



System validation report

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D5.2 SYSTEM VALIDATION REPORT



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Table of Contents

1	Executive Summary	2
2	Introduction	3
2.1	Components	4
2.1.1	Interfacing	4
3	Testing results	5
4	Demonstration	10
4.1	Setup	11
4.1.1	MQTT	11
4.1.2	Data flows	14
4.1.3	Video streaming	15
5	Conclusion	15

1 Executive Summary

This document provides an analysis of measurement results from a 5G system deployed in an industrial environment, alongside a showcase of 5G applications in industry. The focus is on evaluating the performance of 5G in real-world industrial conditions, addressing critical communication aspects of real industrial use cases defined in the scope of the project. For this purpose, measurements of radio conditions and throughput in multiple test cases were performed with multiple static and mobile devices. Additionally, a demonstrator was designed and implemented to show the capabilities of 5G in an industrial environment.

2 Introduction

A 5G testbed demonstration in an industrial environment showcases the potential of 5G technology to transform industrial operations. The testbed allows for real-time monitoring, automation, and control of industrial processes, highlighting efficiency, safety, and scalability improvements, thus enabling researchers and the industry to gain insights into 5G capabilities and develop and evaluate new ideas. Following the outputs from other deliverables, but most importantly, D2.1 [2] and D5.1, this deliverable presents the results of test cases specified in D5.1 [5] and describes the demonstration that was developed. For the purpose of testing the specified use cases in different test scenarios, a commercial 5G standalone system deployed in an industrial environment was used. The 5G system was composed of the Huawei 5G [radio access network \(RAN\)](#) and different 5G core solutions. The 5G system capabilities, design guidelines and configuration are presented in the deliverable D4.1 [3].

Fig. 1 illustrates the industrial environment and represents a schematic of a local factory where a private campus 5G network is deployed.

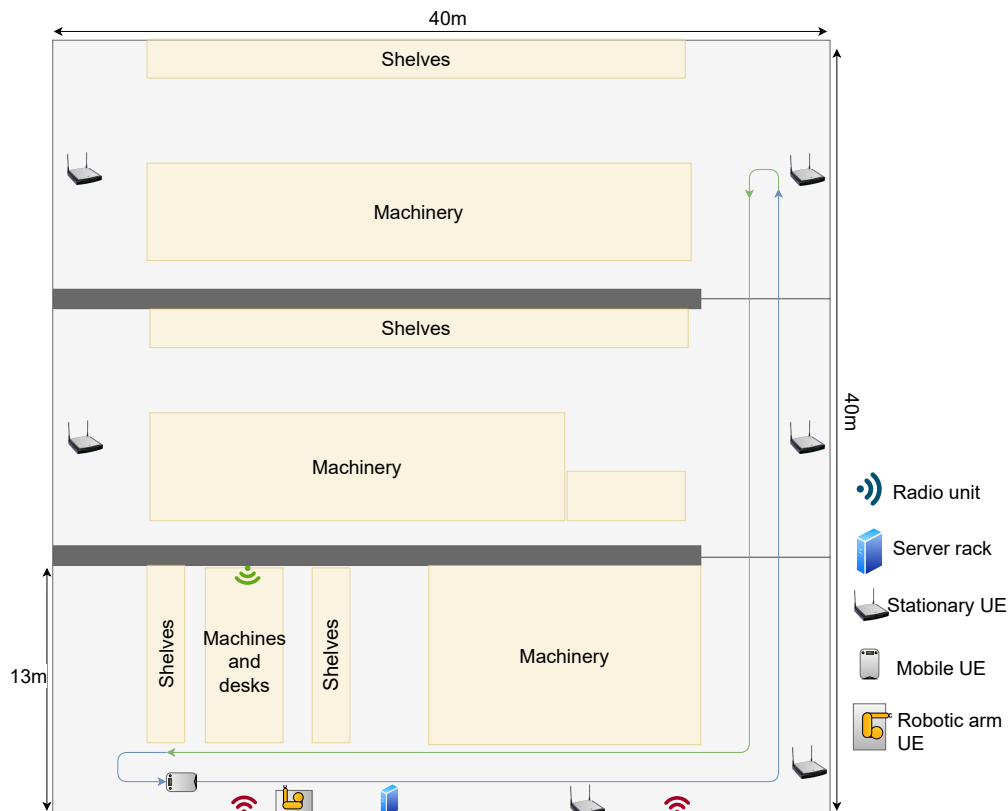


Figure 1: Factory schematic

The factory is equipped with heavy metal machinery for plastic molding, shelves, cranes, forklifts, protection glass panels, metal heating systems, etc. A total area of $40 \times 40m$ was used for testing purposes. However, deploying wireless communication in factory environments presents distinct challenges. Industrial settings often involve significant electromagnetic interference from heavy machinery, large metal structures, and constantly moving equipment such as cranes and forklifts. These conditions can affect signal strength and quality, leading to potential disruptions in communication. Moreover, the presence of various obstacles, including walls, protection glass, and metal heating systems, can cause signal reflection and attenuation, further complicating connectivity. Ensuring low-latency, high-reliability communication in such environments is crucial for enabling real-time monitoring and automation. The introduction of a 5G testbed in this industrial setting addresses these challenges by allowing customized configurations, such as, cell planning, traffic prioritization, application customization, etc.

2.1 Components

The [Commercial Off The Shelf \(COTS\)](#) components were used for the testing and demonstration. The [user equipment \(UE\)](#) was composed of a Raspberry Pi 5 single-board computer and a Quectel RM530N-GL 5G modem [1]. For testing purposes, different computing devices such as UpBoard Squared Pro [8] and laptops were also used with the same 5G modem. The testbed is also equipped with one mobile [UE](#), the [Autonomous Mobile Robot \(AMR\)](#) LD250 from OMRON Global [6] and the [Universal Robot 5 \(UR5\)](#) Cobot [7] with camera object recognition capabilities. For communication testing cases, 5 stationary [UEs](#) were used and 1 mobile [UE](#) that was either stationary or mobile. The Tab. 1 lists all used components of the 5G testbed used for tests and demonstration.

2.1.1 Interfacing

The [AMR](#) and Cobot robot do not have integrated 5G communication capabilities by default. Therefore, our Raspberry Pi + 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 [Advanced Robotics Command Language \(ARCL\)](#) 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 cam-

Table 1: 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

eras with the necessary power levels. Both, computing devices and active USB hub were powered from the internal battery of the AMR as it is illustrated in Fig. 2. For this purpose, power converters were required to provide 5V and 12V power supply from the robot's 30V battery output.

3 Testing results

Following the defined testing guidelines in D5.1, 9 different testing cases were performed. The focused Key Performance Indicators (KPIs) were Throughput (TP), round trip time (RTT) and Signal to Interference plus Noise Ratio (SINR). The Fig. 3 shows SINR heatmap of the entire factory floor. Although the testbed is equipped with multiple Transmission and Reception Points (TRPs), for testing purposes we used only one at the time and the presented SINR is provided by the TRP1 marked with the green color on Fig. 1.

Detailed signal coverage maps for each TRPs are presented in the deliverable D4.2 [4] together with additional testing results related to the fine-tuning of the network with different priority levels for the UEs. This deliverable shows the results of stress tests with a higher number of UEs in different constellations on the factory floor. The testing location points are grouped into three groups depending on the radio conditions as shown in Tab. 3. Good radio coverage is considered if SINR is greater than 30 dB, while bad radio conditions are in areas with SINR lower than 20 dB. The third category for testing is when UEs are distributed arbitrarily on the factory floor spanning the full SINR range. It is important to emphasize that uplink (UL)

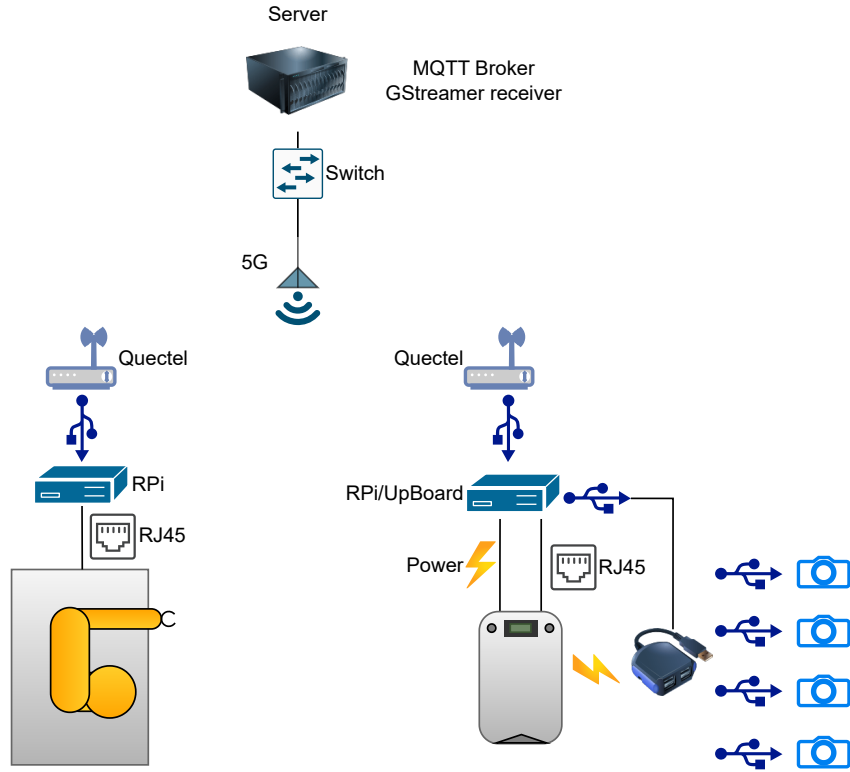


Figure 2: Components and interfacing

and downlink (DL) resources are not the same. The 5G system (5GS) uses agreed time division duplex (TDD) pattern 8 : 2, resulting in 80% times more resources in DL traffic direction.

The first set of test cases is performed with a single UE in different areas of the factory as shown in the first three rows of Tab. 2. The goal of this test case is to test the maximum, minimum and realistic TP of mobile UE that can be achieved on the factory floor. The positions of UEs in good, bad and arbitrary positions are shown in figures Fig. 4a, Fig. 4b and Fig. 4c respectively (yellow-black dots). It is important to emphasize that the chosen positions for the good and bad radio conditions are not the areas with the highest and lowest SINR but areas with signal conditions as defined previously. For the test cases with static UEs, the TP was measured in the duration of 30s with IPerf3 tool, while for the test cases with a mobile UE the measurement lasted longer in order to cover full factory floor. Figure. 4d illustrates the mobile UE path during the measurements.

The Tab. 4 shows minimum, average and maximum TP values for each test case. Although the UE1 was stationary in test cases 1 and 2, the factory environment was not. Therefore, there was a variation of measured TP around the average value of

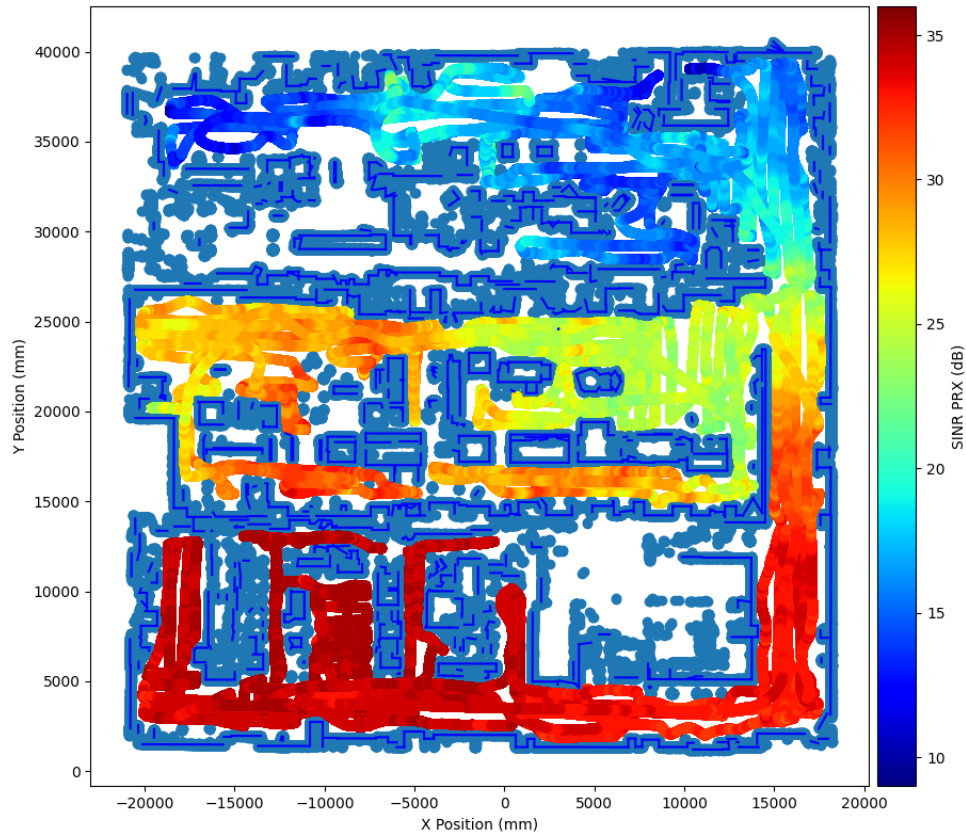


Figure 3: Factory SINR heatmap

Table 2: Test cases

Test case	UEs	Radio condition (dB)
1	1 static	Good
2	1 static	Bad
3	1 mobile	Arbitrary
4	6 static	Good
5	6 static	Bad
6	6 static	Arbitrary
7	5 static 1 mobile	Good Arbitrary
8	5 static 1 mobile	Bad Arbitrary
9	5 static 1 mobile	Arbitrary Arbitrary

Table 3: Radio conditions

Description	SINR (dB)
Good	> 30
Bad	< 20
Arbitrary	10 – 35

Table 4: Test cases results

Test case	UE	UL Min. TP (Mbps)	UL Avg. TP (Mbps)	UL Max. TP (Mbps)	DL Min. TP (Mbps)	DL Avg. TP (Mbps)	DL Max. TP (Mbps)
1	UE1	147.62	156.16	170.86	880.79	918.55	943.67
2	UE1	45.37	47.83	52.66	293.58	309.33	325.06
3	UE1	55.69	112.69	162.67	356.52	629.66	828.38
4	UE1-6	15.72	26.37	37.74	67.1	142.75	179.30
5	UE1-6	3.14	13.54	27.26	11.53	32.4	68.15
6	UE1-6	6.29	21.53	44.04	34.60	110.8	174.06
7	UE1-5	15.72	25.88	36.69	119.61	129.49	179.06
	UE6	8.38	18.47	26.21	62.91	110.85	142.6
8	UE1-5	0	12.85	29.36	0	28.77	57.61
	UE6	13.63	21.71	27.26	69.205	120.69	144.70
9	UE1	4.19	17.72	32.5	56.62	67.18	81.78
	UE2	9.43	21.74	35.65	82.77	99.26	116.31
	UE3	9.43	10.67	12.58	67.1	82.65	103.81
	UE4	14.67	26.65	39.84	56.62	117.79	130.02
	UE5	17.81	27.84	39.84	130.02	142.17	165.67
	UE6	9.43	20.35	28.27	58.71	109.68	144.8

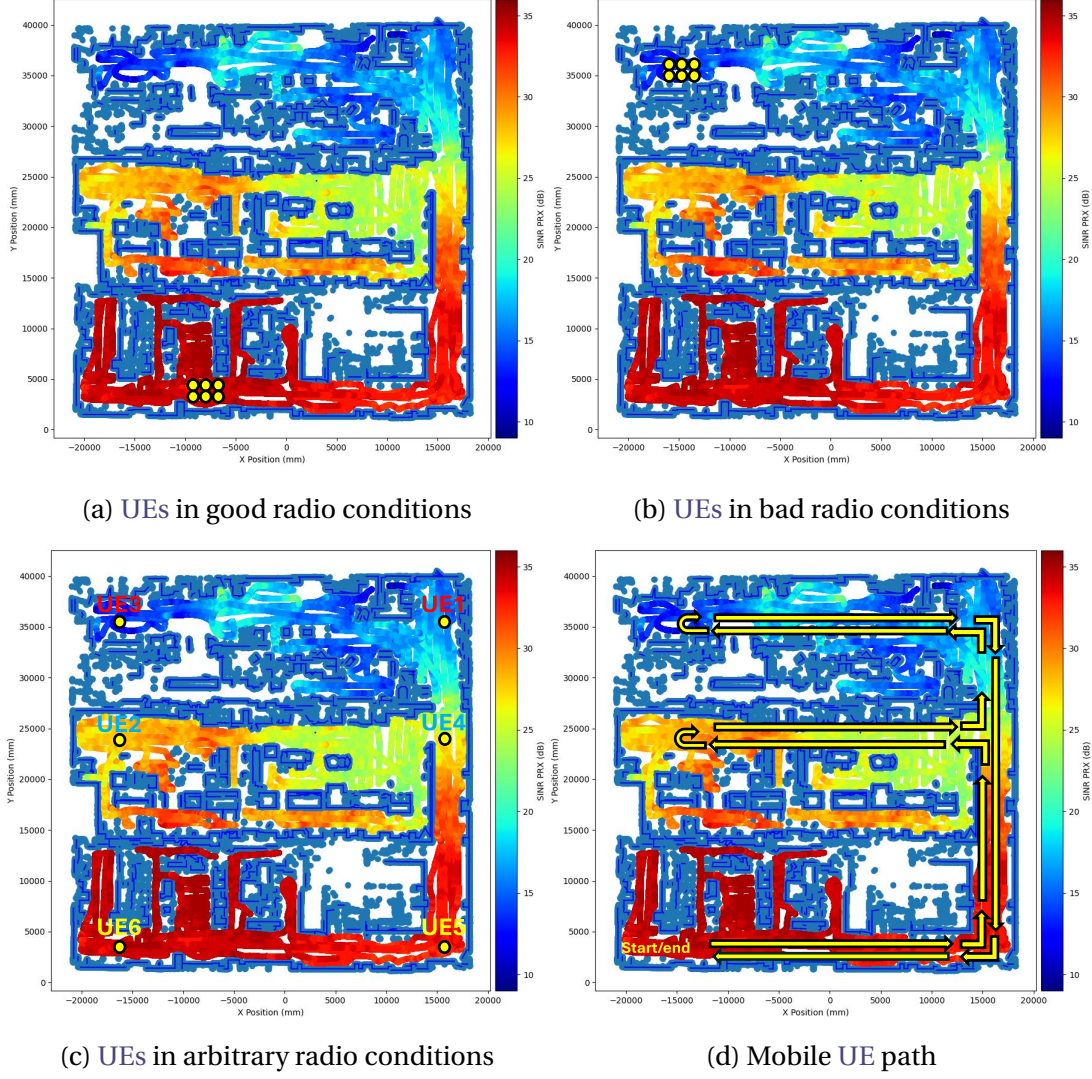


Figure 4: UE placement and navigation path

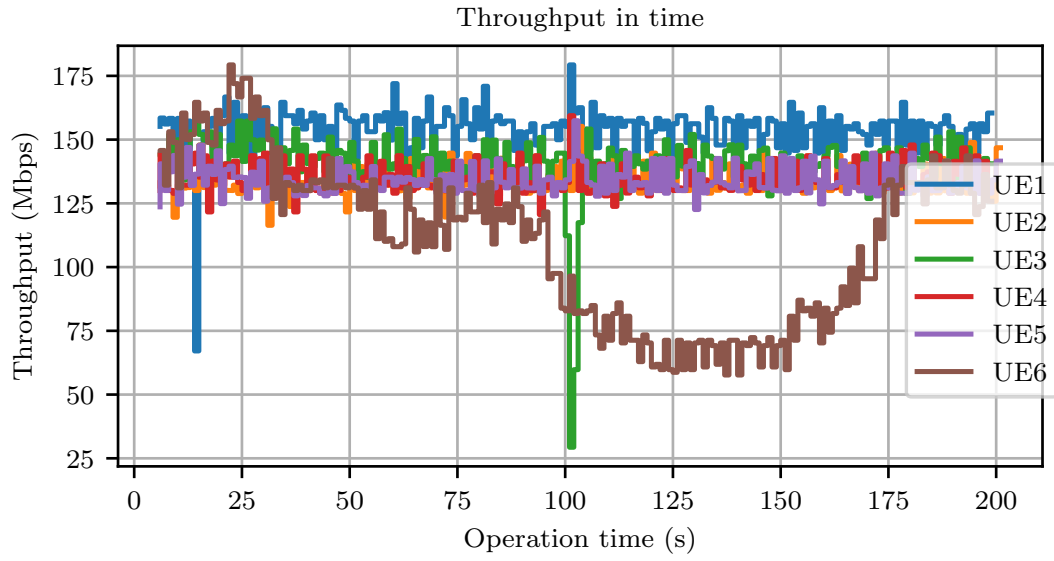
918.55 Mbps. The values of DL and UL TP with single UE are also our benchmark for testing the distribution of resources among multiple UEs in the remaining test cases from Tab. 2. In the test cases with multiple UEs, we can see that the scheduler evenly distributes available resources among the UEs. The results match with the results from [3] if the priority level is the same for all UEs. In the results from test cases 7, 8 and 9 we have 5 stationary UEs and one mobile UE that has an arbitrary position during the measurements. We can see that the roaming of mobile UE between good and bad radio conditions does not influence the TP performance of other stationary UEs. This can be also seen in Fig. 5 which presents the results of test case 7. The TP changes for the mobile UE6, while other UEs maintain their TP with certain drops. Observed drops of TP can be the result of inadequate power supply. The UE (Raspberry Pi 5 + Quectel module) were powered via the portable

power supply i.e. power bank. As power banks are intended for slow charge of internal batteries of devices, their power rating does not meet maximum requirements that are given by Raspberry Pi 5 datasheet. Additionally, their response to sudden power demand peaks might not be optimal. As a result, the Quectel module underperforms. This behaviour can be seen also in test case 8 and Fig. 6, where all UEs are in an area with poor signal coverage and even higher power requirement in UL TP tests. When referring to the specification of communication requirements given in [2] scaled to testbed factory size, it can be concluded that with the default TDD scheme 8 : 2 (DL:UL) and channel bandwidth of 80 MHz the 5G network can not support the required UL traffic of around 500 Mbps. However, with measured DL TP it can be concluded that with different TDD scheme, required UL traffic can be provided.

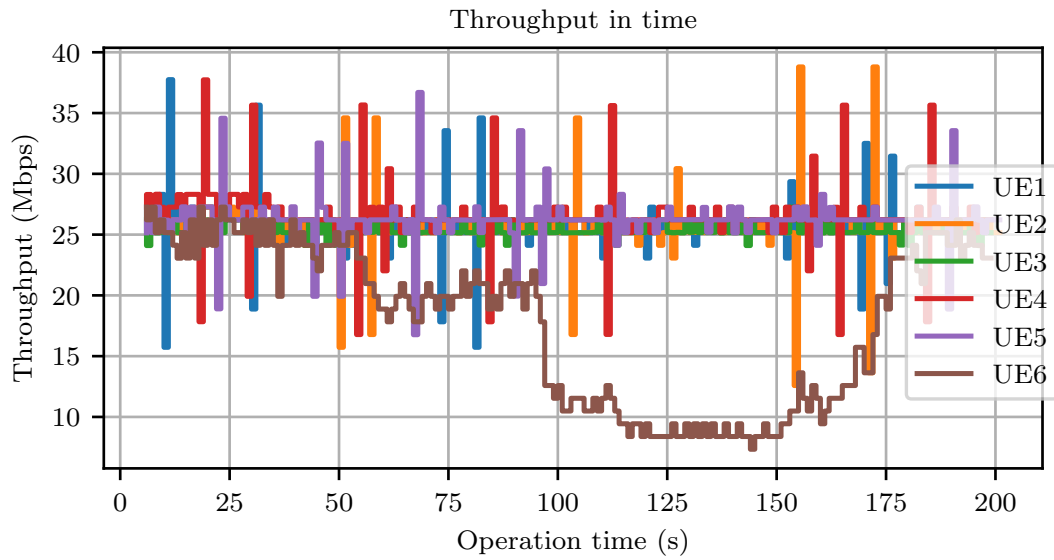
In the second part of measurements the tests were focused on RTT as KPI. In this case the UEs had arbitrary placement as in test case 9. Each UE was running an Isochronous Round-Trip Tester (IRTT) client which was connected to IRTT server hosted on our edge server. As IRTT tool requires external time-synchronization for one way latency measurements, we could only test round-trip time latency. As shown in Fig. 7a the RTT latency was distributed over 12.5 ms where variance can be correlated with the position of UEs and radio conditions at their location. Figure 4c shows where each UE was placed during the measurements for test case 9 and IRTT. Figure 7b shows tail distribution of measured delay and gives insight in dependability of deployed 5G system.

4 Demonstration

The prepared demonstration showcases collaboration between stationary and mobile robots over 5G communication in an industrial environment. In the showcase, the stationary robot UR5 Cobot, developed by Universal Robots, performs a Pick-and-Place operation of an arbitrary object. The Cobot uses an integrated camera module to recognize the object and the object rotation for successful pickup operation. On the other side, an AMR developed by OMRON Global, moves on the factory floor following the predefined route and approaches the Cobot to receive or give an object as shown in Fig. 1. Robots exchange information stating their location and status for the successful and repeatable completion of the tasks. However, although possible, the robots do not communicate directly with each other, but instead via a controller service deployed on a local edge server. For the simplicity of interaction and flexible network configuration, we use a Message Queuing Telemetry Transport (MQTT) protocol for the communication between the nodes. The communication data flows are explained in the following sections of this document. Figure 9 shows



(a) DL



(b) UL

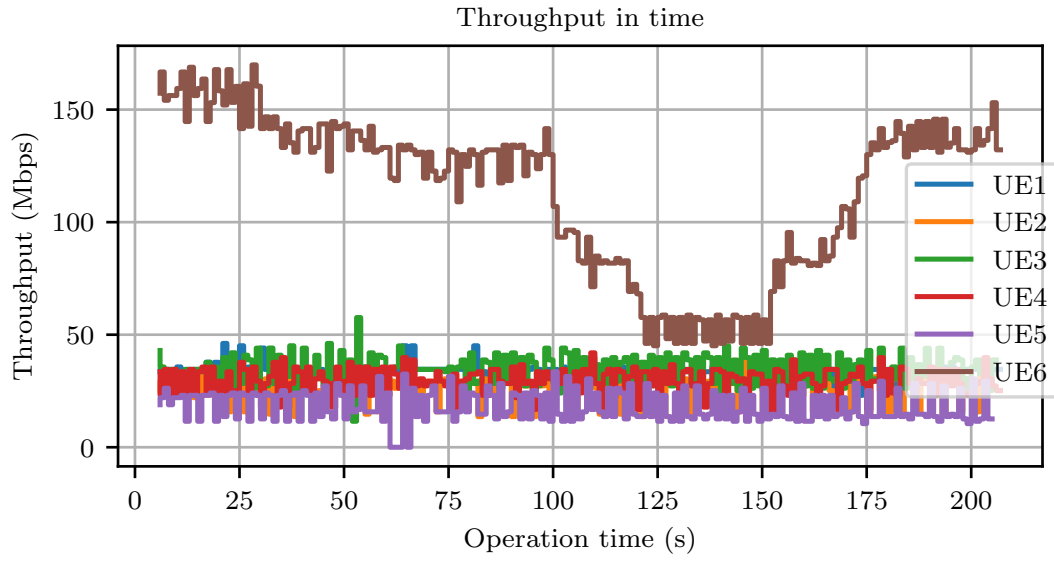
Figure 5: Results of test case 7

the collaboration between the robots.

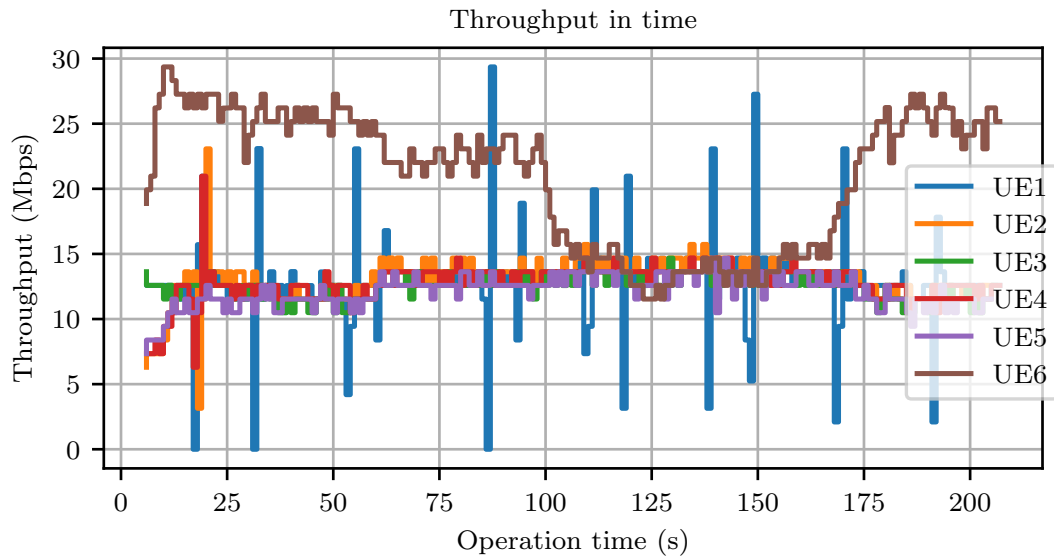
4.1 Setup

4.1.1 MQTT

Message Queuing Telemetry Transport (MQTT) is a lightweight, publish-subscribe messaging protocol that is highly efficient and well-suited for communication be-



(a) DL



(b) UL

Figure 6: Results of test case 8

tween devices in [internet-of-things \(IoT\)](#) environments. Its primary advantage lies in its minimal overhead, making it ideal for constrained devices with limited processing power.

In [MQTT](#), communication is facilitated by a broker that acts as an intermediary between publishers (devices that send messages) and subscribers (devices that receive messages). This decoupling of producers and consumers allows for a scalable system where devices don't need to be aware of each other's existence, only of the

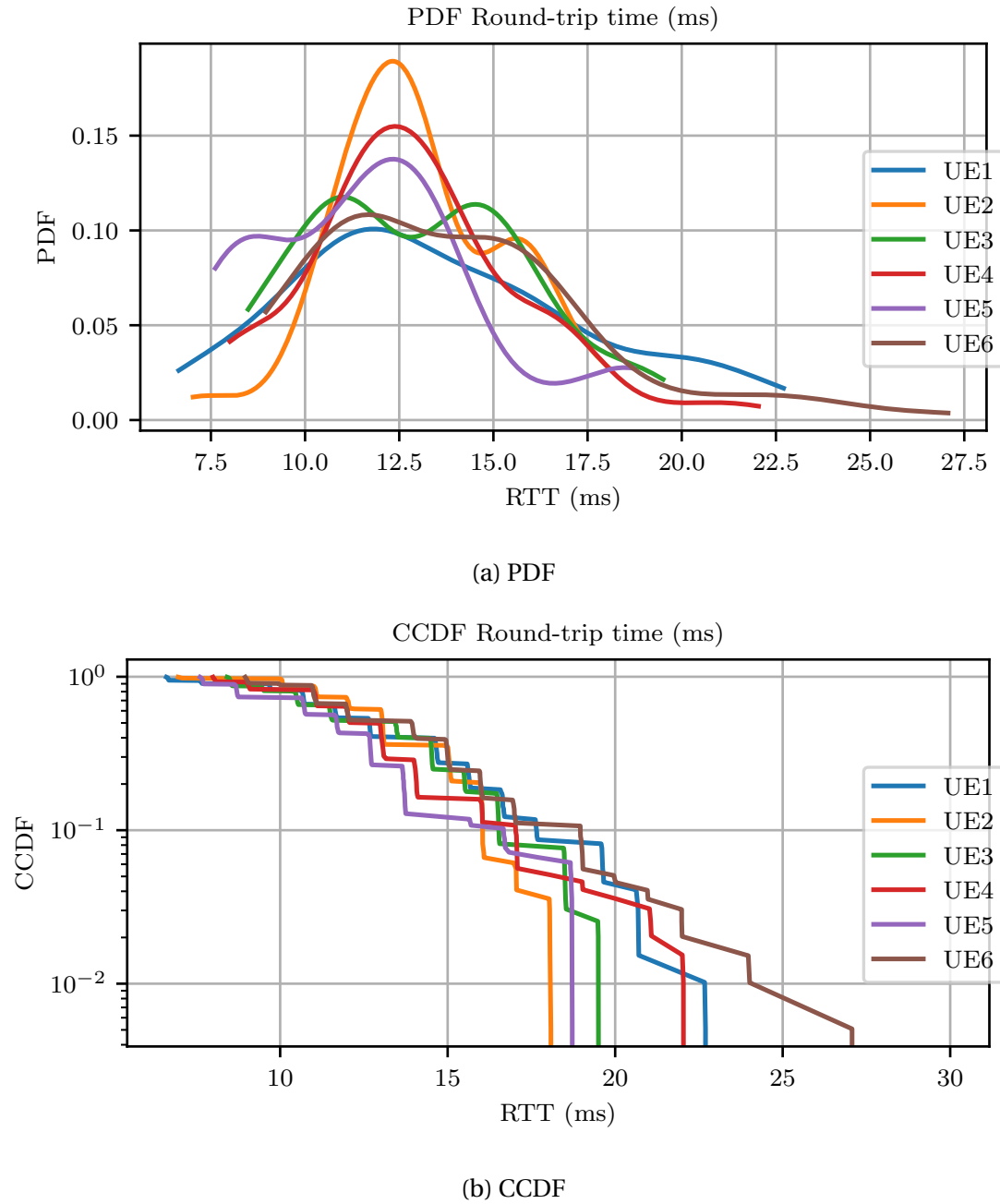


Figure 7: RTT measurements

topics they are interested in.

MQTT is designed to optimize communication in resource-constrained environments. Its small packet size and minimal protocol overhead help reduce bandwidth consumption and power usage, which is crucial for **IoT** devices that often run on battery power or limited resources. Additionally, **MQTT** supports long-lived connections, which can reduce the need for frequent reconnections, improving both performance and reliability.

MQTT provides three levels of **quality of service (QoS)** to ensure reliable message delivery, depending on the needs of the application:

Table 5: MQTT QoS

QoS	Meaning
0	At most once
1	At least once
2	Exactly once

QoS 0 (At most once): The message is delivered once, with no acknowledgment from the receiver. This is the fastest mode, but messages may be lost if the network fails. It's suitable for applications where occasional data loss is acceptable, such as sensor data that is frequently updated.

QoS 1 (At least once): The message is delivered at least once, with an acknowledgment required from the receiver. This mode ensures the message reaches its destination, but duplicates may occur if the acknowledgment is lost and the message is resent. It balances reliability and performance.

QoS 2 (Exactly once): The message is guaranteed to be delivered exactly once, through a four-step handshake process. This mode is the most reliable but also the slowest, making it suitable for critical applications where data duplication or loss cannot be tolerated.

These **QoSs** levels allow **MQTT** to provide a flexible and efficient communication mechanism, tailoring the level of reliability and overhead based on the specific use case. This versatility, combined with its lightweight nature, has made **MQTT** a popular choice for **IoT** applications, smart home systems, and other environments where real-time, reliable communication is needed.

4.1.2 Data flows

Two separate data flows are used in the demonstration. The main data flow is used to control the robots, **AMR** and **Cobot**, and maintain coordination between them. As shown in Fig. 8 the communication between **AMR**, the controller on the edge server and the **Cobot** robot, is established over **MQTT** protocol. The **MQTT** broker is hosted on the edge server and each **UE** implements the **MQTT** client to subscribe

to specific topics. With the usage of [ARCL](#), the local computer (Raspberry Pi/Up-Board) on the [AMR](#) can acquire the location and monitoring data from the [AMR](#) every 100ms. At the same or even higher rate, the local computer acquires radio parameters from the Quectel module. Data from both sources are sent over the [MQTT](#) to the controller service. The controller service is a Linux service that processes each received packet from [AMR UE](#) and implements logic to calculate the position and state of [AMR](#) in relation to the Cobot robot. On specific, locations and headings, the controller sends commands to the Raspberry Pi computer to issue [ARCL](#) commands over the local LAN network to the Cobot. In the same way, the status reports from the Cobot robot are sent to the controller resulting in a new set of commands for the [AMR](#). Additionally, the data received at the controller is used for the visualization of [AMR](#) movement and radio conditions. Visualization also includes Iperf [UL](#) and [DL](#) measurements, as well as [UL](#), [DL](#) one-way delay and round trip delay obtained with Irtt tool.

A second data flow is used for the video streaming from [AMR](#) cameras and it is not based on [MQTT](#).

4.1.3 Video streaming

For the purpose of the demonstration and by following the requirements form D2.1, the [AMR](#) was equipped with four cameras. Each camera is capable of streaming a video with maximum resolution of 3840x2160 pixels (4K video) at 60fps (frames per second). The streaming was established with the GStreamer multimedia framework. The host device (Raspberry Pi/UpBoard) mounted on the [AMR](#) was executing a GStreamer server/sender pipeline for each camera, while the edge server on the network side of 5G system was running four GStreamer client/receiver pipelines. Testing results showed smooth streaming of FullHD video (resolution 1920x1080 pixels) at 60fps. Streaming higher resolutions with the same frame rate resulted in a poor and laggy streaming experience. However, by inspecting the data [TP](#) and logs from GStreamer, it was concluded that the bottleneck was not the network but rather the processing of GStreamer pipelines. The generated [TP](#) of 35 *Mbps* was significantly lower than the maximum [UL TP](#) measured in the testing scenarios with the Iperf tool.

5 Conclusion

The 5G demonstrator and throughput measurements presented in this document illustrate the 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 in chal-

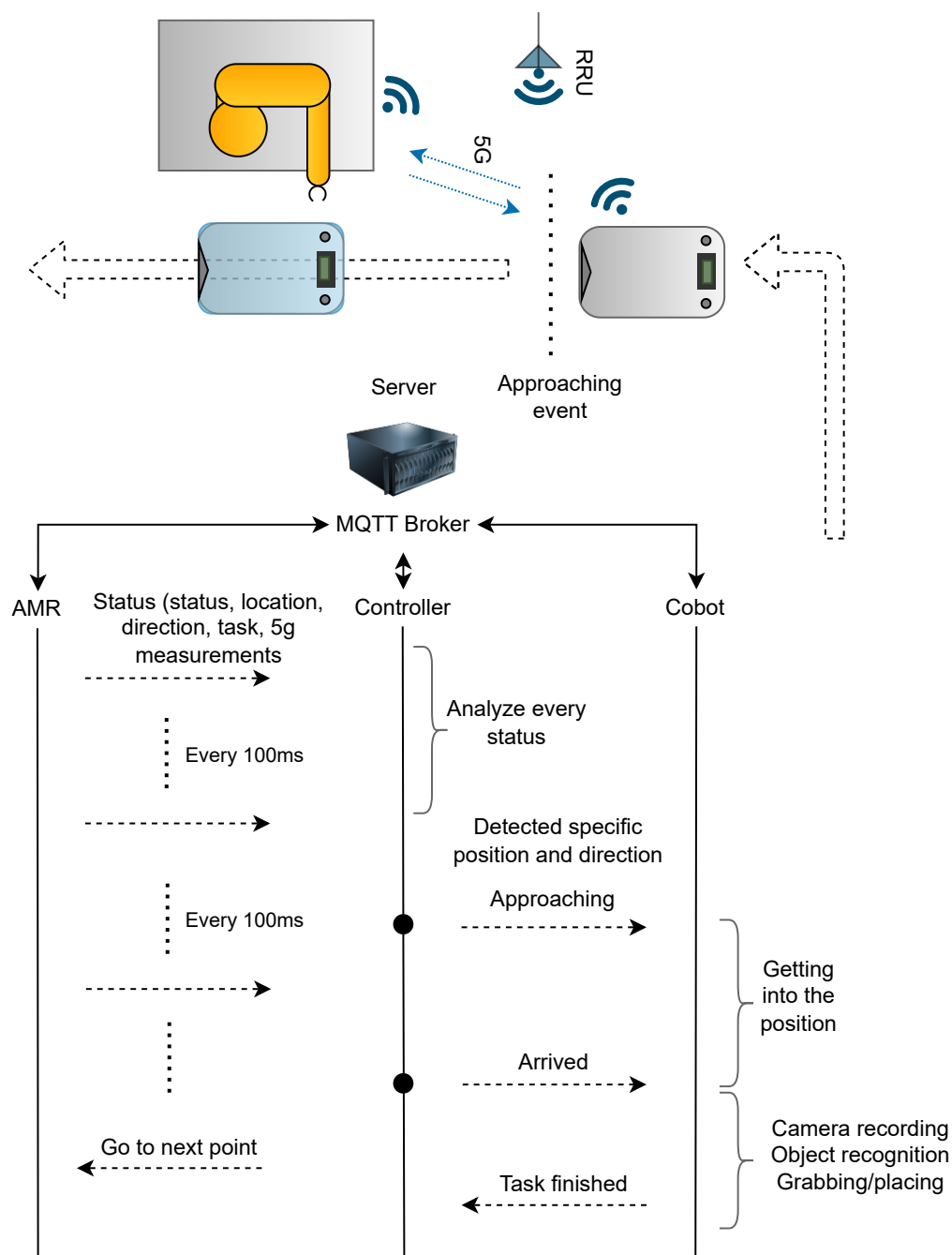


Figure 8: Robots interaction over MQTT

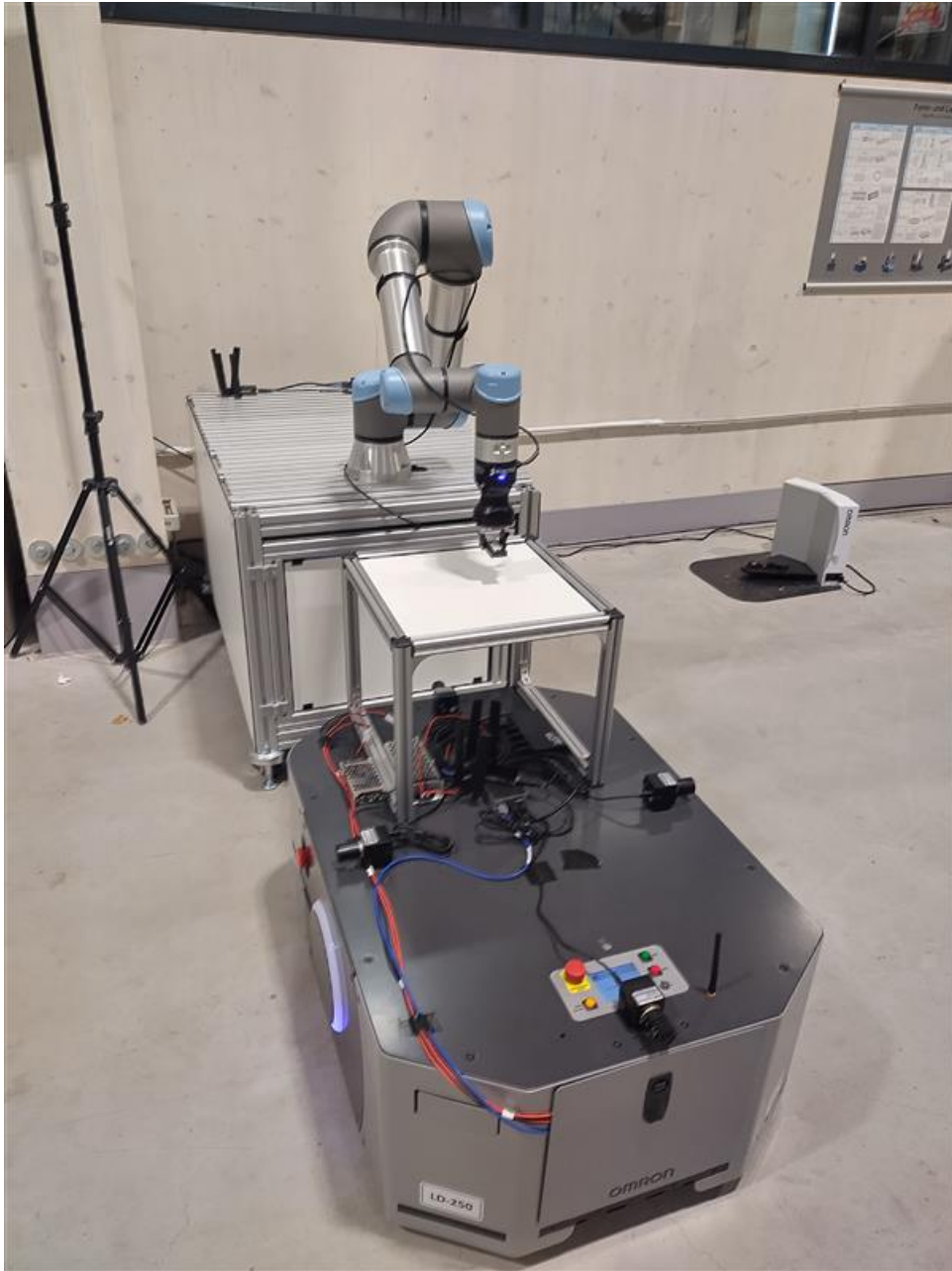


Figure 9: Demonstrator

lenging industrial scenarios characterized by interference and complex physical layouts. These capabilities are crucial for real-time monitoring and seamless automation.

The demonstrator serves as a tangible proof of concept, demonstrating how 5G can be leveraged to optimize industrial operations, improve safety, and unlock new possibilities for innovation. By validating performance metrics under real-world conditions, the findings provide valuable insights for both researchers and industry stakeholders, highlighting areas for further development and refinement. Ultimately, this work underscores the transformative potential of 5G as a foundational technology for future-ready industrial systems, paving the way for smarter, more efficient, and scalable operations.

Acronyms

5GS 5G system. [6](#)

AMR Autonomous Mobile Robot. [4](#), [5](#), [10](#), [14](#), [15](#)

ARCL Advanced Robotics Command Language. [4](#), [15](#)

COTS Commercial Of The Shelf. [4](#)

DL downlink. [6](#), [9](#), [10](#), [15](#)

IoT internet-of-things. [12–14](#)

IRTT Isochronous Round-Trip Tester. [10](#)

KPI Key Performance Indicator. [5](#), [10](#)

MQTT Message Queuing Telemetry Transport. [11–15](#)

QoS quality of service. [14](#)

RAN radio access network. [3](#)

RRU remote radio unit. *Glossary:* [RRU](#)

RTT round trip time. [5](#), [10](#)

SINR Signal to Interference plus Noise Ratio. [5–7](#)

TDD time division duplex. [6](#), [10](#)

TP Throughput. [5](#), [6](#), [9](#), [10](#), [15](#)

TRP Transmission and Reception Point. [5](#)

UE user equipment. [4–7](#), [9](#), [10](#), [14](#), [15](#)

UL uplink. [5](#), [9](#), [10](#), [15](#)

UR5 Universal Robot 5. [4](#), [5](#), [10](#)

USB Universal Serial Bus. [4](#), [5](#)

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