Horizon Europe Framework Programme

OPTI-6G

OPTICAL 6G CELL-FREE NETWORKS

D2.2 OWC Cell-Free Network Architecture

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ABSTRACT

This deliverable provides an overview of the OPTI-6G cell-free optical wireless communication and positioning system. It details its architecture with a block diagram illustrating the links between its various core blocks, which are briefly described and about which further details can be found in dedicated sections (listed here) of deliverables D3.1 (for the cell-free communication function) and D4.1 (for the positioning function). The components and know-how already available at the start of the project and on which the system will thus be built are also described, along with a proposed timetable for system integration and testing.

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Executive summary

In this deliverable D2.2, the top-level architecture of the end-to-end OPTI-6G system is described. Knowing that the main objective of this system is to enable cell-free optical wireless communication using 5G protocol layers while ensuring at the same time positioning of the user equipment served with high accuracy using optical wireless positioning techniques, the top-level architecture described here highlights the core blocks that are vital to each function with a short description of their role and relation with the other blocks.

More details are then available in deliverables D3.1 and D4.1, which are respectively dedicated to the design of the cell-free communication and localization sensing functions. For each block, the section of D3.1 or D4.1 where these details are provided is identified in this D2.2, so that the interested reader can easily refer to it. D2.2 can therefore be seen as a good starting point for understanding the architecture and operation of the OPTI-6G system.

In addition, this deliverable presents the hardware and software components as well as the know-how mastered by the various partners at the start of the project (5G components, optical transmission/reception components, communication and positioning test benches in particular), to highlight the technical basis on which the OPTI-6G project will be able to develop its system, as well as the new developments required to set up this system. To provide a framework for these various developments and the tests that will follow, a proposed timeline for the integration and testing plan is finally provided.

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Abbreviations and Acronyms

5G	Fifth generation
AFE	Analog front-end
AP	Access point
CU	Control unit
DL	Downlink
DU	Distributed unit
GPS	Global positioning system
MIMO	Multiple-input multiple-output
NIB	Network in a box
NMS	Network management system
OFE	Optical front-end
O-RAN	Open-radio access network
ORU	Open radio unit
OWC	Optical wireless communication
OWP	Optical wireless positioning
PD	Photodiode
PHY	Physical (layer)
PMU	Power management unit
RF	Radiofrequency
RSS	Received signal strength
RU	Radio unit
SW	Software
TDOA	Time-difference-of-arrival
TOA	Time-of-arrival
UE	User equipment
UL	Uplink
VCSEL	Vertical-cavity surface-emitting laser
WLAN	Wireless local area network
WP	Work package

1 Introduction and Objectives

The main objective of the OPTI-6G project is to design, implement and experimentally validate a cell-free optical wireless communication (OWC) system compatible with fifth-generation (5G) protocol layers, which at the same time enables positioning of the user equipment (UE) served with high accuracy using optical wireless positioning (OWP) techniques.

Within this project, the role of the second work package (WP) is, as its name suggests, to define the use cases of such a system along with its functional and technical requirements, and its architecture. The goal of WP3 and WP4 is then to define, design, develop and experimentally validate respectively the communication and localization functions of the OPTI-6G system. These three WPs, and the deliverables that should result from them, are therefore closely linked, as **Figure 1** suggests.

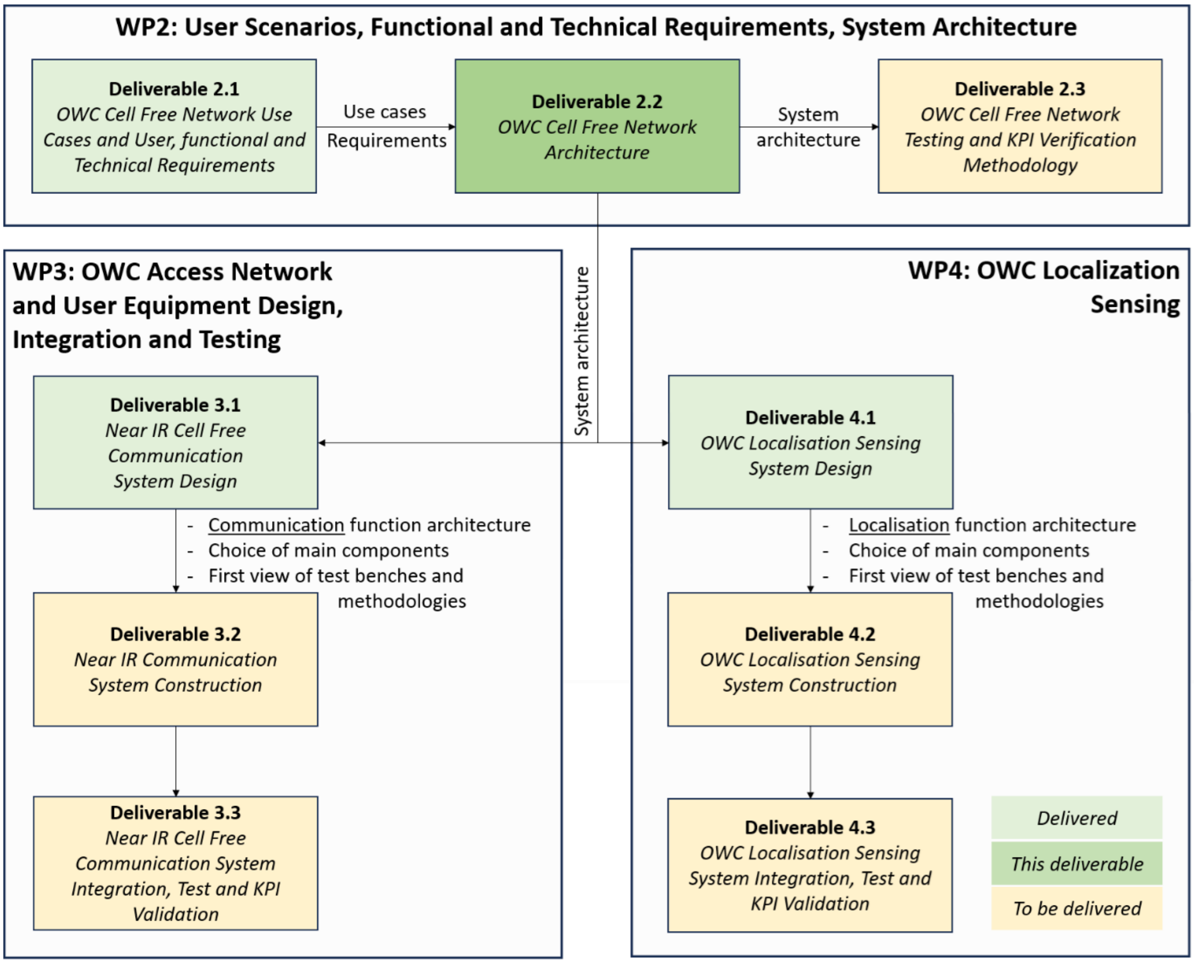


Figure 1 – Workflow of the OPTI-6G project with the input/output of the deliverables

In deliverable D2.1 [OPT24a], we defined the use cases – in particular for Industry 4.0 applications – for which the OPTI-6G system would be relevant, and extracted general system specifications from them.

These use cases and specifications have then been used to define the architecture of the OPTI-6G system, which is presented in this deliverable D2.2. The structure of this deliverable is therefore as follows:

- In Section 2, we present the OPTI-6G system architecture and the general operating principles of the communication and localization functions. More details about these functions are then provided in D3.1 [OPT24b] for the communication part, and D4.1 [OPT24c] for the localization part. Section 2 therefore lists in which sections of these deliverables the various fundamental blocks of the OPTI-6G system are more extensively described (see Table 1).
- Then, in Section 3, we give some initial inputs about the implementation and experimental validation of the OPTI-6G system, by detailing the systems and test benches already in our possession, and on which we can build the OPTI-6G system, as well as a Gantt chart for the development, integration and validation of this system.
- Finally, Section 4 provides some concluding remarks.

2 Top level OWC Cell Free Network System Architecture

In this section, we present the general architecture of the OPTI-6G system, designed for both cell-free OWC and OWP (Section 2.1) and give a brief overview of its operating principle (Section 2.2).

2.1 Overview of the Proposed OPTI-6G System Architecture

The general architecture of the OPTI-6G system is shown as a block diagram in **Figure 2**, with the elements relating to the access point (AP) and therefore the infrastructure above the dotted line, and the elements relating to the UE below it. Different colors are also used to highlight the OPTI-6G project partner primarily responsible for deeloping the building block in question (but other partners may be involved).

Each of the building blocks shown in **Figure 2** is also listed in Table 1, where their role is briefly described, and where the partner primarily responsible for their development is listed, as well as the reference to the specific section in D3.1 or D4.1, where further details are available.

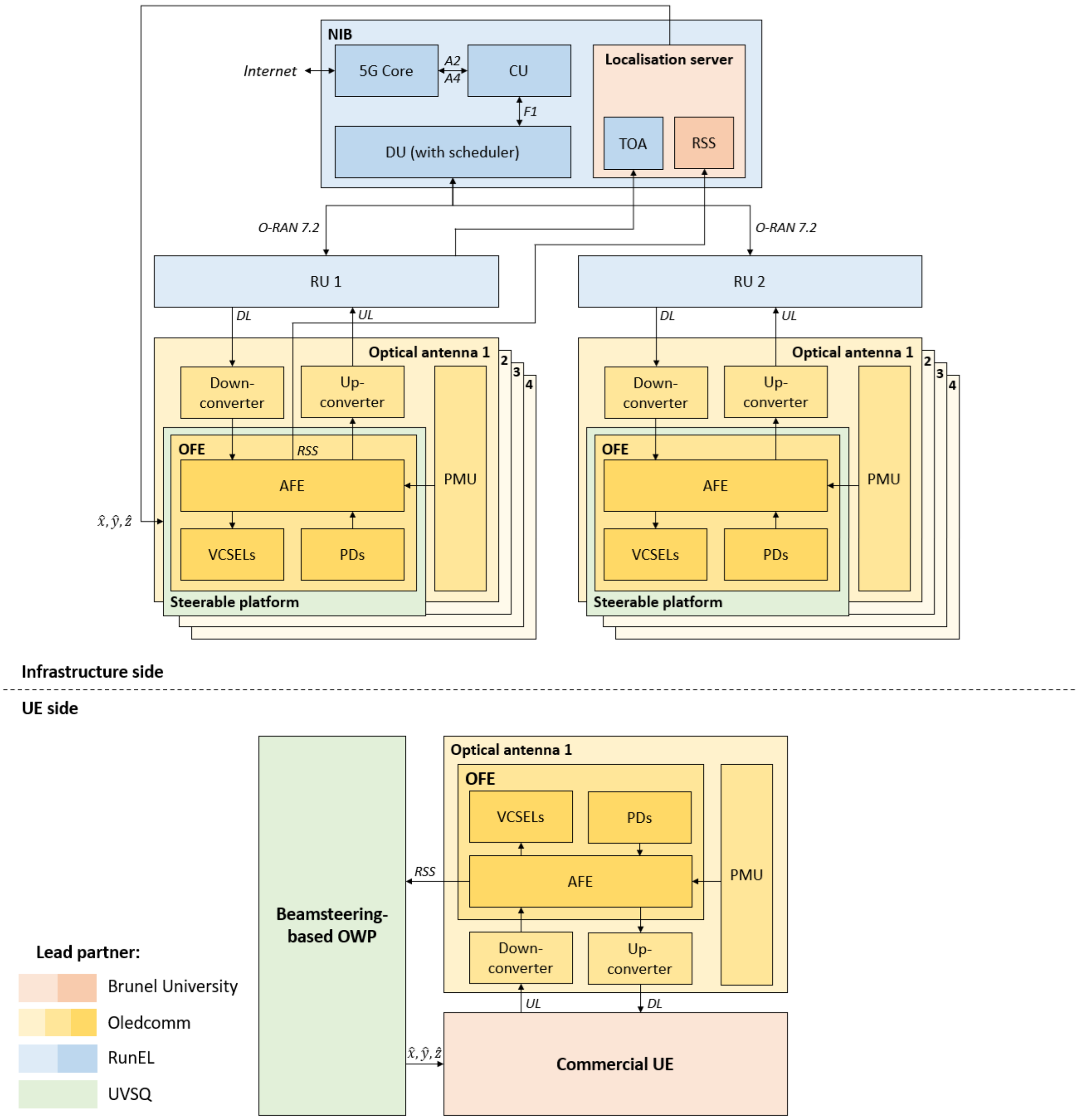


Figure 2 – General architecture of the OPTI-6G system

Building block	Role	Lead partner	Detailed description
NIB	Network in a box (NIB) server that includes the 5G Core, the Control Unit (CU) and the Distributed Unit (DU) protocol stack – RunEL product Sparq-2025-NIB.	REL	D3.1 ↳ Section 3.1.1

NIB ↳ 5G Core	5G Core software (SW) installed in the NIB.	REL	D3.1 ↳ Section 3.1.1
NIB ↳ CU	CU SW installed in the NIB.	REL	D3.1 ↳ Section 3.1.1
NIB ↳ DU	DU SW installed in the NIB.	REL	D3.1 ↳ Section 3.1.1
NIB ↳ Localisation server	Dell 730/40 server hosting a MySQL location server.	Brunel	D4.1 ↳ Section 6
NIB ↳ Localisation server ↳ RSS	Interface to received signal strength (RSS) experimental platform and service application to store and access distance data and compute UE location.	Brunel	D4.1 ↳ Section 6
NIB ↳ Localisation server ↳ TOA	Interface to time-of-arrival (TOA) experimental platform and service application to store and access distance data and compute UE location.	REL	D4.1 ↳ Section 3
RU	5G Radio Unit (RU) – RunEL product Sparq-2025-ORU.	REL	D3.1 ↳ Section 3.1.1
Optical antenna	Elements that permits emission and reception of optical signal for communication. It also includes an interface with RU and the required power and amplification stages.	OLED	D3.1 ↳ Section 3.2
Optical antenna ↳ Up/Down-converter	Allows conversion of the radio frequency (RF) 5G signal in baseband for the OWC system. This means down-converting the emitted 5G signal to 100 MHz to be used in the OWC on the one hand. On the other hand, the received signal will be up-converted from baseband (100 MHz bandwidth centred at 50 MHz) to frequency centred around 3.5 GHz (5G).	OLED	D3.1 ↳ Section 4.2.4
Optical antenna ↳ PMU	The power management unit (PMU) provides power with required continuous voltage level for each of the core bricks.	OLED	D3.1 ↳ Section 3.2
Optical antenna ↳ OFE	The optical front-end (OFE) enables signal conditioning, preamplification and amplification of the vertical-cavity surface-emitting laser (VCSEL) and photodiodes (PDs) signals thanks to its analogue front-end (AFE), thus ensuring electrical-to-optical signal conversion and vice versa.	OLED	D3.1 ↳ Section 3.2 & 4.2
Steerable platform	A mechanical platform enabling to change of the orientation of the OFE.	UVSQ	D4.1 ↳ Section 5.4
Beam-steering-based OWP	OWP algorithm enables the UE to find its location from RSS measurements acquired after at least one OFE on the infrastructure side is oriented in different directions using the steerable platform.	UVSQ	D4.1 ↳ Section 5.2
Smartphone UE	UE will consist of Raspberry Pi with a Quectel Air Interface	Brunel	D2.2 ↳ Section 3

Table 1: Overview of the main building blocks of the OPTI-6G system

2.2 Working Principles of the OPTI-6G System

The OPTI-6G system has been designed for cell-free communication and positioning using optical wireless signals. According to the end-to-end block diagram in **Figure 2**, we can describe the main working principles of this system. Note that more details are then provided in D3.1 for the communication part and D4.1 for the localization part.

2.2.1 Working Principles of the Communication Function

From a communication point of view, the 'NIB' brings together on the AP side all the fundamental functions for building the downlink signal (DL, i.e. the signal to be transmitted to the UE) and processing the uplink signal (UL, i.e. the signal sent by the UE). For example, in the DL direction, data from an external network (e.g. the Internet) to be sent to the UE is first processed successively by the 5G core, then by the 'CU' (interface A2/A4) and 'DU' (interface F1) to obtain the 5G baseband signal to be sent. This signal embeds in particular all the features enabling cell-free communication, especially thanks to the scheduler in the DU.

Once built, this baseband signal is forwarded using open-radio access network (O-RAN) 7.2 interfaces to several 'RU'. Note that in **Figure 2**, only two RUs are represented to ease readability and because the final OPTI-6G demonstrator will include two RUs, but more RUs could be connected in practice. In any case, each RU will transpose the incoming baseband 5G signal on a carrier frequency in the 3.5 GHz band, in order to then feed up to four antennas. In common 5G, RF antennas would be used but the major novelty of the OPTI-6G system is that 'Optical antennas' are used instead.

Each optical antenna enables to convert the incoming 5G signal on carrier frequency into an optical signal (DL direction) and conversely (UL direction). More precisely, because the optical components we use are not suited for transmission/reception in the frequency range of 3.5 GHz, the 5G signal is in the DL direction first down-converted back to its baseband form and then converted in the optical domain by an 'OFE'. This OFE is composed itself of an 'AFE' which reshapes the baseband signal so that it can correctly drive the VCSELs used to emit the 5G DL signal in the optical domain.

Note that in the UL direction, the reverse operation is performed, i.e. the optical signal received by the OFE from the UE is first converted in the electrical domain using 'PDs', which produce electrical signals then forwarded to the AFE, where they are filtered and amplified in order to recover the baseband 5G signal transmitted (plus noise). This baseband signal is finally transposed to the 3.5 GHz band using an 'Up-converter' so that it can be forwarded to the RU, where it is transposed back to baseband, and sent to the NIB through the O-RAN 7.2 interface for processing and data recovery. Note also that all the core building blocks of the optical antenna are powered by a 'PMU', in charge of providing the different voltages needed for them to operate properly.

Back to the DL direction, after emission in the optical domain by the VCSELs, the signal propagates in free space to be finally collected on the UE side by the PDs of the UE's OFE. These PDs convert the incident optical signals into electrical signals which are then forwarded to the AFE, where they are filtered and amplified in order to recover the baseband 5G signal transmitted (plus noise). This baseband signal is then transposed to the 3.5 GHz band using an 'Up-converter' so that it can further be processed by the 'Commercial UE', which embeds the necessary 5G layers to retrieve the transmitted data.

2.3 Working Principles of the Localisation Function

In addition to data transmission, the OPTI-6G system enables UEs to be located using three main OWP methods: TOA, RSS and a new beam-steering-based method.

TOA-based OWP enables to accurately position of the UE by measuring the difference in TOA of the signals sent by the UE and received by the four optical antennas connected to RU1. Since these optical antennas are distributed across the space, the distance from the UE to each antenna is different, and so are the propagation delays. Therefore, by comparing the TOA of these four signals, time-difference-of-arrival (TDOA) values can be calculated and then processed to obtain estimates $\hat{x}, \hat{y}, \hat{z}$ of the coordinates x, y, z of the UE. In practice, these estimates are produced by a 'TOA' algorithm run by a 'Localisation server' embedded in the 'NIB', after the signals received by the four optical antennas of RU1 have been forwarded by the latter.

RSS-based OWP relies on similar principles as TOA, but exploits RSS values rather than TDOA values. More precisely, in the UL direction, each baseband signal produced by the AFE of each optical antenna after reception of the UE's signal is forwarded to the localization server, where its RSS is measured. The four resulting RSS values are then processed by an 'RSS' algorithm using trilateration in order to get a second set of estimates $\hat{x}, \hat{y}, \hat{z}$ of the coordinates x, y, z of the UE.

On its side, the beam-steering-based OWP method operates in the DL direction rather than in the UL direction and exploits RSS values measured by the UE on signals received from at least one optical antenna whose orientation is successively changed at least three times. This explains why, on the AP side, the OFE of each optical antenna is mounted on a 'Steerable platform' that enables to change the orientation of the OFE, and thus of its VCSELs. For each orientation, the UE measures the RSS of the received signal, then transmits the three resulting RSS values to a 'Beam-steering-based OWP' platform which eventually deduces estimates $\hat{x}, \hat{y}, \hat{z}$ of the coordinates x, y, z of the UE and provides them to the UE. The UE may then embed this data in the UL payload so that it is sent back to the AP, which can eventually forward them to the localisation server. Note that if a single optical antenna is successively steered in three different directions, positioning is possible in two dimensions only. To perform three-dimensional positioning, two steerable antennas should be used.

The location server eventually has at least two estimates of the UE's location (three if the estimates obtained with the beam-steering-based method are also sent to it), which it can fuse to obtain a more robust position estimate. This final estimate can then be used as input to the steerable platform of the optical antenna(s), so that it knows the coordinates in space to which it should globally point the OFE to optimize the performance of the communication link, while enabling the beam-steering-based positioning method to work.

3 System Implementation and Validation: Starting Point and Plan

In order to implement the system corresponding to the architecture given in **Figure 2**, the OPTI-6G consortium will be able to rely, as a starting point, on a certain number of technological building blocks they have developed, and which are described in Section 3.1. However, further development will of course be required to build the fundamental building blocks of the system, which will then need to be assembled and tested for validation, as highlighted in Section 3.2.

3.1 Available Technological Building Blocks

3.1.1 Available Components and Know-How for Communication

The components that are already available for the OWC cell-free communication function are:

- The Oledcomm LiFiMAX OWC solution, which includes in particular high-end OFE and AFE, but without any up/down-conversion of the electrical signal.
- The RunEL Sparq-2025-NIB server, which includes the 5G Core, the 5G CU and the DU protocol stack SW, as well as the Sparq-2025-ORU 5G RU that communicates with the NIB via an O-RAN link (Split option 7.2).
- The 5G/6G Autonomous Systems lab at Brunel University, which enables communication tests and performance evaluation.

3.1.1.1 The LiFiMAX OWC solution

Oledcomm's existing LiFiMAX solution, shown on **Figure 3**, offers an OWC solution for connectivity from 1 AP (with up to 6 antennas) to up to 16 users simultaneously. The current solution provides 150 Mbps (up and downlink), with each antenna covering an 83° field-of-view to ensure an extension of the AP coverage area.

The architecture of the solution relies on the ITU-T G.vlc standard [ITU19] which is a derivative from G.hn. It combines off-the-shelf G.hn baseband and "in-house" designed OFE to transmit and receive a baseband signal from 0 to up to 200 MHz. Existing OFE solutions could support a frequency range from 0 to a maximum of 400 MHz, the limitation being the nature of the IR light sources and sensors used to emit and detect communication signals.

However previous experiments as part of the IEEE 802.11bb standard allowed to interface signals in the 2.4 GHz band (WiFi signal) to be used as input signal for OWC in order to bridge the gap between RF and optical domain. With this knowledge, OPTI-6G is willing to demonstrate that other kinds of high-frequency RF signals (e.g. 5G signals in the 3.5 GHz band) can be used to build a communication system in the optical domain enhancing in the meantime the performances and opening new other technological use cases. Additional information on the exiting LiFi solution can be found in [OLE24].

Figure 3 – LiFiMAX product range (from left to right: AP, optical antenna and UE)

3.1.1.2 The Sparq-2025-NIB server and Sparq-2025-ORU

On the one hand, the following **Figure 4** shows the architecture of the RunEL Private 5G Network, which includes the Sparq-2025-NIB and the Sparq-2025-ORU in the 3.5 GHz band. The system supports the O-RAN split physical (PHY) architecture option 7.2 category B with an O-RAN interface between the open RU (ORU) and the NIB.

The NIB includes all the 5G network high-level components including DU, CU, NgCore and multi-access edge computing from the high PHY (OSI layer-1) to the application layer (OSI Layer-7).

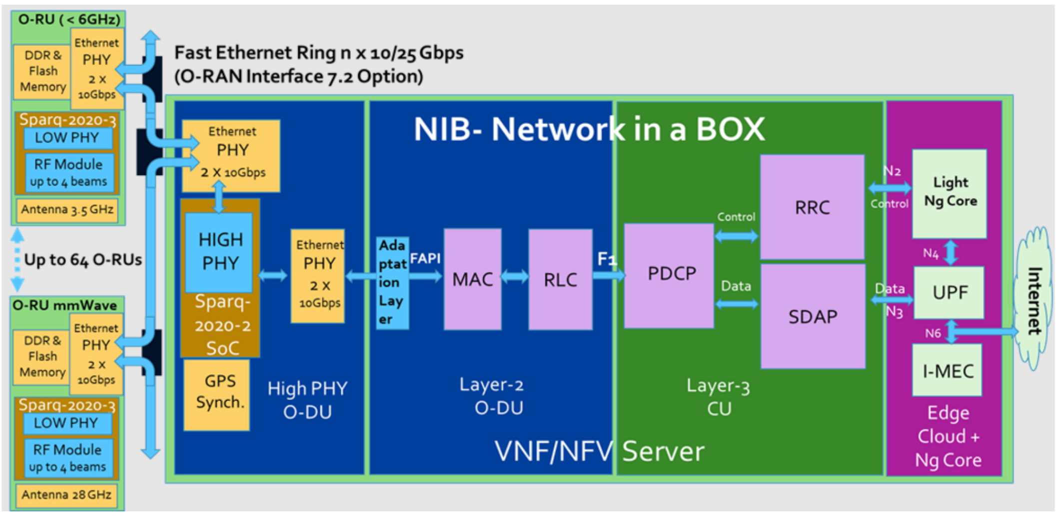


Figure 4 – RunEL private 5G network architecture.

On the other hand, the following **Figure 5** illustrates the Sparq-2025-ORU-3.5G components.

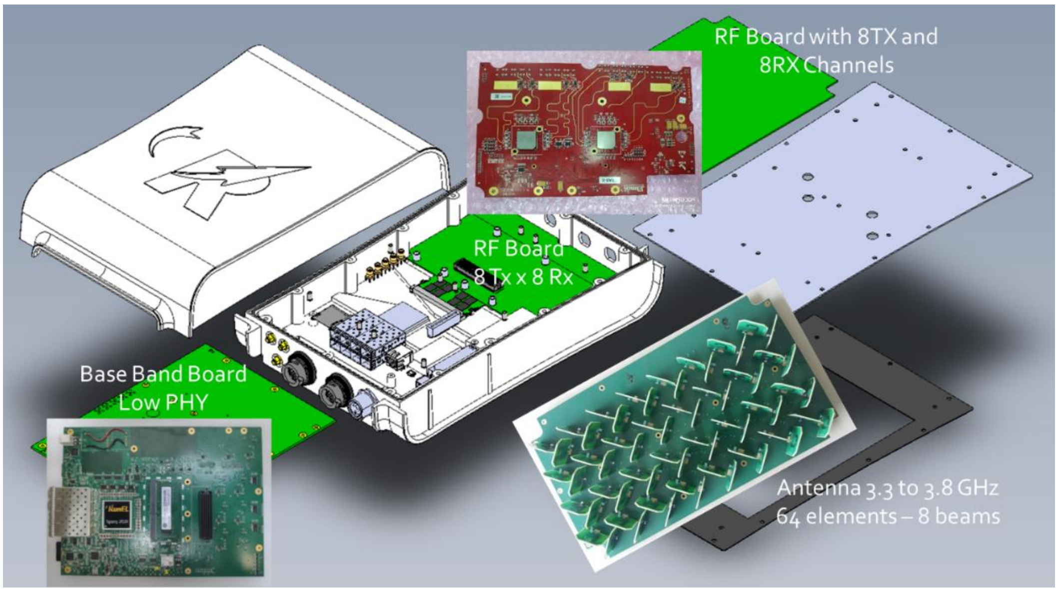


Figure 5 – Sparq-2025-ORU-3.5G components

RunEL's Sparq-2025-ORU-3.5 is the radio component of the RunEL Private 5G Network solution. It provides flexible, cost-effective 5G outdoor network deployment solutions where increased capacity and coverage is required.

'All-in-one' architecture combined with simple, single-handed installation and fast rollout make these ORUs an ideal solution for private and public operators that want to get in on the ground floor of 5G deployment at significant capital expenditure reductions and maximum return on their network deployment.

The ORU is designed for coverage flexibility: depending on the required scenario, the same ORU can be configured to cover more sectors with relatively sparse concurrent user requirements or fewer sectors with higher needs.

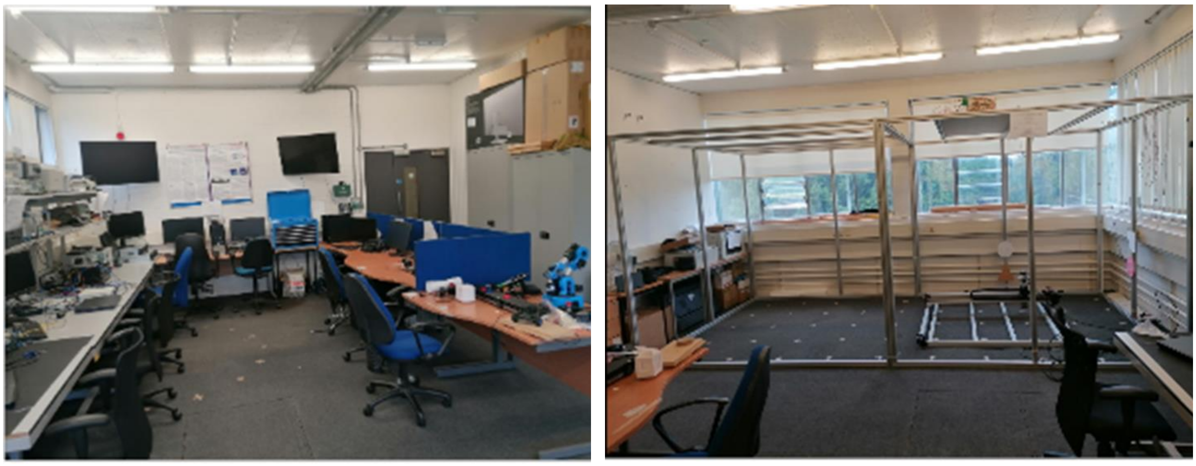
Sparq-2025-ORU-3.5G ORUs provide adaptable solutions, allowing interoperability with other vendors' ORAN 5G devices, thanks to the following features:

- All-in-one integrated packaging of 5G RF and Baseband (low PHY) components.
- Full compliance with 3GPP Release 15 Standard.
- Frequency bands: 3.3GHz to 3.8GHz (n78 5G new radio frequency band, other bands are optional).
- Supports multiple-input multiple-output (MIMO) 2x2 or MIMO 4x4.
- Beamforming of up to 4 dual-polarized beams.
- Antenna support (model dependent): either four external antennas or one beamforming internal antenna with 4 dual-polarized beams.
- Support for internal global positioning system (GPS) receiver for time division duplexing synchronization.
- IEEE-1588 synchronization.
- Flexible coverage capabilities: greater coverage area or greater penetration capabilities.

- Small footprint, single-handed quick installation and simple provisioning.
- Fast roll-out for service providers.
- Seamless and cost-effective integration with 5G DU with O-RAN Interface (Option 7.2 Category B).
- High performance with quality-of-service settings.
- Remote network management system (NMS) via RunEL's NMS application.

3.1.1.3 The 5G/6G Autonomous Systems lab

The 5G/6G Autonomous Systems lab at Brunel University consists of a student work area and an experimental work area, as illustrated in **Figure 6**. The plan layout is illustrated in **Figure 7**.



(a) Student work area. (b) Experimental work area.

Figure 6 – 5G/6G Autonomous Systems lab

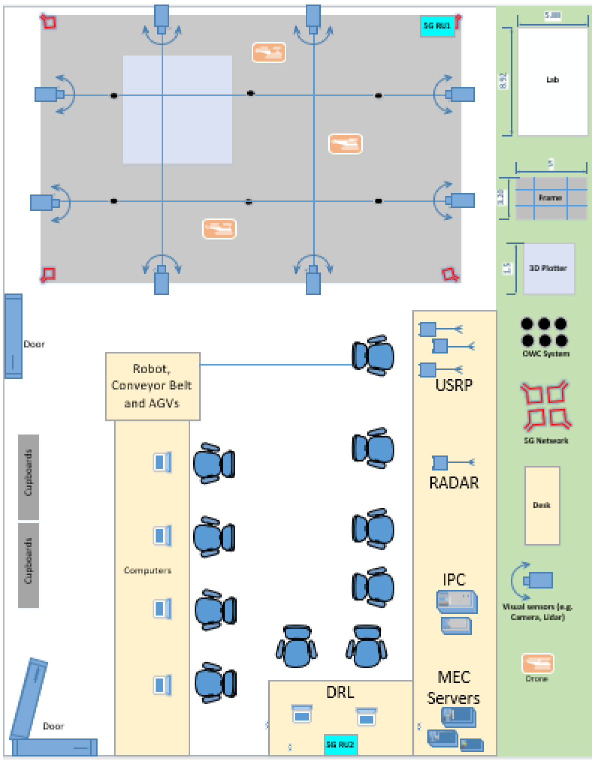


Figure 7 – 5G/6G Autonomous Systems lab layout map

The 5G/6G Autonomous Systems lab contains a fully functional 5G network with 2 RU APs and NIB Amarisoft core containing CU and DU. The air interface of the 5G network is currently using a sub-6 GHz antenna array. In the OPTI-6G project, this air interface will be enhanced so that it switches to an infrared OWC air interface.

The private 5G network is a compact solution for 5G deployment in dedicated areas that need high-performance 5G networks for ultra-reliable low latency communication applications. It consists of two types of modules: the Sparq-2025-NIB and the Sparq-2025-ORU from RunEL. Images of the 5G network are shown in **Figure 8** and the 5G UE and wireless local area network (WLAN) AP is shown in **Figure 9**.

(a) 5G RU Access.

(b) 5G Amarisoft Core.

(c) 5G RU Access view from outdoors.

(d) 5G RU Access view from indoors.

Figure 8 – Core components of the 5G network

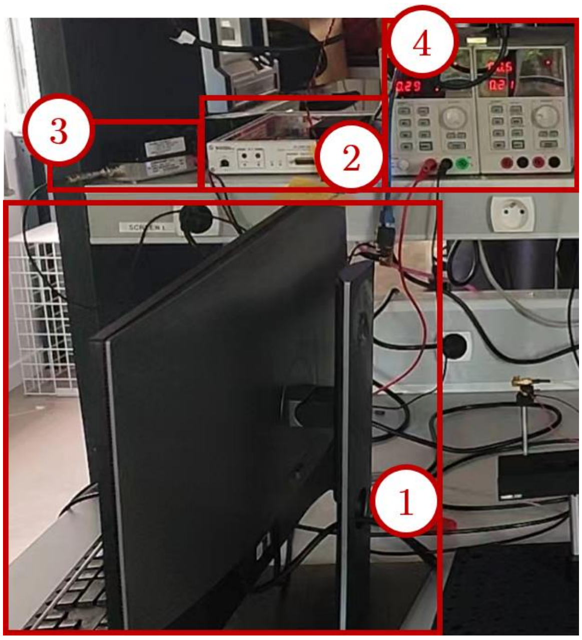
(a) Quectel 5G Air Interface. (b) 5G Smart Phone. (c) 5G WLAN access.

Figure 9 – 5G UE

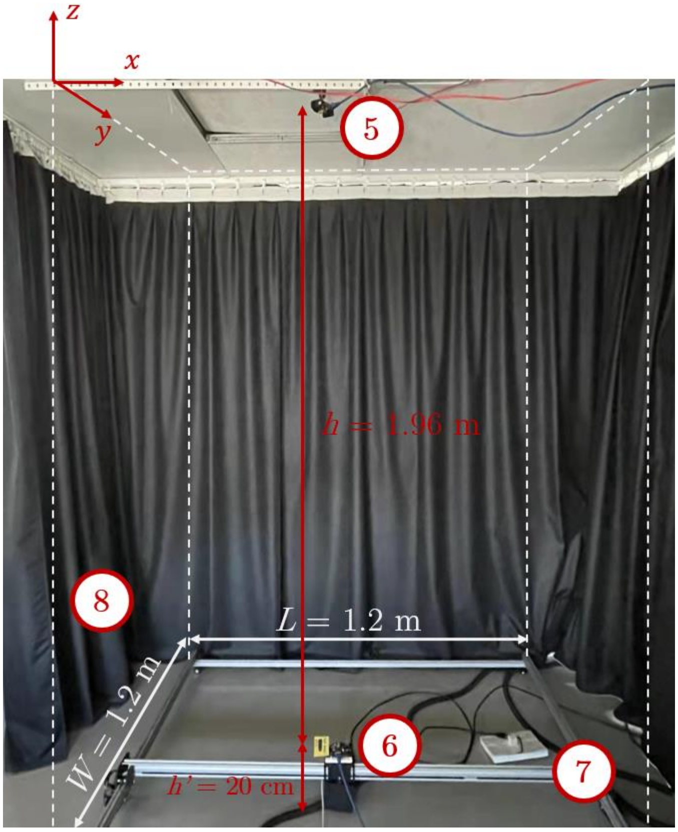
3.1.2 Available Components and Know-How for Localisation

From a positioning point of view, the OPTI-6G consortium was also able to capitalize on the previous 6G-BRAINS project, acquiring knowledge and know-how that will be crucial to the successful realization of the OPTI-6G demonstrator.

In particular, a first RSS positioning demonstrator, reproduced in **Figure 10** and commented in more detail in Section 4.3 of D4.1, has been built and tested, leading to promising results [SHI24]. This experience has been very useful within the OPTI-6G project to build a first demonstrator for the beam-steering-based OWP method, as reported in Sections 5.4 and 5.7 of D4.1.



(a) Control area of the OWP prototype, with ① the control computer for signal modulation and post-processing, ② the USRP X300, ③ a power amplifier for transmit signal amplification and ④ the power supply



(b) Test area of the OWP prototype, with ⑤ the transmit optical antenna, ⑥ the receive optical antenna, ⑦ a double rail to position the receive optical antenna and ⑧ black curtains delimiting the test area

Figure 10 – Example of testbed for RSS-based positioning performance evaluation

Note also that within the experimental work area of the 5G/6G Autonomous Systems lab at Brunel University are also six OWC antennas and access nodes of a LiFi WLAN system on which RSS measurements from uplink transmissions are being measured to calculate distance and compute location.

3.2 Integration and Test Plan

To design, implement and validate experimentally the OPTI-6G system, we intend to follow the integration and test plan schedule shown in **Figure 11**.

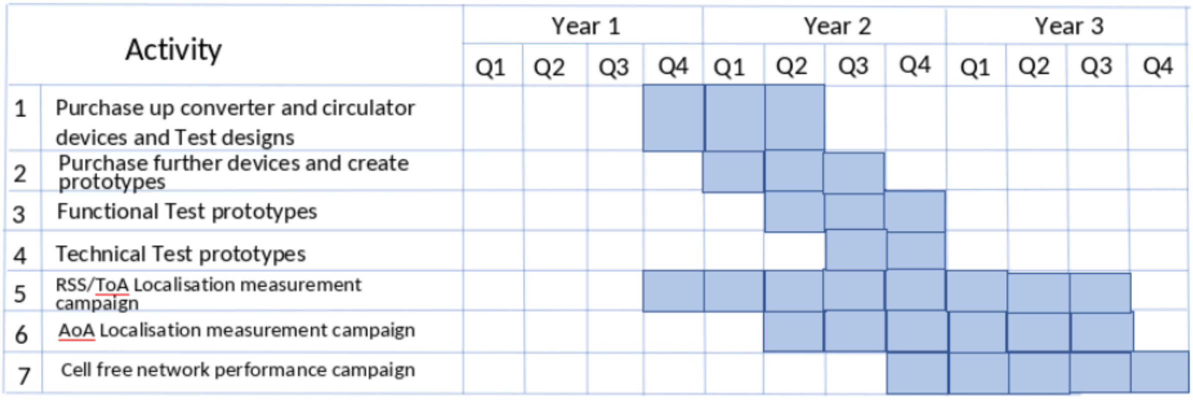


Figure 11 – Integration and test plan schedule.

A critical aspect in the development of the OPTI-6G system is the interface between the 3.5 GHz RU and the optical antennas, which requires up/down conversion of the signal between baseband and 3.5 GHz. Initially, the up/down converter and circulator necessary to perform this operation will be purchased and tested on a single set of components to test if it works functionally and technically (see line (1) in **Figure 11**). Once this has been established, then further converters and circulators will be purchased (2) and final functional (3) and technical tests (4) performed.

At this point, RSS and TOA localization measurement campaign can then proceed to be performed (5), before proceeding to making enhancements and performing the beam-steering-based localization measurement campaign (6). Finally, the cell free network enhancements can be tested in cell free network performance campaign (7). Note the cell free network functionality depends on the synchronisation of the transmission from the two RU transmission points, which is an ongoing enhancement to the RunEL DU and RU networks. Since there are two access points in Brunel University's 5G network, cell-free access will be tested between the OWC access points from each of the two cell-free access networks.

4 Summary and Conclusions

This deliverable first provides in Section 2.1 an overview of the OPTI-6G system architecture (**Figure 2**), with its cell-free communication and localization functions, which are described in greater detail in deliverables D3.1 and D4.1 respectively. Table 1, which summarizes the role of the various system blocks, refers the reader to the sections of these deliverables where further details can be found. A general description of the system's operating principle is then provided in Section 2.2.

The hardware and software components as well as the know-how already available to the partners and which will be vital to the realization of the OPTI-6G system are then detailed in Section 3.1. These include RunEL's 5G components (Sparq-2025-NIB and the Sparq-2025-ORU), Oledcomm's optical antennas, Brunel University's 5G/6G Autonomous Systems lab and UVSQ's positioning test platform. All these components will need to evolve in new forms to implement the OPTI-6G system and to be able to validate its performance experimentally, which will be done according to the schedule detailed in Section 3.2.

References

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