D2.2 Initial 6G-BRICKS overall architecture design

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Glossary of terms and abbreviations used

Abbreviation / Term	Description
3GPP	3rd Generation Partnership Project
5G-PPP	5G Infrastructure Public Private Partnership
AI	Artificial Intelligence
AMF	Access Management Function
AoA	Angle of Arrival
API	Application programming interface
AUSF	Authentication Server Function
BSS	Business Support System
CCSA	China Communications Standards Association
CDSO	Cross-Domain Service Orchestrator
CEC	Cloud-Edge-Continuum
CF	Cell Free
CN	Core Network
COTS	Commercial Off the Shelf
CPU	Central Processing Unit
CSI	Channel State Information
CU	Centralized Unit
DE	Decision Engine
DMO	Domain Manager Orchestrator
DRL	Distributed Reinforcement Learning
DU	Distributed Unit
eCPRI	evolved Common Public Radio Interface
eMBB	Enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
FaaS	Function-as-a-Service
FDD	Frequency Division Duplexing
FFT	Fast Fourier Transform
IBN	Intent-Based Networking
ICT	Information and communications technology

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IDAN	Intent Driven Autonomous Network
IETF	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
KPI	Key performance Indicator
KPM	Key Performance Measurement
LCM	Lifecycle Management
LMF	Location Management Function
MANO	Management and Orchestration
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MEC	Multi-Access Edge Computing
MHU	Mast Head unit
MDAS	Management Data Analytics Service
MIMO	Multiple-input and multiple-output
ML	Machine Learning
MR	Machine Reasoning
mMIMO	massive Multiple-input and multiple-output
mMTC	Massive Machine-Type Communications
M-SDO	Multiple Standards Developing Organization
NBI	NorthBound Interface
NEF	Network Exposure Function
NF	Network Function
NFV	Network Function Virtualisation
NFVO	Network Function Virtualisation Orchestrator
NI	Network Interface
NoC	Network on Chip
NOS	Network Operating System
NRF	Network Repository Function
NS	Network Slice
NSA	Non Standalone
NSO	Network Service Orchestration
NSSF	Network Slice Selection Function

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NWDAF	Network data analytics function
OAI	OpenAirInterface
OFDM	Orthogonal Frequency-Division Multiplexing
ONIE	Open Network Install Environment
OSS	Operations Support System
OTA	Over The Air
PaaS	Platform as a Service
PCF	Policy Control Function
PRB	Physical Resource Blocks
PTP	Precision Time Protocol
RAN	Radio Access Network
RC	RAN Control
RIC	RAN Intelligent Controller
RIS	Reconfigurable Intelligent Surface
RO	Resource Orchestration
RRM	Radio Resource Management
Real TIme	RT
RU	Radio Unit
SA	Standalone
SBC	Single Board Computers
SbD	Security by Design
SDI	Software Defined Infrastructure
SDN	Software-defined networking
SE	Spectral Efficiency
SLA	Service Level Agreement
SLO	Service Level Objective
SM	Service Models
SMF	Session Management Function
SMO	Service Management and Orchestration
SO	Security Orchestrator
SSH	Secure Shell Protocol
TaaS	Testing as a Service

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TDD	Time-Division-Duplexing
TMF	Tele Management Forum
TNE	Transport Network Equipment
UDR	Unified Data Repository
UDM	Unified Data Management
UE	User Equipment
UHD	USRP Hardware Driver
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communications
USRP	Universal Software Radio Peripheral
VIM	Virtualized Infrastructure Manager
VNF	Virtual Network Function
VPN	Virtual Private Network
VPNaaS	VPN as a Service
XAI	Explainable AI
ZT	Zero Touch
ZTM	Zero-Touch Management

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1 Executive Summary

This deliverable is part of WP2 “Architecture design and Requirements analysis” describes the architecture of the 6G-BRICKS experimentation platform, as well as the internal design of its constituent components. Moreover, this deliverable will detail the logical interconnection between the various enablers (“bricks”) as well as cross-domain interfaces and physical architectures of the 6G sites. The 6G-BRICKS facility will showcase many unique features such as a disaggregated Management Plane, an Explainable and intent-driven Experimentation Plane, as well as 6G breakthrough technologies such as RIS and Cell-Free networking at the Radio Access Network (RAN).

The 6G-BRICKS architecture adopts the Intent Driven Autonomous Networks (IDAN) paradigm, which builds on a three-layer design featuring intelligence at the Business, Service, and infrastructure domains. This is achieved via the concept of intent, which defines and communicates knowledge about requirements, goals and constraints to a system in a way that allows automated processes to reason about it and derive suitable decisions and actions. Intents are supplied by experimenters via the Experimentation Plane, which are automatically translated to service objectives. Moreover, automated intent activation and conflict resolution mechanisms are explored for the first time in the context of 6G networks.

6G-BRICKS also contributes a decentralized Management Plane via a unified framework of Domain Managers and Orchestrators (DMO)s. One of the key breakthroughs of the 6G-BRICKS DMO is supporting a pluggable framework of domain-specific Explainable AI (XAI) models that undertake the policy translation at infrastructure domain actions (e.g., specific adaptation of Radio resource Management (RRM) parameters at the RAN domain), that are subsequently executed by the underlying Element Managers. Thus, in cases of inability to meet policy, a concrete root cause analysis is performed, and feedback is returned to the experimenter. Inability of policy enforcement can be attributed at lack of resources (hence the experimenter is informed to reserve more) or, business intents leading to direct or indirect conflicts, potentially between different Technological Domains.

6G-BRICKS also contributes groundbreaking 6G RAN enablers, adopting O-RAN interfaces to ensure openness and reusability. 6G BRICKS aims to make the vision of Cell Free massive MIMO (CF mMIMO) a reality, by bringing the concepts of CF mMIMO together with the already widely spread notion of the O-RAN-based architecture. One of the key building blocks with respect to CF mMIMO is the Radio Unit (RU) which has its ORAN-specified counterpart as the ORAN Radio Unit (O-RU). 6G-BRICKS will investigate and implement an OpenRU utilizing an Universal Software Radio Peripheral (USRP) software-defined radio platform by National Instruments Dresden (NI). 6G-BRICKS will further translate Cell-Free to O-RAN architecture by extending E2 interface extensions to support full-fledged CF mMIMO xApp and will offer CF experimenter xApps, allowing experimenters to configure the RAN elements (CU, DU, MAC scheduler) via the Near-RT RAN Intelligent Controller (RIC) framework for the first time.

Finally, 6G-BRICKS will build the first end-to-end RIS-based solution for 6G that integrates a Reconfigurable Intelligent Surface (RIS) reflector with an open-source O-RAN stack operating in the millimeter-wave band. Moreover, 6G-BRICKS platform will be the first RIS platform open for experimentation, allowing experimenters to submit O-RAN compliant xApps following an xApps Descriptor (xD) template. Thus, experimenters can focus on developing the RIS control algorithms since the testbed provides an abstraction of any underlying RIS hardware, provided that it complies with O-RAN specifications.

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2 Introduction

The aim of this deliverable is to provide the architecture design of the 6G-BRICKS Experimentation facility and the internal design of components, that will serve as a blueprint for their implementation. This deliverable will thus serve as an input WP3-WP4, which will detail the low-level implementation and validation of each component, as well as WP5 which addresses testbed deployment and integration.

With this first version, the reader is able to identify:

- the architecture of the overall experimentation facility and it's corresponding layers;
- the modules formulating the experimentation plane of the 6G facility;
- the underlying technologies and software stacks leveraged.

Information in this deliverable is adequate to get the implementation of the facilities and the experimentation modules started. However, as things progress and until the entire facility is ready, things are expected to change to accommodate new requirements. These will be described in the second version of the architecture deliverable. In what follows, Section 3 contributes the overall Logical and Physical architecture of the 6G-BRICKS facility, along with the main requirements and guiding architecture principles. Section 4 details the 6G-BRICKS RAN architecture, focusing in particular at the CF mMIMO and RIS breakthrough technologies explored within the project. Section 5 details the Orchestration architecture and Experimentation Plane innovations (e.g., Explainable AI) and Section 6 concludes the deliverable. In the following table (Table 1) the adherence of this deliverable to the 6G-BRICKS GA is outlined.

Table 1 – Adherence to GA Deliverable & Tasks Descriptions

6G-BRICKS Tasks and Objectives	Respective Document Chapters	Justification
Task 2.4: Architecture Design • Derive the detailed architecture specification of the 6G-BRICKS Facility. • Produce the logical interconnection between the various enablers and 6G sites • the federation and integration APIs will be defined • the detailed modular architectural design of the Management Plance (DMO) will be completed • Finally, the respective Business Layer and TaaS conponents will be defined.	Chapter 2: Introduction Chapter 3: Overall Architecture Chapter 4: 6G-BRICKS RAN Architecture Design Chapter 5: Management & Orchestration Architecture design	The deliverable D2.2 • Designs the overall 6g-BRICKS architecture and logical interconnections with the 6G testbeds within architecture planes and 6G Sites in Chapter 3 • Designs the RAN Architecture (including CF mMIMO and RIS) in Chapter 4 • Designs the Management and Experimentation Plane architecture (for TaaS) in Chapter 5

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3 Overall Architecture

3.1 Architecture principles

6G-BRICKS offers a trusted, agile and evolvable 6G Experimentation Facility, federating two experimentation platforms in Belgium (KUL) and France (EUR) from previous 5G-PPP initiatives under a Core Site (ISI/ATH) acting as the facility entry point, and offering experimentation services. The Facility will be accessible by third party consortiums in the framework of Open Calls, vertical application owners, as well as experimenters from the vertical and component industry. The detailed list of requirements for the end-to-end architecture is included in D2.3. These shaped the following list of architecture principles that are guiding the design of the 6G-BRICKS overall architecture:

1. **Management Plane Disaggregation**, in line with the "Network of Networks" 6G vision. 6G networks of the future are expected to federate 6G RANs and Cloud-Edge-Continuum deployments from multiple stakeholders, hence will add a level of unprecedented management complexity due to the sheer scale and heterogeneity of the orchestration domains involved. To this end, decentralized orchestration and analytics collection paradigms need to be considered, to increase the scalability of 5G Network data analytics function (NWDAF) and Management Data Analytics Service (MDAS) functions.
2. **AI Explainability**, to be delivered in the application domain of Compute and Network infrastructures. The output of the Explainable AI (XAI) model, along with the Machine Learning (ML's) prediction, is communicated to the experimenters and domain manager. XAI outputs can be attributive, to investigate why the model produced an output and contrastive, to explain why the model did not give another outcome that is different from the current output.
3. **Intent-driven Human-in-the-loop experimentation**. A web-based experimentation plane should act as the entry point to the Facility; mature frontend elements and experimentation engines will be leveraged and extended as part of the Experimentation Plane, to deliver intent-driven, human-in-the-loop experimentation workflow. This allows automated onboarding and instantiation of vertical applications, while providing the actionable explanations that provides an answer to how they can achieve a more desirable outcome (i.e., performance optimization).
4. **Cognitive Compute Continuum.** The 6G design envisions close integration of computation and communication, deploying a new type of network architecture for (extreme) edge to cloud continuum resource orchestration by interconnecting computing and storage resources located anywhere in the network. Cognitive services must be adopted, conducting complex placement and scaling operations, and delivering intelligence on demand (when/where needed) across the communication system.
5. **6G RAN technologies**, including support for RIS and cell-free networking, aiming to support the increased requirements of emerging applications, like the Metaverse and Digital Twinning. These emerging applications exceed the current and future capabilities of 5G networks, both in terms of Key performance Indicators (KPIs) that must be supported, and in terms of their requirements on an ultra-dense computational infrastructure.
6. **Reusable, self-contained enablers with Open APIs ("Bricks")**. Towards this scope, O-RAN interfaces are adopted to ensure the openness and reusability of the developed components, while supporting on-device experimentations via xApps.

3.2 6G-BRICKS Logical architecture

The 6G-BRICKS facility will showcase many architecture innovations, such as a disaggregated Management Plane and Operations Support System, to support extendibility, evolvability, and multi-tenancy. The aforementioned innovations are going well beyond centralized Cross-Domain Service Orchestrators (CDSOs) and Operations Support System/Business Support System (OSS/BSS) systems typically supported in 5G-PPP experimentation

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platforms. The 6G-BRICKS Reference architecture is shown in Figure 1. More specifically, the 6G-BRICKS architecture will include the following architectural tiers:

- The **Experimentation Plane,** further detailed in **Section 5.1**, acts as the entry point to the Facility. Mature frontend elements as part of the System Portal, a Service Catalogue and intent engine will be leveraged and extended as part of the Experimentation Plane, delivering intent driven, human-in-the-loop experimentation functionality. A unique testing tool based on Near-RT RIC is scheduled for the first time, giving experimenters access to low-level Radio Resource Management (RRM) and RAN slicing capabilities via standardized xApps. Moreover, the Experimentation Plane will offer BSS services to the 6G-BRICKS facility, allowing vertical application owners to upload their applications and Business Intents.
- The **Management & Orchestration** plane, further detailed in **Section 5**, is deployed at each facility site as a unified controllability framework, via the groundbreaking Domain Management and Orchestration (DMO) framework. Explainable AI mechanisms are leveraged for policy translation and unification. This breakthrough architecture design supports provides explainable feedback to experimenters for potential SLA breaches and facilitates a loose coupling with the Experimentation Plane, avoiding bottlenecks. Moreover, Cloud-
- **6G RAN infrastructure domain**, further detailed in **Section 4,** where breakthrough 6G RAN technologies are integrated in reusable, self-contained modules with O-RAN interfaces to ensure the openness and reusability of the developed components. At the KUL site, a Distributed Cell-Free RAN is delivered, while the EUR site builds on the EUR OpenAirInterface O-RAN stack, which will be integrated with a RIS platform.

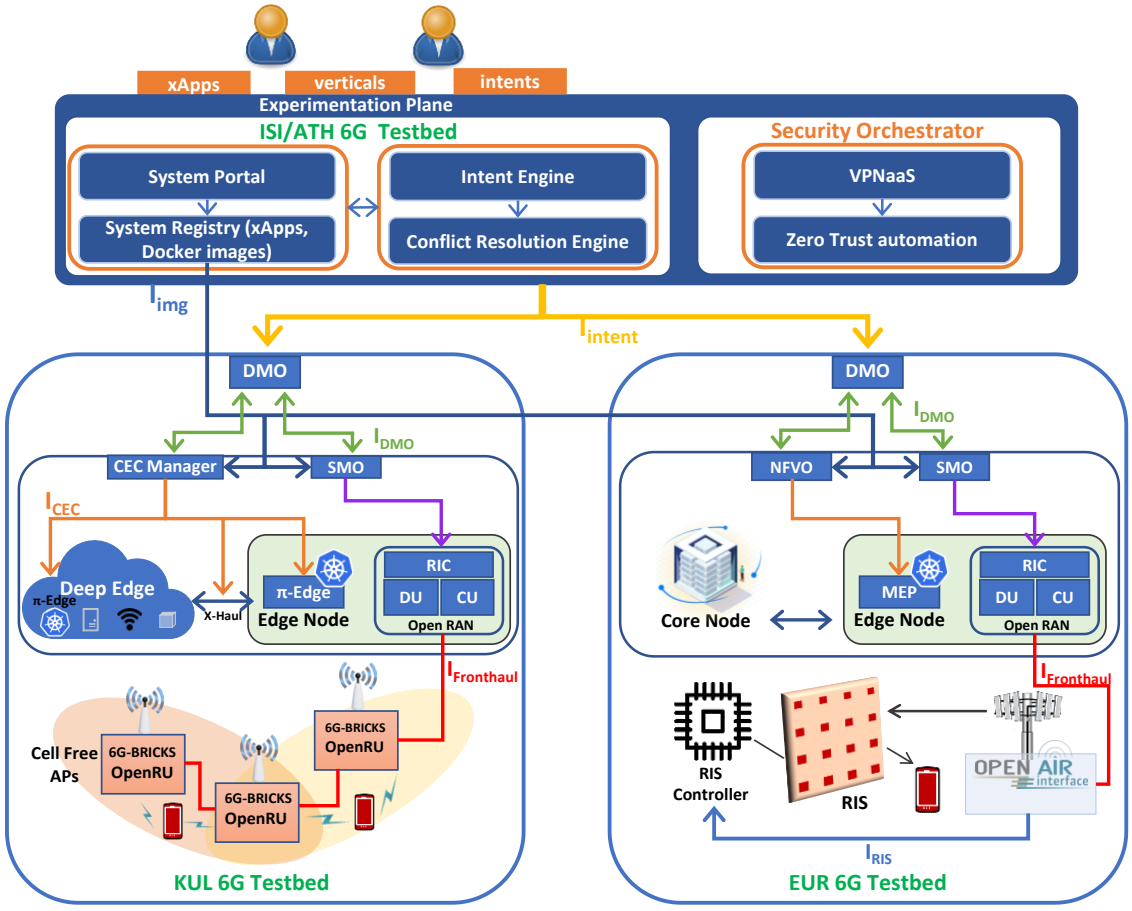

Figure 1 - The 6G-BRICKS overall architecture

The 6G-BRICKS architecture tiers and their constituent building blocks are interconnected via a set of reference points, detailed in Table 2. These reference points will be implemented within the technical WPs (WP3-WP4), ensuring the end-to-end integration of the 6G-BRICKS facility.

Table 2 –6G-BRICKS architecture interfaces

Interface-ID	Related Modules	Description
I_{intent}	Intent engine, DMO	The interfaces interconnecting the Experimentation Plane with the set of DMOs deployed at the 6G testbeds
I_{img}	Repository, CEC Manager, NFVO, SMO	The interface exposed from the Repository, where docker images and xApps are stored
I_{CEC}	CEC Manager, πEdge	Orchestration interface, for managing multiple πEdge instances at the CEC
X-Haul	πEdge	Transport / Midhaul interface, interconnecting multiple CEC nodes
$i_{Fronthaul}$	Open RU, O-RAN DU	Fronthaul interface, interconnecting the 6G-BRICKS Open RAN RUs with the respective DU.
i_{RIS}	RIS, O-RAN DU	Control Interface interconnecting the RIS device with the OAI DU

3.3 6G-BRICKS Physical architecture

6G-BRICKS aims to deliver an evolvable 6G experimentation facility that will federate two testbeds from KUL and EUR, under a common set of experimentation tools deployed at the ISI/ATH site. Accessibility by external entities and openness are key objectives of 6G-BRICKS testbeds, where breakthrough components and technologies are built around the concept of reusable and interoperable "bricks". These are typically based on Beyond-5G technologies that started in previous research initiatives (e.g., in the framework of the 5GPP ICT-52 call) ensuring already existing infrastructures. In what follows the 6G-BRICKS testbeds and their planned interconnectivity in an end-to-end 6G facility is detailed.

3.3.1 KUL testbed

3.3.1.1 Testbed Overview

KUL operates a distributed massive MIMO testbed since 2014, and a private 5G Standalone Network for end-to-end experiments since 2021. The distributed testbed has been extended to allow more distributed and cooperative processing (the controllers were split and fibers were added for distribution), mmWave connectivity and also other advanced features such as full duplex communication, joint communication and sensing, as well as public access through Fed4FIRE. In addition to remote access of the testbed, the KU Leuven has also provided

multiple publicly available datasets. KUL also has a full antenna measurement facility, a network analyser (67 GHz PNA-X) and a 4-channel 110 GHz real-time oscilloscope. For processing, the group also owns several GPU servers with multiple state-of-the-art GPU and CPUs. The KU Leuven testbed structure is summarized in Figure 2.

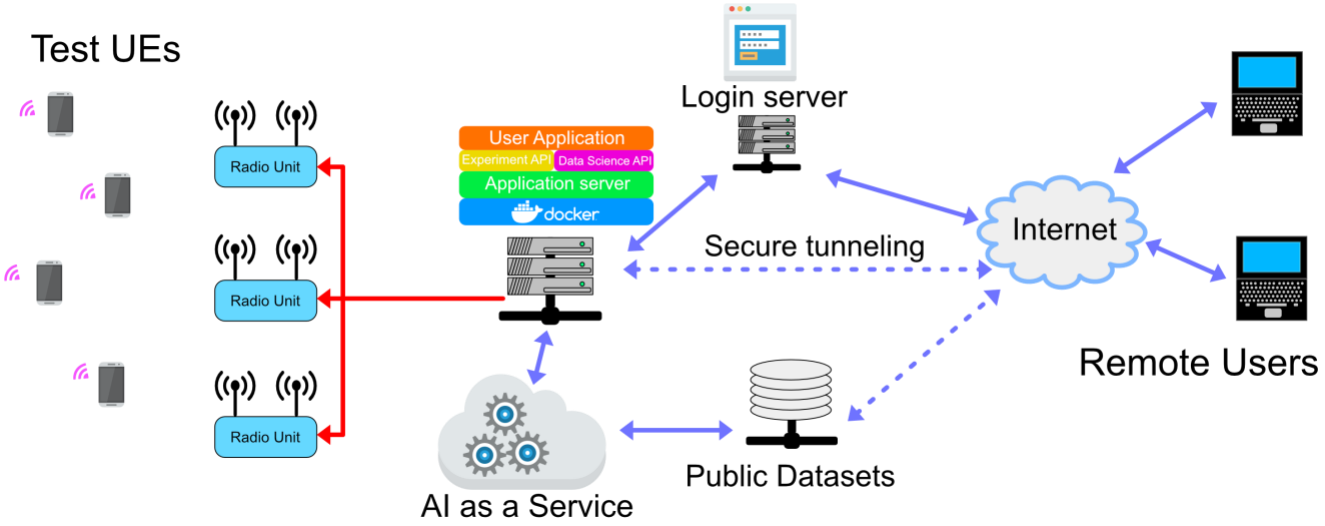

Figure 2 - Schematic view of the KU Leuven testbed

3.3.1.1 Radio Infrastructure

The distributed architecture CF mMIMO testbed in KUL consists of 32 National Instruments Universal Software Radio Peripherals (USRPs) (2942R/USRP RIO). The 32 USRPs are equally divided into two sub-systems, where each of them supports 32 APs. The system further has a lot of centralised and distributed processing power (32 distributed FPGA's doing processing per two antennas, and 3 centralised FPGA's for central processing). The two subsystems are connected to the MIMO processor (analogous to CPU) (right) via two 40 meters optical fibers responsible for the front-haul. In the framework of 6G-BRICKS, KUL testbed is being extended with "SuperIQ" capabilities, supporting 400 MHz CF mMIMO Radio Units (RUs) via NI X410 USRPs. The radio units, denoted as USRP x410 by National Instruments, are capable of operating either in a stand-alone (embedded) mode or as host-based systems with network streaming capabilities. These units cover a frequency range from 1 MHz to 7.2 GHz, with tunability extending up to 8 GHz. The RUs have an instantaneous bandwidth capacity of up to 400 MHz. The testbed uses a dedicated custom set of antennas for beamforming and MIMO experimentation in different bands (multiband scenario), both in the sub 6GHz cellular bands and mm Wave bands. To ensure precision in timing and synchronization, a Rubidium clock governs the entire testbed. This meticulous timekeeping mechanism is instrumental in maintaining synchronization across the system. Finally, the testbed includes a set of cartesian robot positioners for accurate positioning of the test user equipment. This will allow experiments with beam forming, accurate position prediction and tracking, and accurate power measurement at different positions in the test area.

3.3.1.1 Cloud, edge computing infrastructure

KUL's Radio Infrastructure (i.e., RUs) are interconnected via a dedicated high-speed 100GbE fiber link to a compute cluster. KUL's compute cluster was deployed within 6G-BRICKS, offering full-scale K8S support through a HP Enterprise Edge server configuration featuring a dual Xeon Gold 6430 processor boasting 32 cores and 64 threads in total. Complementing this robust processing power is 1 TB of DDR5 PC5-4800-2R memory and 960GB SATA SSD storage. The computing infrastructure facilitates the core operational aspects of the testbed but also encompasses provisions for machine learning, training, and data processing. Users can perform number

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crunching and AI training using an NVIDIA A100 accelerator card, in conjunction with Tensor Flow or PyTorch. Data sets are stored locally and are accessible to the public, ensuring transparency and availability. Moreover, the compute cluster can host the DU (Distributed Unit) and RIC (Ran Intelligent Controller) modules that operate cohesively within the main computer's environment, each residing within its dedicated container. The software stack is completely configurable by the user, which can either choose the RIC/DU stack provided by IS Wireless (ISRD) or write custom code to directly control the RU's.

3.3.1.2 Testbed goals and offer towards experimenters

The primary objective of the KU Leuven facility lies in conducting experiments pertaining to Cell-Free MIMO, with a specific focus on Over the Air Synchronization, channel estimation, and fronthaul aware precoding/decoding techniques. Leveraging its robust hardware infrastructure, the facility enables the execution of experiments and the accumulation of datasets across various frequency bands, constituting a Multiband scenario. External researchers engaging with the facility have multifaceted avenues for exploration. Firstly, they can either adopt one of the pre-existing 5G stacks hosted on the server or deploy their proprietary stacks. Utilizing the O-RU provided by NI a comprehensive simulation of a complete access network becomes feasible. Secondly, the facility offers comprehensive tools for synchronization research. An explicit goal within the framework of 6G-BRICKS involves delving into distributed Remote Unit (RU) synchronization, achievable through either the employment of a cabled rubidium clock reference or wireless synchronization methods. Thirdly, the facility presents diverse antenna array configurations and precise target positioning capabilities, conducive to research endeavors in joint communication, sensing, and channel estimation. This includes the collection of channel measurements across the experiment area, with the precise positioner serving as the ground truth for algorithms related to joint communication and sensing. Lastly, the facility houses GPU clusters that facilitate accelerated data processing and enable research in deep learning. The acquired datasets can be directly analyzed on the facility server, obviating the need for complex and costly transfers of multi-gigabyte data over the internet. Furthermore, the outcomes of these analyses can be swiftly applied back to the testbed, enabling a rapid iteration of ideas and experiments. Other kinds of experiments are possible on request. Areas of interest for experimenters can be distributed I/Q processing, custom xApps or programs which interface with the IS Wireless DU via their public API.

3.3.2 EUR testbed

3.3.2.1 Testbed Overview

EURECOM is located at the Sophia Antipolis science park within the SophiaTech Campus. Open5GLab at EURECOM provides experimental 5G/6G services including enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC) and massive Machine Type Communications (mMTC). Based on fully open-source tools and open-architecture design, it provides the means to on-board new network functions to the running 5G/6G infrastructure and test them in both a controlled laboratory setting and in a deployed live network. It is the main experimental playground for OpenAirInterface (OAI) software packages.

3.3.2.2 Radio Infrastructure

The testbed's FR2 setup is based on OpenAirInterface (OAI) [31] which is a 3GPP compliant and an opensource 5G platform. The FR2 RAN platform is split into CU, DU and RU following two different functional splits.

(i) Split 7.2: OAI CU and DU uses commercial RUs from LiteON.

(ii) Split 8: OAI CU and DU uses USRPs (X410).

The first option (split 7.2) is O-RAN compliant.

The minimal hardware setup for an O-RAN compliant system is shown in Figure 3. It comprises

1. two servers (one playing the role of the 5G core network and RAN control plane functions and another for the real-time gNodeB-DU)
2. at least one O-RAN compliant O-RU radio unit
3. a fronthaul switch with Precision Time Protocol (PTP) support and an optional PTP grandmaster.

Note that some switches such as the FibroLan Falcon-RX can provide PTP grandmaster functionality when tuned with an external GPS signal.

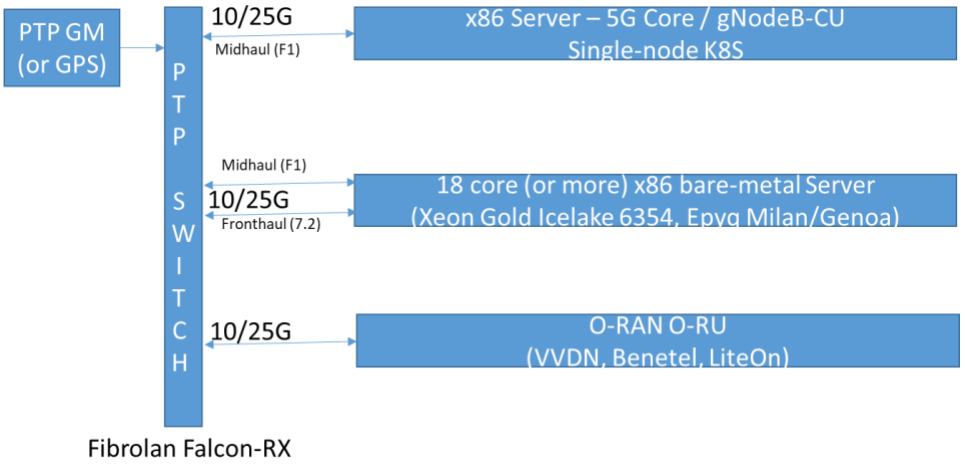

Figure 3 - O-RAN Equipment Overview

EURECOM's ORAN interoperability testing configuration is shown in Figure 4.

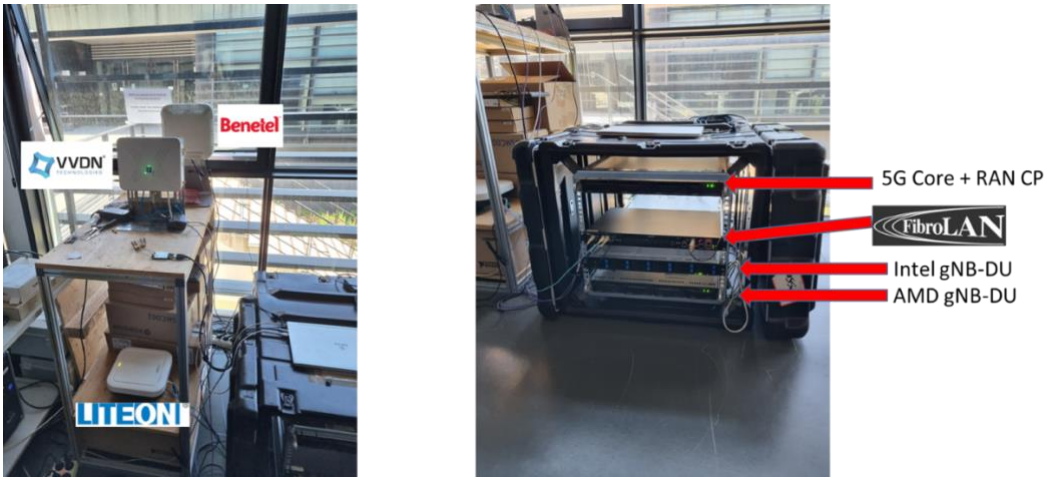

Figure 4 - O-RAN Interoperability Testing Environment at EURECOM

The FR2 setup is currently tested with USRP X410 and a 24-27GHz front-end radio unit developed by InterDigital (MHU) in a non-standalone (NSA) configuration. In parallel EURECOM started interoperability testing with the new FR2 O-RU developed by LiteON in June 2023 in both NSA and SA configurations.

The InterDigital Mast Head unit (MHU) provides a single-beam per MHU using a 64-element array. A single USRP X410 can control 2 MHU to allow for two concurrent beams for OAI baseband processing. The MHU is capable

of 200 MHz channel bandwidth although current testing with OAI is limited to single 100 MHz channels. It provides 64 independent beams in three-dimensions with a horizontal opening of 90 degrees.

The LiteON FR2 O-RU provides two independent concurrent beams on the same 64-element (8x8) array with 49 dBm EIRP output power. It uses the O-RAN 7.2 fronthaul interface and operates as a Category-A O-RU providing 120 degree horizontal and vertical beam widths. The unit operates in band n257 (26500MHz -29500MHz) with up to 400 MHz operating bandwidth. Beam selection is handled by the O-RAN 7.2 C-plane API.

3.3.2.3 Core Network

The core network solution is a partial 3GPP 5GC service-based architecture including the following Network Functions (NFs): Network Repository Function (NRF), Access Management Function (AMF), Session Management Function (SMF), User Plane Function (UPF), Unified Data Management (UDM), Unified Data Repository (UDR), Authentication Server Function (AUSF), Network Slice Selection Function (NSSF), Policy Control Function (PCF), Network Exposure Function (NEF), Location Management Function (LMF) and Network data analytics function (NWDAF). Figure 5 depicts the Core Network (CN) architecture where the blue components are already available and the orange components are under development.

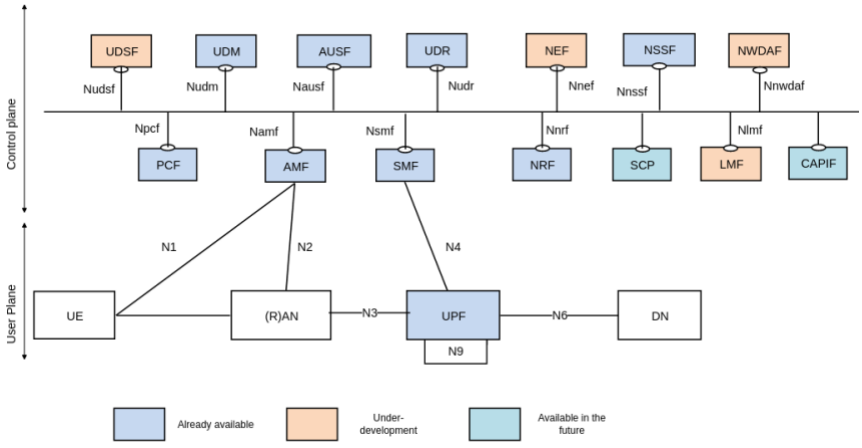

Figure 5 - OAI 5G CN architecture

The core is fully open and configurable within the limitations of the OAI implementation. All the NFs can be deployed as docker containers either using docker, Kubernetes or Openshift. Each NF is initially configured using configuration files and can be configured during run time using exposed interfaces. The UPF can be deployed as a SW entity on a general-purpose machine (e.g., intel i7 CPU based machine) or as an application on a P4-programmable switching fabric. OAI 5G CN can be used with OAI gNB, RAN simulators (e.g., OAI RFSIM, UERANSIM, Gnbsim, My5G-RANTester) and some commercial gNBs such as Nokia gNB and Amarisoft gNB.

3.3.2.4 Cloud, edge computing infrastructure

The site's cluster computing resource is split into several clusters used for different purposes, ranging from production use-cases for RAN/CORE/Edge, testing use cases and development. New clusters can be created reasonably easily, and network topologies are fully configurable using the facility's Software-defined networking (SDN) switching fabric. Three types of clusters are currently deployed, (a) a full-scale K8S cluster making use of RedHat's OpenShift 4.9 container platform (OCP); (b) a single node RT OCP cluster used primarily for gNodeB-DU pods; (c) an experimental cluster to experiment with the NFVO including machines configured as a vanilla K8S or OpenShift cluster and others for deployment of docker/podman containers. The NFVO could also act as the E2E Service and Telco CNF Orchestrator to deploy all the services including one service for the UE.

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3.3.2.5 Control, Management and Orchestration platforms

To allow for integration of vertical service SW directly on Open5GLab fabric, EURECOM makes a service creation and deployment framework available via an http-based portal, with which KPIs and other monitoring services can be accessed. Means for retrieving measurements in the RAN and Core CNFs are provided by FlexRIC and OAI OEM [32][33].

3.4 6G-BRICKS facility interconnection and deployment considerations

The 6G-BRICKS facility will securely interconnect the 6G sites from KUL and EUR with the Experimentation Plane, offered by ISI/ATH, which provides access to experimenters. High bandwidth connectivity will be ensured between the experimentation servers deployed at ISI with the KUL and EUR Sites, leveraging on the fast GEANT VPN network, while security perimeters will be setup via SDP gateways deployed at the 6G Sites. To ensure the security of the facility, Virtual Private Network (VPN) tunnels will be established in a programmatic manner, using a VPN as a Service (VPNaaS) Security Service. This is required within the project to set up a secure channel where a new, unauthenticated experimenter connects to a testbed, aiming to access its features via some exposed APIs (e.g. attempting to connect to some ORAN APIs). In such scenario, the user's request will be derived towards the Security Orchestrator (SO) and the SDP framework over encrypted connections, so that the SDPC can setup the adequate isolated perimeters and secure channels between the experimenter and accessed resources (I.e. services offered by the testbed). In the end, the user gains access and visibility towards the infrastructure. Such a service shall be based on an open-source solution, such as OpenVPN or Wireguard; and potentially be configurable at runtime for further tailoring. Similar to the decision of the underlying L2 or L3 network, the decision criteria between the available open-source solutions will be guided by factors like throughput, reliability or flexibility. The 6G-BRICKS security architecture is further detailed in Section 5.5.

Regarding deployment considerations, the architecture modules introduced in Section 3.2 will be implemented with the technical WPs (i.e., WP3-WP4) and deployed at the testbed infrastructures within WP5. More specifically, the 6G-BRICKS deployment plan involves:

- Infrastructure plane components, that include the computational infrastructure (e.g., private cloud nodes, deep edge nodes, etc.) with their respective Local Managers (e.g., k8s) and the networking infrastructure (e.g., RUs, RIS elements, gNBs) with their respective RAN Controllers (e.g., O-RAN RIC).
- The Management Plane components, namely the DMOs, are deployed at KUL and EUR, to control the computational and networking infrastructure. Moreover, components related to the Cloud-Edge-Continuum (CEC), namely the CEC manager and the X-HAUL are deployed at KUL.
- The Experimentation Facility components, including the Service Catalogue and System Portal, will be deployed at the ISI/ATH testbed and securely interconnected with the EUR and KUL 6G sites via VPN, and integrated with the respective DMOs.

4 6G-BRICKS RAN architecture design

The 6G-BRICKS RAN is aligned with the Open RAN initiative, aiming to evolve Open RAN compliant breakthrough technologies and evolve them in the 6G era. To this end, 6G-BRICKS will deliver **the first open and programmable Open RAN Radio Unit (RU) for 6G networks**, termed as the **OpenRU**, based on an NI USRP-based platform. Moreover, 6G-BRICKS **will integrate a RIS** into the OpenAirInterface software stack. In addition, 6G-BRICKS will deliver breakthrough experimentation tools, going well beyond the current Testing as a Service (TaaS) capabilities of current initiatives, and allowing experiments also on devices via O-RAN compliant xAPPs. Consequently, the 6G-BRICKS facility aims to serve a dual role, both as a playground for testing of advanced vertical applications and for validation testing and showcasing of the clear benefits and capabilities of 6G breakthrough technologies and devices. In what follows, the design of the ground-breaking 6G-BRICKS CF

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mMIMO and RIS technologies is detailed.

It should be noted that for CF mMIMO 6G-BRICKS will propose E2 interface extensions that are not part of the O-RAN standard; moreover, while the CF mMIMO RU is as close as possible to the standard, 6G-BRICKS will not implement a fully standards compliant Open Fronthaul 7.2 split (but rather a simplified fronthaul design and control interface as detailed in the following section). Hence, the respective CF mMIMO CU and DUs are referred to as "Open RAN" in Section 4.1. On the other hand, a fully O-RAN compliant RIS solution is being delivered, as detailed in Section 4.2.

4.1 Cell-Free Massive MIMO (CF mMIMO)

6G-BRICKS will move the CF mMIMO concept towards a real implementation of the key innovation components (sync, channel estimation, distributed precoding/combining). The best of these previously identified combinations of distributed/centralised processing will be made available to the research users of the test site as software of 6G-BRICKS. 6G-BRICKS aligns for the first time CF mMIMO with an Open RAN framework, providing a vital steppingstone from the very theoretical foundations of CF mMIMO to software implementations of Open RAN DU or RU components. No open RU platform for cell-free prototyping is currently available, which severely limits experimentation and deployment of cell-free enablers in an end-to-end platform. To this end, 6G-BRICKS offers an open, USRP-based cell-free RU for the first time. Moreover, 6G-BRICKS will support mmWave and multi-band synchronization as a key enabler for mmWave CF. 6G-BRICKS further considers the translation of Cell-Free to O-RAN architecture by extending E2 interface extensions to support full-fledged CF mMIMO xApp and will offer CF experimenter xApps, allowing experimenters to configure the RAN elements (CU, DU, MAC scheduler) via the Near-Real TIme (RT) RIC framework for the first time.

Figure 6 illustrates an overview of RAN components for CF mMIMO and how they map with several reference points and innovations from the baseline scenario of single band CF mMIMO processing towards multi-band CF mMIMO processing.

One of the main advantages of CF mMIMO systems is the implementation of spatial multiplexing via transmit precoding for downlink or receive combining for uplink. This allows simultaneous communication between multiple users using the same bandwidth. Interestingly, all CF mMIMO research focuses on a single frequency band and the clustering algorithms that are developed in the baseline implementation from MARSAL project aims to exploit spatial multiplexing maximally with the aspects of considering single band APs[29].

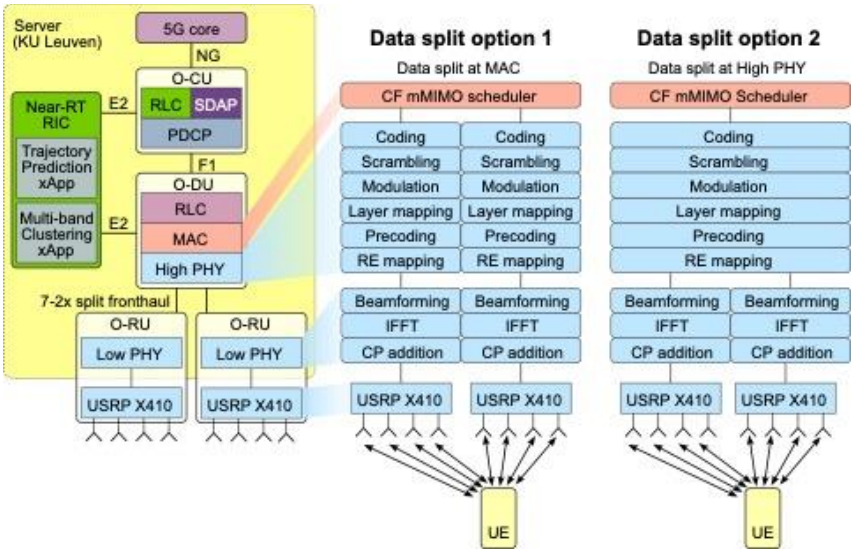

Figure 6 - Overview of RAN components for CF mMIMO technology in 6G-BRICKS.

In 6G-BRICKS, we are leaping forward by developing a CF mMIMO network that can operate in a distributed way across multiple frequencies. Consequently, the multi-band clustering approach as shown in Figure 6 will further develop as a BRICKS enabler that will decide which UEs will be served by multiple RUs. However, in the special scenario, when the UE is served by O-RUs connected to different O-DUs, Inter-O-DU cooperation may be enabled to boost the performance of spectral efficiency of CF mMIMO as investigated for baseline scenarios[30]. In the baseline scenario, to serve the edge users the cooperation between two separate O-DUs is essentially as shown in Figure 7. However, the challenging part of this cooperation is to transfer the data to the users when the users are served by multiple O-RUs as shown in Figure 6. Moreover, if the O-RUs are connected to two different O-DUs as shown in Figure 8, selection of primary O-DU needed in where the data can be splitted at the Medium Access Control (MAC) and/or at the High PHY where the CF mMIMO scheduler will scheduler will schedule the resources based on receiving the clustering decision from the xApp running at the Near-RT RIC and provide the decision at the O-DU by E2 interface. The detailed functional architecture along with signalling mechanisms of the O-DU for CF mMIMO, CF mMIMO scheduler, and the *Open API to CF mMIMO scheduler*, which will allow third parties to investigate an impact of different scheduling strategies on the data transfer performance are discussed in Section in this deliverable.

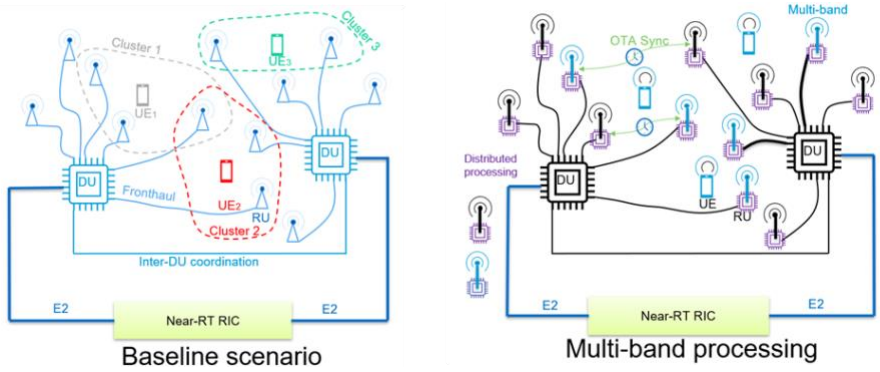

Figure 7 - The transition from the baseline to our proposed multi-band CF mMIMO.

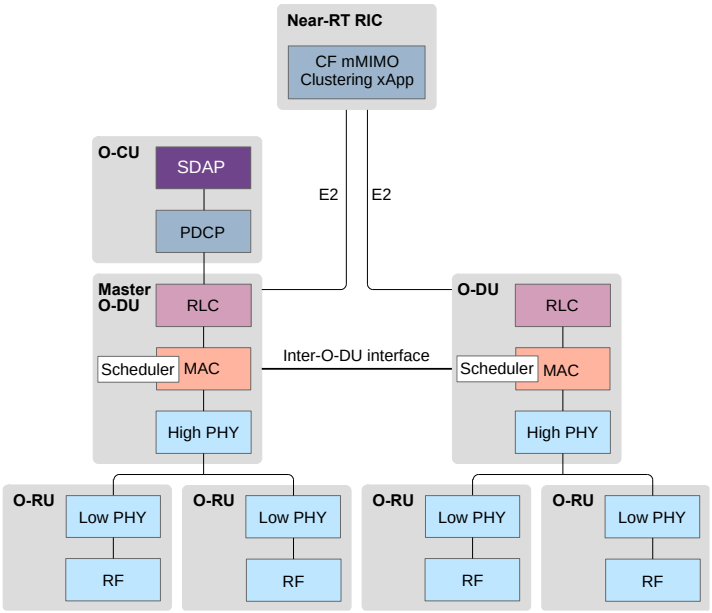

Figure 8 - The multi-DU transmission in CF mMIMO.

As a part of 6G-BRICKS architecture, we will focus on designing OpenRU functional architecture based on considering the concept specified by the O-RAN Alliance which is briefly described in 4.1.1. As shown in Figure 9, the DU will be responsible for PHY-High functional blocks. The 3GPP/O-RAN standard baseline O-DU architecture is not sufficient to support novel CF mMIMO in 6G networks. Therefore, the baseline DU architecture from current 3GPP/O-RAN specifications need to be enhanced to support CF mMIMO network. The detailed design of the DU to support the CF mMIMO is further described in 4.1.2 of the deliverable. Moreover, the baseline approaches for CF mMIMO consider single band distributed processing while the multi-band aspects and enabling distributed processing in multi-band scenario is one of the architectural innovations in 6G-BRICKS. Such a distributed multi-band approach that is further discussed in 4.1.3 that hypothetically reduces channel estimation, synchronization, clustering, and fronthaul cost significantly.

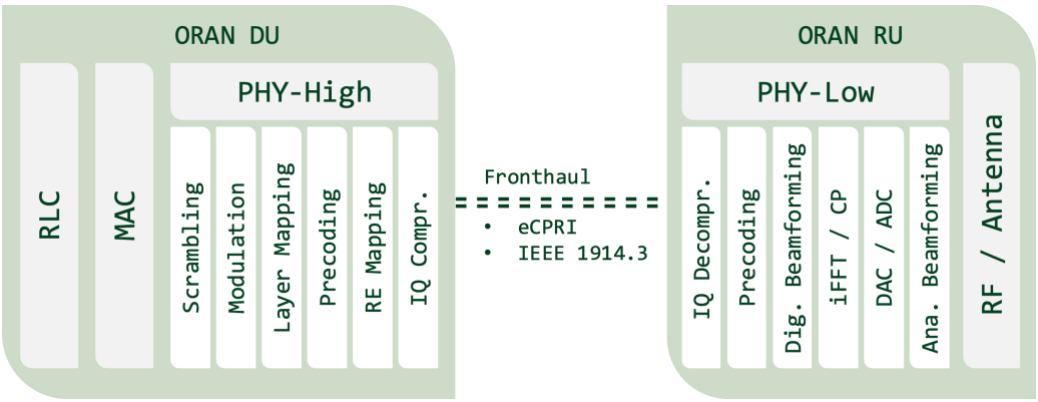

Figure 9 - Architecture of RU and DU with standard building blocks according to the O-RAN standard.

4.1.1 OpenRU Functional Architecture

The O-RAN standard proposes a RAN disaggregation that splits monolithic base stations into dedicated functional units, each responsible for different layers of the network stack [1]. The Open Radio Unit (O-RU) combines several lower layer PHY and RF functionalities that can be handled close to the antennas as depicted in Figure 10. The Distributed Unit (DU) is responsible for the higher part of the physical layer, the MAC, and RLC. With that, the O-RAN alliance follows the 7.2x functional split between the Distributed Unit (DU) and RU as described by 3GPP.

To allow for flexibility in the architecture and implementation, two main O-RU types are described in the O-RAN standard: category B RUs provide precoding functionality (split 7.2b), whereas for less capable category A RUs the precoding is done at the DU (split 7.2a).

The fronthaul interface between RU and DU is organized into several planes (user-, control-, management-, and synchronization plane) where the user plane can carry either evolved Common Public Radio Interface (eCPRI) or IEEE 1914.3 payload. More detailed information on the functional split between RU and DU and the respective fronthaul interface can be found in [2].

6G-BRICKS Open-RU implementation

The 6G-BRICKS project makes some adaptations and customizations to the standard architecture proposed by the O-RAN alliance. While the RU implementation shall be as close as possible to the standard, 6G-BRICKS focuses on the key building blocks necessary to enable the CF mMIMO vision and research. A high level of flexibility will allow faster prototyping and implementation of certain use-cases and operation scenarios. For instance, a simplified fronthaul design and control interface for the transfer of all necessary information between RU and DU based on the USRP Hardware Driver (UHD) will be provided as depicted in Figure 10.

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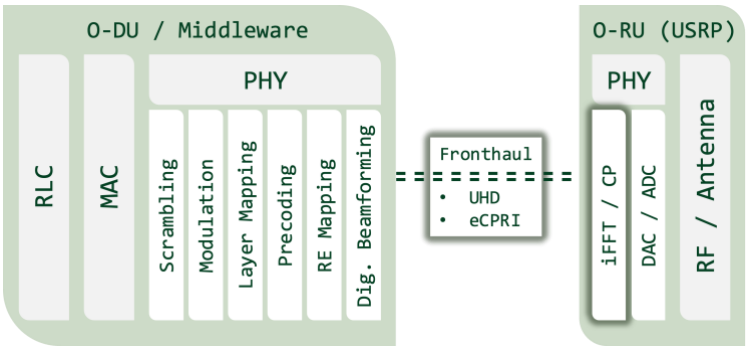

Figure 10 - 6G-BRICKS Open-RU based on the USRP X410 SDR with flexible fronthaul interface and OFDM processing block.

The Open-RU is based on the USRP X410 software-defined radio by NI and consists of analog RF processing blocks as well as analog-digital conversion. Additionally, it will offer Orthogonal Frequency-Division Multiplexing (OFDM) processing functionality like Fast Fourier Transform /Inverse Fast Fourier Transform (FFT/IFFT) and the cyclic prefix handling. The most relevant system parameters are listed in 3.3.1, while a comprehensive specification of the USRP X410 can be found in [3].

The FFT/IFFT and cyclic prefix processing will be as an open-source RF Network on Chip (RFNoC) [4] block on the FPGA of the USRP. The openness of the USRP platform allows for additional functionality to be added and deployed as user-defined RFNoC blocks to further extend the functionality of the Open-RU by researchers and potential experimenters.

The RU-DU fronthaul is realized by using two dedicated physical interfaces:

1. A highspeed 100 Gigabit Ethernet connection (QSFP28) is used to transmit and receive data in the form of frequency domain IQ samples between RU and DU.
2. A 1 Gigabit Ethernet connection is utilized to send configuration and control commands to the RU via the USRP Hardware Driver (UHD) [5].

Additionally, an O-RAN compliant, eCPRI-based fronthaul implementation will be considered throughout the project based on the feasibility within the KU Leuven testbed as well as from experimenters' feedback in the first open call.

As a category A RU, the precoding functionality is handled in the DU / Middleware. The digital beamforming (which is optional according to the O-RAN specification) is processed in the DU / Middleware as well.

4.1.2 DU Functional Architecture

The CF mMIMO is a network paradigm shift to an architecture where several UEs in a geographic area is served by multiple O-RUs. To provide coherent transmission from the antennas of several O-RUs following further enhancements are required to enable CF mMIMO at the DU:

- **Coherent transmission from antennas of several O-RUs**.
  Transmission to a UE can be extended beyond antennas of a single O-RU. If more than one O-RU is used for transmission to the UE, then a *data split* (not to be confused with the *functional split*) is necessary within the O-DU. We investigate two data split options, as shown in Figure 6. The data split option 1 has split at the MAC. The data split option 2 with data split at the High PHY seems to be a better solution, because the functions of coding, scrambling, modulation, layer mapping and precoding, which are done per UE, are not duplicated.
- **CF mMIMO capable scheduler.**

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Transmission through several antennas of the same O-RU as well as transmission through antennas of several O-RUs require coordinated Physical Resource Blocks (PRBs) scheduling carried out by the MAC scheduler which manages radio transmission controlling several physical layer functions, as shown in Figure 11:

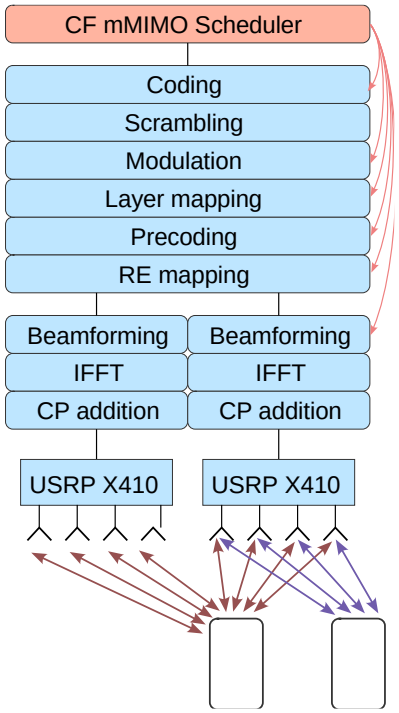

Figure 11 - CF mMIMO Scheduler

- **Coding**, which aims at reducing the number of MAC packet retransmissions. The coding needs to consider the radio conditions interference level, target delay of the data delivery and mobility of the UE.
- **Modulation**, which aims at increasing the data transfer rate to the UE by transmitting several bits in one modulation symbol. The DU decides about the coding and modulation by selecting the modulation and coding scheme (MCS) for each MAC packet.
- **Layer mapping**, which aims at increasing the data rate by transmitting to the UE several simultaneous independent data streams referred to as layers. Each layer can be sent in different direction by selecting a precoder.
- **Beamforming**, which aims at transmitting each layer in the requested direction. Note that, in the context of O-RAN, precoding us used to differentiate between different layers of signal to the same and beamforming is used for each layer to direct it in a required direction.
- **RE mapping,** which places the transmitted data to the UE in the required PRBs.

One of the ***bricks*** of the 6G-BRICKs projects is the *Open API to cell free scheduler*, which will allow third parties to investigate an impact of different scheduling strategies on the data transfer performance. Figure 12 shows the CF mMIMO Scheduler framework including ***datasets***, i.e., inputs and outputs made available by the CF mMIMO Scheduler Open API:

- The RLC provides the amount of data buffer for each logical channel of the UE.
- The O-CU provides the QoS parameters for each logical channel.
- The xApp of the Near-RT RIC provides the UE serving cluster including the list of O-RUs to be used for the

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transmission to the UE.

- The MAC provides the data to be retransmitted in case of QARQ negative acknowledge.
- The HARQ acknowledge transmitted by the UE is delivered from the High PHY. This HARQ is used by the scheduler to take a decision about data retransmission, but it is also the main feedback provided to the scheduler to be used to tune the scheduler performance.
- The received signal strength power (RSRP) measurements are obtained from the High PHY.
- The scheduler decides about the amount of data transmitted to the UE, Modulation and Coding Scheme (MCS), the number and location of the PRBs, precoding and beamforming to be uses.

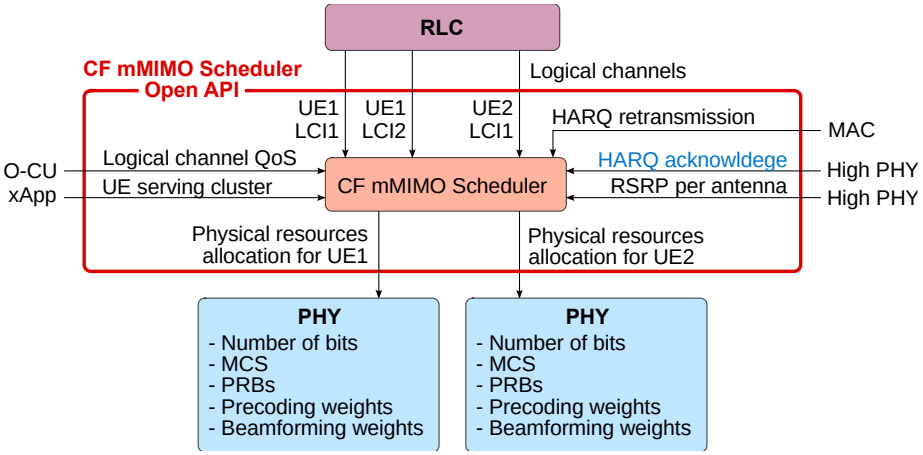

Figure 12 - CF mMIMO Scheduler Open API framework.

4.1.3 Cell-free mMIMO Multiband Processing and Functional Blocks

In this subsection, we discuss the envisioned enablers for Cell-Free mMIMO. We will first work on general distributed processing, extend these algorithms to benefit from multi-band operation. Finally, some of these solutions will be implemented as standalone ***bricks*** which will be tested at the KUL testbed. An overview towards the development of distributed and multi-band Cell-Free bricks is shown in Figure 13.

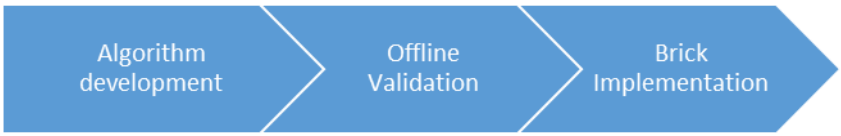

Figure 13 - Our approach from initial theoretical development to eventual brick implementation

In an initial stage, we aim to develop our solutions offline and validate them via simulation, in parallel we work on the implementation of a channel sounder on our testbed. Once this channel sounder is operational, we can validate our proposed solutions offline. After an initial selection stage via the offline validation of the proposed methods, we can then select the most promising algorithms to implement as standalone bricks in the testbed.

4.1.3.1 Distributed processing

Cell-Free network refers to a network with many distributed Radio Units (RUs) cooperatively serving User Equipment units (UEs) through coherent joint transmission and reception [8] using the same time-frequency resources. Many works have already addressed this mode of operation. However, there are several remaining challenges that need to be solved to achieve scalable and efficient CF communication: (i) *channel estimation*, (ii) *synchronisation*, and (iii) *fronthaul-aware distributed processing*.

Channel Estimation

We aim to improve channel estimation in CF mMIMO in three main ways: improved reciprocity calibration, scalable pilot assignment, and exploiting correlation between the channels from a specific UE to different Rus. Improved reciprocity calibration is need because Time-Division-Duplexing (TDD) is widely adopted in CF mMIMO, where wireless channel reciprocity is exploited to estimate CSI from only uplink pilot signals [9]. However, this reciprocity holds only antenna-to-antenna, hence realizing it requires careful calibration of the transmit and receive chains in each RU. Furthermore, uplink pilot assignment (PA) is crucial for performant channel estimation in CF mMIMO to minimize the so-called 'pilot contamination' effect. Current works focus on a structured/clustered network-wide PA [11], which introduces significant overhead. Current channel estimation methods also don't sufficiently focus on exploiting the channel correlations between different RUs, and the best structure to achieve accurate channel estimation at limited pilot and fronthaul communication cost is still unknown. We will focus on theoretically and experimentally driven channel estimation methods for CF mMIMO [5] and aim to develop efficient and viable channel estimation and reciprocity calibration.

Synchronisation and Phase Coherency

Traditional methods rely on sharing the Local Oscillator combined with a trigger signal [14] from a central clock. Relying on this central clock to synchronize the distributed RUs in CF mMIMO introduces excessive overhead. Hence, we envision fully distributed synchronisation of different RUs. Recently, there is increased interest in over-the-air synchronization, addressing scalability and geographical infrastructure limitations. To resolve time offsets between RUs, with minimal overhead, synchronization algorithms need to be designed, exploiting a stochastic model for each RU clock. Autoregressive stochastic models have shown promising performance in capturing clock time offset behaviour [15] for target localization; however, pushing their performance limits further to enable coherent processing is still an open research question to be addressed in this project.

As a key requirement of CF mMIMO transmission, phase coherency between different entities in the RAN needs to be established. Therefore, NI und KUL will investigate and implement different techniques for RU synchronization. While the baseline will be cable-based synchronization techniques and algorithms, a new approach of over-the-air synchronization will additionally be considered for investigation as a promising solution to ease the burden of fronthaul capacity. This approach has many implications as, e.g., the propagation channel needs to be incorporated into the synchronization model. Additionally, the emphasis of new synchronization approaches shall be ideally focused on the PHY layer to minimize the impact on other layers of the stack.

Fronthaul-aware distributed processing

Another important consideration is the fronthaul capacity that is required for the corresponding computational split between the RUs and the DU. For instance, increasing the computational load on the RU, lowers the fronthaul capacity requirements. However, the trade-off with this lower capacity requirement is a degraded spectral efficiency compared to the concentrating more computational load on the DU. As a result, the fronthaul capacity is seen as the bottleneck of the system. A serial fronthaul approach with serially connected RUs is proposed as a potential scalable solution to densify RU deployments and reduce infrastructure requirements [16]. The selection of the optimal scheme that minimizes interference and guarantees scalability is an open research question.

Our multi-band approach focusses on four main innovation areas (i) *channel estimation*, (ii) *clustering*, (iii) *synchronisation*, and (iv) *fronthaul-aware distributed processing*:

Multi-band channel estimation

Because of the increased number of subcarriers, channel estimation becomes much more computationally demanding in the high frequency ranges. However, the channels in those frequency ranges are more dominated by the Line-of-Sight component and less by the small-scale fading. This inspires us to derive location-based information from higher frequency bands and exploit them at lower frequency bands our vice versa. An example

of this is exploiting Angle of Arrival (AoA) information from one band and then using this in the channel estimation or directly in the beamforming for another band [8], this seems promising, even for bands that are far apart (frequency-wise). Such methods simplify the computation for the channel estimation by transforming it to the polar domain and thus only requiring a slight adjustment for different bands. Another option is to use covariance matrix extrapolation [9]; this has so far only been studied in the context of Frequency Division Duplexing (FDD) MIMO systems [10][11][12]. For these works, the bands are assumed to be close together, it is within scope for this project to also explore which methods could simplify these calculations for multi-band systems that are further apart. This could greatly reduce fronthaul signaling by forgoing the gathering of statistical information for certain frequency bands.

Multi-band clustering

In mmWave, beamforming is much more directional and thus inter-cell interference isn't as much of an issue. However, mmWave is extremely limited because of its sensitivity to blocking in the radio propagation environment. Cell-Free can provide a solution here by employing multiple RUs to serve a single user [13], this way the probability of maintaining at least one LoS beam is much higher [14]. Since serving all UEs with every RU is not a scalable solution, a subset of RUs should be selected to serve a user (User-Centric Clustering). For now, most clustering solutions rely heavily on the large-scale information, like large-scale coefficients, location of UEs and APs, and distance between UEs and Aps [15]. Most of this large-scale information is either constant over multiple bands (location, distance, etc.) or can be extrapolated over different bands (path loss, shadowing, user mobility). This heavily inspires clustering algorithms to be reused over multiple bands because of this dependency on large-scale information and the high cost of the clustering (computed at the RIC level).

Multi-band synchronization

Because of the shorter wavelength in mmWave, the synchronization requirements are quite stringent. Already at this moment, synchronization protocols exist that can achieve sub-nanosecond accuracies [16]. The main question is how to integrate these into an operational RAN in a scalable fashion. We propose over-the-air synchronisation, where a more reliable sub6-GHz band can be used to synchronise whereas the mmWave-band can be used for data transfer (comparable to LTE cells that are synced over GPS). Over-the-air synchronization fits perfectly in our completely disaggregated architecture since distribution of the network procedures is the end-goal.

Multi-band fronthaul aware distributed processing

Further, because of the extremely high throughput of mmWave systems, back/fronthauling will be an even bigger issue and should be a strong consideration during the design phase. Most of the processing can be heavily based upon the work that is conducted for the sub-6GHz bands. It is however important to note that here the motivation is completely different due to the very different propagation conditions and general constraints imposed upon mmWave deployments. However, various aspects such as path loss, doppler spreading, and shadowing mainly depend on the environment and user mobility. Thus, these show important statistical similarities between frequency bands that are very distinct. By reducing the amount of signalling for the collection of these statistics, a larger portion of the constrained fronthaul can be used to transmit user-plane data. At this point it is already identified that by sharing statistical averages amongst DUs instead of real-time channel estimates, spectral efficiency isn't greatly diminished [17]. The next step is to share these statistical averages across multiple bands, thus, reducing the fronthauling cost even further.

4.1.4 RIC architecture for cell-free experimentation

The reference Near-RT RAN Intelligent Controller (RIC) architecture proposed by O-RAN is shown in Figure 14.

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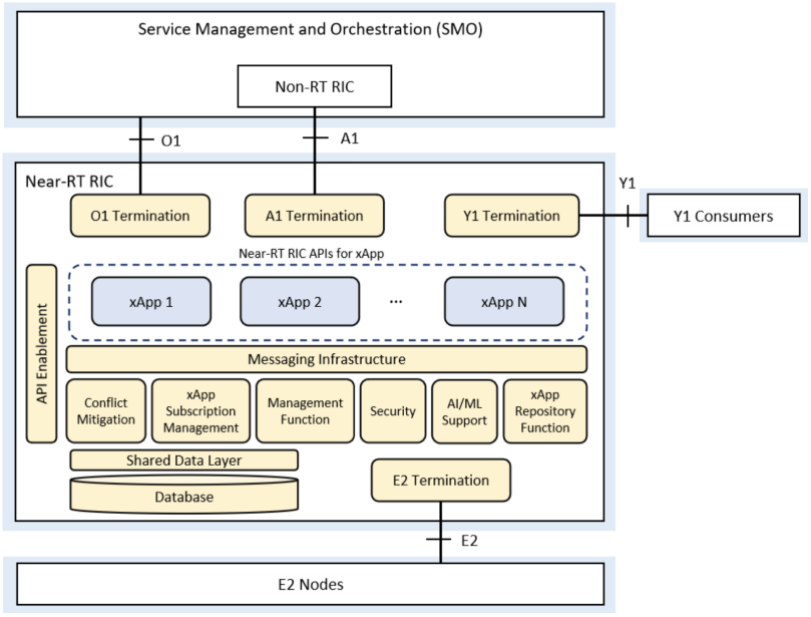

Figure 14 - O-RAN Near-RT RIC architecture.

The general 6G-BRICKS Near-RT RIC architecture for CF mMIMO networks is shown in Figure 15. The architecture is focused on the implementation aspect of the ASN.1 coding, which is specific to the E2 interface Service Models (KPM, RC, CF), therefore, the Near-RT RIC architecture includes Key Performance Measurement (KPM) Service, RAN Control (RC) Service and CF Service which allow an xApp to communicate through the E2 interface, and the Policy Service, which is used to deliver Non-RT RIC policies to the xApps. The xApps communicates with the Near-RT RIC infrastructure through the *Service Interfaces*, namely KPM Service Interface, RC Service Interface, CF Service Interface and Policy Service Interface. Each E2 Service Model has other objectives and capabilities:

- Network Interface (NI) Service Model is ASN.1 based and aims at monitoring and modification of 3GPP interfaces messages.
- Key Performance Indicators (KPM) Service Model is ASN.1 based and aims at monitoring the RAN and UE performance.
- RAN Control (RC) is ASN.1 based and aims at monitoring and modification of RAN parameters per UE.
- Cell-Free (CF) Service model is JSON based proprietary IS-Wireless Service Model to support CF mMIMO networks.

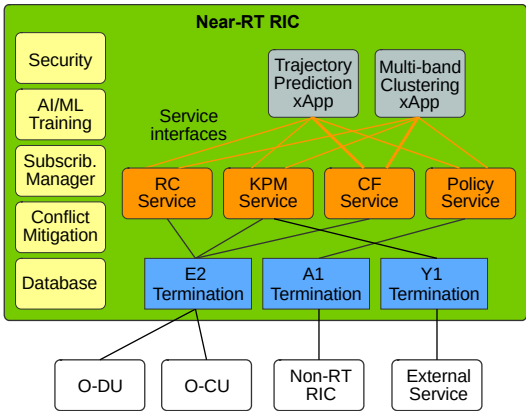

Figure 15 - Near-RT RIC to support CF mMIMO networks.

The Near-RT RIC will be equipped with two xApps:

- **Trajectory Prediction xApp** as shown in Figure 16. The xApp will optimise future cluster considering the UE location change, amount of data in the UEs' buffer, QoS requirements of the radio bearers. The xApp will output the serving O-RUs for each UE. Next, the Scheduler at the MAC will allocate the PRB resources for the UE in the O-RUs selected by the xApp. When selecting the serving cluster, the xApp will collect RSPR values for measurement cluster and based on the measurements will select the serving cluster as a subset of the measurement cluster.

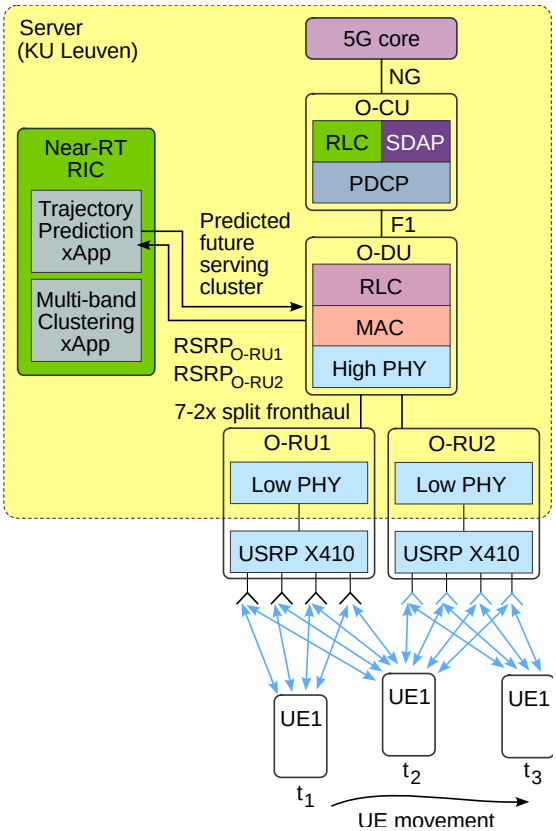

Figure 16 – The user trajectory prediction xApp for CF mMIMO networks.

- **Multi-band Clustering xApp**, shown in Figure 17. The xApp will determine the serving cluster in the multi-band networks. Considering different channel propagation conditions for different frequencies, amount of data in the UEs' buffer and QoS requirements of the radio bearers, the xApp will output the serving O-RUs and frequency for each UE. Next, the Scheduler at the MAC will allocate PRB resources for the UE in the O-RUs selected by the xApp. When selecting the serving cluster the xApp will collect RSPR from measured on different frequencies.

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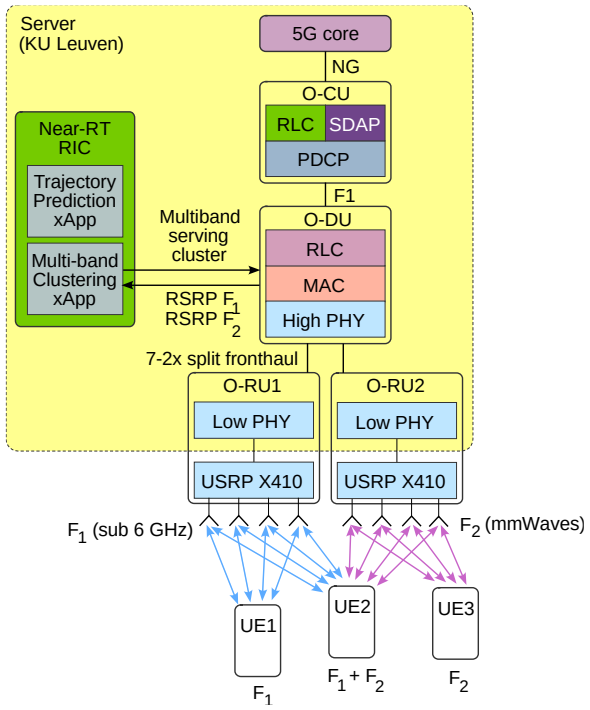

Figure 17 – The multi-band clustering xApp for CF mMIMO.

4.2 O-RAN compliant RIS for 6G networks

RIS relates to a new type of system node with surfaces that may have reflection, refraction, and absorption properties through many small antennas or metamaterials elements that can be adapted to a specific radio channel environment. RIS surfaces are programmable and can be used to control the propagation of electromagnetic waves by changing the electric and magnetic properties of the surface. In 6G-BRICKS, we will build the first end-to-end RIS-based solution for 6G that integrates a RIS reflector with an open-source O-RAN stack operating in the millimeter-wave band. Moreover, 6G-BRICKS platform will be the first RIS platform open for experimentation. Besides experimenting RIS related components (like RIS controller and RIS element, 6G-BRICKS will allow experimentation of end-to-end services, focusing on indoor scenarios like industry 4.0.

4.2.1 6G-BRICKS RIS hardware design

6G-BRICKS has access to two types of RIS hardware, transmissive (T-RIS) or reflective (R-RIS). The two architectures are presented in Figure 18. They are essentially flat electromagnetic surfaces composed of subwavelength structures that can modify the phase and/or the amplitude of incident waves to achieve a desired reflected or transmitted pattern. In practice, RIS can manipulate an impinging electromagnetic field and generate anomalous reflection, transmission, deflection, etc. In the case of an R-RIS (Figure 18(a)), the impinging wave is phased and reflected in the same half space region as the incoming wave. In the case of a T-RIS (Figure 18(b)), on the other hand, the electromagnetic wave is controlled in phase and retransmitted as in the case of a lens.

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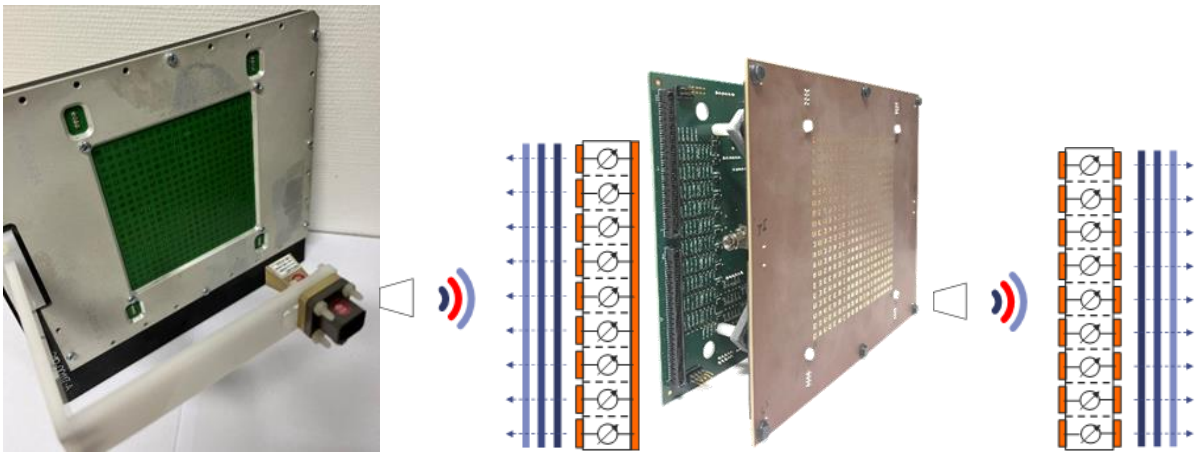
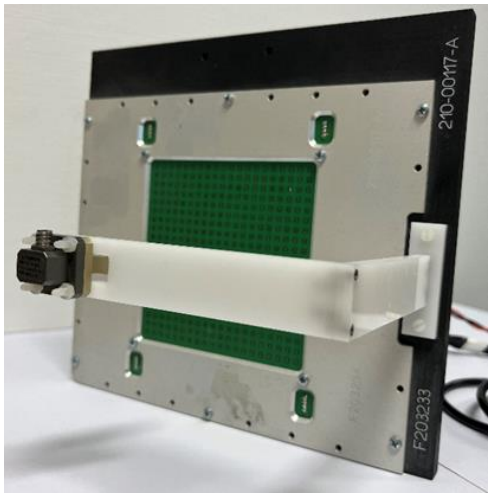
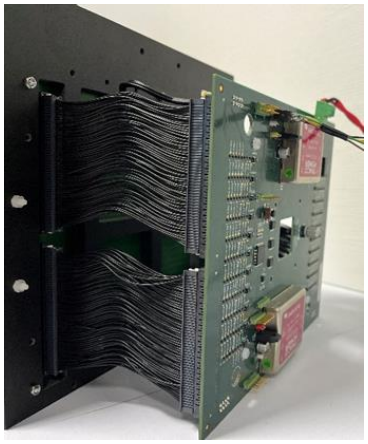


Figure 18 - RIS available architectures. (a) R-RIS and (b) T-RIS

If we exclude the operation principle, the two RIS are identical from the point of view of the digital control interface. They are composed of two boards, the radiofrequency analog system which includes the radiating elements with p-i-n diodes (Figure 19(a)) and the digital control board (Figure 19(b)). Four hundred radiating elements or unit-cells compose the analog beamforming board. Each unit-cell is controlled in phase thanks to the use of two p-i-n diodes. The digital control board can be interfaced to the control unit using a simple USB cable. A DC cable is used to connect the board to a 24 V power supply. The digital control board (Figure 19(c)) is composed of a µ-controller, two DC/DC 24 V/2.5 Va converters, a DC/DC 24 V/3.3 V converter, 50 shift registers, a buffer, 400 MOS transistors, and 800 resistances. The control board is controlled by a Matlab tool, which uses a specific codebook data set. The codebook is generated considering a specific numerical tool based on a hybrid simulation strategy based on analytical equation and data extracted by electromagnetic full-wave simulation. A specific codebook represents the state of each unit-cell required to generate a required radiation beam.



(a)



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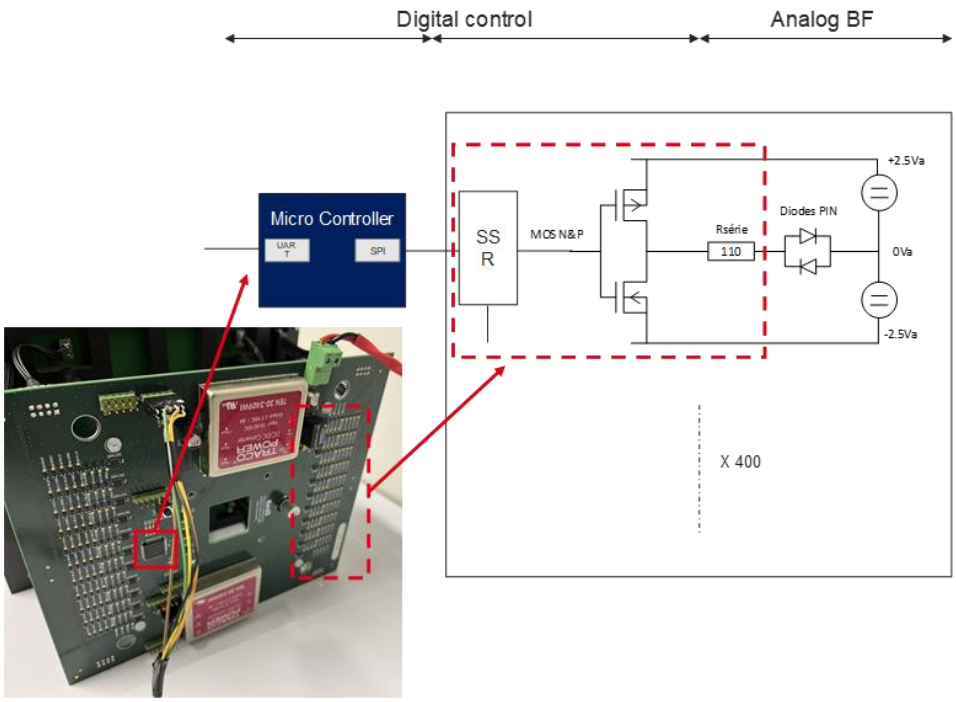

(c)

Figure 19 - R-RIS available architectures. (a) Analog beamforming board and (b) digital control. (c) Description of the building blocks.

4.2.2 Functional architecture for RIS experimentation

6G-BRICKS will deliver the integration of RIS testbed to the EUR 6G site, which allows the experimenter to describe O-RAN compliant xApps following an xApps Descriptor (xD) template. The main innovation of the testbed is the RIS integration with the EUR FR2 setup (see Figure 20) allowing openness from different perspectives: the vertical experimenter, the RIS provider and the RAN provider perspectives. This openness is achieved thanks to O-RAN open-interfaces.

In such setup, the experimenter will focus on developing the RIS control algorithms since the testbed provides an abstraction of the RIS via the O-RAN E2 Service Model. For the RIS provider, whatever technology he uses, a RIS local controller is deployed at the RIS and will be able to understand the E2 RIS Service Model and hence will be able to communicate with the O-RAN near real-time RIC. For the RAN provider, he just needs to deploy the proposed RIS Service Model to allow the communication with the RIS.

In what follows, we describe the 6G-BRICKS planned contributions to the O-RAN SMO and RIC blocks.

Service Management and Orchestration (SMO)

The O-RAN Service Management and Orchestration (SMO) platform is an intelligent automation platform which applies automation at scale to simplify the complexity of networks, as well as improve network performance, enhance customer experience and minimize RAN operational costs.

In the context of 6G-BRICKS project, the SMO will enable the automation of xApps life cycle management at the EUR testbed. Indeed, after describing the xApps at the vertical portal, the DMO sends the xApp Descriptor to the SMO. The latter will on-board and instantiate the described xApps on the top of the near real-time RAN intelligent Controller (RIC). At the end of the experimentation/trial, the SMO terminates and destroys the xApps.

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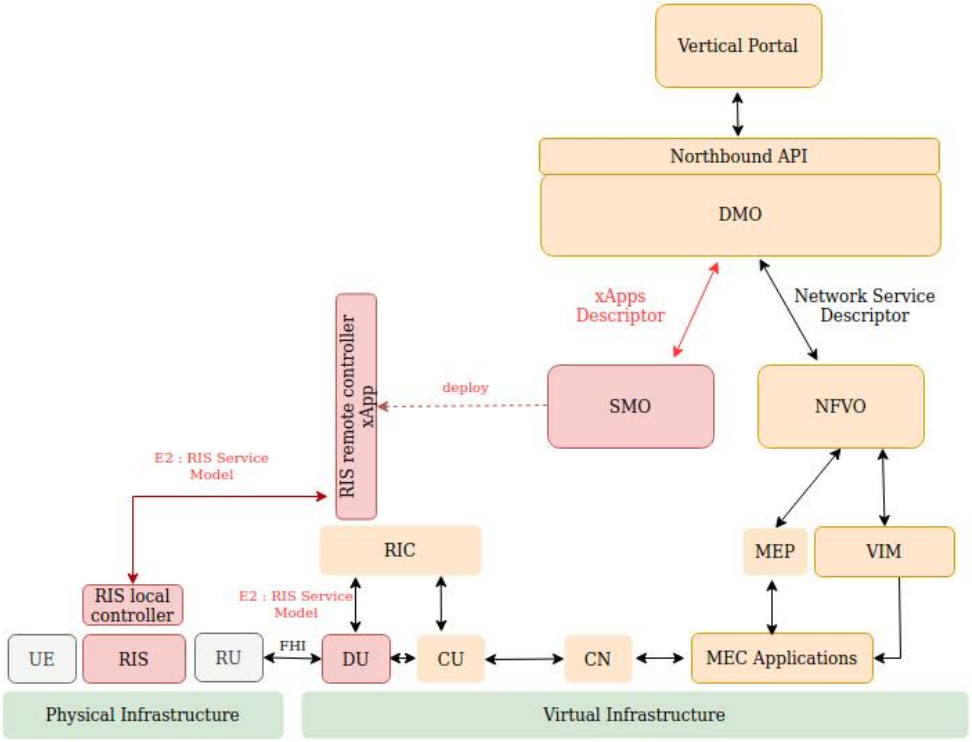

Figure 20 - RIS integration architecture at the EUR testbed

The near real-time RAN Intelligent Controller (RIC)

FlexRIC is an O-RAN compliant RAN Intelligent Controller (RIC) allowing to develop xApps and interface them with the gNB. Service Models (SM) are the main part of the RIC, allowing the xApp to interface with the RAN functions at the gNB. Basically, a SM is a contract between the xApp and the RAN functions, which describes the methods and the data models used by both terminations. (I.e., xApp and RAN function).

Currently, we are supporting two types of service models as follows:

Custom: including MAC, RLC, PDCP, RRC, NGAP, RAN Slicing (SC), and Traffic Control (TC) service models

O-RAN: KPM v2.02, RAN Control (coming on Q1 2024) and CCC (coming on Q2/Q3 2024)

In this project, we add a new SM allowing the RIS remote controller to communicate with the RIS local controller. In particular:

- RIS Remote Controller xApp: 6G-BRICKS will develop and deploy a custom O-RAN compliant Service Model (SM) for RIS control. The proposed SM will allow the experimenter xApps to collect channel related information from the RAN (such as RSRP, SNR, BLER, etc) and send beam control messages to the DU and the RIS in order to enable smart beam management and beam synchronization between the DU and the RIS.
- RIS Local Controller: 6G-BRICKS will develop and deploy a local controller at the RIS to play the role of the E2 node agent. The latter will decode/encode the E2 messages from/toward the RIC. Particularly, encoding and decoding the messages containing the RIS SM information elements. Besides, the RIS local Controller applies the RIS reflection coefficient updates upon reception of control messages from the RIC.

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5 Management & Orchestration architecture Design

The 6G-BRICKS orchestration architecture adopts the TMForum Intent Driven Autonomous Networks (IDAN) paradigm, which builds on a three-layer design featuring intelligence at the Business Layer, Service intelligence, and infrastructure intelligence. 6G-BRICKS further introduces the concept of an XAI-driven Distributed Manager and Orchestrator (DMO) to help experimenters understand failure modes for experiment onboarding and execution, supporting an **innovative workflow** termed as Intent-driven, Human-in-the-loop experimentation. Moreover, 6G-BRICKS decentralizes automation and in particular analytics collection, which is fully centralized in the 5G SBA via the NWDAF function. The 6G-BRICKS solution instead collects service requirements from the Experimentation Plane via the intent mechanism, and decentralizes analytics collection and explanation via a set of DMOs. DMOs are deployed at each testbed, which represents a Cloud-Edge-Continuum (CEC) domain, abstracted by the CEC manager. Finally, the security of the facility is managed by a Security Orchestrator. In what follows, the internal designs and external interfaces of all aforementioned components, i.e., the Experimentation Plane, DMO, CEC, and Security Orchestrator, are further detailed.

5.1 Experimentation Plane

5.1.1 Overview

The 6G-BRICKS Experimentation Plane, deployed at the ISI/ATH testbed, acts as the entry point of experimenters to the Facility. This includes the Experimenters Portal, which provides experimenters and vertical application owners access to the various functionalities of the Experimentation Facility. The 6G-BRICKS Portal will specifically support third-party UCs, simplifying the onboarding of applications coming from open calls and offering a private Docker Image service repository. Moreover, the portal allows experimenters to onboard xApps, providing access to experimentation at the RAN domain (e.g., changing parameters related to the RIS). Finally, an intent engine is part of the Experimentation Plane, simplifying service onboarding and SLA definitions. The purpose of intent is to define and communicate knowledge about requirements, goals and constraints to a system in a way that allows automated processes to reason about it and derive suitable decisions and actions. The 6G-BRICKS Experimentation Plane contributes a prototype intent engine implementation, derived from TMF921 specifications.

5.1.2 Functional Architecture

The Experimentation Plane provides experimenters and vertical application owners a set of integrated components that offer simplified access to the various functionalities of the Experimentation Facility. More specifically, the Experimentation Plane offers the following components:

- An Experimentation Portal, which facilitates the onboarding and instantiation of (dockerized) applications along with their requirements, expressed with an intent language, as well as the onboarding and execution of xApps. The Experimenter's portal technology stack will be based on a React [34] Frontend and a Python backend, leveraging the Flask [35] micro web framework. Flask is based on the WSGI (Web Server Gateway Interface) specification and provides a simple API for developers to create web applications. It supports routing, request handling, templating, and more.
- The 6G-BRICKS repository, which offers centralized storage of artefacts such as Docker images and xApps. This centralized component is accessible from both testbed sites, offering private Docker and Helm chart repositories for to the project. These will be leveraged for storage of both UC-specific and Open Calls specific containers, that can be automatically provisioned to the underlying Cloud-Edge-Continuum infrastructures. The 6G-BRICKS repository will be based on the JFROG Artifactory framework, appropriately configured and integrated with the Portal services and the underlying K8s Testbed infrastructures.

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- An Intent Engine, which is responsible for processing, reasoning and fulfilling intents related to Service onboarding at the 6G-BRICKS facility (i.e., autonomously driving decisions and actuations that fulfil requirements, goals and constraints expressed by intent). The intent engine is instantiated from the TMF921 IDAN project reference implementation [36]; it accepts intent definitions following the TMF921 data model, and implements *intent negotiation* and *intent reporting* workflows. Conflict resolution is an integral part of the intent engine, aiming to achieve decentralized consensus among owners of intents (i.e., tenants) and owners of infrastructure.

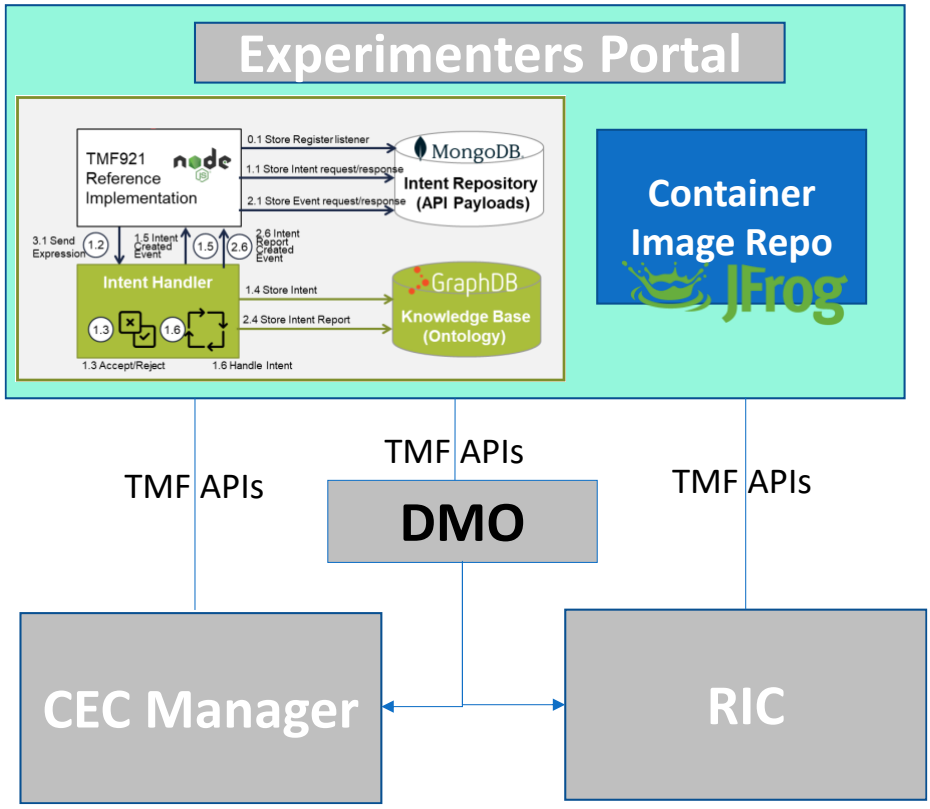

Figure 21 – Experimentation plane

5.2 Domain Manager and Orchestrator (DMO)

5.2.1 Overview

One of the major limitations of the 5G SBA is related to the data analytics functions governing the operation of the 5G Core to deliver network automation and orchestration. These functions then inform management functions at the OAM layer, resulting in a tightly integrated system where Network Service Orchestration (NSO) and Resource Orchestration (RO) is linked. A similar approach is followed by the NFV architecture, which assumes that the NFVO orchestrator is responsible for the orchestration of Services, as well as the underlying NFVI. This centralized approach is not compatible with 6G, where a high number of services from different tenants need to be managed and orchestrated over the CEC (Network of Networks vision). 6G-BRICKS envisions instead a new decentralized Management Plane via a unified framework of Domain Managers and Orchestrators (DMOs) being responsible for policy translation and unification via Explainable AI (XAI) mechanisms. The 6G-BRICKS DMO generalizes the concept of the NFVO in the 6G era, offering policy unification and automation for all orchestration domains (e.g., Edge, Core, Network, IoT) while supporting a loose coupling of the management plane of the 6G

sites from the centralized Business Plane for scalability purposes. In what follows, the internal design of the DMO is contributed.

5.2.2 Functional Architecture

The comprehensive architecture of the Domain Manager and Orchestrator (DMO) is illustrated in Figure 22, comprising three layers: Monitoring, Fault Management, and Runtime Management. The DMO's workflow begins with the Monitoring layer, which gathers Key Performance Indicators (KPIs) from domain-specific technological components, including KPM xApps in the Radio Access Network (RAN), Network Data Analytics Function (NWDAF) in the Core Network (CN), and Network functions virtualization Orchestration (NFVO) Collectors in the Edge Network. Additionally, the Monitoring layer facilitates communication with the vertical portal, providing experimenters visual representations of network KPIs. The Fault management layer utilizes the collected network KPIs to identify anomalies and establishes communication with the slice orchestration layer to address and resolve these issues. It ensures that experimenters are informed about the root cause and resolution of anomalies through the vertical portal. The Runtime Management layer plays a vital role in optimizing network performance. It applies new configurations to different technological domains, utilizing SMO/RIC for RAN, CN Manager for the Core network, and NFVO for the Edge network. Additionally, experimenters can manually configure technological domains through the Vertical Portal. It should be noted at the DMO level the experiments are run as network slices ensuring multi-tenancy at the infrastructure level.

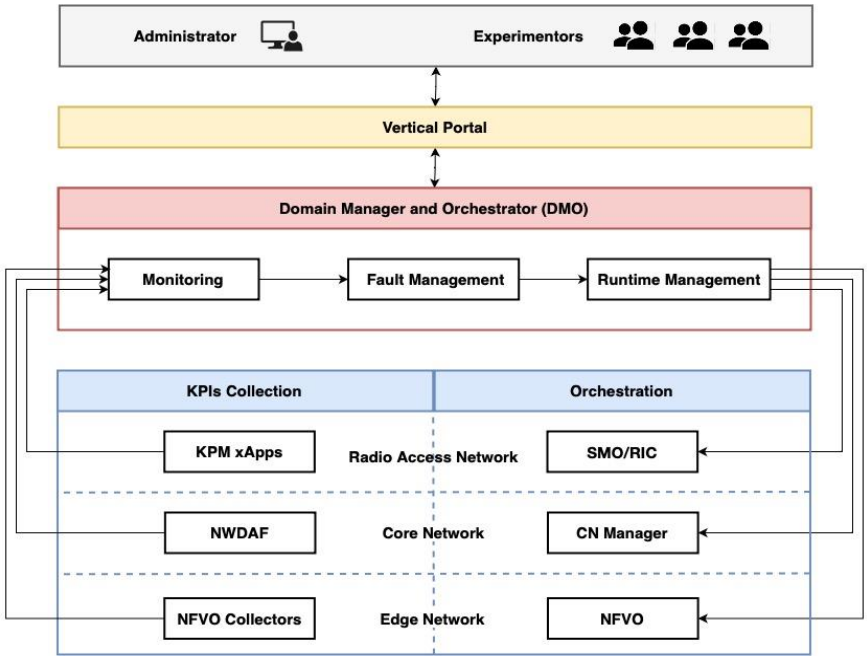

Figure 22 – DMO Architecture

5.2.2.1 Monitoring

Figure 23 provides an overview of the comprehensive architecture of the monitoring layer, encompassing three technological domains: RAN, CN, and Edge Network. This architecture comprises several key components, including Data Collection Servers, Data Presentation Servers, and a KPIs database. The Data Collection Servers consist of two levels of Brokers. At the high level, there is a Broker based on RabbitMQ, which exposes the collected monitoring data to end-users in its RAW format. At the low level, there is a Broker built on Kafka, responsible for collecting data from different technological domains using specific components like KPM xApps

in RAN, NWDAF in CN, and NFVO Collectors in the Edge Network. The collected data from the Brokers is stored in a database, acting as a repository for the network KPIs gathered from the various technological domains. Data Presentation Servers play a crucial role in this architecture, as they are responsible for presenting the collected data per slice to the respective slice owners. This presentation is accomplished through the vertical portal, which serves as the interface through which slice owners can access and view the data.

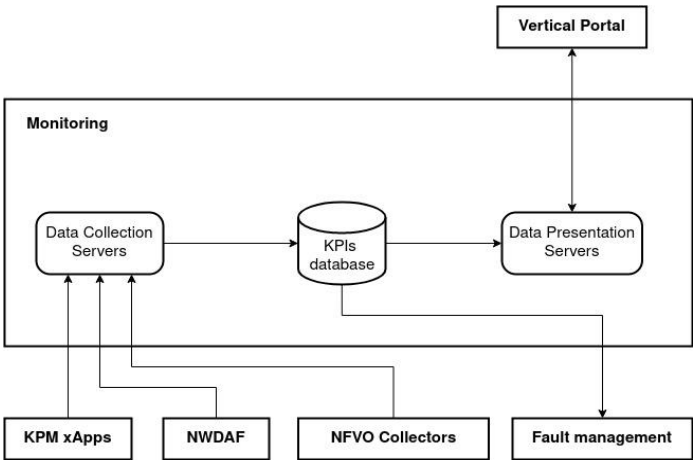

Figure 23 – Architecture of the Monitoring layer

5.2.2.2 *Fault Management*

The Fault Management module, illustrated in Figure 24, is responsible for effectively managing faults within the system. It comprises several components that work together to identify, analyze, and resolve anomalies. The first component is the Data Collection component, which gathers data from the Monitoring layer. This collected data is then passed on to the AI-based Anomaly prediction component, where Transformers/RNN/LSTM-based algorithms will be employed to detect/predict abnormalities.

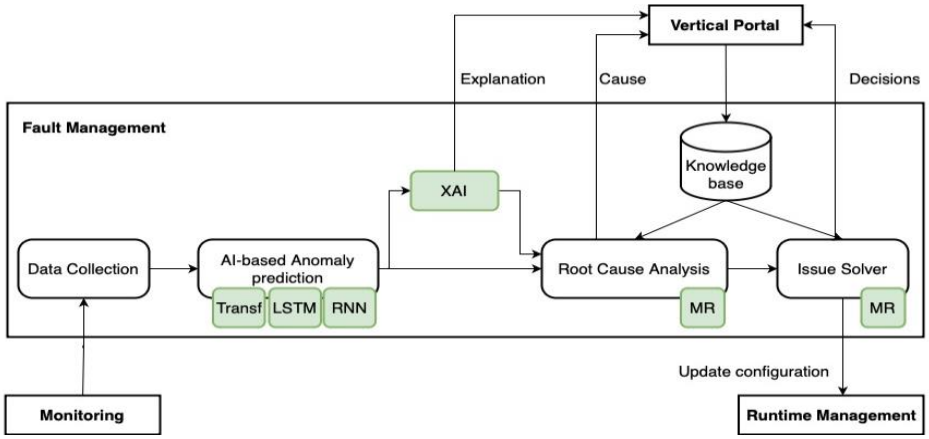

Figure 24 – Architecture of the Fault management layer

For instance, researchers in [24] proposed a novel Transformers-based approach to detect anomalies in network flow data. Once an anomaly is detected, the data is forwarded to the Root Cause Analysis component, which utilizes eXplainable AI (XAI) explanations to determine the underlying cause of the anomalies. As an illustrative example, Authors of [25] used XAI to analyze root causes of service degradation within their proposed Zero-

Touch Management (ZTM) framework for cloud-native environments. Finally, the Issue Solver component uses the insights from the root cause analysis and expert knowledge to make informed decisions and updates the relevant domains using the Runtime Management layer. In this latter component, Machine Reasoning can be used in order to update network configurations. For example, Yan et al. in [26] utilized Case-Based Reasoning (CBR) to optimize network slicing resource allocation in 5G radio access networks (RAN) by identifying similar cases and determining the best slice bandwidth ratio based on their stored cases.

5.2.2.3 Runtime Management

Figure 25 illustrates the Runtime Management layer, which is utilized by the vertical portal and fault management components. This module implements Life Cycle Management (LCM) components for three technological domains: RAN, CN, and Edge Network, following 3GPP specifications. Its main functions include commissioning, operations, and decommissioning of Network Slices (NS) within each domain. To configure the network slices, the Runtime Management module leverages the Northbound Interfaces (NBI) exposed by specific components in each technological domain: SMO/RIC for radio resource management, CN Manager for core network resource management, and NFVO for edge network management.

Intent-Based Networking (IBN) is a groundbreaking concept that introduces a user-centric approach to network management. It aims to revolutionize network management by prioritizing user intent and creating a dynamic, adaptable network ecosystem. Although IBN is a relatively new term and technology, significant efforts have been dedicated to defining and standardizing it. It involves five essential steps: intent profiling, translation, resolution, activation, and assurance [27]. The Decision Enforcement component in the Runtime Management layer will receive the output of the intent resolution step, which derives from Language models within the vertical portal [28]. Subsequently, it will employ intent resolution and activation steps to facilitate the deployment of the vertical slice within the infrastructure.

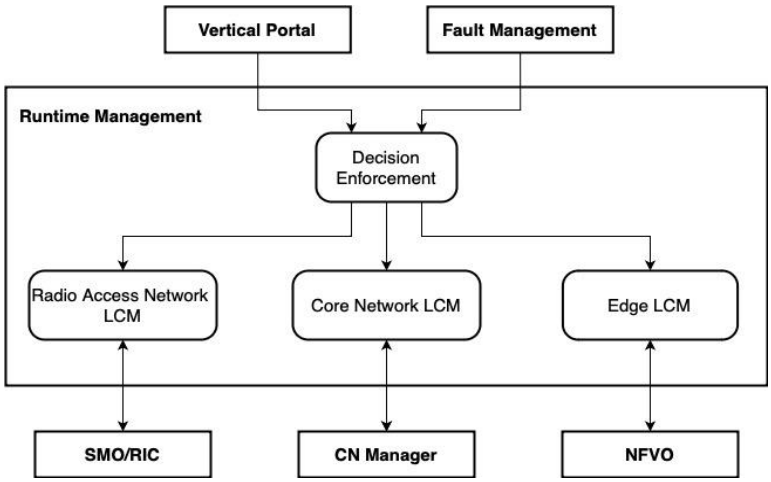

Figure 25 - Architecture of the Runtime Management layer

The intent activation in the runtime component will ensure that the intent will be satisfied at the moment of its deployment. However, networks are not static. In reality they present a highly dynamic nature both in time and space. Thus, another indispensable component to create the envisioned autonomous behavior, is intent assurance. This latter will use monitoring data to ensure the correct behavior of the network and satisfy users' demands throughout its lifetime.

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5.3 Compute continuum abstraction

5.3.1 Overview

The compute continuum abstraction is comprised of two basic components, the Continuum Manager and the π-Edge platform. Each edge-cloud is orchestrated by a π-Edge platform, while the Continuum Manager is responsible for higher level decisions and for several edge-clouds, i.e., several π-Edge platforms.

The π-Edge Platform is a cloud-native edge management platform, whose main goals are to incorporate automation, maintainability and interoperability across the full Life-Cycle Management (LCM) of services running on Edge Cloud, while managing and utilizing edge resources properly. By combining the Platform-as-a-Service (PaaS) and Function-as-a-Service (FaaS) service models for autonomous management capabilities, the platform significantly reduces the management overhead required by local cloud management entities or central orchestrators (e.g., Network Function Virtualization (NFV) Management and Orchestration (MANO)), for the operation and interoperability of Edge Clouds. For persistent services at the Edge, such as the ones used to support common application functions like authorization and storage, the PaaS model is adopted. These services are configurable, reusable and integrable, while their provisioning can be defined in a declarative way by end-users and then automatically be translated by π-Edge into low-level LCM primitives, including runtime evolution (auto-scaling and auto-healing). On the contrary, for lightweight functions, the FaaS model is used instead. These functions are launched as instances to perform a single task (e.g., ML inference) and are decommissioned when the task is completed. All application logic is modelled using these highly scalable FaaS services, which comprise workflows with other FaaS and PaaS services to implement edge application processes.

5.3.2 Functional Architecture

The π-Edge Platform provides a wide range of Edge Intelligence and Automation services such as *Monitoring*, *Edge Catalogue*, *MLOps*, a set of *external services* (e.g., Security Automation), *5G core integration* and *Internet of Things (IoT) platform*, while it will also be extended with a *Software Defined Network (SDN) Controller*, as depicted in Figure 26. The MLOps services follow a microservices architecture and their main purpose is to provide automated quality assurance throughout the Life-Cycle Management of the edge services. The π-Edge platform is currently extended in order to include more ML-based prediction models into the *MLOps* component, and be able to trigger events or make decisions based on this accessible information. Additionally, π-Edge uses *MEC platform services* proposed by ETSI, which can provide data (e.g., network quality, location of User Equipments (UEs), etc.) to MEC applications. These applications can then use the provided data for ML-driven analysis towards their specific goal. As mentioned earlier, each π-Edge is responsible for a single cluster. So, a *Cluster Manager* service is required as well.

All the above-mentioned services relate to the Intelligent Edge Agent, which is the "brain" of the π-Edge platform that handles automation features for the translation of high-level requests related to PaaS into low-level requests that can be handled by the *Container Cluster Manager*. In Figure 26 the API Gateway is displayed, which acts as a reverse server to accept PaaS and FaaS delivery model requests made on the π-Edge platform. Then, it forwards them to the *Intelligent Edge Agent* to register/deregister PaaS and Service functions in the Edge Catalog, deploy/update/terminate available PaaS and FaaS services on a particular edge node, and retrieve information about the status of each edge infrastructure node belonging to the Edge Cloud.

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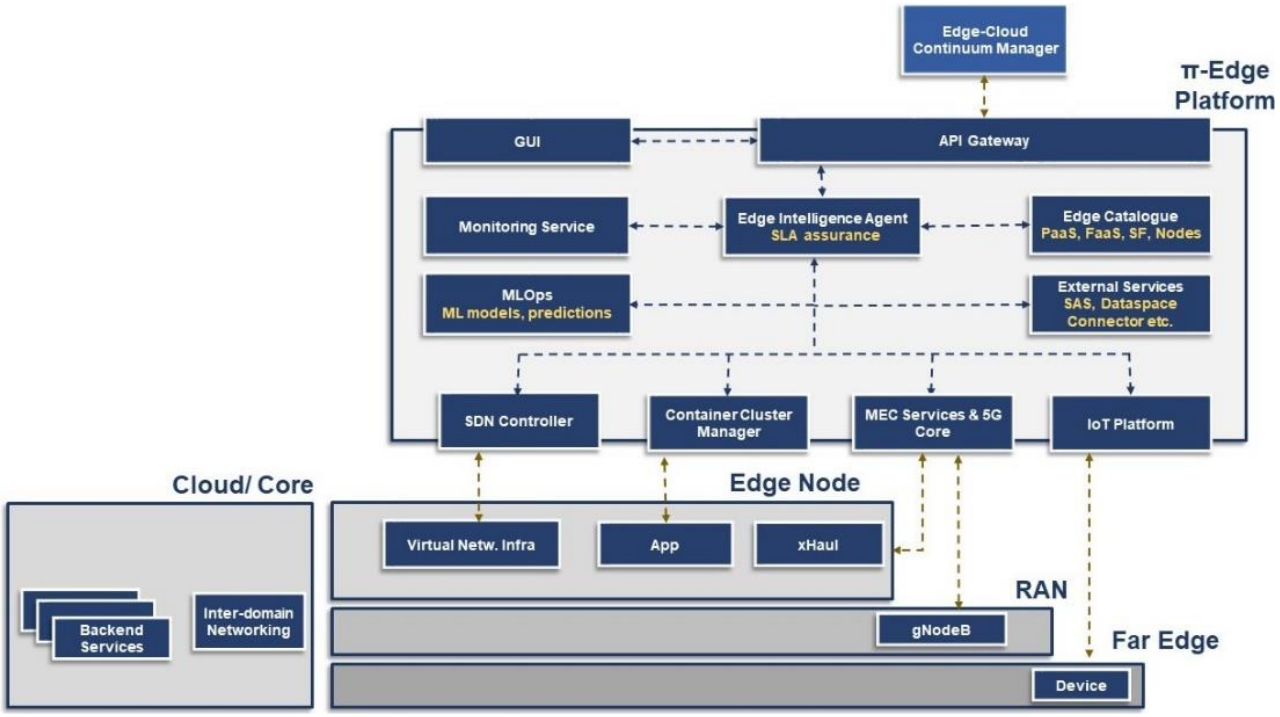

Figure 26: Internal architecture of the π-Edge Platform

The several π-Edge platforms are orchestrated by the Edge-Cloud Continuum Manager, which includes various components for *Network, Infrastructure and Application Orchestration* as well as *Monitoring* services and a *System Catalogue* that provides information about all clusters (see Figure 27). Additionally, the Edge-Cloud Continuum Manager consists of an *API Gateway,* which receives edge domain requests by the DMO and passes them to the respective Edge-Cloud Continuum Manager's orchestrators. The input request should specify the services that should be executed as well as their requirements.

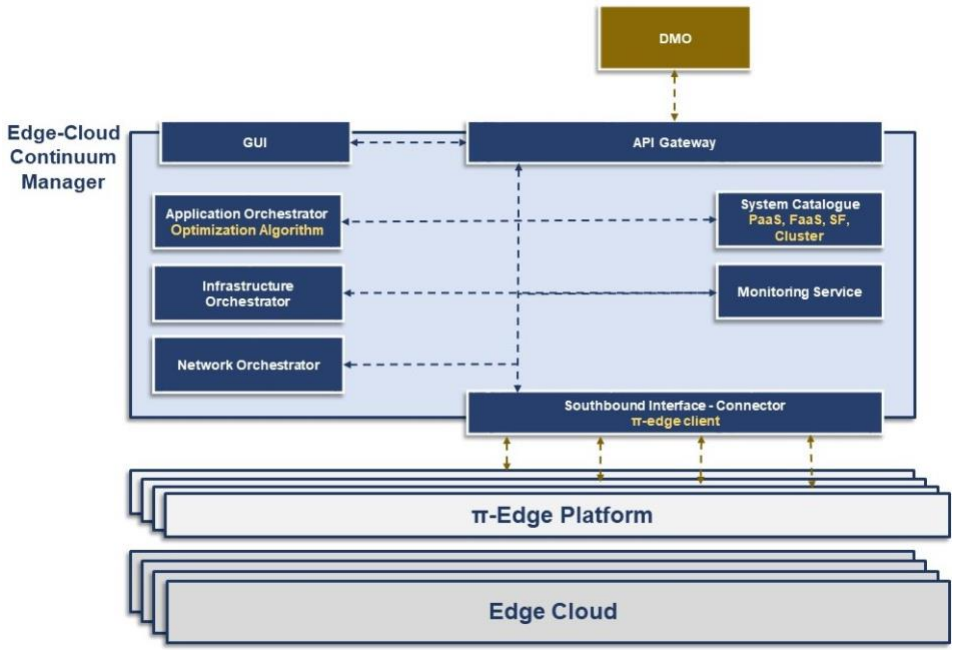

Figure 27: Internal architecture of the Edge-Cloud Continuum Manager

An innovative aspect, which will be implemented in the scope of the project, is located in the *Application Orchestrator*. More specifically, some new features of this module are the optimisation methods that aim to find the best possible allocation of resources that will meet both hard and soft requirements of the requests. The optimisation algorithm takes into consideration the current status of the available nodes, by retrieving information from monitoring services, as well as the application's requirements, as defined in services descriptors and the request itself. Then, when the orchestrator decides where to place each service, the requests for specific resource allocation and/or service execution are sent to the Southbound Interface, which connects to π-Edge Platforms' API Gateways. The overall system optimisation is further enhanced by DMO's Fault and Runtime Management tools, as explained in 5.3.2 for example, if a fulfilment of a request fails, the XAI mechanisms of DMO will be able to indicate to the user what went wrong and to give a piece of advice on how to adapt the request. Moreover, the commands generated by DMO's Runtime Management will be also handled by Edge-Cloud Continuum Manager in an optimal way.

5.4 X-Haul platform

5.4.1 Overview

X-Haul networks refer to the transport network that connects the Radio Access Network (RAN) and the Core Network (CN) in a 5G/O-RAN architecture. Different segments of X-Haul have been named as Fronthaul, Midhaul and Backhaul, where Fronthaul is the network between RRU (Remote Radio Unit) and Distributed Unit (DU) (CPRI and eCPRI interfaces), Midhaul is the network between DU and Centralized Unit (CU) (F interface) and Backhaul is the network between CU and 5G CN (NG interface) and between CUs. Transport Network Equipment (TNE) are the fundamental hardware and software components that are used to build and operate an X-Haul network. While optical fiber-based TNEs are considered the most desirable choice for X-Haul due to their "limitless" capacity and predictable performance, it is clear that the availability of a fiber interconnection is not expedient or economically favorable in many cases. Wireless transport technology is a reliable alternative to optical fiber which has been playing a major role in Mobile RAN transport for decades and is still considered of vital importance in enabling the widespread deployment of mobile networks in the 6G era.

From a system level perspective, wireless X-Haul systems are vendor-specific implementations, where Radio Frequency (RF) modules, modem, network processor and internal interfaces are all proprietary. Only the external physical network interfaces are standardized to ensure interoperability with adjacent network elements (e.g., switches, routers, RAN interfaces, etc.). As a result, in wireless backhaul systems, hardware and software are tightly coupled and always come from the same supplier.

5.4.2 Functional Architecture

X-Haul TNEs and indicative deployment options in the O-RAN ecosystem, to be adopted within 6G-BRICKS, are depicted in Figure 28.

Following the rationale of the disaggregated RAN, wireless 6G X-Haul networks are envisioned as an open and disaggregated architecture that separates hardware and software modules so that they can be sourced from different suppliers.

More specifically the functional components of the disaggregated X-Haul are summarized into 2 main entities:

1. Full Outdoor microwave and millimeter-wave Radios.
2. Disaggregated router which consists of:
    a. An indoor white box solutions which consists of a bare metal/merchant silicon hardware, including Open Network Install Environment (ONIE) and driver layers.

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b. A Linux-based configurable Network Operating System (NOS).

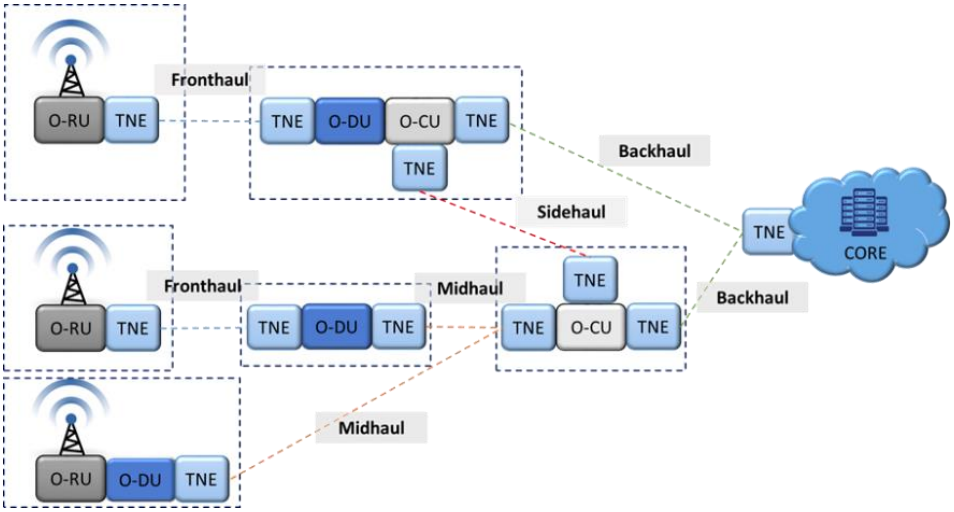

Figure 28 - Different deployment options of TNEs in O-RAN architecture

Figure 29 illustrates the aforementioned two-step transition into the disaggregated X-Haul architecture, which comprises of the functional split of the radio and networking modules and the hardware/software split of the networking sub-system.

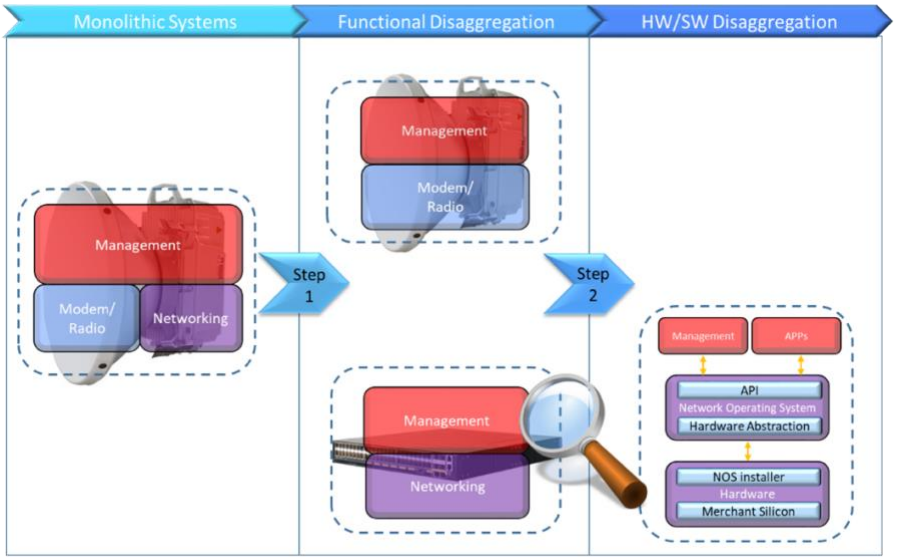

Figure 29 - Wireless X-Haul disaggregation evolution

This architecture is expected to provide cost optimization and foster innovation and network development flexibility. This wireless X-Haul solution, adopting the principles of an open and disaggregated architecture, has several benefits such as:

- Acceleration of innovation by the quick deployment of future features.
- Bigger pool of potential suppliers which prevents vendor lock-in.
- Improved automation and better fit into the SDN-based transport architecture, which leads to performance, operational & cost advantages.

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- Integration & management of network elements based on standard IT tools & processes (like traditional servers).

In 6G-BRICKS project, we go one step further, by leveraging the hardware/software capabilities of disaggregated routers for application hosting in a cloud-native fashion. The use of x86-64 processors and Linux-based NOS, unveils the potential to create innovation by offering similar capabilities as other "more traditional" edge computing hardware platforms, such as Single Board Computers (SBCs) and mini-PCs. Thus, the X-Haul systems serve a two-fold role in the network, both as traditional networking equipment, as well as a fundamental component of the next-generation compute continuum.

5.5 Security Orchestration

5.5.1 Overview

To provide automated security to the connectivity from the experimenters towards the testbed infrastructures, 6G-BRICKS provides a Security by Design (SbD) approach named Zero Trust (ZT). This implies that any access to the infrastructure (and, thus, the ability to map or reach internal services) is denied by default, until each connecting client is explicitly granted access. To that end, there two main building blocks: (i) the SO, interpreting security and trust-related requests and establishing secure connections to the services in the testbed; and (ii) the SDP framework, dynamically enforcing the perimeters according to a subset of services.

5.5.2 Functional Architecture

Security Orchestrator (SO)

The SO is an NFV-based orchestration framework (based on ETSI MANO OSM,) that enables the deployment, control and monitoring of security services and the overseeing of the underlying Virtual Infrastructure Manager (VIM). In the context of 6G-BRICKS, this component contributes towards the required end-to-end trust management of any connection from the experimenter to the testbed services. Departing from a high-level request (i.e. human-like intent) on the expected security and trust baseline, it shall translate into respective low-level actions that enact the desired level of trust and security through means of Security Services (e.g. through security NFs). For instance, one of the expected Security Services is the Virtual Private Network as a Service (VPNaaS), introduced in "*Testbeds and connectivity*" (Section 3.3).

Internally, the expected architecture of the SO component contains the following modules:

- Application Programming Interface (API): northbound layer receiving external requests and exposing OpenAPI-documented interfaces.
- DB layer: persistence layer in MongoDB to store different abstractions and data to present.
- Intent evaluator: extraction of high-level requests from the experiment and interpretation into more understandable, actionable low-level actions.
- Security & trust resolver: evaluation of the request and needs of the service(s) to be protected and translation into specific security & trust features and the relevant services to be deployed.
- Configuration: transversal setup of all abstractions required for the workflows at hand.
- Life-Cycle Management: handle the life-cycle operations (deployment, termination) of the Security Services and the runtime actions (day2 actions) submitted to them.
- Package: management of the packages or bundles keeping the logic of the Security Services.
- Monitoring: extraction of basic, common metrics from the xNFs
- Authentication & Authorisation Control: following a Security-by-Design (SbD) approach, the SO implements a ZT approach also regarding other components, in that each communication with them will

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be received by the API and must be properly authenticated (disregarding their location) before being served.

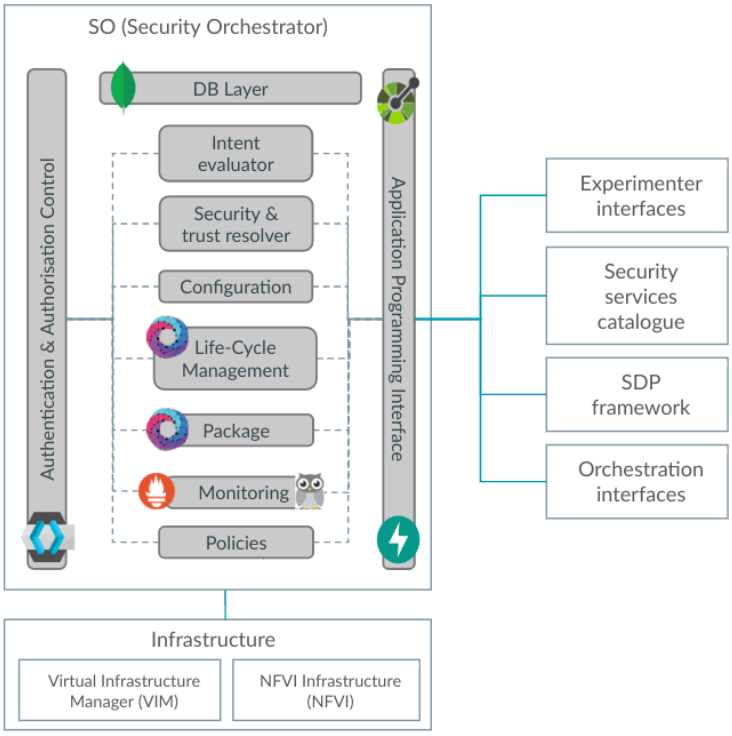

Figure 30 - High-level architecture and design for the SO

SDP framework

6G-BRICKS will implement a radical solution based on SDP technology that will allow an arbitrary number of perimeters/zones to be dynamically defined by an SDP controller at the NF level (i.e., specifying the NFs that are part of a given perimeter). The SDP architecture consists of Controllers and Services. Our main focus will be the protection of Services, which could serve as an entry point for attackers via their Northbound APIs. As shown in Figure 31, SDP Gateways acts as the border firewall of the 6G-BRICKS testbed NFVIs, controlling access to Services' Northbound Interfaces. The SDP Gateway (SDP GW) is derived from VyOS Network Operating system [37], which supports stateful, zone-based firewall, as well as a CLI and multiple security configuration options. The SDP Gateway will allow access only to a specific set of Northbound APIs to authenticated users, ensuring a very fine-grained micro-segmentation of entitlements which is known as the Zero Trust model.

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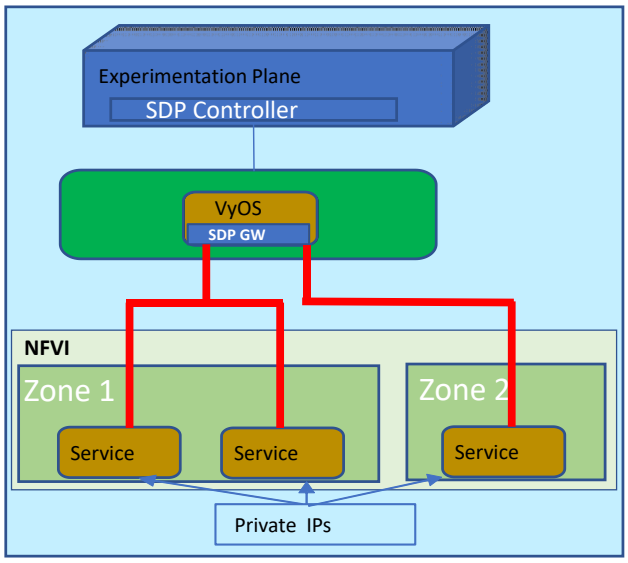

Figure 31 – 6G-BRICKS SDP framework

6 Conclusions

This deliverable defined the architecture design of the 6G-BRICKS Experimentation facility, along with the internal design of components, that will serve as a blueprint for their implementation, as well as the physical architecture and interconnection of the 6G sites. Moreover, the 6G-BRICKS orchestration architecture was defined, which builds on a three-layer design featuring intelligence at the Business Layer, Service intelligence, and infrastructure intelligence. 6G-BRICKS further introduces the concept of an XAI-driven Distributed Manager and Orchestrator (DMO) to help experimenters understand failure modes for experiment onboarding and execution, supporting an **innovative workflow** termed as Intent-driven, Human-in-the-loop experimentation. Finally, this deliverable detailed the 6G-BRICKS RAN technologies, showcasing their alignment with the Open RAN initiative, aiming to evolve Open RAN compliant breakthrough technologies and evolve them in the 6G era.

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