demo is that it mimics the operation of the DU in the real product. The channel emulator is a very powerful tool and is used to generate scenarios which emulate real-world deployments. In this demo, the power consumption of the DU under test can be either derived like in **use case 1** (by tools such as the “Jetson Stats Package” and utilisation counters) or by power measurement tools. The receiver performance can be measured using the test automation entity, which will collect receiver outputs and statistics and analyse them.

Table 3-4 PoC4 Scenarios for LDPC Decoder

| # | Propagation conditions <sup>4</sup> | Modulation | LDPC Code Rate |
|---|-------------------------------------|------------|----------------|
| 1 | TDLB100-400                         | QPSK       | 193/1024       |
| 2 | TDLC300-100                         | 16QAM      | 658/1024       |
| 3 | TDLA30-10                           | 64QAM      | 567/1024       |

Table 3-5 PoC4 Scenarios for Sphere Decoder

| Scenario  | MIMO Mode | # of layers | Target Environment |
|-----------|-----------|-------------|--------------------|
| PoC4 Sen1 | SU-MIMO   | 4           | Rural              |
| PoC4 Sen2 | SU-MIMO   | 4           | Urban              |
| PoC4 Sen3 | MU-MIMO   | 4           | Rural              |
| PoC4 Sen4 | MU-MIMO   | 4           | Urban              |

The simulated scenarios (in use case 1) or emulated scenarios (in use case 2) are listed in Table 3-4 for LDPC decoder. For sphere decoder the scenarios are listed in Table 3-5.

The intent is that these scenarios will cover different deployment options and different environments. When a UE requires very high throughput and the available allocation is limited, we increase the channel’s capacity by introducing Single User MIMO (SU-MIMO), where multiple layers can be allocated to a single UE. On the other hand, when there are many users requiring UL allocation and the available allocation is not sufficiently large, we use Multiuser MIMO (MU-MIMO) to be able to multiplex several UEs. The ability to multiplex multiple layers to the same UE or multiple UEs on the same physical resource is possible thanks to the spatial diversity introduced by the channels.

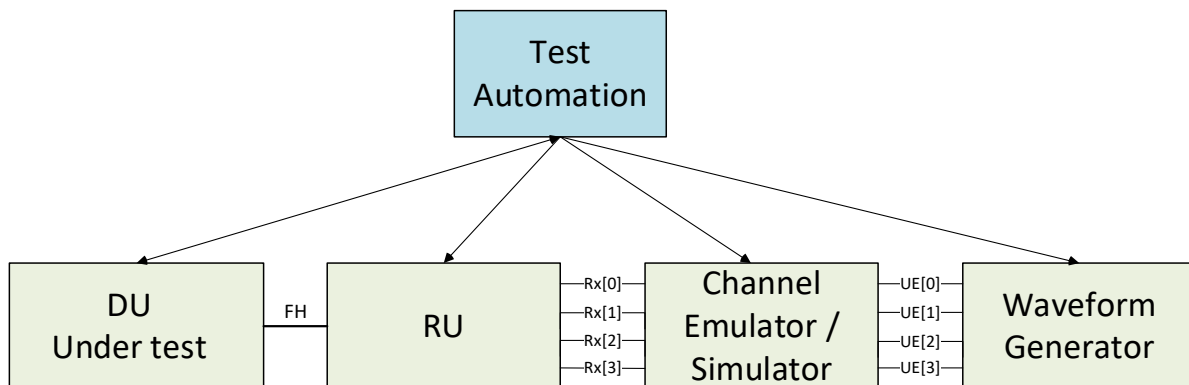


Figure 3-13 PoC4 DU HW accelerator setup

<sup>4</sup> Propagation conditions are defined in Annex G of [10].



When this diversity is large, we can use a simple linear Minimum Mean Square Error (MMSE) equalizer as the demodulator. However, when the spatial separation is not very good (which is a very common case), we would need to use the sphere decoder, which performs much better in such scenarios. In the PoC4, we will use both linear MMSE and the sphere decoder and compare them while running on the different environments and platforms. In addition to the demodulator, when working with MIMO, as the number of layers increases, the load on the LDPC decoder will increase. Hence, we will also compare the LDPC processing and run it on the different MIMO modes, environments, and platforms.

PoC4 will measure various key performance indicators (KPIs) focusing on power consumption using a metered Power Distribution Unit (PDU). It is anticipated that the BeGREEN implementations on ARM or GPU will exhibit a minimum 15% reduction in power consumption compared to legacy implementations, and a comparison between x86 and ARM architecture factors will be established for benchmarking against the state-of-the-art. In BeGREEN, the modules under development, such as the LDPC decoder and Sphere Decoder, are integral components of the gNB PUSCH receiver, and their performance is evaluated in two key ways, BLER versus Signal-to-Noise Ratio (SNR), with particular interest in the 10% point, and Throughput versus SNR, with a focus on the 70% point. As a fundamental performance benchmark, tests outlined by 3GPP under title “Base Station conformance testing” ([10] Section 8.2.1) will be conducted. Subsequently, BLER and throughput tests representing BeGREEN’s use cases, as defined in BeGREEN D2.1 Section 2.3 1, will be carried out in the next testing phase.

In the EuCNC demo we have achieved significant reduction in power consumption as shown in D3.2 [3]. Table 2.2, where we see that ARM power consumption is 22% lower than x86 on average.

### 3.4.2 PoC4 updated planning

The planning of this PoC is outlined in Table 3-6.

**Table 3-6 Updated Planning of PoC4**

| PoC4 Version | Description                                         | Functionalities                                                                                                                  | Required Developments                                                               | Month              |
|--------------|-----------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------|
| <b>V1</b>    | Use case 1: Simulation mode demo for LDPC - CPU     | DU algorithms running on x86, ARM with simulated RF signal                                                                       | DU algorithms implemented on x86, ARM<br>Testing scenario definition and generation | <b>DONE</b><br>M18 |
| <b>V2</b>    | Use case 1: Simulation mode demo for LDPC - GPU     | DU algorithms running on GPU with simulated RF signal                                                                            | DU algorithms implemented on GPU                                                    | <b>DONE</b><br>M22 |
| <b>V3</b>    | Platform bring up                                   | Emulated mode setups ready                                                                                                       | Fronthaul integration between DU and RU for CPU<br>Bring-up of demo setup           | <b>DONE</b><br>M22 |
| <b>V4</b>    | Use case 2: Emulation mode demo for LDPC            | DU algorithms running on x86, ARM with emulated RF signal<br>DU algorithms running on GPU with emulated RF signal – nice to have | Testing scenario generation<br>Algorithms modification and improvements             | M28                |
| <b>V5</b>    | Use case 3: Simulation mode demo for Sphere Decoder | Same as V2, but for sphere decoder                                                                                               | Sphere decoder implemented on CPU and GPU                                           | M30                |

### 3.5 PoC5: RU power amplifier blanking

The diagram in Figure 3-14 shows the main components of the PoC5 that consist of a 5G end-to-end (E2E) system with three main modules:

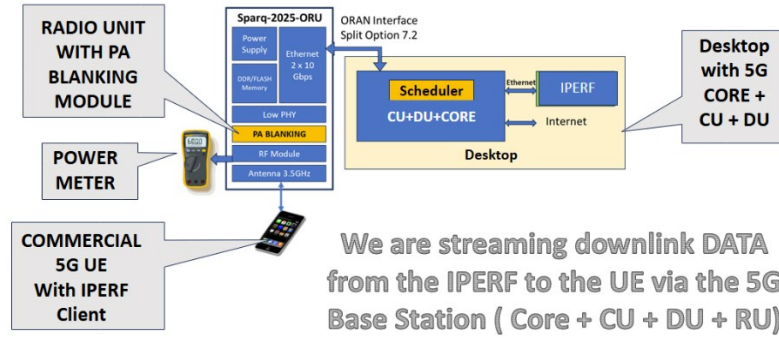


Figure 3-14 RU PA power blanking demo

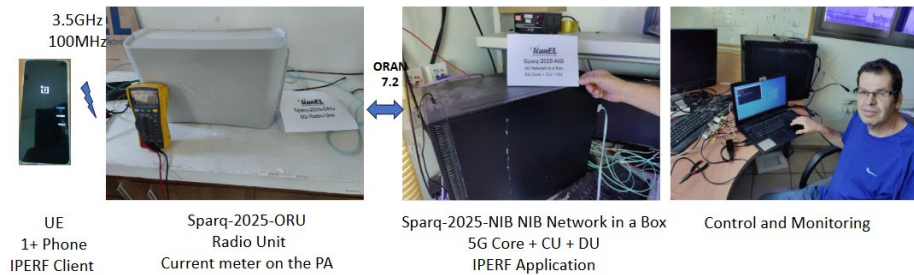


Figure 3-15 PA blanking tests carried out in Sept. 2024

- REL 5G Sparq-2025-ORU Radio Unit (with PA blanking module).
- Server with (Intel Based) that includes the DU, CU and 5G Core of a 5G SA network as well as a Video streaming application that will create data to be sent over the network to the UEs.
- Commercial UE devices.

### 3.5.1 PoC5 – purpose and use cases

PoC5 purpose consists of comparing the power consumption of the RU when the power blanking module is active to the power consumption of the RU when the power blanking module is not active and estimating the power saving that this solution can achieve. The algorithm inspects each orthogonal frequency-division multiple access (OFDMA) symbol that the scheduler (in the DU) plans to transmit via the RU, and if the next symbol to be transmitted does not include any data, it switches off the RU PA.

To make the PA blanking solution more efficient, it is required to configure the Medium Access Control (MAC) scheduler in the DU to allocate the data to be transmitted mainly in the frequency domain rather than the time domain as depicted in Figure 3-16. This process maximizes the period that PA is turned off for a specific amount of data to be transmitted in a symbol.

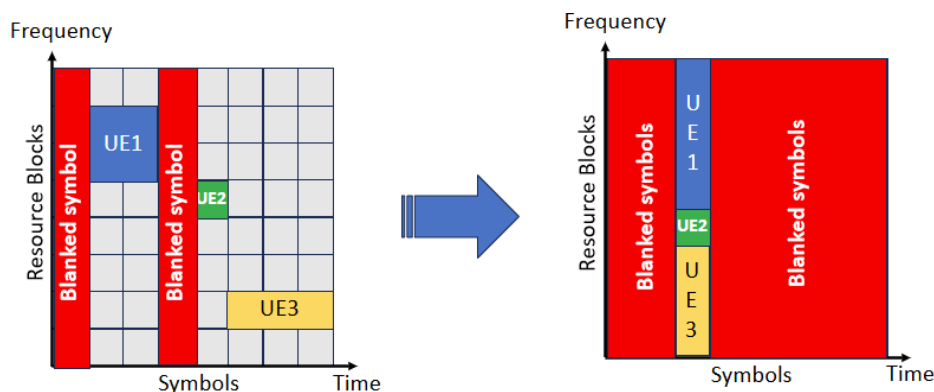


Figure 3-16 Powering-off the PA during more symbols with the PA blanking module

PoC5 plan was to do the test in three different use cases as follows:

**PoC5 - Use case 1** – Indoor over cables (no over the air transmission) - This test was performed at EuCNC 2024 and was reported in BeGREEN D5.1 (also a video is available at BeGREEN Portal and YouTube channel).

**PoC5 - Use case-2** – Indoor over the air – This test was made at RunEL labs and fully reported in BeGREEN D3.3.

**PoC5 - Use case-3** – Outdoor over-the-air – This test was performed at Brunel University/UK in November 2024 and will be fully reported in BeGREEN D5.3 (also a video is available at BeGREEN Portal and YouTube channel).

### 3.5.2 PoC5 use case 3 updated planning

The initial plan was to deliver the 5G E2E system to BT test site in Adastral Park (UK); install the RU in one of the 5G masts in the site and connect it to the Server that will be installed in an indoor cabinet rack. Once that system is installed and powered on, video streams will be delivered from the application server to the commercial 5G UEs connected to the network and the power consumed by the RU will be monitored to measure the power consumption saving achieved when the PA blanking algorithm is activated. Table 3-7 shows the updated planning for PoC5.

**Table 3-7 Updated Planning of PoC5**

| PoC5 Version | Description                                   | Functionalities                                                                           | Required Developments                                                                                                                                  | Month       |
|--------------|-----------------------------------------------|-------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| V1           | Implementation of PA blanking in lab scenario | Lab implementation and testing of the PA blanking for energy reduction.                   | DU implementation for Energy Aware scheduling.                                                                                                         | DONE<br>M20 |
|              | Adaptations to outdoor demo                   | Implementation of outdoor measurements                                                    |                                                                                                                                                        | DONE<br>M24 |
|              | Delivery to UK, Installation and Testing      |                                                                                           | Need Spectrum License 100MHz from 3.3 to 3.8GHz                                                                                                        | DONE<br>M27 |
|              | RU Power Amplifier Blanking Test              | Turn off the RU PA when there is no down link data to be transferred in a specific Symbol | RU internal algorithm that checks the data to be transmitted in the next symbol and turn off the RF module PAs when there is no data to be transmitted | DONE<br>M30 |

Due to difficulties to find an available date for the test at BT's Adastral Park as well as the lack of 100 MHz Bandwidth in the B78 5G spectrum (only 50 MHz are available), it was decided to do the outdoor portion of PoC5 at Brunel University site near London where an experimental 100 MHz license for the required spectrum is available. The final PoC5 test was conducted in November 2024 and results will be available in BeGREEN D5.3. BeGREEN WP3 and WP4 Results will be included in the next deliverables.

## 3.6 Final demonstrations

The testbed at Adastral Park, described in Section 2.4, will host a number of BeGREEN demonstrations, which will be a subset of the PoCs described in Chapter 3. The Adastral Park O-RAN testbed will be used to test some of the BeGREEN extensions to its baseline O-RAN setup. This can provide an additional opportunity to integrate the BeGREEN PoCs into other O-RAN networks. As we approach the demonstration period, BT will assess whether additional O-RAN systems may be made available for testing. For instance, the BeGREEN Intelligence Plane demo will use the TeraVM AI- RSG (previously known as TeraVM RIC Tester).

To showcase the Intelligence Plane as part of PoC1, we focused on implementing the approach based on VIAVI's AI-RSG capabilities to emulate RAN scenarios. Although we did not deploy real radios in this phase, the use of TeraVM enabled the emulation of realistic traffic patterns and network deployments, offering more flexibility and scope than the initial testbed setup at Adastral Park. In particular, we are considering the use of traffic patterns based on a Mobile Network Operator (MNO)'s data, as referenced in deliverables D2.3 and D4.2. For the demonstration of PoC1 UC1 and UC3—including the Intelligence Plane's core components and the VIAVI AI-RSG emulator—we have identified three key events:

- **INFOCOM 2025:** A demo paper submitted by BeGREEN has been accepted [12], and BeGREEN will take part in the demo sessions to present PoC1.
- **EUCNC 2025:** The BeGREEN project will participate in a Joint Booth on Sustainability, showcasing project outcomes and their relevance to the ongoing work in the 6G-TWIN project. Additional PoCs will be presented through videos highlighting the project results.
- **BeGREEN 8th Plenary:** The BeGREEN project will showcase the final PoCs demos in videos and presentations by all partners, aggregating the results of their implementations and concluding a project wide aggregated result in BT premises.

## 4 BeGREEN PoC mapping to BeGREEN KPIs

This chapter shows how the measurements from the different PoCs align with BeGREEN KPIs. This mapping is crucial to demonstrate the real-world impact of the project and how it contributes to the attainment of our defined KPIs. The work in the technical WPs, i.e. WP2, WP3 and WP4, provide an in-depth analysis of the metrics and measurements that underpin our BeGREEN project, helping us to navigate toward a more energy-efficient future in mobile networks.

The work carried out in BeGREEN is being evaluated in different angles and degrees of implementation: (a) the definition and evaluation (in simulation) of four mechanisms to enhance EE in RANs (WP2), (b) the evaluation of several methods at PHY layer for reducing power consumption (WP3); and (c) the development status and the initial validation of the BeGREEN Intelligence Plane and the methods assisted by proposed AI and ML to enhance the EE of the RAN and Edge domains (WP4).

The mapping of the PoC's results to the project KPIs ensures that we can effectively measure and evaluate BeGREEN results. A comprehensive list of KPIs have been meticulously selected and captured in BeGREEN D2.2 [7], which stem from the evaluation of BeGREEN technical contributions from WP3 and WP4 that play a role in integrated testbeds that host the BeGREEN PoCs.

Table 4-1 outlines all BeGREEN KPIs, where the results obtained (rightmost column) are stemming from running a preliminary version of the PoCs (PoC1 to PoC5).

**Table 4-1 BeGREEN KPI Evaluation (based on that initially included in BeGREEN D2.2 [7])**

| KPI NO | WP | Verification Method        | Tech Spec and reference values for 6G Use Cases                    | Description                                                                                                            | Measured value (results obtained)                                                                                                                                                                                         |
|--------|----|----------------------------|--------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| #1     | 2  | Simulation                 | Energy consumption, N/A                                            | Energy consumption model for 5G/B5G base-stations and proposing energy efficiency enhancements                         | Reported in WP2, results included in D2.3                                                                                                                                                                                 |
| #2     | 2  | Simulation                 | Energy consumption, N/A                                            | System level simulator (AIMM) to enable area-wide assessment of energy consumption over time.                          | Reported in WP2, results included in D2.3                                                                                                                                                                                 |
| #3     | 2  | Simulation                 | Energy efficiency optimization across BeGREEN components, N/A      | Balance between different network evolution strategies to optimize energy efficiency in different target service areas | Reported in WP2, results included in D2.3                                                                                                                                                                                 |
| #4     | 3  | In-Lab PoC4                | Power reduction of at least 15%, N/A                               | Optimization of the implementation of accelerated LDPC and sphere decoder                                              | From BeGREEN D3.2 [3], we obtain 22% average power reduction.                                                                                                                                                             |
| #5     | 3  | Simulation vs. In-Lab PoC4 | Implementation loss of up to 2 dB, BLER and throughput comparisons | Accelerated processing, performance compared to Matlab system level simulations                                        | Achievable results are better than standard requirements by:<br><b>From sim shown on D3.2 [3]</b><br>[2.9dB, 3.2dB, 2.3dB, 2.8dB]<br><b>From conducted RF lab tests running on the platform:</b><br>[2.8dB, 3.8dB, 1.8dB] |



|     |     |                                                                                           |                                                                  |                                                                                                                                                                                                 |                                                                                                                                                                                               |
|-----|-----|-------------------------------------------------------------------------------------------|------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| #6  | 3   | In-Lab PoC4                                                                               | Utilization and processing time                                  | Comparison CPU (x86 and arm architectures) vs GPU for the LDPC and sphere decoder                                                                                                               | Reported in D3.3                                                                                                                                                                              |
| #7  | 3,4 | PoC1, Adastral PoC                                                                        | Functionality, latency                                           | Cell on/off scheme by xApp based in geolocation information                                                                                                                                     | Integration between Viavi RIC Tester, dRAX and NonRT RIC is presented. ES Algorithms work under A1 policies                                                                                   |
| #8  | 3   | <b>Simulation: ET and DPD, Lab Test &amp; Final Demo (BT Testbed): RF blanking - real</b> | RU energy saving better than 40%                                 | Demonstrated energy reduction of RU of $\geq 40\%$ for emulated day/night (busy/idle) scenario                                                                                                  | 60% energy savings when using ET together with DPD                                                                                                                                            |
| #9  | 3   | PoC5, EuCNC 2024 Demo                                                                     | RU energy saving of 40%                                          | Demonstrated energy reduction of RU of $\geq 40\%$ by use of RU PA Blanking method                                                                                                              | 54% energy reduction for small cell up to 90% for the case of zero traffic                                                                                                                    |
| #10 | 3   | Simulation and In-lab test (PoC2)                                                         | Angle and range precision for localisation                       | Precision of the developed sensing algorithm for detecting potential users                                                                                                                      | 30° angle, 2'5 m (with Sub-6 system)                                                                                                                                                          |
| #11 | 3   | Simulation                                                                                | Use identification with 20% less wireless medium (channel) usage | Sensing assisted beam search – 20% performance improvement with respect to extensive search and hierarchical search.                                                                            | Reported in WP2, results included in D2.3                                                                                                                                                     |
| #12 | 3   | Simulation                                                                                | 50% accuracy improvement in user estimation                      | Detection of users/user density in order to estimate the presumed network load – at least 50% accuracy of estimation of potential mobile users                                                  | Reported in WP2, results included in D2.3                                                                                                                                                     |
| #13 | 4   | PoC1                                                                                      | Working version of the Intelligence Plane                        | BeGREEN Intelligence Plane                                                                                                                                                                      | Done: UC1 & UC3<br><b>Work in Progress (WiP): UC2</b>                                                                                                                                         |
| #14 | 4   | PoC1                                                                                      | Energy rating                                                    | Overall energy rating is provided at use case and deployment level.                                                                                                                             | <b>Done</b>                                                                                                                                                                                   |
| #15 | 4   | PoC1                                                                                      | Energy rating                                                    | Orchestration strategy to achieve improved energy rating                                                                                                                                        | <b>WiP: UC2</b>                                                                                                                                                                               |
| #16 | 4   | In-Lab PoC                                                                                |                                                                  | >20% bare metal server energy consumption reduction at low load with respect to bare metal server energy consumption at peak load, without noticeable impact on user plane traffic performance. | From BeGREEN D4.2 [5]:<br><b>vRAN:</b> aprox. 17% energy savings (initial validation)<br><b>UPF:</b> aprox. 30%-45% energy savings (initial validation)<br><b>WiP: To be reported in D4.3</b> |
| #17 | 4   | In-Lab PoC, PoC1                                                                          |                                                                  | At least 2 AI/ML adaptation strategies for energy efficiency demonstrated in laboratory environment with TRL4.                                                                                  | <b>Done</b>                                                                                                                                                                                   |
| #18 | 4   | In-Lab PoC, PoC1                                                                          |                                                                  | An energy rating that effectively                                                                                                                                                               | <b>Done</b>                                                                                                                                                                                   |

|     |   |                                                                                                                                                                                                    |                                                                                                                             |                                                                                                                                                                                                                                      |                                                                                                      |
|-----|---|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
|     |   |                                                                                                                                                                                                    |                                                                                                                             | rates the VNFs (e.g., in the scale of A to E where A is highly efficient, and E is least efficient). A scoring method (value between 0 to 100) measure the energy efficiency of VNFs with its influencing factors including traffic. |                                                                                                      |
| #19 |   | Simulations and in-lab tests (NEC)                                                                                                                                                                 |                                                                                                                             | >20% power consumption reduction on the server that runs the edge AI service AI service power consumption                                                                                                                            | WiP: To be reported in D4.3                                                                          |
| #20 |   | Analytical analysis based on lab tests with x86 and ARM servers with the same test scenario. The metric used will be Joules/bit to include the performance improvement of the system in this test. | Scenario for low throughput 1 UE Both Energy Consumption and Energy Performance (Joules/bit) must fulfil the 20% reduction. | >20% power consumption reduction on running CU on ARM and HW accelerating PDCP of CU-UP                                                                                                                                              | 22% energy savings for UC1 (15% ES for UC2) as described in D3.2.                                    |
| #21 | 3 | Analytical analysis based on lab test with x86 and ARM servers with same test scenario.                                                                                                            | General Adastral park Scenario with 6 Cells and 20 UEs in mid traffic.                                                      | >20% power consumption reduction on running Near-RT RIC on ARM and HW accelerating xApp                                                                                                                                              | Reported in WP3, results to be included in D3.3                                                      |
| #22 | 4 | -                                                                                                                                                                                                  | -                                                                                                                           | O-RAN compliant sub-millisecond control interface for RIS                                                                                                                                                                            | WiP                                                                                                  |
| #23 | 4 | -                                                                                                                                                                                                  | -                                                                                                                           | An extension of the O-RAN RT-RIC that can configure RIS surfaces to optimize energy consumption for edge tasks                                                                                                                       | WiP                                                                                                  |
| #24 | 4 | Simulation                                                                                                                                                                                         | Energy consumption                                                                                                          | Energy consumption reduction, spectral efficiency improvement and coverage hole mitigation through a deployment of fixed relays.                                                                                                     | From BeGREEN D4.2 [5]: Power consumption reduction in the range between 35%-70% (initial validation) |
| #25 | 4 | Simulation                                                                                                                                                                                         | Energy consumption                                                                                                          | Energy consumption reduction through smart relay activation/deactivation algorithms based on AI/ML.                                                                                                                                  | From BeGREEN D4.2 [5]: Energy consumption reduction around 100Wh each day (initial validation)       |

## 5 Updated Risks and Mitigation Plans

This section provides an overview of the risks that are being identified as part of the PoCs development and integration activities. Table 5-1 shows the risks that have been considered throughout the evaluation of the PoCs and that are considered as “Unforeseen risks” to the Project, i.e. not defined in the DoW.

**Table 5-1 Unforeseen Risks per PoC**

| Unforeseen Risk Nº | Related PoC | Description of the Risk                                                                                                                                                      | Likelihood of the risk | Mitigation Measures                                                                                                                                                            |
|--------------------|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1                  | PoC1        | Unavailability or delayed availability of the required TeraVM licenses/features                                                                                              | Medium                 | Focus developments on available features, and adapt control-loops and scenarios <b>(Done)</b>                                                                                  |
| 2                  | PoC1        | Integration complexities due to lack of a common infrastructure                                                                                                              | High                   | VPN-based integration <b>(Done)</b>                                                                                                                                            |
| 3                  | PoC1        | Data availability to train AI/ML models                                                                                                                                      | Medium                 | TeraVM offers diverse methods to generate and collect data from the emulated scenarios                                                                                         |
| 4                  | PoC1        | xApps algorithms do not create sufficient conflicts in the selected scenarios                                                                                                | Medium                 | Validate scenarios and policies that can generate conflicts and provide accountable conflict to guide and avoid. <b>(Done)</b>                                                 |
| 5                  | PoC1        | Latency in distributed integrated testbed provide inconsistencies in the data collection and processing                                                                      | Low                    | Revise the proposed infrastructure for more stronger servers and high bandwidth. <b>(Done)</b>                                                                                 |
| 6                  | PoC1        | Over the Air implementation in Aadastral is not possible due Radios and spectrum licences.                                                                                   | High                   | Implementation and testing in emulated RAN scenario such TeraVM RIC tester. <b>(Done)</b>                                                                                      |
| 7                  | PoC2        | The operating frequency of the RIS is 5.3 GHz and the Sub-6 ISAC antenna (ULA) is optimized for 5.25 GHz                                                                     | High                   | Materialized, slight loss of performance                                                                                                                                       |
| 8                  | PoC2        | When carrying out RIS measurements in the anechoic chamber, we need to consider that we may be doing the measurements in near-field, given the “reduced” size of the chamber | High                   | Take the RIS to an environment where reflections are scarce and use the desired distance to the Tx, or expect loss of performance for the measurements in the anechoic chamber |
| 9                  | PoC2        | Small RIS – limit of the target Radar Cross Section (RCS), Not able to detect obstacles                                                                                      | High                   | Increase transmit power of the system                                                                                                                                          |
| 10                 | PoC2        | Bandwidth of the RIS low Approx. 100-120 MHz, ISAC needs 200 MHz – sub-optimal results                                                                                       | High                   | Nothing can be done to mitigate this risk, expected slight reduction of the range resolution, precision and accuracy                                                           |
| 11                 | PoC3        | Comparison between ARM and x86 based on the specifications do not lead to significant differences                                                                            | Medium                 | Revise de proposed configuration of servers to extract the best configuration for ES. <b>(Done)</b>                                                                            |
| 12                 | PoC3        | Porting into ARM all the components of the RIC is not viable                                                                                                                 | Low                    | Implement new code for the not compatible functions. <b>(Done)</b>                                                                                                             |
| 13                 | PoC3        | General BeGREEN scenario will not lead to savings in ARM or x86                                                                                                              | Low                    | Revision of the use cases to investigate elements that                                                                                                                         |

|           |             |                                                                                                                             |      |                                                                                                                                             |
|-----------|-------------|-----------------------------------------------------------------------------------------------------------------------------|------|---------------------------------------------------------------------------------------------------------------------------------------------|
|           |             | configurations                                                                                                              |      | impact on the energy consumption. <b>(Done)</b>                                                                                             |
| <b>14</b> | <b>PoC5</b> | Over the air testing is not possible in Adastral park due lack of spectrum licence                                          | High | Implement in Brunel University site near London where an experimental 100MHz license for the required spectrum is available . <b>(Done)</b> |
| <b>15</b> | <b>PoC1</b> | The capabilities and licensing of the VIAVI RIC tester will be insufficient to fully test and demonstrate the PoC use-cases | Low  | Mitigation plan as described in section 5.1                                                                                                 |

## 5.1 Risks associated with the final demo and the mitigation plan

As pointed out in Risk #6, one of the main risks of PoC1 was the unavailability of radio hardware and licenses to demonstrate Intelligence Plane in Adastral Park. The defined mitigation was to relay on VIAVI's AI-RSG capabilities to emulate RAN scenarios. Once this risk materialized, our efforts were concentrated on implementing this mitigation approach. Although we could not demonstrate the Intelligence Plane with real radios, TeraVM provides the opportunity of emulating more realistic traffic patterns and deployments than what could be achieved at the Adastral Park testbed. In fact, we are considering the emulation of realistic traffic patterns from an MNO, as BeGREEN in D2.3 and BeGREEN D4.2

To demonstrate PoC1 UC1 and UC3, including the Intelligence Plane's main components and the VIAVI AI-RSG emulator, we have selected two relevant events:

- INFOCOM 2025: A demo paper submitted by BeGREEN has been accepted [12] , and BeGREEN will participate in the demo sessions to showcase PoC1.
- In EuCNC 2025, the BeGREEN project will participate with a Joint Booth on Sustainability to present the results for BeGREEN and how they leverage the work that need to be done in 6G-TWIN project. Other PoCs will also be present via videos showcasing the results of the project and its obtained results.

Additionally, we are considering a collocated event with the last plenary in BT premises where all the PoCs can demonstrate their results in form of videos or posters to a wider audience presenting aggregated results of the consortium and the BeGREEN project.

## 6 Summary and conclusions

This BeGREEN D5.2 provides an updated overview of the Proof of Concepts (PoCs) and their related use cases. It expands on the descriptions of the PoCs, highlighting their core technologies and presenting updated implementation plans compared to those in BeGREEN D5.1 [1]. It additionally identifies which PoCs or BeGREEN innovations will be integrated for the final demonstration. The document also outlines the KPIs each PoC will cover, along with the related measurements and metrics to assess their impact. T5.2 of BeGREEN is responsible for careful planning, managing PoC implementation, demonstrating results, and integrating selected PoCs into the final demonstration testbed.

The purpose of this deliverable is to demonstrate how these PoCs are paving the way toward more energy-efficient and sustainable future networks. This document details the ongoing integration efforts and presents an in-depth look at the associated technologies, showcasing their effectiveness in enhancing network efficiency while maintaining optimal performance levels. The BeGREEN team remains committed to exploring innovative approaches to energy savings, aiming to ensure a significant positive impact on the future evolution of mobile networks.

Based on the analysis and integration activities described in this deliverable, the BeGREEN project has made significant progress toward demonstrating energy-efficient solutions for future mobile networks. The PoCs described in this document emphasize the feasibility of integrating advanced technologies—such as AI/ML-driven optimizations, Reconfigurable Intelligent Surfaces (RIS), and hardware acceleration—into current 5G and future 6G architectures. The implementation and integration of PoC components are already in progress, showcasing real-world applications of these innovations in improving EE.

The BeGREEN PoCs conducted provided valuable insights into advancing EE in mobile networks. These PoCs have revealed several key findings that contribute to BeGREEN overall objectives. The results of each PoC are as follows:

- **PoC1- BeGREEN Intelligence Plane:** Regarding PoC1, we have updated the initial planning described in the BeGREEN D5.1 according to the current status of the implementations and validations, and to the BeGREEN milestones associated with events, demonstrations, and deliverables. The scope of the integration between the RICs and with TeraVM has been finalized, clarifying the required O-RAN interfaces and the role of the AI Engine and the control rApps and xApps. To this end, we have followed the work done in WP4 and reported in BeGREEN D4.2 [5], and adapted the scope to the features available in TeraVM. Additionally, we have incorporated a new use case related to conflict management, which requires the cooperation of the RICs. By utilizing AI/ML-based approaches, PoC1 underscores the role of intelligent automation in streamlining network operations, ultimately contributing to reduced energy consumption across the system.
- **PoC2- Sensing-Assisted Communications using RIS:** The implementation of sensing-assisted communications demonstrated how user location data can be effectively used to optimize energy consumption, particularly by dynamically controlling network elements like Radio Units (RUs). This PoC showed that user location data can be used to extend network coverage through RIS, optimizing energy consumption. The benefits of integrating RIS into the network were evident, as it enabled targeted optimizations based on the environment and user behaviour, leading to more efficient power usage and improved coverage while minimizing energy waste.
- **PoC3- Energy-Efficient CU and O-RAN RIC:** The use of hardware acceleration in Central Units (CUs) and the O-RAN RIC significantly improved efficiency, achieving enhanced performance while reducing power consumption. This PoC validated the benefits of implementing O-RAN components in x86 and ARM servers to improve EE in CUs and O-RAN RIC. Through optimized processing capabilities, PoC3 highlighted how deploying specialized hardware accelerators can streamline



computational tasks and reduce overall power usage, while still ensuring that the network's performance is maintained at a high level.

- **PoC4- Energy-Efficient DU Implementation:** The deployment of energy-efficient Distributed Units (DUs) using high-PHY algorithms, combined with hardware acceleration, showed promising results in reducing power consumption while maintaining satisfactory system performance. This PoC highlighted the efficiency gains achieved through high-PHY algorithms with hardware acceleration, leading to significant power reductions without compromising performance. The focus on optimizing the physical layer through advanced algorithms allowed PoC4 to achieve substantial energy savings, demonstrating the value of these techniques for future mobile networks.
- **PoC5- RU Power Amplifier Blanking:** The PA blanking approach for RUs demonstrated the effectiveness of selectively powering down high-consumption components during idle periods, leading to significant power savings. This PoC showed that energy usage in RUs can be effectively reduced by turning off power-consuming components when not in use. The PA blanking technique provided a practical means of reducing the energy footprint of RUs, particularly during times of low activity, thus contributing directly to the goal of minimizing unnecessary energy expenditure in mobile networks.

These findings collectively support BeGREEN overall goals of enhancing EE in the Radio Access Network (RAN) while maintaining system performance and flexibility. The integration and validation efforts outlined in this deliverable have established a strong foundation for further development and final demonstrations of these innovative concepts. Moving forward, the lessons learned from these PoCs will be crucial for refining these technologies for broader implementation and scalability, ensuring that EE remains central to the evolution of future networks.

Moreover, these advancements demonstrate the growing importance of intelligent energy management in the context of 5G and 6G technologies. By integrating AI, hardware acceleration, and adaptive algorithms, the BeGREEN project is effectively addressing the challenges associated with rising energy consumption in mobile communications. The insights gained through the successful execution of these PoCs will not only contribute to the BeGREEN project but also set the stage for broader adoption of these energy-efficient solutions across the telecommunications industry.

## References

- [1] BeGREEN, D5.1, "Use case identification and demonstration plan", Dec 2023.
- [2] BeGREEN, D3.1, "State-of-the-art on PHY mechanisms energy consumption and specification of efficiency enhancement solutions", Jan 2024.
- [3] BeGREEN, D3.2, "Initial developments and evaluation of the proposed PHY layer energy efficiency enhancements and optimization strategies", Aug 2024.
- [4] BeGREEN, D4.1, "State-of-the-art review and initial definition of BeGREEN O-RAN Intelligence Plane, and AI/ML algorithms for NFV user-plane and edge service control energy efficiency optimization", Jan 2024.
- [5] BeGREEN, D4.2, "Initial evaluation of BeGREEN O-RAN Intelligence Plane, and AI/ML algorithms for NFV user-plane and edge service control energy efficiency optimization", Oct 2024.
- [6] BeGREEN, D2.1, "BeGREEN Reference Architecture", July 2023.
- [7] BeGREEN, D2.2, "Evolved architecture and power enhancement mechanisms", July 2024.
- [8] O-RAN Alliance "O-RAN Working Group 1 (Use Cases and Overall Architecture); O-RAN Architecture Description".
- [9] M. Rossanese, et al. "Designing, building, and characterizing RF switch-based reconfigurable intelligent surfaces." Proceedings of the 16th ACM Workshop on Wireless Network Testbeds, Experimental Evaluation & Characterization. 2022.
- [10] 3GPP TS 38.141-1, "NR; Base Station (BS) conformance testing Part 1: Conducted conformance testing (Release 16)", September 2021.
- [11] NVIDIA Jetson Stats package for monitoring and control, [https://developer.nvidia.com/embedded/community/jetson-projects/jetson\\_stats#:~:text=jetson%2Dstats%20is%20a%20package,import%20in%20your%20python%20script](https://developer.nvidia.com/embedded/community/jetson-projects/jetson_stats#:~:text=jetson%2Dstats%20is%20a%20package,import%20in%20your%20python%20script).
- [12] M. Catalan-Cid, G. Castellanos, D. Reiss, and J. Armstrong, "Demo: BeGREEN Intelligence Plane for AI-driven Energy Efficient O-RAN management," IEEE INFOCOM 2025 Demo, to be presented.
- [13] M. Catalan-Cid, G. Castellanos, and J. Armstrong, AI-Driven Energy Efficiency for O-RAN: BeGREEN Intelligence Plane Implementation and Evaluation by Simulating Realistic O-RAN Environments using VIAVI TeraVM AI RSG, White Paper, 2025.