

Final project report

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D1.3 FINAL PROJECT REPORT

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1 Executive Summary

This project report provides an overview of the results attained in the 5GEARING project, highlighting the main achievements, deliverables prepared under the work packages (WPs), scientific publications, and the white paper. All WPs reached their corresponding milestones. The achievements and milestones of the WPs are reflected in the deliverables. The main outcomes are: (1) for WP1 (project management) financial coordination by distribution of the finances as per the agreed budget distribution to all partners and administrative coordination through regular meetings and discussion on the progress of the project, (2) for WP2 (Use cases: Communication and service requirements) gathering industry application requirements to characterize them for understanding of communication and service requirements, guidelines on 5G campus network deployment, frequency coverage planning, and planning for placement of 5G radios in an industrial environment, (3) for WP3 (Application development) development of applications for video streaming, robot-to-robot interaction, AI based object detection, and real-time communication, (4) for WP4 (5G network deployment and integration) deployment, configuration, and optimization of 5G CORE and RAN as well as conducting measurement campaigns for understanding 5G communication capabilities, (5) for WP5 (Validation and demonstration) application development and showcasing 5G technology for industrial automation applications, and (6) for WP6 (Dissemination and exploitation) dissemination of the achievements and outcomes of project through various means. Overall, all project milestones were successfully achieved, and a final demonstration on robot-to-robot interaction and video streaming was conducted for a large group of participants.

2 Introduction

5G wireless technology promises connectivity for industrial internet of things scenarios due to its support for high data rate and low latency communication. The digital transformation of industries and emergence of newer applications is resulting in the emergence of distinct services and communication requirements. Not only low latency communication is needed but sometimes high device density, positioning, and use of artificial intelligence along with edge computing is desired to fulfill the application requirements. It becomes essential to carefully investigate these requirements and validate them through experimental analysis.
5GEARING targets 5G technology transfer to the Austrian manufacturing industry. Several aspects including 5G spectrum usage, network deployment, refined network configuration, and methods to satisfy industrial application requirements are considered. Moreover, supporting technologies such as edge computing, machine learning, robotics and automation are used to achieve the objectives of the project. These aspects target to accelerate the process of digitization and automation in the manufacturing industry. Digitization and automation have several associated benefits including increased productivity, agility and innovation, ease of operations, and energy efficiency. A detailed study on multiple industrial use cases is carried out to help analyze the application requirements and understand how the 5G system can be deployed and configured to support these applications. A parametric analysis of the 5G core and RAN based on traffic profiles of the industrial use cases is conducted to tune the system according to the application requirements. Therefore, a feasibility analysis on campus network deployments to better support industrial requirements in terms of performance, reliability, availability, and mobility is carried out. The major outcomes of the 5GEARING project include development of application scenarios and corresponding services needed by the manufacturing industry to showcase the potentials of the 5G technology, integration of advanced technologies, and dissemination of the activities to the local industry. Moreover, feasibility analysis and demonstration of industrial use cases using 5G technology considering trustworthiness and quality of service are targeted.

2.1 Objective of the document

The objective of this report is to provide an overview on the activities and tasks carried out under different work packages of the 5GEARING project. This report provides a summary on the insights gained during the project. A summary on the results obtained for each work package and efforts towards dissemination of the project outcomes are highlighted.

3 Project management

The project management task included financial and administrative coordination. Scientific and technical coordination, and quality and risk management. The financial coordination was per-

formed 1) by distribution of the finances as per the agreed budget allocation to all partners, 2) usage of finances in terms of personal costs, material costs, and travel expenses as per the consortium agreement. The administrative coordination included organization of regular meetings to discuss the progress of the project. Regular meetings were organized per WP to discuss and coordinate the execution plan and progress of the WP tasks. Access to a shared space for exchange of documents and reports was provided to the consortium for effective coordination. Regular face-to-face consortia meetings were also organized to discuss the overall progress of the project and to take mitigation actions in case of potential risks. The technical coordination included collaboration with the consortium on technical aspects for a successful completion of the project tasks, deliverables, and milestones. Regular steering board meetings were organized to review the project progress and track advancements towards the milestones. Lastly, project reporting as part of the project management WP was prepared to document the activities of the project. The corresponding deliverables D1.1: Data management plan, D1.2: Risk mitigation plan, and D1.3: Annual project report as deliverables of this WP is prepared and are available on the project website.

4 Use cases: Communication and service requirements

The tasks of WP2 were to gather industrial application requirements for characterization of the communication and service requirements, formulate guidelines on 5G campus network deployment, frequency coverage planning, and planning for placement of radio heads in an industrial environment. A detailed analysis of the industrial applications was carried out. Use cases from the manufacturing plant and production lines were identified along with their key performance indicators (KPIs) and key value indicators (KVIs). After a detailed analysis, traffic profiling of these use cases was performed to estimate communication requirements and challenges posed to the 5G system. A gap analysis of the 5G system identifying what technological features are currently commercially available and what features are desirable for industrial automation applications. WP2 also extended to network deployment guidelines, deployment options, configuration choices as well as radio and network coverage planning for a reference manufacturing plant. The outcomes of the tasks in WP2 provided inputs to all other implementation tasks since a detailed analysis on the deployment of the 5G system and the application requirements was carried out. The corresponding deliverables of the WP include D2.1: Report on industrial application requirements and communication services and D2.2: Guidelines on 5G campus network deployment, configuration, radio placement, and frequency planning. The deliverables are available on the project website.

4.1 Summary of results

Three use cases were studied in detail identifying the KVIs and KPIs. These use cases include semi-automated production lines, use of autonomous mobile robot (AMR) in the production area, and robotic arms for collaborative manufacturing as well as pick and place operations. The use cases and their requirements are summarized as follows.

A reference manufacturing plant was selected as a baseline where a semi-automated production/assembly line is considered to understand the communication requirements and expectations from the 5G system. The production line has several workstations whereby monitoring and quality control is performed at each work stage. The total data traffic of the whole plant is expected to be 13.107 Mbps. The use of AMR in Industry 4.0 with real-time video streaming for collision avoidance, localization, and material tracing brings numerous benefits. AMRs equipped with real-time video streaming capabilities play a crucial role in enhancing efficiency, safety, and traceability within manufacturing and logistics operations. Considering the detailed requirements of the use case, the total data rate required for the whole production plant is 1600 Mbps.
Robot arms in production have revolutionized manufacturing processes, particularly in collaborative manufacturing and pick and place operations. This use case focuses on the application of robot arms to enhance efficiency, flexibility, and safety in production environments. On average a data rate of 4.67 Mbps is needed for pick and place operation using a robot arm per production line. The communication requirements of these use cases are presented in Table 1.

Table 1: Communication requirements for the use cases

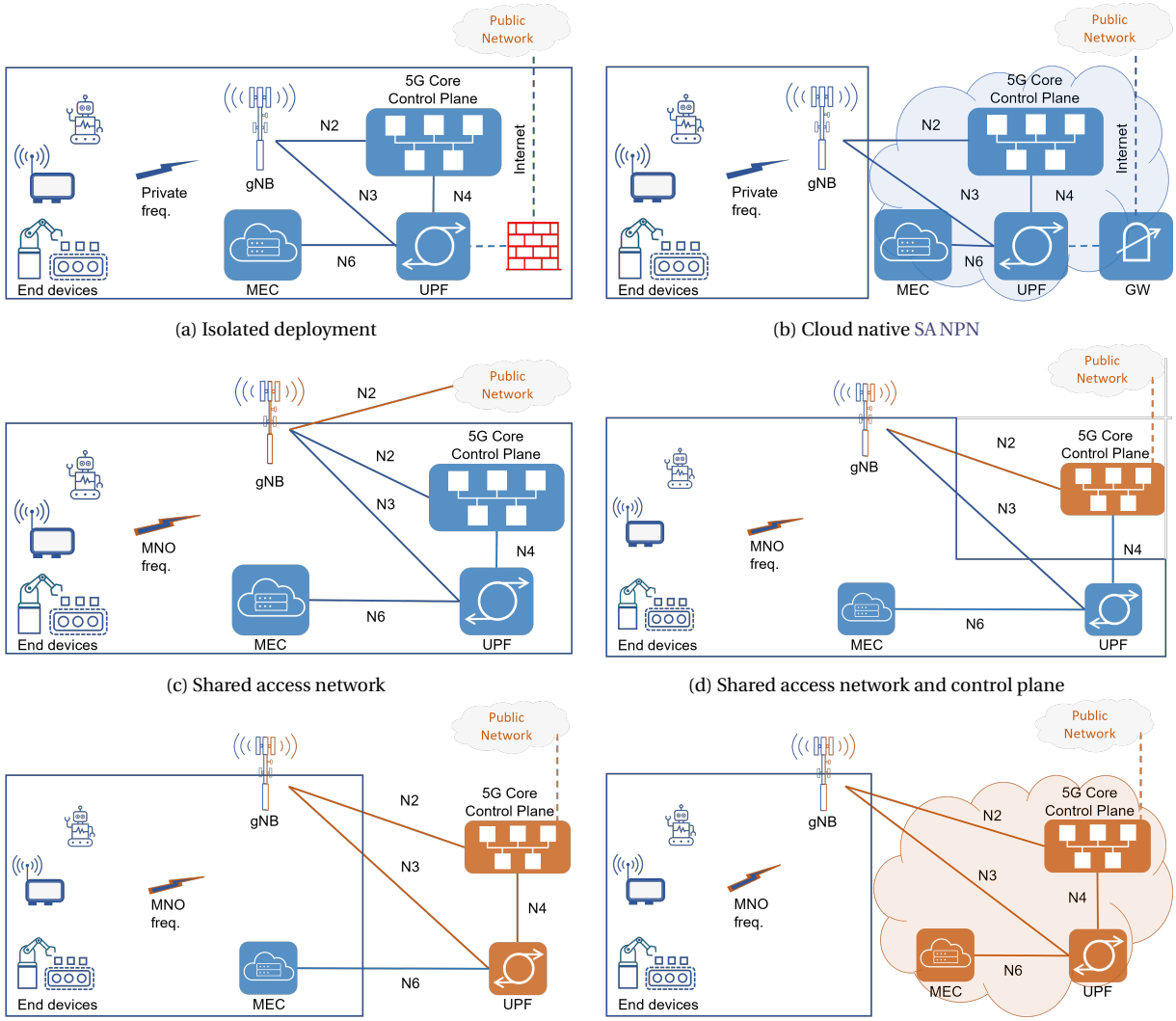
Purpose	Application	Periodic	Recurrence (min)	Bandwidth (Mbits/s)	Cardinality (1:1, 1:n, n:1)	Latency (ms)	Jitter (ms)	Packet loss (%)	Priority	Duration	Number per production line
Optical inspection-camera streaming	Optical inspection of a part takes 10 seconds. Two cameras with 4 megapixel and 60 frames are used. Each camera stream will be H264 coded with results in 8 Mbps. These two camera streams are transferred to a back-end analysis tool.	No	4 to 10	8	1:1	20	10	0.5	High	10	2
Optical inspection-status	The back-end analysis tool sends back the status of the tested component.	No	4 to 10	0.000001	1:1	500	100	0.00	Low	0.001	2
Handover to next station	If processing at the station was completed correctly, a data record with the component number and status of the component is sent to the next station and to the server.	No	4 to 10	0.000002	1:2	500	100	0.00	Low	0.001	14
Handover to rework station	If processing at the station fails, a data record with the component number and number of stations that failed is sent to the rework station and to the server.	No	4 to 10	0.000002	1:2	500	100	0.00	Low	0.001	14
Impression	If processing at the station was completed correctly, a data record with component number and impression pressure is sent to the server	No	4 to 10	0.000002	1:1	500	100	0.00	Low	0.001	1
Screwing data	If processing at the station was completed correctly, a data record with component number and tightening torque of each screw is sent to the server	No	4 to 10	0.000004	1:1	500	100	0.00	Low	0.001	1
Handover from rework station	If processing at the station was completed correctly, a data record with component number and status of component is sent to the station where the part is returned to production and to the server.	No	4 to 10	0.000002	1:2	500	100	0.00	Low	0.001	1

End of Line Test - data stream	End of Line Test takes 90 seconds. Acceleration sensors in three orthogonal directions and a torque sensor are attached to the test part. In addition, the speed signal of the three drives is transmitted. Each sensor has a data rate of 320 kbps, this results in a transfer rate of 2.9 Mbps to a backend analysis tool.	No	4 to 10	2.9	1:1	20	10	0.50	High	90	1
End of Line - status	The backend analysis tool sends back the status of the tested component	No	4 to 10	0.000001	1:1	500	100	0.00	Low	0.001	1
Surround View	Permanent streaming of four cameras with 4 megapixel and 35 frames are used. Each camera stream will be H264 coded which results in approx. 18.7 Mbps. These four camera streams are permanently transferred to the back-end HPC, where additional algorithms are applied (e.g.; object detection)	yes	perm.	18.67	1:1	20	10	0.5	High	perm.	3
Robot - Pick and Place	Permanent streaming of one camera with 4 megapixel and 35 frames is used. The camera stream will be H264 coded which results in approx. 4.7 Mbps. The camera stream is permanently transferred to the back-end HPC, where additional algorithms are applied (e.g.; object detection)	yes	perm.	4.67	1:1	20	10	0.5	High	perm.	1

Table 2: Summary radio and capacity requirements

Coverage Area	Size	40.000 m2
RF requirements	Band	n78
	Bandwidth	80 MHz
	Framing: DL/UL Framing Structure	8:2
Number of devices	Stationary Low-tier (low throughput) devices	5,600
	Stationary high-tier (high throughput / video) devices	1153
	Mobile high-tier /high throughput / video) devices	100
	Mobile data terminals	494
	Total	**7,347**
Total Capacity per plant	Stationary applications	13,107 Mbps
	Mobile applications	1,649 Mbps
	Total	**14,759** Mbps

A summary of requirements for radio planning is provided in Table 2. Considering a wide variety of use cases of the manufacturing industry, 5G network deployment options and their characteristics were studied in detail. These deployment options include isolated deployment and variations of public network integrated NPN (PNI-NPN) including the cloud native standalone (SA) non public network (NPN) and cloud native PNI-NPN hosted by the public network operator approaches as depicted in Figure 1.
Furthermore, a detailed description of network configuration options on CORE, radio access network (RAN), and user equipment (UE) is provided in the deliverable report. Simulation results considering radio placement strategies to understand the capacity and limitations of the 5G system (5GS) are carried out. Finally, frequency spectrum opportunities for campus networks are proposed. The deliverable provides a report to establish an understanding on the state of play of 5G, supporting technologies, and their integration with 5G for industrial systems.



(a) Isolated deployment

(b) Cloud native SA NPN

(c) Shared access network

(d) Shared access network and control plane

(e) Hosted by the public network operator

(f) Cloud native PNI-NPN hosted by the public network operator

Legend	**UPF:** User plane function	**MEC:** Multi-access edge computing	**gNB:** gNodeB	**GW:** Gateway	**MNO:** Mobile network operator

Figure 1: 5G non public network deployment options

5 Application development

The tasks of this WP were to develop applications and algorithms for navigation of robots in a factory environment as well as providing structured interfacing to integrate different technologies to support real-time communication and video streaming. To achieve the tasks of this WP, inputs from WP2 were considered to develop applications. An artificial intelligence (AI) based application was developed for object detection that uses video input from a camera mounted on a robotic arm. A pick and place application was developed to enable interactions of a AMR with the robotic arm using 5G communication and location information. The robotic arm recognizes the size, shape, and form of an object computed over the edge server, picks the object and places it on the mobile robot. The mobile robot then carries the object and leaves for another aisle. In a sim-

ilar way, the AMR returns from an aisle to the robot arm knowing the location information of the robotic arm. The robotic arm then picks the object from the AMR and places it close to itself. The idea of this application is to showcase how 5G can support real-time communication in factory environment, integrates the use of AI, edge-computing, and robot-to-robot interaction, mimicking the scenario of transporting objects from one aisle to another and handover from one robot to another in a manufacturing factory. In addition, the mobile robot is equipped with four cameras that stream high-quality videos to a remote station needed for visual inspection and recording of test operations. Moreover, a streaming application was also developed using industry grade video camera that not only streams high-quality video but can adjust the zoom and field-of-view of the video. These applications showcase multiple aspects of 5G communication including the ability of high data-rate communication, real-time or low latency communication through prioritization of data flows, and application of 5G for factory floor scenarios. The corresponding deliverables D3.1: Standardized interfaces and technologies and D3.2: Applications and algorithms needed for navigation of robots in industrial setup provide details on the activities carried out under this work package.

5.1 Summary of results

The Universal Robot 5 (UR5) (robot arm) and Omron LD250 (AMR) are used to develop the pick and place application. Robot manufacturers use different interfaces and command sets to control their robots and to provide data to external devices. To make robots of different manufacturers collaborate with each other, a software to interface has been developed that communicates between the individual robots. Figure 2 shows the implemented framework that enables the pick and place operation between the UR5 cobot and the Omron LD-250 AMR.

A Raspberry Pi is used on both sides to enable remote control and status data collection of the robots over the LAN ports as well as for establishing a 5G link for wireless communication between the robots. The Raspberry Pi connected to the LD-250 collects the coordinates and rotation data via the advanced robotics command language (ARCL) which is based on a Telnet protocol and informs the cobot when the AMR is approaching or has arrived for a pick or place operation. The Raspberry Pi connected to the UR5 cobot communicates via the real-time data exchange (RTDE) interface to control the actions of the cobot. After finishing a pick or place operation the AMR gets informed to move on to the next production aisle. Moreover, a state machine is implemented to guarantee the right order of the processing steps and path movements. The interaction between the robots is realized via the message queuing telemetry transport (MQTT) protocol. Figure 3 presents interaction of the two robots for the pick and place operation.

A video streaming application is also developed to enhance the location accuracy and object avoidance capability of AMRs. To meet safety constraints in an industrial environment, these visual systems have to work with high resolution at low latency. The Allied Vision G1-319c industrial camera was used as a visual device. Figure 4 illustrates the workflow of the latency measurement.

The camera is connected to a Raspberry Pi that acts as the client in the network and implements

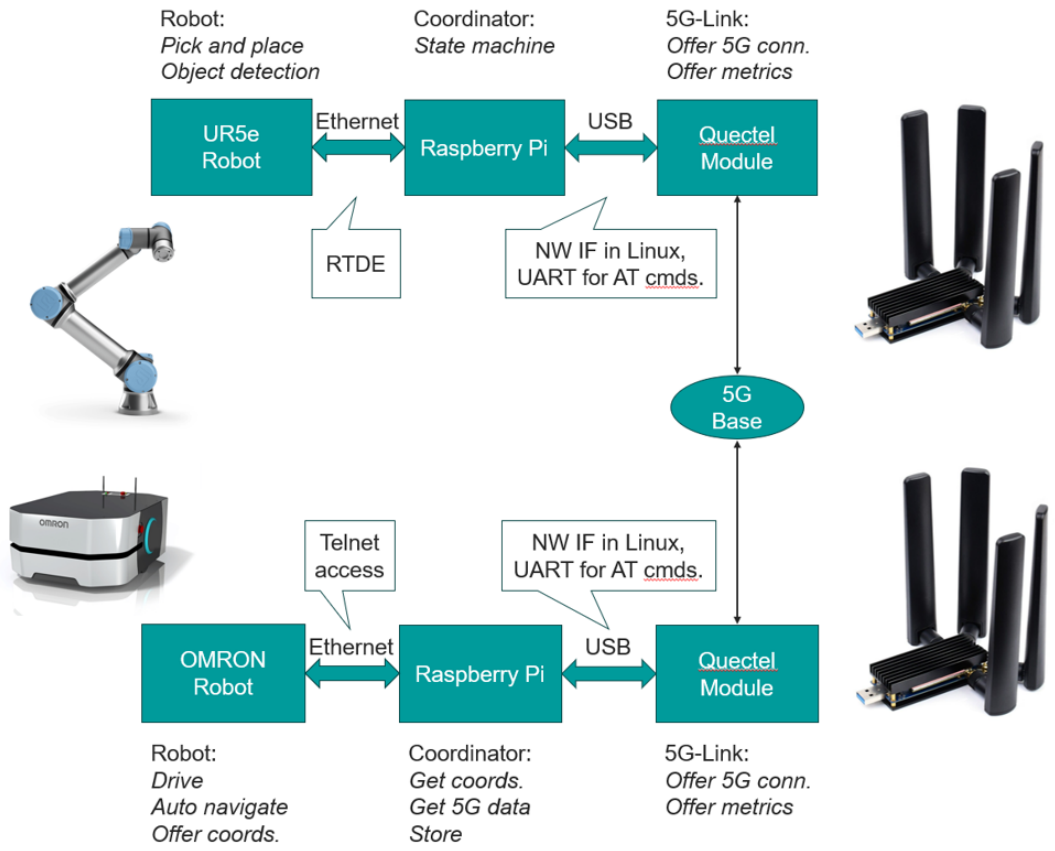


Figure 2: Block diagram of the collaborative robot interaction



Figure 3: Robots collaborating for pick and place operation

a GStreamer based pipeline for encoding and packaging of the video stream. Every encoded video frame gets a unique ID number for later assessment of the round trip time (RTT) and is sent over a User UDP socket via a 5G link to the server where the video stream is de-packed, decoded and displayed on a monitor.

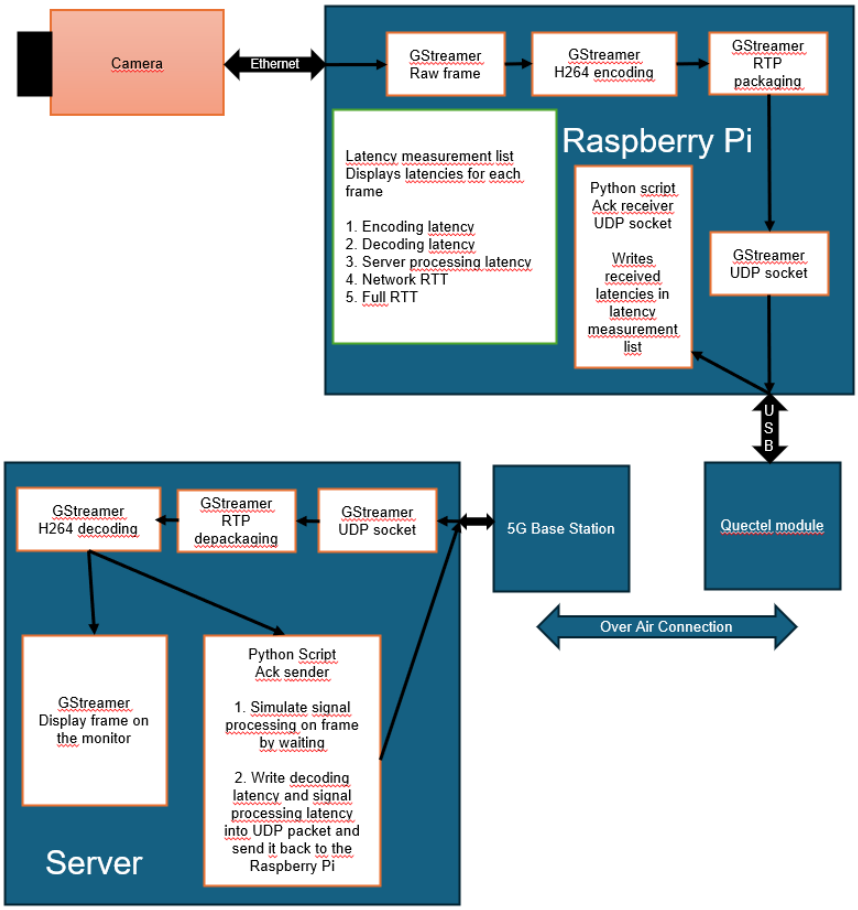


Figure 4: Block diagram of the video stream latency measurement

6 5G network deployment and integration

The tasks of this WP were to set up and configure the 5G campus network in a factory environment. Furthermore, integration of different technologies, devices, application, and algorithms developed in WP3 with the 5G system, and optimization of 5G CORE and RAN parameters are also the tasks performed under this WP. In this regard, 5G CORE network namely the Druid CORE is deployed and configured with the RAN. Several configurations were tested including setting up QoS priorities per UE, various time division duplex (TDD) schemes as well as setting up one or multiple cells with different radio heads. Several measurement campaigns were carried out to record multiple parameters including UE's reference signal received power (RSRP), reference signal received quality (RSRQ), signal to Interference plus Noise Ratio (SINR), channel quality indicator (CQI), modulation and coding scheme (MCS), rank indicator (RI), one-way latency, and throughput (TP) using these different configurations. Moreover, from the mobile robot, precise location and orientation, robot status, and 2D map of the environment were recorded. These measurement campaigns resulted in creating a better understating of the operations and capabilities of the 5G system that generated several useful results. The corresponding deliverables D4.1: Design guideline on 5G campus network deployment, commissioning, and integration with industrial use

cases and D4.2: Report on 5G system configuration parameters and their effects on communication behavior in relation to the application requirements provide details on the results obtained under this work package.

6.1 Summary of results

The work carried out under this WP started by developing guidelines on the 5GS deployment, testing, and commissioning procedures based on an example deployment of the industrial 5GS testbed setup, deployed within this project. Figure 5 presents the pictorial representation of different components of the 5GS deployed in the Linz institute of technology (LIT) factory floor.

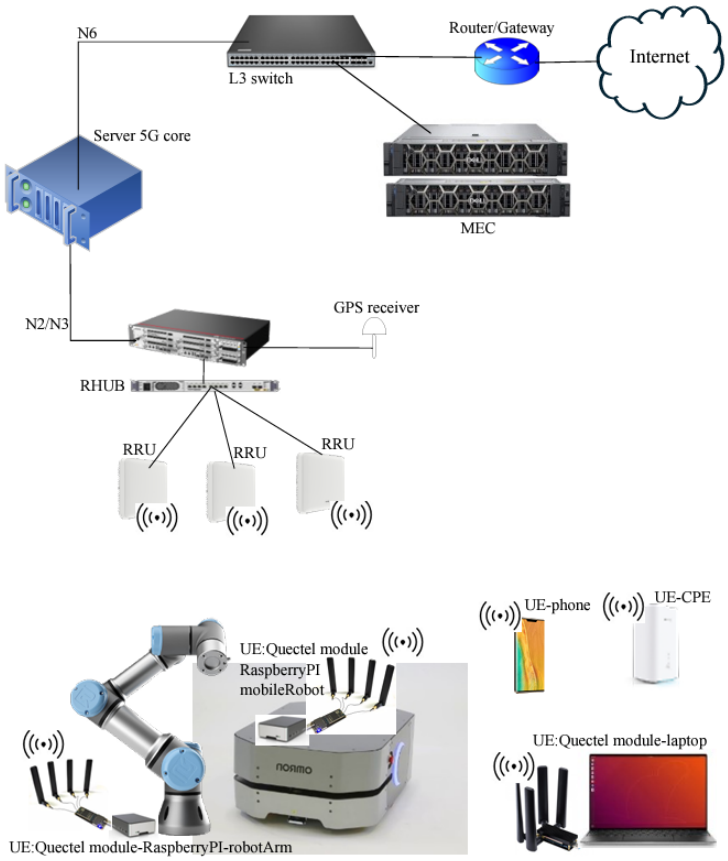


Figure 5: Integrated 5GS-IP/Ethernet network in an industrial testbed setup

Options to deploy 5G core are explored and an example deployment procedure and feature list of the Druid Software 5G core was provided. Moreover, the 5G RAN with the most important parameters, which need to be aligned with UEs on one side and the 5G core on the other side, were presented. The performance of the 5G campus network considering factory floor scenarios is evaluated. The measurement setup is reflected in Figure 6, where the solid black lines represent wired Ethernet connections, while the dashed lines represent logical connections of the setup. The 5GS consists of the 5G core, 5G RAN, and UEs. This SA 5G testbed setup uses 80 MHz of bandwidth (BW) at 3.41-3.49 GHz in band n78, full resource block (RB) allocation, sub-carrier spacing (SCS)

of 30 kHz and a TDD configuration 4:1 (DDDDU).

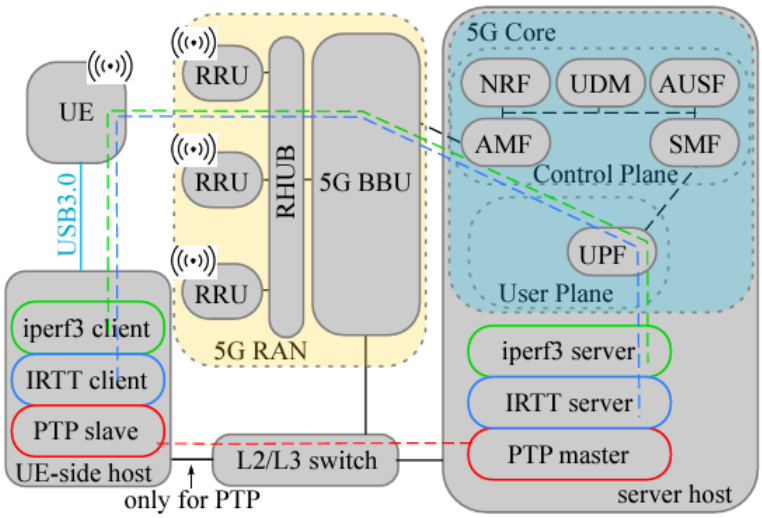
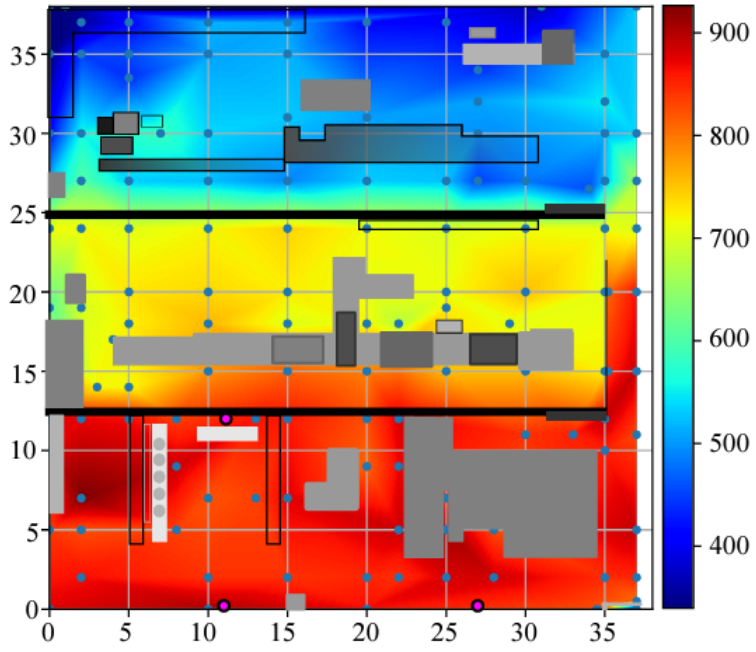


Figure 6: Logical measurement setup of the 5G testbed

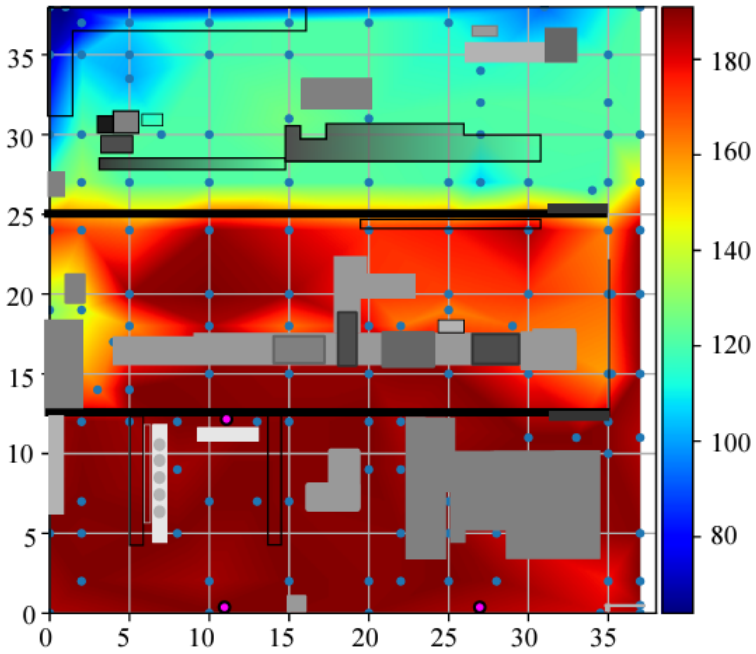
Figure 7 presents the TP coverage heatmap based on the 5G testbed setup in the LIT factory floor. It can be concluded from the coverage heatmaps that the placement of the remote radio unit (RRU)s is suitable to achieve high communication performance in the factory floor area. The TP results show a minimum of 450 Mbps in downlink (DL) and 120 Mbps in uplink (UL) is available in the factory area. These results can serve as a guide in planning for the placement of RRUs in indoor environments. It can be concluded from the TP measurements that with the QoS allocation and retention priority (ARP) parameter, the share of available resources among different QoS flows can be controlled in a deterministic manner, even in scenarios with extremely high traffic load as well as in various channel conditions. However, the channel conditions have to be taken into account while planning the required resource share for a certain QoS flow such that the required TP can be achieved.

7 Validation and demonstration

This WP aimed to integrate and validate the developments carried out in WP3 and WP4 in a systematic manner as well as fine tune the deployed 5GS towards showcasing end-to-end industrial internet-of-things (IoT) solution for the manufacturing industry. To achieve the objectives of this WP automated testing and measurement procedures were developed. These procedures included automated navigation of the AMR to measurements points for data collection and real-time visualization of the gathered data. KPIs including TP, latency, jitter, RSRP, RSRQ, SINR, MCS, etc. values were recorded while the robot navigated in the factory area. Based on the results obtained, the 5GS was further optimized to meet the requirements of the developed applications. Furthermore, robot-to-robot communication as well as high-quality video streaming demonstrations were developed to showcase the outcomes of the project to a wider audience. In lieu of the developments



(a) DL Throughput (Mbps).



(b) UL Throughput (Mbps).

Figure 7: Throughput heatmaps of the factory floor

of the objectives and tasks of the project, further collaborations with industry and academic partners were established that also resulted in developing joint collaborative future project applications. The corresponding deliverable of this work package includes D5.1: Report on test procedures and plans and D5.2: System validation report that provide further details on the efforts and achievements carried out under this WP.

7.1 Summary of the results

The commercial-off-the-shelf (COTS) components were used for the testing and demonstration. The UE was composed of a Raspberry Pi 5 single-board computer and a Quectel RM530N-GL 5G modem. For testing purposes, different computing devices such as UpBoard Squared Pro and laptops were also used with the same 5G modem. The testbed is also equipped with one mobile UE, the AMR LD250 from OMRON Global and the UR5 cobot with camera object recognition capabilities. For communication testing cases, 5 stationary UEs were used and 1 mobile UE that was either stationary or mobile. Table 3 lists all used components of the 5G testbed used for tests and demonstration.

Table 3: Demonstrator and testbed components

Device	Quantity	Usage
UR5 Cobot	1	UE Collaborative robot
OMRON LD250 AMR	1	Mobile UE Collaborative robot
Quectle RM530N-GL	6	5G modem
Raspberry Pi 5	6	Computing device/UE
Up Board Squared Pro	1	Computing device/UE
Camera	4	4K 60fps camera
Active USB hub	1	USB hub for connecting cameras to UE
Power converter	2	Power converters 5V and 12V
Server	1	Edge server

The AMR and cobot robot do not have integrated 5G communication capabilities by default. Therefore, our Raspberry Pi and Quectel module UE was used for bridging the local LAN network of the robots over the 5G, thus enabling the 5G communication capability. The local computing device on the robots was also used to control them. It was receiving commands from the remote server and translating them to ARCL commands that were recognized by the AMR and cobot. Additionally, the computing device on the AMR maintained a Universal Serial Bus (USB) connection to 4 cameras used for recording the environment of AMR. Due to power output limitations of Raspberry Pi 5 and UpBoard devices on their USB interfaces, an active USB Hub was required to supply the cameras with the necessary power levels. Both, computing devices and active USB hub were powered from the internal battery of the AMR as is illustrated in Figure 8 For this purpose, power converters were required to provide 5 V and 12 V power supply from the robot's 30 V battery output. The 5G demonstrator and throughput measurements illustrate significant potential of 5G technology in addressing the communication demands of modern industrial environments. The results show the ability of 5G to deliver high data rates, low latency, and reliable connectivity, even

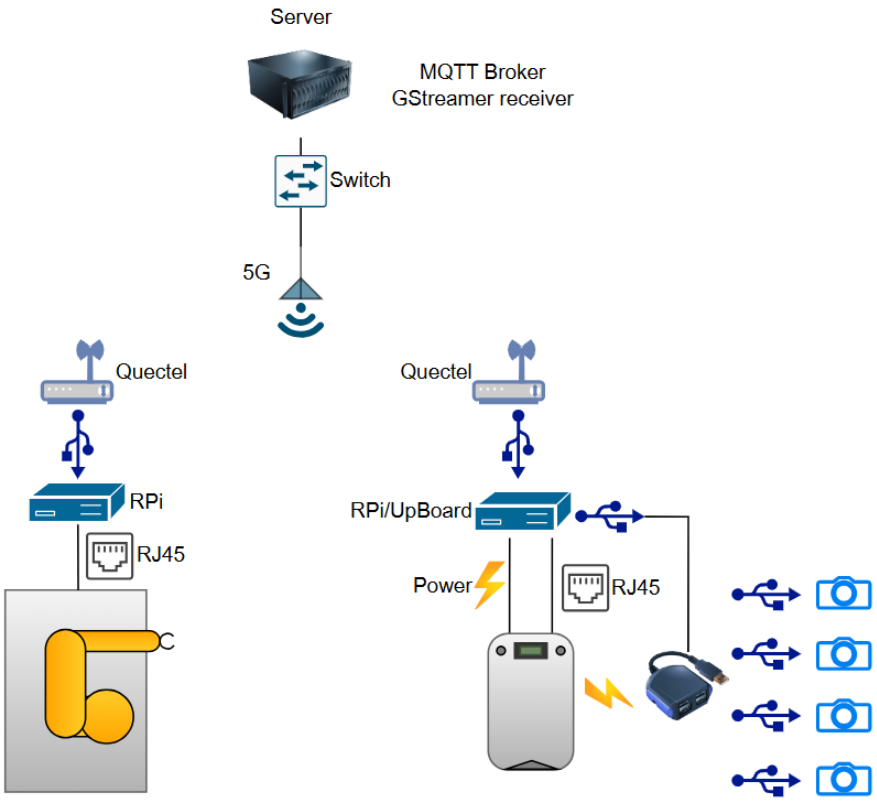


Figure 8: Components and interfacing

in challenging industrial scenarios characterized by interference and complex physical layouts. These capabilities are crucial for real-time monitoring and seamless automation. The demonstrator serves as tangible proof of concept, demonstrating how 5G can be leveraged to optimize industrial operations, improve safety, and unlock new possibilities for innovation.

8 Dissemination and exploitation

This work package focused on dissemination and exploitation of the project results among the industrial, academic, and research community. To start with, a project webpage (https://www.5gearing.at) is maintained that provides information about the project objectives. All project deliverables are also openly available following findable, accessible, interoperable, and reusable (FAIR) principles. Moreover, a LinkedIn page (https://www.linkedin.com/company/5gearing) was created where project activities were regularly posted to increase the outreach of the project dissemination activities. As per the technical outcomes, four peer-reviewed conference and journal papers have been published at highly ranked scientific venues. Moreover, to create a wider impact of the project, dissemination of the project activities was made at different events including FFG Gigabit Academy, SAL 6G Symposium, 6G Summit in Dresden, INTERACT 9th MC and 9th Technical Meeting, and SAL roadshow. A white paper was also prepared that summarizes the achievements and outcomes of the project. A final showcase of the project was made during the SAL road show

where around 50 participants from 25 industry organizations participated. The corresponding deliverable D6.1: Dissemination, exploitation, and communication plan and D6.2: Impact and dissemination report on scientific contributions, awareness to industry on potential benefits, and public awareness provide details on the impact and dissemination activities carried out during the project.

Table 4: List of publications in 5GEARING

Title	Type	Venue	DOI
5G Deployment Models and Configuration Choices for Industrial Cyber-Physical Systems - A State of Art Overview	Journal	IEEE Transactions on Industrial Cyber-Physical Systems	TICPS.2023.3311394
5G Campus Network Factory Floor Measurements with Varying Channel and QoS Flow Priorities	Conference	IEEE IECON	IECON51785.2023.10311715
Enhanced Modeling of Uplink Configured Grant Transmissions for URLLC	Conference	IEEE Globecom	GLOBECOM54140.2023.10437699
Analyzing Multi-Hop WSN Connectivity using Poisson Point Processes: A Layered Model for Quality of Service Assurance	Conference	IEEE PIMRC	PIMRC59610.2024.10817340

8.1 Summary of results

- Setup and maintenance of 5GEARING webpage (https://5gearing.at)
- Four peer-reviewed publications, Table 4 presents the list of publications
- Challenge host at Gigabit academy 2023 and 2024 GigaLab events
- Poster presentation of 5GEARING at SAL 6G Symposium in November 2023
- Presenting 5GEARING at 6G Summit in Dresden in May 2024
- 5GEARING demo presentation at INTERACT 9th MC and 9th Technical Meeting

- 5GEARING final demonstration at SAL Roadshow Linz in November 2024. The demonstration of the 5GEARING project for advanced robot-to-robot communication and management using 5G communication was presented. Around 50 participants representing 25 industrial organizations attended the roadshow. The attendees highly appreciated showcases of the 5GEARING project and showed interest to collaborate in future projects.
- Press release: 5GEARING: Ein Innovationsschub für die Fertigung (https://www.cancom.at/presse/5gearing-ein-innovationsschub-fuer-die-fertigung)

9 Contribution towards sustainability goals

5GEARING contributes to the goals of environmental, social and economic sustainability. In terms of economic sustainability, the activities performed in 5GEARING contribute to the creation of services, automation and digitization for the manufacturing and automotive industry, however, can also be extended to other industrial scenarios.
Industrial applications that require services such as localization, reliable communication, and use of advanced technologies including AI, edge computing, and robotics enable greater flexibility for the manufacturing process. The timely and reliable information exchange and intelligent use of resources creates a positive towards environment through flexible production and lower consumption of resources or increased productivity. In addition, security and trustworthiness are ensured to improve the sustainability and flexibility of production. The benefits lie in improving operational effectiveness, enhancing control inputs to increase production efficiency and energy. These sustainability measures and use of advanced communication technologies, tools, and services contribute towards the goal of responsible consumption and production.

10 Conclusions

5GEARING mainly targets the manufacturing industry which is undergoing a profound change through digitization and automation under industry 4.0 vision. 5G with its advanced capabilities promises reliable and efficient communications and brings new operating models to design products and services for smart factories. These aspects of 5G are highlighted under the 5GEARING project. A LIT factory 5G testbed as a test and trial facility under the 5GEARING project helped in demonstrating the potential of the technology for industrial scenarios. In addition to digitization and automation, 5G communication supports in minimizing production line downtime using reliable and scalable networks, enables manufacturing flexibility through wireless connectivity, allows monitoring and control of critical manufacturing applications, supports real-time decision making using locally deployed edge processing, and increases production yield through efficient use of resources. The activities and outcomes of 5GEARING created a high impact towards the use and deployment of 5G campus network and related technologies required for automation and

digitization of the manufacturing processes. The requirement analysis of the use cases and service provisioning for localization and tracking, tele-operations, as well as high-quality video streaming produced significant results through dissemination of the project activities towards local and regional industries as well as the scientific community.

Acronyms

5GS 5G system. 8, 13, 14

AI artificial intelligence. 9, 10

AMR autonomous mobile robot. 4, 5, 9, 10, 14, 16

ARCL advanced robotics command language. 10, 16

ARP allocation and retention priority. 14

BW bandwidth. 13

COTS commercial-off-the-shelf. 16

CQI channel quality indicator. 12

DL downlink. 14

FAIR findable, accessible, interoperable, and reusable. 17

IoT internet-of-things. 14

KPI key performance indicator. 4, 14

KVI key value indicator. 4

LIT Linz institute of technology. 13, 14, 19

MCS modulation and coding scheme. 12, 14

MQTT message queuing telemetry transport. 10

NPN non public network. 8, 9

PNI-NPN public network integrated NPN. 8, 9

RAN radio access network. 8, 12, 13

RB resource block. 13

RI rank indicator. 12

RRU remote radio unit. 14, *Glossary:* RRU

RSRP reference signal received power. 12, 14

RSRQ reference signal received quality. 12, 14

RTDE real-time data exchange. 10

RTT round trip time. 11

SA standalone. 8, 9, 13

SCS sub-carrier spacing. 13

SINR signal to Interference plus Noise Ratio. 12, 14

TDD time division duplex. 12, 14

TP throughput. 12, 14

UE user equipment. 8, 12, 13, 16

UL uplink. 14

UR5 Universal Robot 5. 10, 16

USB Universal Serial Bus. 16

WP work package. 2, 4, 9, 12–15