



OPTI-6G

OPTICAL 6G CELL-FREE NETWORKS

D2.1 OWC Cell Free Network Use Cases and User, Functional and Technical Requirements

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ABSTRACT

This deliverable presents very flexible and dynamically repurposable future material handling, smart vehicles and offloading of the PLC control function to the edge production use cases for realising the Industry 4.0 factory of the future vision. The technology mix of interest that is applied includes near infrared Optical Wireless Communications, cell-free 6G networks and combined time of arrival, received signal strength and angle of arrival localisation with sub cm accuracy, supporting a low total cost of ownership and resilience to eavesdropping, sniffing and snooping cyber-attacks. Finally, we identify and specify the user, functional and technical requirements for the 6G system to provide the KPIs and KVI required in those use cases.



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Executive summary

This is the first technical deliverable of the OPTI-6G project. It starts with presenting the project objectives and high-level ambitions.

Then it presents the project motivations including the manufacturing vertical and the technology mix of interest, which includes near infrared Optical Wireless Communications, cell-free 6G networks and combined time of arrival, received signal strength and angle of arrival localisation with sub cm accuracy, expected to enable the use cases.

The document goes on and describes the industrial manufacturing use cases that include very flexible and dynamically repurposable future **material handling, smart transportation vehicles** and **offloading of the PLC control function to the edge** in production systems.

Last, but not least the user, functional and technical requirements are identified and summarised as Key Performance and Key Value Indicators for each of the use cases.

We conclude this document with a summary of findings. The results of this deliverable will guide the development of the system architecture, which will be presented in Deliverable 2.2.

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Abbreviations and Acronyms

5G-ACIA	5G Alliance for Connected Industries and Automation
AGV	Automated Guided Vehicle
AoA	Angle of Arrival
AP	Access point
CU	Central Unit
DU	Distributed Unit
FoV	Field of View
GDP	Gross Domestic Product
HD	High Definition
I4.0	Industry 4.0
IoT	Internet of Things
IR	Infrared
IRT	Isochronous Real-Time
IT	Information Technology
ITU-T	International Telecommunication Union Telecommunications
LED	Light Emitting Diode
LIDAR	light detection and ranging
MEC	Multiaccess Edge Computer
NPN	Non-Public Network
O-RU	Open-Radio Unit
OWC	Optical Wireless Communications
PLC	Programmable Logic Controller
PN	Pseudo-Random Noise
QoS	Quality of Service
RSS	Received Signal Strength
RU	Radio Unit
TCO	Total Cost of Ownership
TDoA	Time Difference of Arrival
ToA	Time of Arrival
UE	User Equipment
VCSEL	Vertical Cavity Surface Emitting Lasers
XR	Extended Reality

1 Introduction and objectives

OPTI-6G focuses on the very demanding Industry 4.0 (I4.0) use cases to progress technology development. It draws considerably on the results and achievements of the previous 5G-PPP project 6G BRAINS, where the industry player Robert Bosch GmbH pursued I4.0 use cases [Art21].

The precursor H2020 6G BRAINS project addressed a broad range of challenges and technologies, researching into enhancing and validating the performance of individual 5G/6G network technologies rather than integrating 5G/6G network technologies to produce a working demonstrable solution. For example, H2020 6G BRAINS included (1) the measurement of distance and location accuracy for sub 6 GHz in a 5G laboratory; (2) measurements of location accuracy in a factory with OWC; (3) design and optimisation of 5G cell-free sub 6 GHz network. However, 6G BRAINS did not go as far as integrating these technologies, for example, for the autonomous control of an Automated Guided Vehicle (AGV) within an Industry 4.0 factory.

OPTI-6G takes development further with a specific focus on Optical Wireless Communications (OWC), cell-free networks and the use of a combination of techniques for determining position with high accuracy. To demonstrate the capabilities of the developments, OPTI-6G focuses on the I4.0 use cases from the 6G BRAINS project and devises a research laboratory realisation of these use cases. OPTI-6G will select and use some of those use cases in which it can demonstrate the potential of the OWC technology and localisation developed most effectively.

2 Motivations

Private 5G/6G and enterprise Wi-Fi both offer high speeds and high device density that are suited to I4.0. Both have similar deployment and maintenance costs, but each is ideally suited to different use cases. Frequently, both will be deployed together in an I4.0 factory, will complement each other with their respective strengths, and can co-exist without interference [Tea22]. The interest in 5G/6G Non-Public Network (NPN) is because it potentially offers more benefits in terms of security and guaranteed throughput, low latency, high location accuracy and high reliability performance.

People are reluctant to use 5G/6G because it is more difficult to deploy so this project will demonstrate how easily is to deploy OWC 5G/6G network and develop 5G/6G-enabled AGVs, extended reality (XR) headsets, drones, Internet of Things (IoT) devices and robots in particular those that require high location and orientation accuracy, high data rate, high coverage distances, fast movement speed of the user, time critical handover support, user equipment density, user equipment size and cost, energy efficiency (user equipment battery lifetime), and service availability.

However, Wi-Fi is a complementary interim solution for algorithms and systems development but without security and guaranteed throughput, low latency, high location accuracy and the high reliability performance provided by 6G. These attributes could be realised on a 6G network thus providing a substantial differentiation to Wi-Fi networks. Thus, this means that wireless computer communication system development can start using a Wi-Fi solution and subsequently migrate towards higher-performance 6G systems.

2.1 Manufacturing vertical of interest

The EU's manufacturing sector employs close to 30 million people in 2.1 million enterprises and accounts for almost 20% of the total Gross Domestic Product (GDP). The challenge for the sector is to work towards the full digitization of manufacturing to promote automation and foster sustainable manufacturing. 5G technology in the current US 5G market, as well as the available predictions are shown in Figure 1 [GVR24]. Based on our observations, we selected the applications of Information Technology (IT) and Telecoms to Manufacturing for the OPTI-6G project:

- Manufacturing,
- IT and Telecoms.

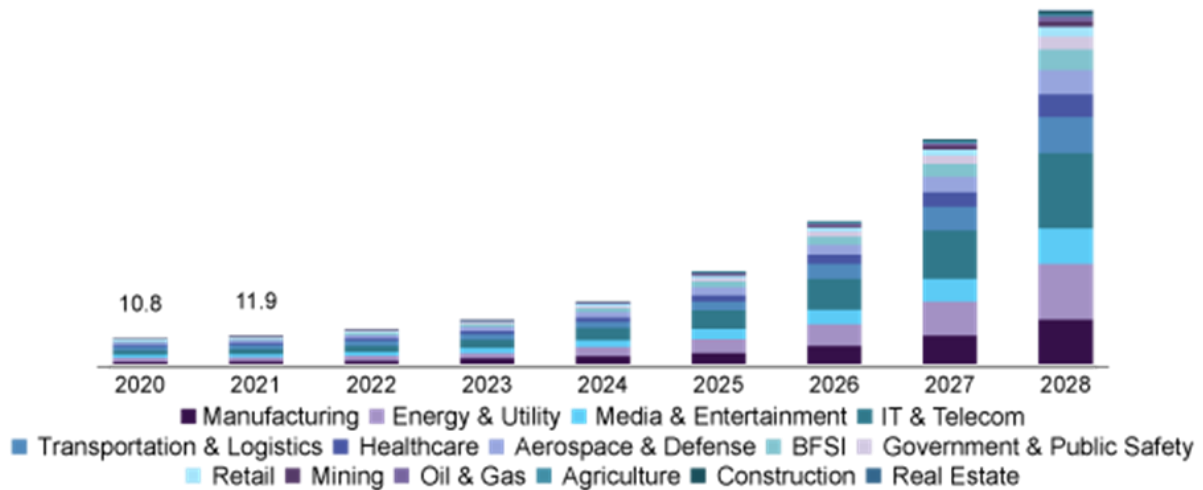


Figure 1 – 5G mobile services market evolution prediction in the U.S. by verticals in 2020-2028 in Billion USDs

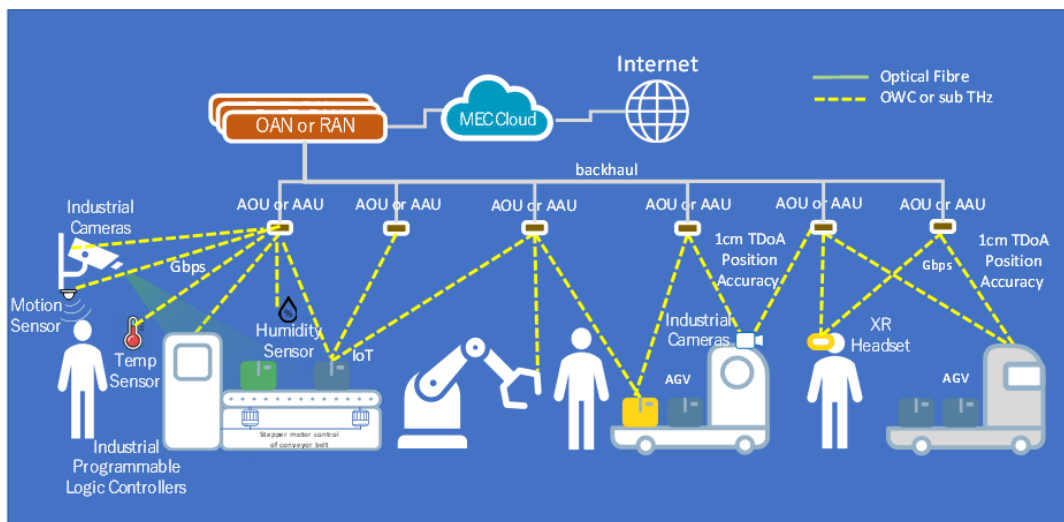


Figure 2 – Mix of autonomous applications for Industry 4.0

Industry 4.0 incorporates data and connectivity, analytics, human-machine interaction, and improvements in robotics into the mix of autonomous applications for Industry 4.0 ranges from process automation, mobile robots and motion control.

Industry requirements change from large batch production runs towards small and individual batch production runs. Such novel use cases produce challenging requirements such as a wider range of production run sizes ranging from very small to large-scale, highly configurable factories, reduction of set-up times, significant reduction of investments and fast integration of the newest manufacturing network and automation technologies.

Process automation – closed-loop control [3GP20]

Sensors are installed in a plant and each sensor performs continuous measurements. The measurement data are transported to a controller, which takes decision to set actuators. The latency and determinism in this use case are crucial.

Mobile Robots [3GP20]

Mobile robots and mobile platforms, such as AGVs, have numerous applications in industrial and intra-logistics environments and will play an increasingly important role in the factory of the future. A mobile robot essentially is a programmable machine able to execute multiple operations, following programmed paths to fulfil a large variety of tasks. This means, a mobile robot can perform activities like assistance in work steps and transport of goods, materials and other objects and can have a large mobility within the industrial environment. Mobile robot systems are characterised by a maximum flexibility in mobility relative to the environment, with a certain level of autonomy and perception ability, i.e., they can sense and react with their environment.

AGVs are a subgroup of mobile robots. AGVs are automatically steered and are driverless vehicles used to move materials efficiently in a restricted facility. Mobile robots and AGVs are monitored and controlled from a guidance control system. Radio-controlled guidance control is necessary to get up-to-date process information to avoid collisions between mobile robots, to assign driving jobs to the mobile robots and manage the traffic of mobile robots. The mobile robots are track-guided by the infrastructure with markers or wires in the floor or guided by own surround sensors, like cameras or laser scanners, for instance.

Mobile robot systems are sophisticated machines that represent a complete material handling solution and which are installed in numerous industries with a wide range of applications and environments. A detailed overview of the state of the art of AGV systems with modern areas of applications, AGV categories and AGV technologies is given in [Oye20].

Mobile robot systems can be divided into operation in indoor, outdoor and both indoor and outdoor areas. These environmental conditions have an impact on the requirements of the communication system, e.g., the handover process, to guarantee the required cycle times.

Motion Control [3GP20]

A motion control system is responsible for controlling moving and/or rotating parts of machines in a well-defined manner, for example in printing machines, machine tools or packaging machines. Due to the movements/rotations of components, wireless communications based on powerful 5G systems constitutes a promising approach.

A schematic representation of a motion control system is depicted in

Figure 3. A motion controller periodically sends desired set points to one or several actuators (e.g., a linear actuator or a servo drive) which thereupon perform a corresponding action on one or several processes (in this case usually a movement or rotation of a certain component). At the same time, sensors determine the current state of the process(es) (in this case for example the current position and/or rotation of one or multiple components) and send the actual values back to the motion controller.

This is done in a strictly cyclic and deterministic manner, as shown in Figure 1, such that during one communication cycle time T_{cycle} the motion controller sends updated set

points to all actuators, and all sensors send their actual values back to the motion controller. Nowadays, typically Industrial Ethernet technologies are used for motion control systems. Examples for such technologies are Sercos®, PROFINET® Isochronous Real-Time (IRT) or EtherCAT®, which support cycle times below 50 μ s. In general, lower cycle times allow for faster and more accurate movements/rotations.

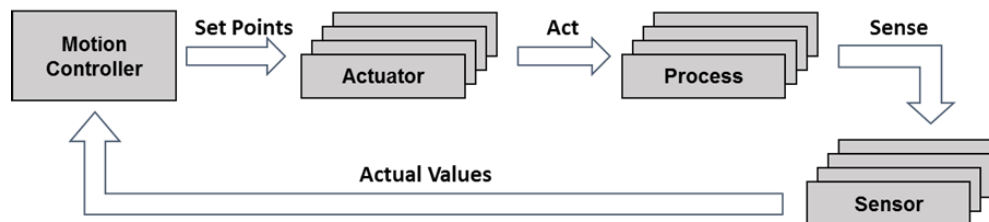


Figure 3 - Motion control system

2.2 Technology mix of interest

2.2.1 Cell-free networks

The merit of deploying OPTI-6G OWC networks for I4.0 is that it removes the barrier of a frequency license requirement for deploying NPN with a zero-touch control, cell-free low total cost of ownership network where multiconnectivity and macrodiversity with multipoint transmissions is implemented, which increases throughput, increases security and reduces interference. Illustration of a cell free network is presented in Figure 4.

Existing optical antenna from OLEDCOMM, shown in Figure 5, is based on ITU-T G.9991 (provisionally known as G.vlc), which is a standard developed by ITU-T for indoor line-of-sight optical networking. Its actual size is dependent on the form factor of the optical antenna, the existing one of which is shown in left hand side of Figure 5.

OLEDCOMM has built an access point with much smaller form factor which can be mounted on user equipment or a gimbal to be physically oriented. The new optical antenna of a much smaller 1 cm x 1 cm size has been developed incorporating both the IR LED as well as photo sensor, as shown on the right-hand side of Figure 5. This smaller form factor is suited for use in both access points as well as user equipment.

The top view of the OLEDCOMM photonic antenna can be seen in Figure 8. The retrieved signal at reception can be measured on the differential pair (1) and grounding on (2).

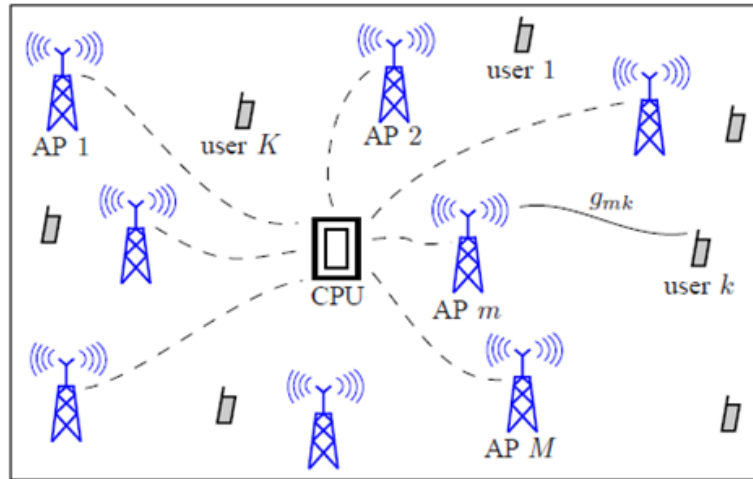


Figure 4 - Cell-free network

2.2.2 OWC and cell-free networks

The merit of using Vertical Cavity Surface Emitting Lasers (VCSEL) phase array solution that operates in near Infrared (IR) 1550 nm wavelength is that it provides 1 Gbps data rates up to 5 m over a field of emission of 34° (supporting a coverage area with a radius of 1.46 m) or 3 Gbps with an angle of 15° up to 5 m (supporting a coverage area with a radius of 0.65 m), as shown in **Error! Reference source not found..**

Table 1: Possible optical field of emission configurations

Case	FoV	Power (W)	Power for Total Area (W)	Targeted Performance
1	15°	1	15	5 Gbps
2	34°	1	10	1 Gbps
3	60°	1	2	300 Mbps
4	90°	1	2	200 Mbps
5	125°	4	4	400 Mbps

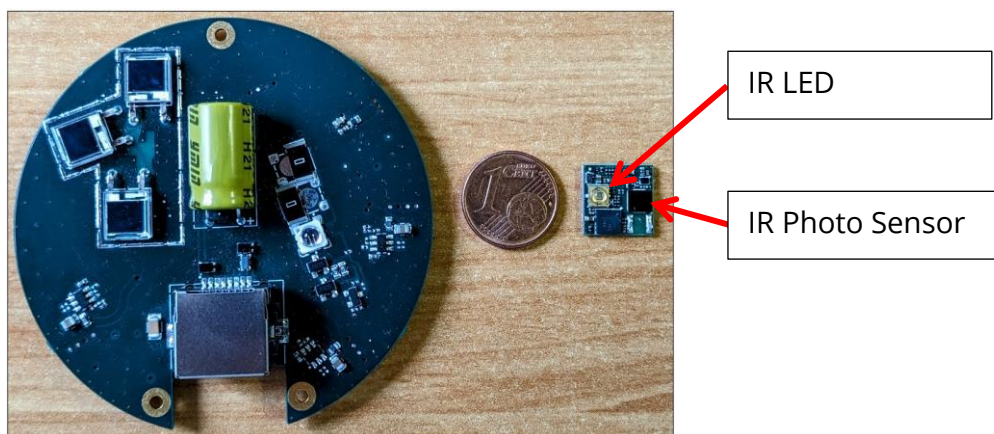


Figure 5 - Optical antenna form factors

Overall architecture access ITU G.9991 provides access for up to 6 antennas, of two form factors (large and small) as shown in Figure 5. A typical G.vlc OWC network consists of access points (AP) supporting up to 6 OWC antennas, as shown in Figure 6. An OWC antenna has a single RJ45 connector as shown in Figure 7b which connects to a single access point with up to nine RJ45 connectors as shown in Figure 7a. The position of the connectors (1. differential pair and 2. ground) to measure Received Signal Strength (RSS) to estimate distance is shown in Figure 8.

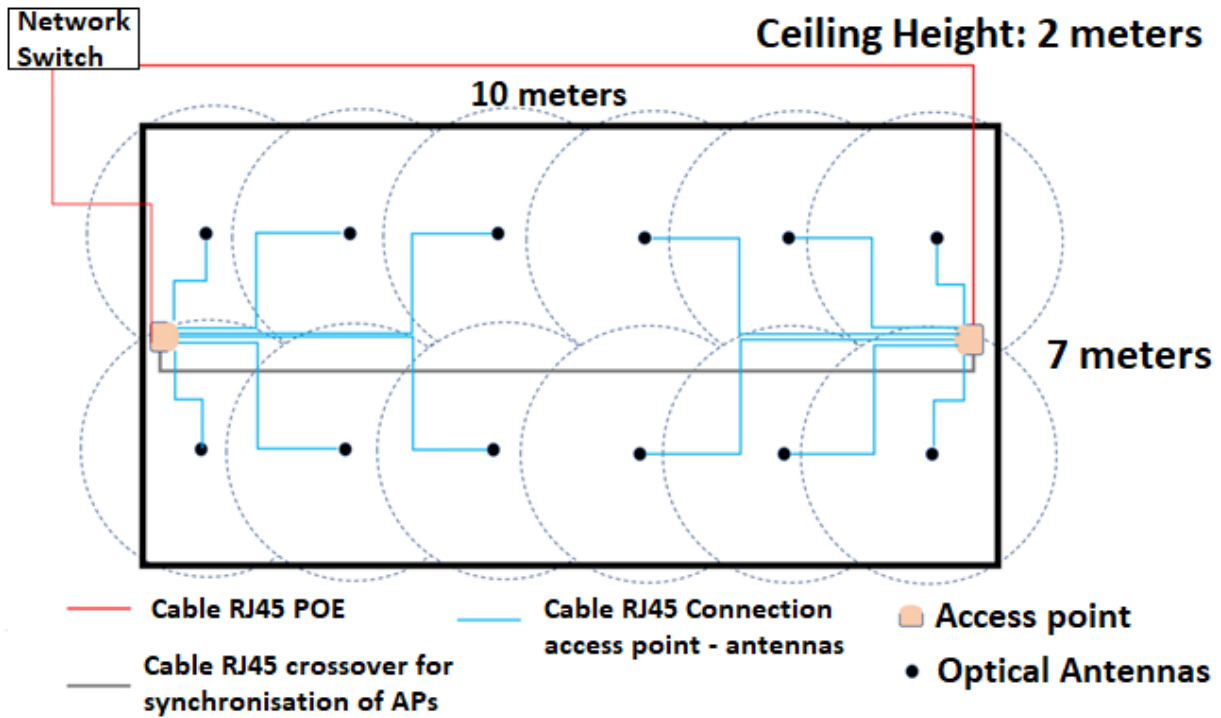
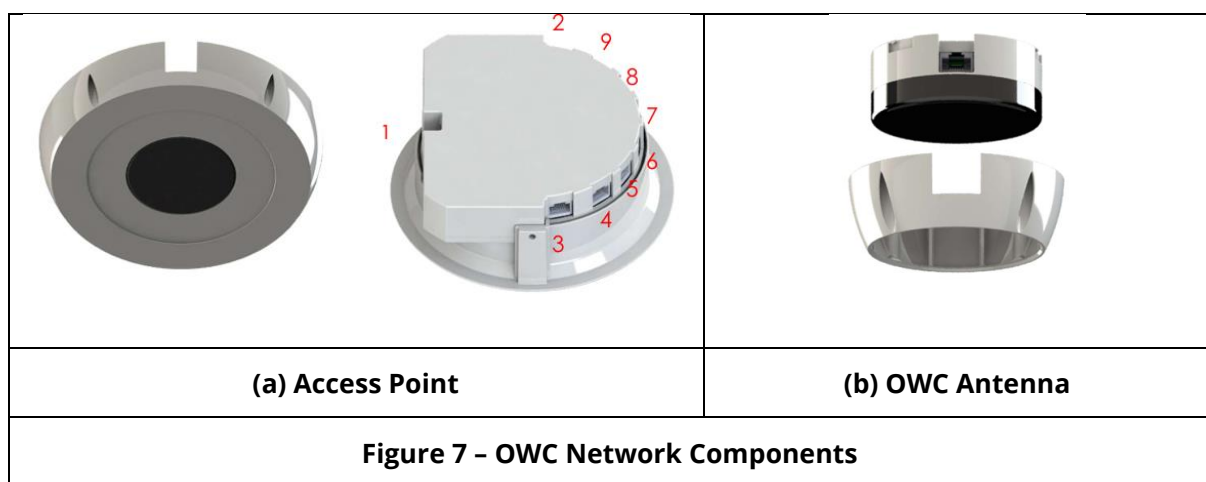


Figure 6 - OWC Network with 2 access points



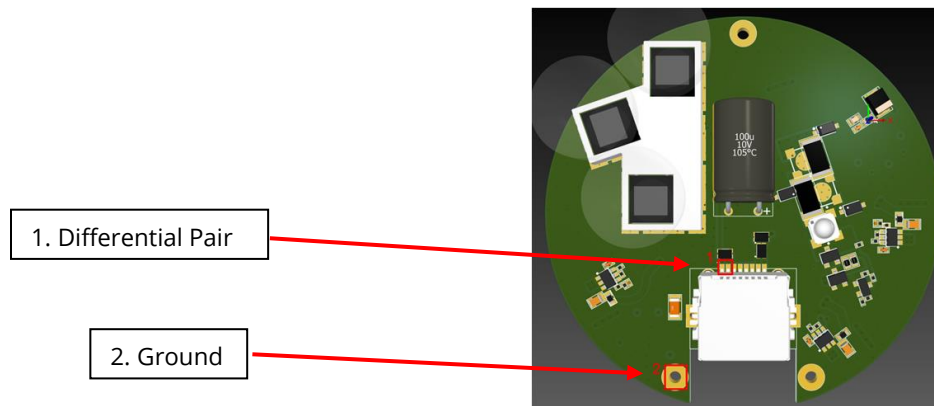


Figure 8 - Position of connectors for measuring RSS at the Optical Antennas

Although OWC networks are inherently cell-free within this cluster of 6 OWC photonic antennas controlled by a single OWC access point to typically support a 4 m x 5 m coverage area, handover is required between clusters of 6 OWC photonic antennas controlled by different OWC access points, see Figure 6.

Clearly this poses a challenge for a large factory such as Bosch's I4.0 factory in Feuerbach ([The Bosch plant in Feuerbach – where tradition meets high-tech - Bosch Media Service \(bosch-presse.de\)](https://www.bosch-presse.de)) with a floor space area of 109,100 m², which would not only require 5455 OWC access point clusters, but also the mobility of user equipment within the coverage area would incur excessive number of handovers and signalling.

So the first motivation is to design a cell-free network where handover between access point clusters is no longer needed for mobile users. This paves the way towards a beamsteered OWC system, which will ultimately produce much wider access angles and would subsequently require much fewer OWC access points. Increasing the radius by a factor of 4 with a field of emission angle of 70° provides a coverage area from one access point of 16 m x 20 m = 320 m² which would require 340 OWC access point clusters for a factory with a floor space area of 109,100 m². This is much more commercially viable.

The RunEL 5G Network Distributed Unit (DU) supports up to three Radio Units (RUs), which for usual mobile radio use provide access to four horizontally and vertically polarised Radio antennas or up to eight optical antennas, as shown in Figure 9.

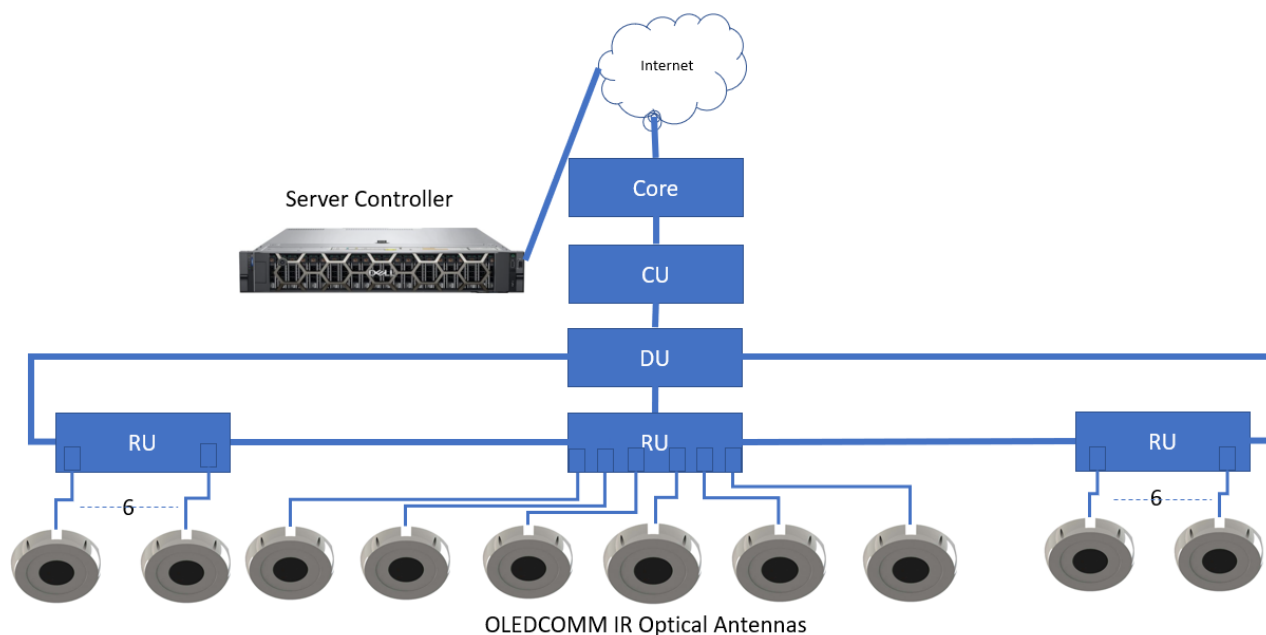


Figure 9 – RunEL 6G network

Extending the network in an I4.0 factory involves adding more CU and DU to the Core as shown in Figure 10.

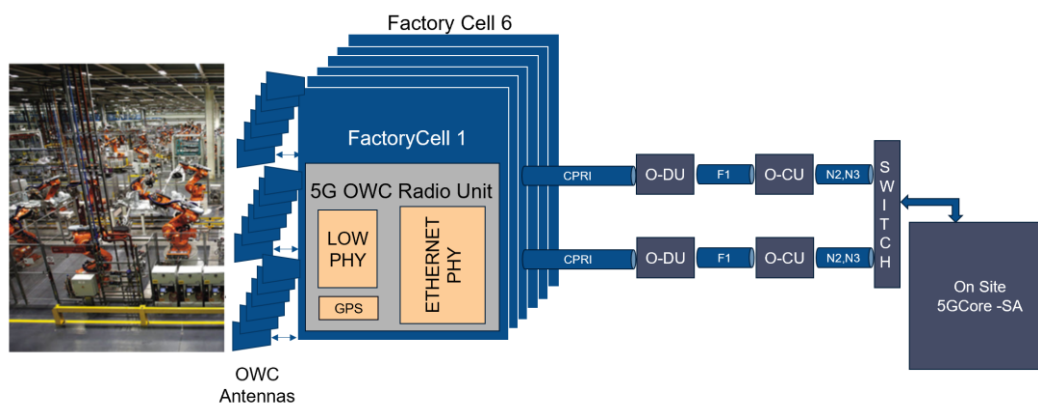


Figure 10 – Sparq-2025-P 5G Private Network with Optical Air Interface

2.2.3 5G/6G autonomous IoT lab

5G/6G Autonomous IoT Lab will be used to build and test identified I4.0 use cases. It is subdivided into experimental test and development areas, as shown in Figure 11. A photograph of the experimental area is shown in Figure 12 and the development area in Figure 13. The dimensions of the target experimental test area are $L = 5 \text{ m} \times W = 2.5 \text{ m} \times H = 2.2 \text{ m}$ which is enclosed by an aluminium frame on which optical wireless radio antennas can be fixed. Thus, the maximum horizontal distance of communication is 5 m and vertical is 2.2 m.

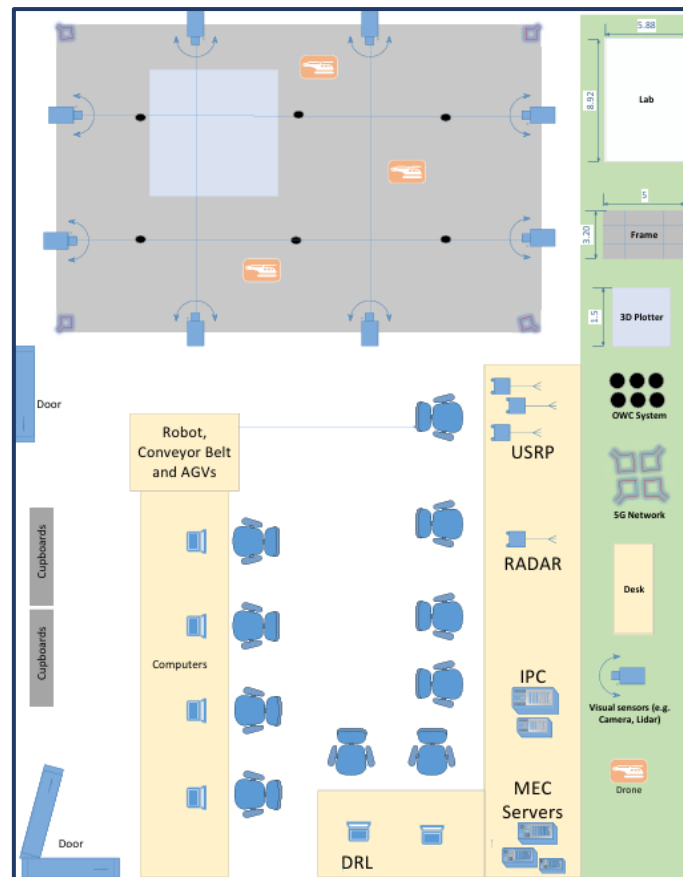


Figure 11 - Dimensions of the 5G/6G autonomous IoT Lab



Figure 12 - 5G/6G Autonomous IoT Lab - Experimental Test area

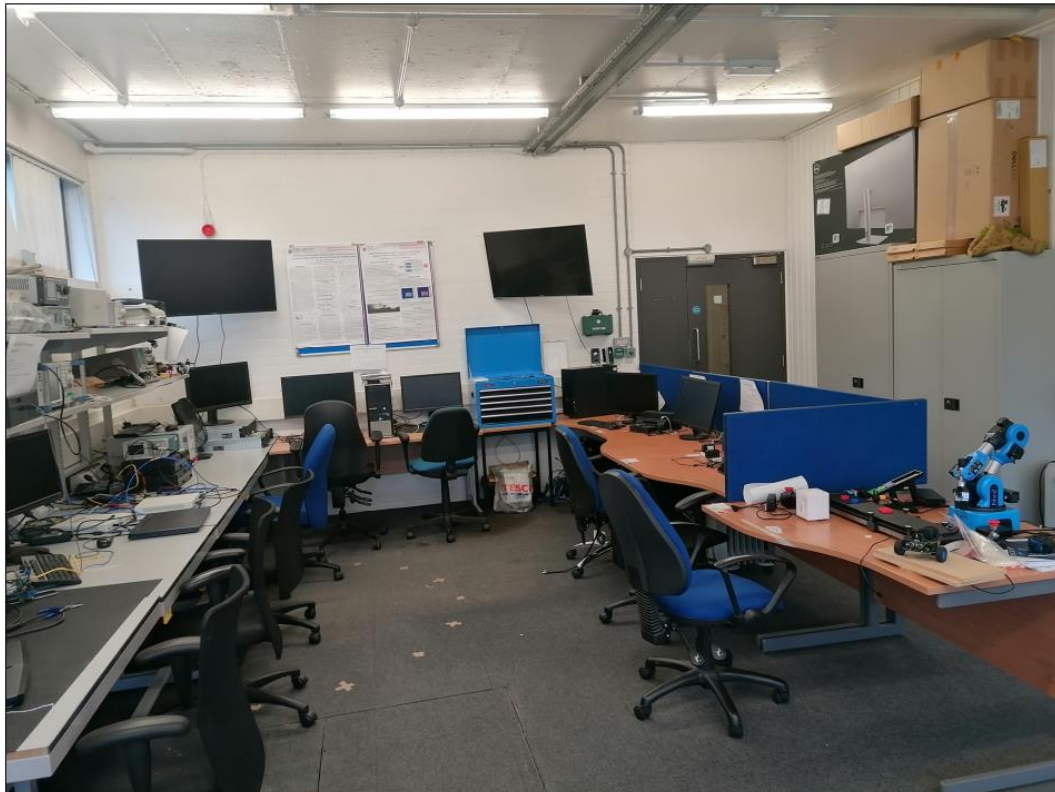


Figure 13 - 5G/6G Autonomous IoT Lab - Development area

Advantages of having a narrow field of view (FoV) include increased propagation distances as shown in Table 2, because with a narrow FoV the EM energy is more focused and directed towards the intended direction of transmission.

Table 2: Propagation distance against field of view

Case	FoV	Covered Area	Number of Antennas	Propagation Distance
1	15°	0.6 m x 0.6 m = 0.36 m ²	15	50 m
2	34°	1.2 m x 1.2 m = 1.5 m ²	8 or 10	25 m to 30 m
3	60°	2.6 m x 2.6 m = 7 m ²	2	15 m
4	90°	4.4 m x 4.4 m = 19 m ²	1 or 2	10 m
5	125° (multi-source)	8 m x 8 m = 64 m ²	1	25 m to 30 m

2.2.4 Localisation

2.2.4.1 ToA

The aim is to demonstrate RunEL's capability to functionally measure the location of 5G/6G Mobile User equipment (UE) Terminals within a centimetre accuracy. This capacity is accomplished by measuring the Time Difference of Arrival (TDoA) of the terminal transmissions received and processed by several antennae elements connected to access points of the base station. This has already been performed in an experiment employing

5G sub 6 GHz radio communications, which measured distance between 3 cm to 4 cm accuracy with a beam from a fixed directional antenna array, as reported in [Cos24] but the algorithm used to measure ToA at the O-RU was not able to successfully measure distance from an isotropic antenna due to the effects of multipath.

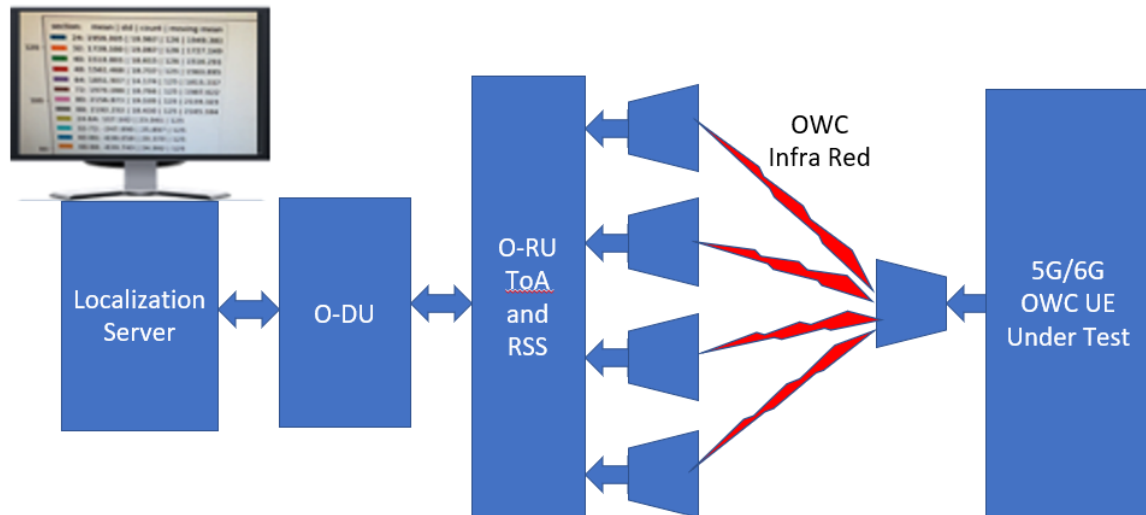


Figure 14 - Combined RSS and ToA Accurate Measurements Experiment diagram

Since the system would need to simultaneously measure distance from four differently located access points to successfully compute position, the distance measurement algorithm needs to be able to perform with isotropic transmissions from the UE. One approach to finding a solution is to operate the algorithm with a transmission medium that does not suffer so acutely from multipath effects, such as an IR emitter. The ToA measurement algorithm uses a cross-correlation between the transmitted Pseudo-Random Noise (PN) transmission and the known received PN sequence to measure propagation time. The experiment aims to observe if the ToA measurement algorithm performs more robustly with IR OWC communication with isotropic emissions since it does not suffer so acutely from multipath effects. It is possible that also measuring RSS could reduce ToA ambiguity that results from multipath.

A second approach to finding a solution is to make the ToA measurement algorithm more robust by combining it with RSS, which may help for additional confidence. A third approach to finding a solution is to increase the field of view of the APs by steering the OWC antennas at the access points in different directions.

2.2.4.2 AoA

The aim is to be able to measure location from a distance (measured using ToA or RSS) and an angle, especially when there are insufficient access points to measure position from 4 ToA or RSS measurements. Figure 15 (red, green, blue, black) within a rectangular 5 m x 2.5 m area. A UE located in a roughly circular area of 1 m diameter in the centre of the coverage area would have access to emissions from all four access points. These can be used to compute location using ToA and RSS estimates of distance.

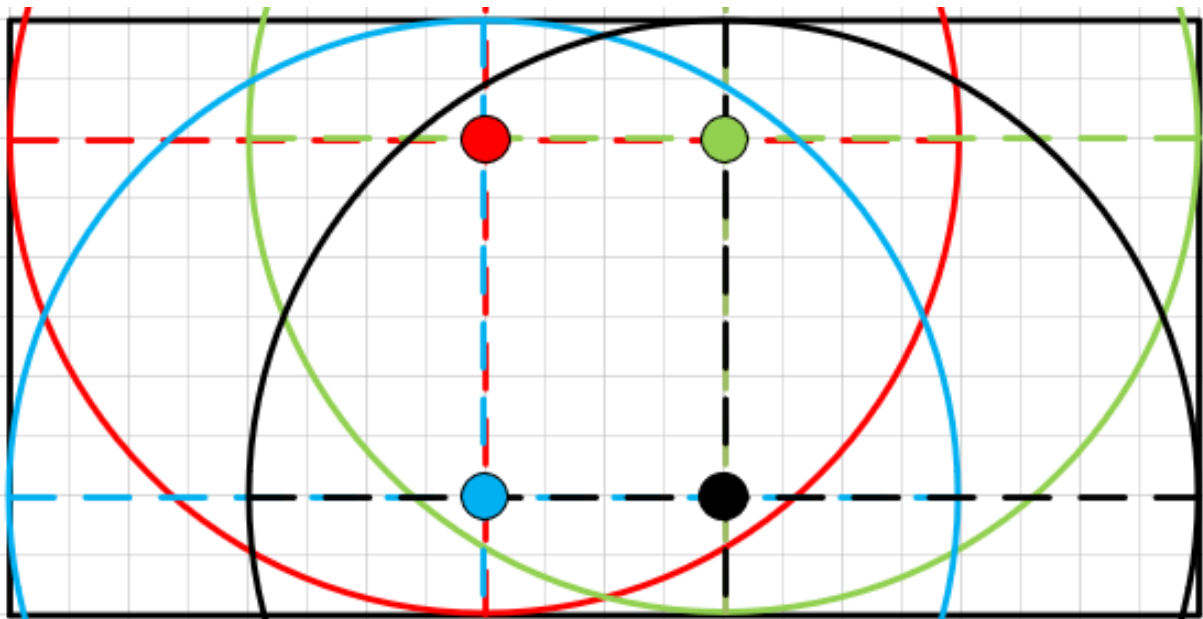


Figure 15 - Emissions from all four access points in a 5 m x 2.5 m area

In some other parts of the coverage area, there are only emissions from two access points or even one access point to estimate distance, which is insufficient to uniquely estimate location.

In these two cases, an AOA-based technique can be used instead. Its operating principle is illustrated in Figure 16, for a single IR optical source at point T emitting its signal in the direction $\mathbf{n}_{t,i}$, and a UE at point R pointing in the direction \mathbf{n}_r . Assuming the beam pattern of the source and the vertical distance between the optical source and the UE are known, we can then determine the UE's coordinates along the x and y axes using the following method:

- The optical source is successively oriented in three different directions $\mathbf{n}_{t,i}$, $\mathbf{n}_{t,j}$ and $\mathbf{n}_{t,k}$, e.g. using a motorised gimbal or any other optical beamsteering technique.
- For each orientation, the optical power received $P_{r,i}$ (respectively $P_{r,j}$ and $P_{r,k}$) is measured at the UE, knowing that this power is linked to the optical power emitted, the propagation distance, and the angles of irradiance $\phi_{t,i}$ and of incidence ψ_r , and the beam pattern of the source.
- Once these three power measurements have been realised, we then calculate their respective ratios (two ratios are sufficient, e.g. $P_{r,i}/P_{r,j}$ and $P_{r,i}/P_{r,k}$), from which we can extract the x and y coordinates by solving a system of equations, which will be detailed in a later deliverable.

If the z -coordinate of the UE is not known, it can then be estimated using a similar process with not a single source but two optical sources.

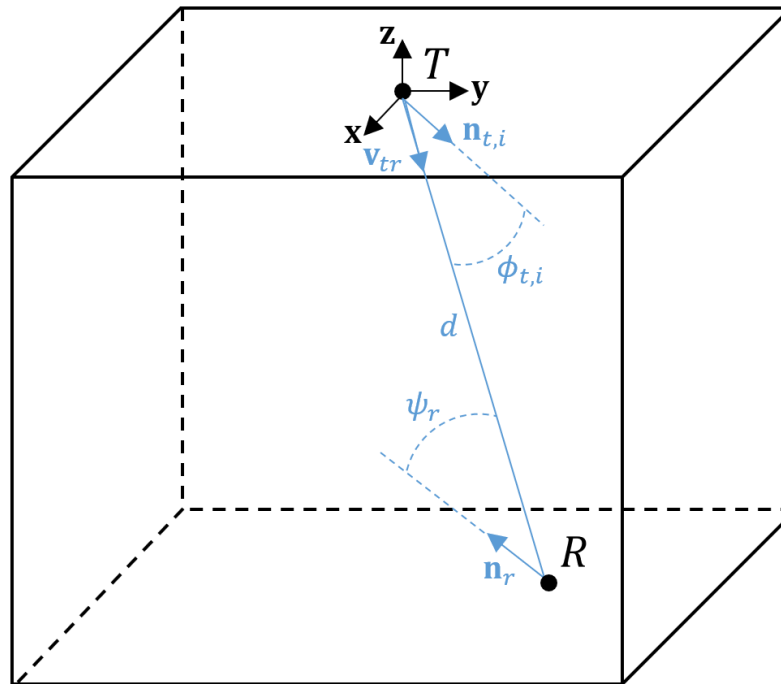


Figure 16 – Principles of operation of Angle of Arrival localisation

We need to successively switch off the transmit antenna (so that only one is transmitting at any one time), which requires shutting down and starting up the access points. This is not practical to achieve in the current set-up because it takes minutes to start up.

This illustrates the benefit for photonically switching wireless signal to optical access points.

Alternatively Perform the transmission on the uplink from the UE to measure distance using Time of arrival on uplink by controlling the output of each UE directly without switching of optical antenna could be developed as a further capability in project.

3 Use case descriptions

As a primary use case for the OPTI-6G solution the project team has identified the factory of the future. In Bosch's vision of the factory of the future [ZIE19] [Art21], the same infrastructure and environment (production facility) shall serve:

1. Mass production with small lot sizes,
2. Mass production with large lot sizes,
3. Flexible and reconfigurable customised production,

with a workflow of the following major steps and stages:

1. Incoming order,
2. Provision/allocation of equipment,
3. Material flow and production.

So OPTI-6G's solution should support such very flexible and dynamically repurposable future production systems.

Going more into the details 3GPP has identified use cases where communication between different AGVs and industrial controllers in large machines is required [Art21], [3GP20], [3GP21], namely: **material handling, smart transportation vehicles** and **offloading of the PLC control function to the edge**.

3.1 Material handling by collaborating mobile robots

5G ACIA has identified common use cases for mobile robots that include material handling (picking/put-away) in warehouses and at production plants [ACI20]. In Factory of the Future, picking robots retrieve items from various storage positions and convey them to a predetermined destination, such as a packing station or container. At production plants, mobile robots are used to retrieve products and to move them from one production step to the next.

The interaction between a robot actuator and parts on a conveyor belt observed from HD cameras is an example of material handling by robots use case which will be considered in the OPTI-6G project, as shown in Figure 17. In this use case, we focus on two important features:

- Video processing offloading from a robot and conveyor belt cameras to the neighbour edge computing node (see Figure 18Figure 17) with high requirements on data rate (>500 Mbps),
- Coordination of two collaborating autonomous systems i.e. robot and conveyor belt from the edge.

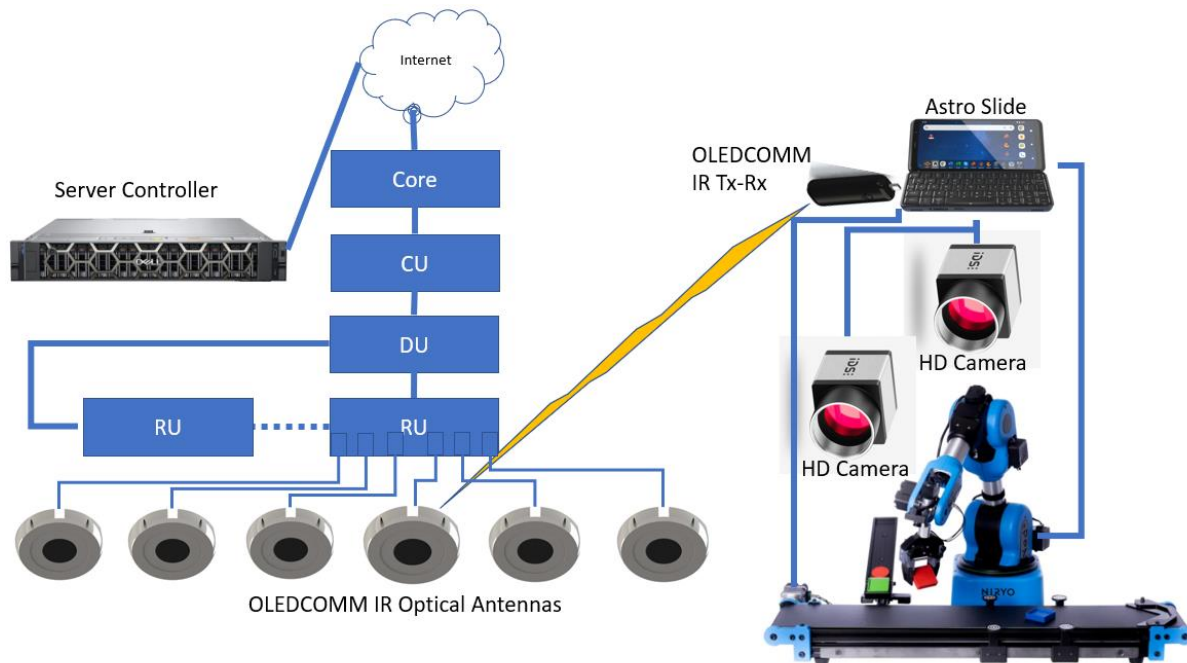


Figure 17 – Niryo Ned 2, a 6-axis robotic arm and conveyor belt

3.2 Smart transportation vehicles

5G ACIA has identified mobile robots/AGVs use cases where mobile robots and autonomous guided vehicles (AGVs) represent mobile systems on a shop floor [ACI20]. In factory of the future, AGVs play an important role and take care of such tasks as driverless and autonomous transport of material and goods from and to production lines. They can also carry robot equipment (e.g., a robot or gripper arm) to flexibly support the assembly process. In this use case, we focus on two important features of AGVs:

- Video processing offloading from an AGV camera to the neighbour edge computing node (see Figure 18) with high requirements on data rate (>500 Mbps),
- Localisation of an AGV in different scenarios with high requirements on accuracy for the localization (< 1 cm).

These functions require a wireless communication network for data transfer and localization purposes to be processed in a local or remote data centre. The localisation of an AGV using ToA and AoA from one or more 6G NB access points to identify position and an HD camera observing the AGV environment to avoid collision with moving objects is an example of a Mobile AGV application in industry, as shown in Figure 18.

An AGV fleet provides intra-logistic transportation and traversing in the factory. An AGV can also be part of an assembly process by picking and placing parts using a gripper arm with sensors mounted on the AGV. An example of the AGVs that are being built is shown in Figure 19(b) [Lynxmotion - A4WD3 Rugged Wheeled Rover](#) and Figure 19(a) Pimoroni AGV robot [Trilobot](#). Fifteen of the latter are being built to create a swarm of AGVs for illustrating I4.0 use cases.

Wireless high-quality video cameras and co-located LIDARs are easily deployed on mobile platforms like AGVs. The video from these cameras can be used to send high-quality and high frame rate video to an image analysing system located at the “factory edge”. By this, a new level of production monitoring is unleashed enabling a long list of new features such as accurate object detection and tracking around AGVs, anomaly detection on the shop floor, improved safety, process tracking and logging, etc. This use case has high requirements on the data rate consuming up to 3 Gbps per camera in case of state-of-the-art industrial 3D camera systems (130 uncompressed HD frames per second: $130 \times 1280 \times 720 \times 24 = 2.8$ Gbps). In this project, however, we consider lower data rate of up to 600 Mbps for only 30 frames per second ($30 \times 1280 \times 720 \times 24 = 632$ Mbps). Since the compression is very time-consuming process, we consider an uncompressed video stream. A 128-channel Ouster OS1 LIDAR bit rate can be as high as 254.3 Mbps.

With this use case, we want to analyse the requirements on the data rate and localisation accuracy with respect to the current state of the art in driverless transportation systems.

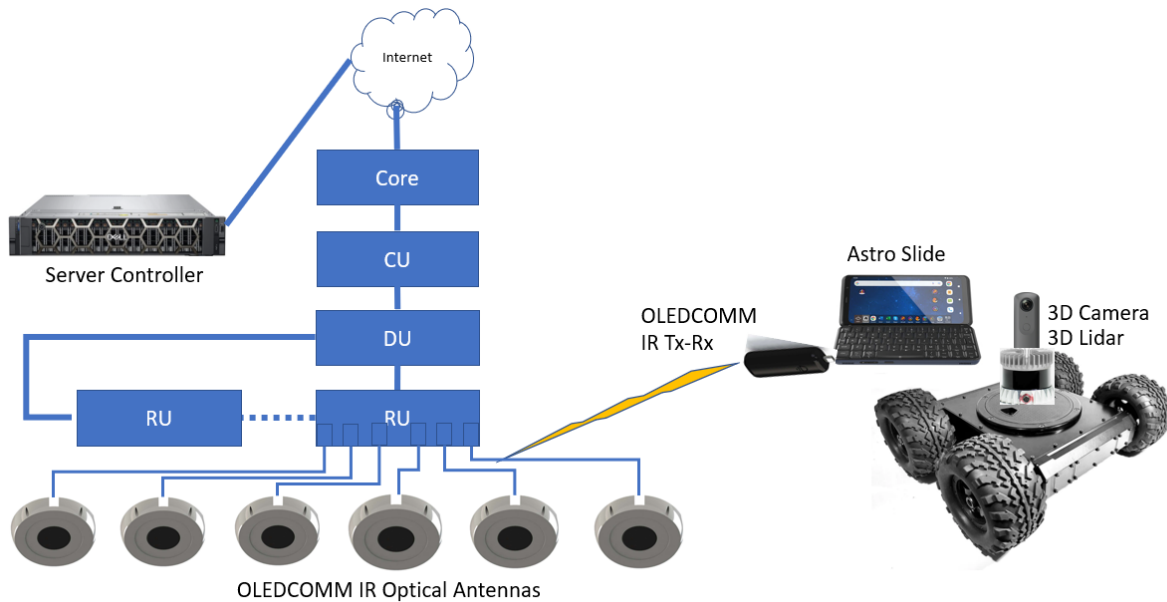




Figure 18 – AGV navigation - localisation and video processing offloading for collision avoidance

	
<p>(a) Pimoroni AGV robot Trilobot Base Kit (pimoroni.com)</p>	<p>(b) Rugged Wheeled AVG Lynxmotion - A4WD3 Rugged Wheeled Rover Kit - RobotShop</p>
<p>Figure 19 – AGV robots</p>	

Whilst the AGVs are being built, an already constructed and operational voice-controlled Ooznest 3D flatbed plotter with a co-located Ouster OS1 LIDAR and a Ricoh Theta V XYZ 3D Camera is used as a mobile platform whose moving head can be positioned with millimetre accuracy, as shown in Figure 20.

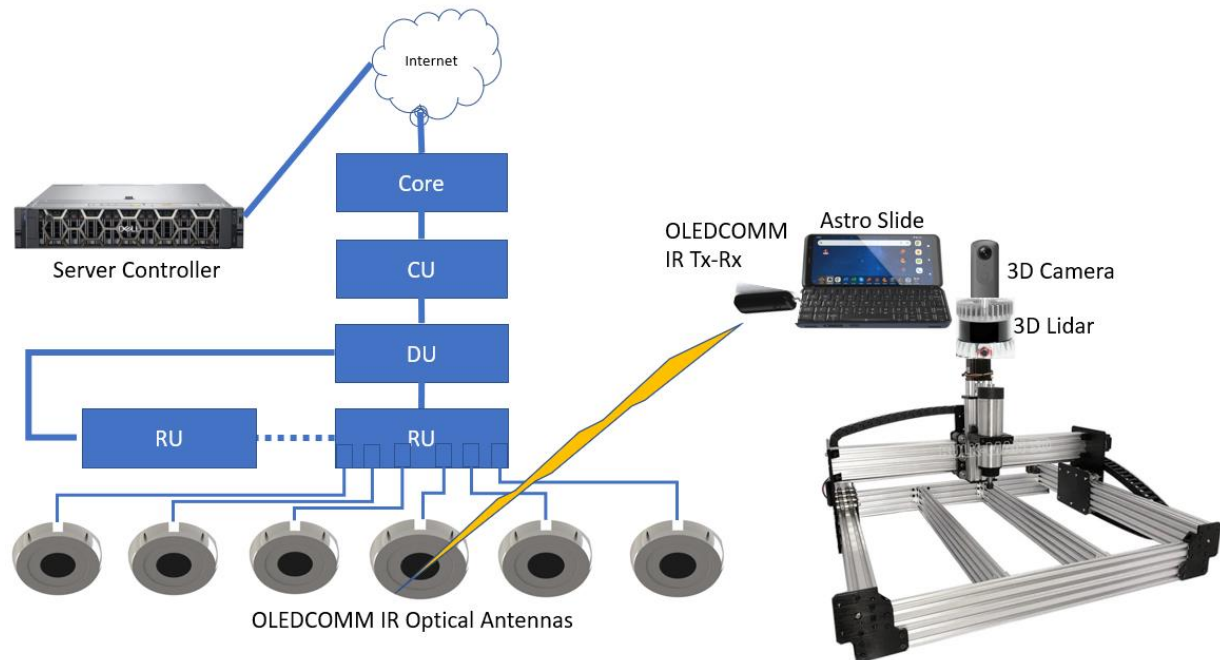


Figure 20 – Voice-controlled Ooznest flatbed plotter

3.3 Motion control - offloading of the PLC control function to the edge

The factory of the future requires a very high level of flexibility of the involved software and hardware components. For this, “soft” controllers running in a virtualised environment are going to replace solid and fixed machine controllers like PLCs. The communication networks between “soft” controllers and machine components get an important role in realization of the new control methods.

A “soft” industrial controller is an evolution from a “hard” industrial controller, which is shown in Figure 21 consists of a master controller and a doubly wired Ethernet loop connected to industrial IoT devices. The master controller generates two Ethernet packets every 1 ms, which are transmitted around the doubly wired Ethernet loop in opposite directions.

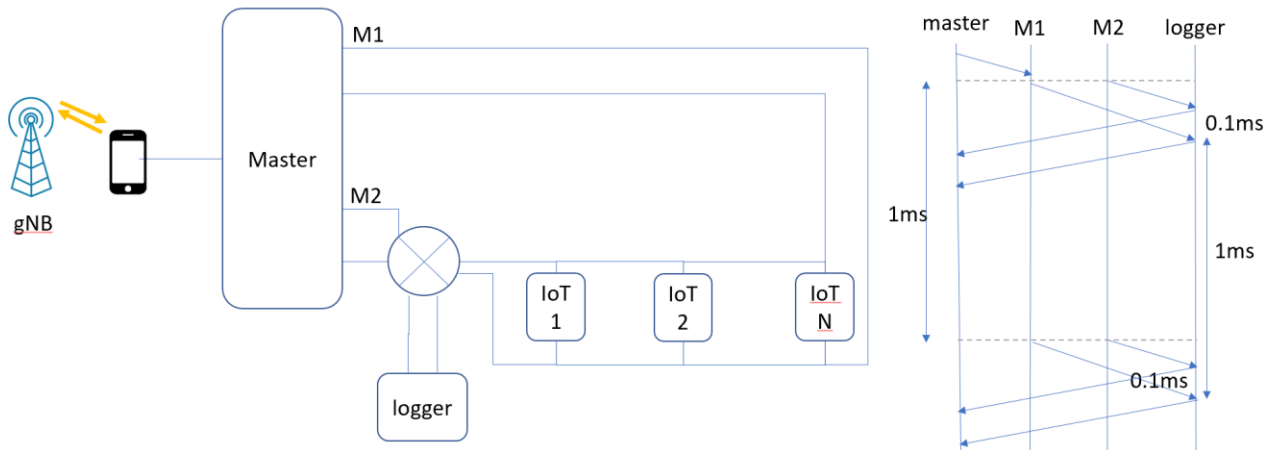


Figure 21 – “Hard” industrial controller

The probability distribution of the interarrival times of Ethernet packets measured at the logger is shown in Figure 22. It shows that the Ethernet packets' interarrival times are 0.1 ms and 0.9 ms as also illustrated in Figure 21.

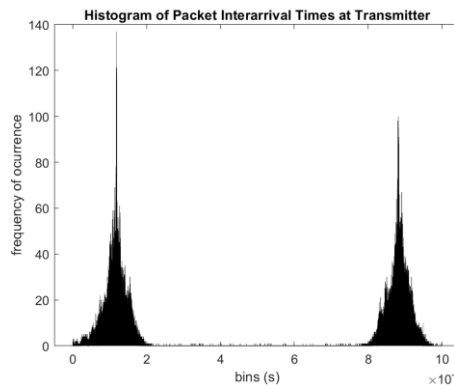


Figure 22 – Probability distribution of the interarrival times measured at the logger of Ethernet packets

Offloading of the PLC control function to a neighbour data centre such as Multiaccess Edge Computer (MEC) servers provides a lot of benefits for controlling the production process in a most flexible way. Such “soft” controllers can run as containers or virtual machines on a classical IT infrastructure. The communication between these “soft” controllers and the machine components requires high QoS provisioning. To enable the ease of product line modification, the communication should include wireless segments.

A “soft” industrial controller consists of a master controller located at MEC servers, as shown in Figure 23. This requires latency to be small and minimally variable.

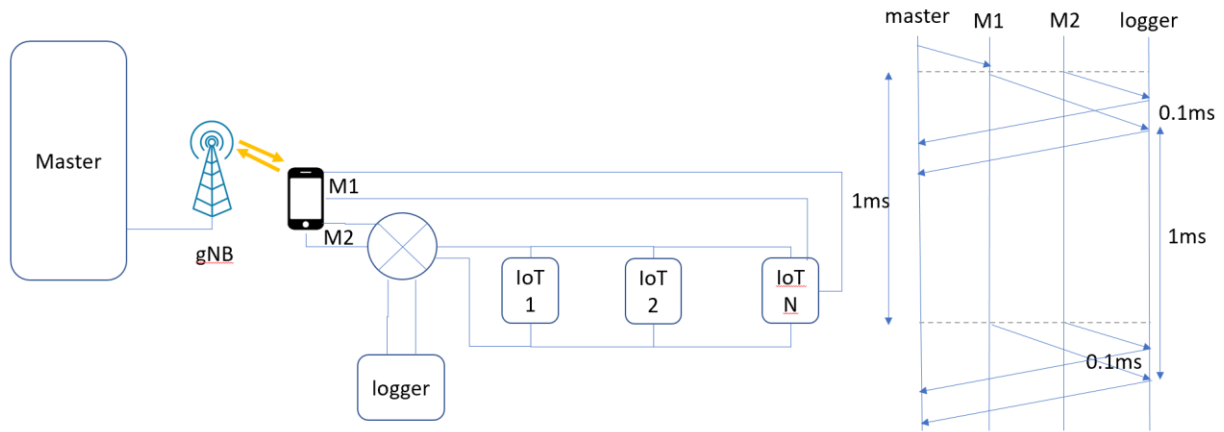


Figure 23 - "Soft" industrial controller

A more centralised approach, where all controllers (real or virtualised) are placed in the same area significantly increases the flexibility of the production process by introducing the possibility of seamless function update and reducing the cost (see Figure 24) for example to control the stepper motor of an inverted pendulum controller. Connecting the production cells through the OPTI-6G communication system to the "factory edge" shall enable the ease of reconfiguration of hardware and software components on demand. This use case sets very high expectations on the guaranteed latency and deterministic communication that should support low industrial application cycle times and very precise synchronicity.

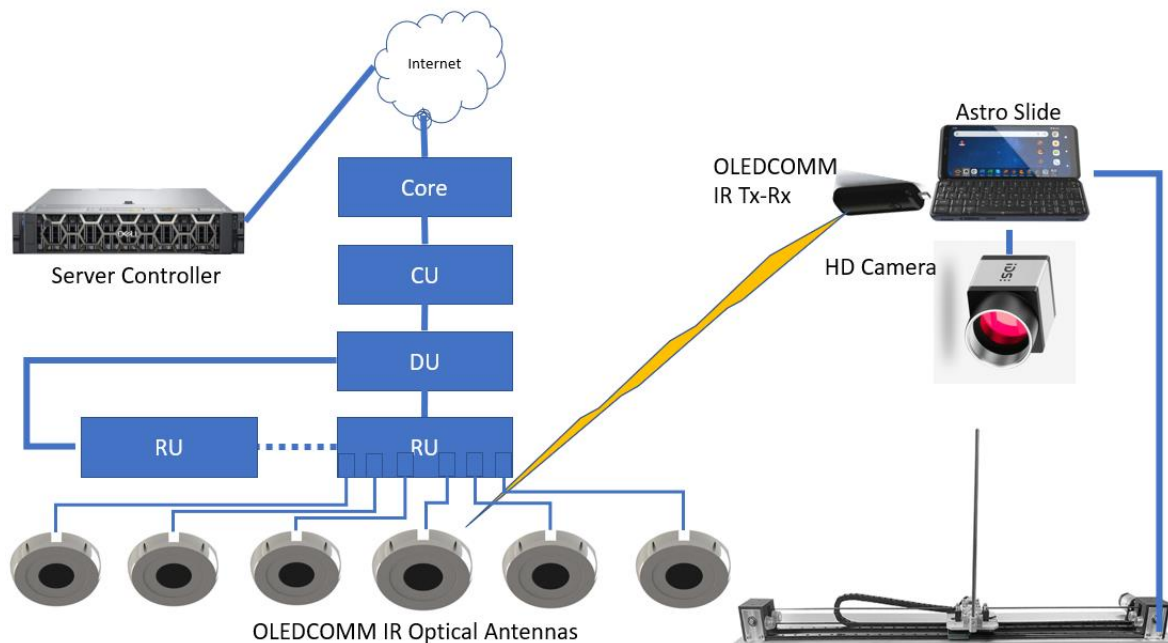


Figure 24 - Programmable Logic Controller - Remote Control Function

With this use case, we want to analyse the requirements on the transmission latency and jitter with respect to the current state of the art in communication between PLCs and machine components.

The current production machines do not allow wireless communication networks to be part of the control loop, because current wireless network technologies do not support very low latency and jitter required in bus systems. The majority of the PLCs in production support cycle times below 1 ms and expect jitter in data transmission as low as 100 ns or lower, as shown in Figure 22. Within a single cycle time, data exchange occurs among hundreds of machine components. However, cabling is one of the most popular pain points in production and costs a lot of effort.

4 KPI and KVI requirements

Here, in this section we list the user, technical and functional requirements relevant and pertinent to the use cases considered in OPTI-6G.

Generally speaking, we can say that I4.0 use cases demand from the connectivity and communication network low latency, flexibility, production-grade QoS, resilience and above all, low cost, low total cost of ownership (TCO).

4.1 KPIs

Table 3: KPIs Related to Industrial Use Cases

	Offloading of the PLC Control Function to the Edge	Smart Transportation Vehicles		Material Handling
		Localization	Video Processing Offloading	
Round-trip time (sensor to controller to actuator)	< 10 ms (250 μ s - 10 ms)	50 ms	50 ms	10 ms
Reliability (packet error rate within latency reqs.)	10 ⁻⁸	10 ⁻⁶	10 ⁻⁴	10 ⁻⁶
Data rate	kbit/s-Mbit/s	kbit/s-Mbit/s	Mbit/s-Gbit/s	Mbit/s-Gbit/s
Packet size	up to 1500 Byte	20-50 Byte	1500 Byte	>200 Byte
Covered distance (from an access point)	within the facility	within the facility	within the facility	<100 m
Movement speed of the user	< 1 m/s	<10 m/s	<10 m/s	< 3 m/s
Time critical handover support	Yes	Yes	Yes	No
User equipment density	0.33-3 per m ²	0.001 per m ²	0.001 per m ²	0.03-0.02 per m ²
Energy efficiency (user equipment battery lifetime)	n/a	n/a	n/a	1 day
Location detection accuracy	<50 cm	1 cm to 5 cm (see note 1)	n/a	< 1 cm to 5 cm (see note 1)
Service availability	99.999 %	99.999 %	99.999 %	99.9 %

Slice configuration / reconfiguration time	1 s	1 s	1 s	1 s
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Note 1: A tolerance of 1 cm to 5 cm for the location of AGV may be acceptable for most navigation in factories and warehouses. A tolerance of 1 cm to 5 cm for material handling may be acceptable for some categories of material. It is known that the location accuracy of 4 cm has been measured for localisation using TDoA operating with sub 6GHz transmission frequencies on the air interface. It has not performed as well as expected due to reflections from multiple scatterers in the coverage area making it difficult for the TDoA timing algorithm to measure propagation time. It is expected that the DoA timing algorithm to estimate propagation time may perform better when operating with IR transmission frequencies on air interface because the reflections from multiple scatterers in the coverage area are not as prominent.

4.2 KVIs

Key Values are those that are defined to be important to people and society that may be directly addressed or indirectly impacted by future network technology, and specifically be considered for 6G. Examples of societal KVIs to be targeted by technology and how to assess them are presented in [WIK22] from which Environmental, Social and Economic were selected to be considered in the OPTI-6G project.

Table 4: KVIs related to Industrial Use Cases

Type of KVIs	KVI	Offloading of the PLC Control Function to the Edge	Smart Transportation Vehicles		Material Handling
			Localization	Video Processing Offloading	
Environmental	Carbon Footprint Reduction	1%	2%		2%
	Energy Efficiency	0%	10%		20%
	Resource Consumption	5%	5%		10%
Social	Employee Safety and Well-being	100%	100%		100%
	Skills Development	AI + Programmable Control	AI + AGV		AI + Robot
	Job Creation vs.	50:50	50:50		50:50

	Automation Balance			
	Community Engagement and Impact	High	High	Very High
Economic	Productivity Growth	100%	100%	100%
	Market Share	Disruptive technology enhancing existing solutions	Disruptive enhancing solutions	Disruptive technology enhancing existing solutions
	Cost Efficiency	20% Reduction in personal costs	90% Reduction in personal costs	90% Reduction in personal costs
	Supply Chain Resilience	50% enhanced	50% enhanced	50% enhanced

5 Summary of findings

OPTI-6G promotes B5G-enabled industrial OWC network focusing on the **factory of the future** use case, in which every part of the production environment is fluid, except for the walls and ceilings. This vision was also adopted for the OPTI-6G use cases, namely: **material handling, smart transportation vehicles and offloading of the PLC control function to the edge.**

A fluid industrial environment is one in which industrial automation deploys reconfigurable production systems that can be configured and adapted in real-time to actual demand and tasks at hand. This means that every piece of equipment in these new factories should be connected by wireless, and be located with high-resolution using radio-light communications.

Near infrared Optical Wireless Communications cell-free 6G networks provide a low total cost of ownership solution that is resilient to eavesdropping, sniffing or snooping cyber-attacks. The aim is to combine time of arrival, received signal strength and angle of arrival localisation and provide sub cm accuracy across the whole coverage area.

The MEC (multi-access edge computing) connectivity enables analytical applications like predictive maintenance and Artificial Intelligence to bring flexibility and real-time intelligence capabilities to help production managers handle even frequently changing production routines. The cell-free network architecture should increase the ease of connectivity and reliability of the communication to the end devices (e.g. sensors and machines) and drastically reduce the latency by eliminating the handover delay.

Finally, we identify and specify the user, functional and technical requirements for the 6G system to provide the KPIs and KVI's required in the identified use cases.

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