Deliverable D2.3

VALIDATION OF 5G CAPABILITIES FOR INDUSTRIAL ROBOTICS

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Short abstract:	This deliverable describes the validation scenarios defined for the use cases in the 5G-based testbed for industrial robotics at the Kista trial site: vision-assisted robot collaboration, real-time human-robot interaction, and advanced visualization of robot status. It also presents test results from use case validations, network performance characterization, encountered issues, and lessons learnt.

Keywords:	Lead-through teaching of robot arm motion, mobile robot navigation, machine vision, vision-assisted mobile robot docking, vision-assisted execution of robot pick-and-place, augmented reality visualization, 5G system, mmWave radio, edge cloud

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Executive summary

This report is the third and final deliverable for 5G-based testbed at the Kista trial site and validation trials for 5G-enhanced industrial robotics of the 5G-SMART project. The report describes the validation scenarios and achieved test results for the three use cases implemented, deployed, and validated at the Ericsson smart factory in Kista, Stockholm: *5G-connected robots and their collaboration*, *Vision-supported real-time human-robot interaction,* and *Advanced visualization for the factory floor*.

We first briefly introduce the use cases and present the general methodology adopted to validate and evaluate the use cases. Next, we introduce the industry goals for each use case to determine the impact of using 5G network technology. Network characteristics are evaluated in detail, in terms of throughput, coverage, and latency, for the millimeter (mm) wave 5G network.

All use cases are briefly summarized (for more detail, we refer to 5G-SMART Deliverables D2.1 [5GS20-D21] and D2.2 [5GS22-D22]). The industry goals for each use case are then discussed, followed by an introduction to the Key Performance Indicators (KPIs) to evaluate the defined industry goals. Validation scenarios are then presented along with their validation results, discussions, and conclusions.

Finally, we conclude that 5G supports the implemented use cases, allowing to execute high-level motion control for mobile robot platform and stationary robot arm from a close-proximity edge cloud server. This is despite the fact that the functional design and implementation of the industrial robotics use cases were only prototyped, and the 5G network was designed for MBB services, without functionality for, e.g., bounded latency. Further development of communications network functionality, ecosystem, and robotics applications has been identified.

Contents

1 Introduction

1.1 Objective of the report

This report aims to introduce the validation scenarios defined for the use cases in the 5G-based testbed for industrial robotics at the Kista trial site: vision-assisted robot collaboration, real-time human-robot interaction, and advanced visualization of robot status. Furthermore, the report introduces the industry goals set for these use cases and describes the validation KPIs for various validation scenarios. It also presents test results from use case validations, network performance characterization, encountered issues, and lessons learnt.

1.2 Relation to other documents in 5G-SMART

This report takes input from the previously published 5G-SMART Deliverables D1.1 [5GS20-D11], D2.1 [5GS20-D21], and D2.2 [5GS22-D22]. Deliverable D1.1 describes the "storyline" for the three use cases from the industrial robotics domain trialed at the Kista site and their general functional and non-functional requirements. The three use cases are considered as representative examples of smart manufacturing. They encompass an autonomous, vision-assisted robot collaboration, real-time human-robot interaction for robot commissioning, and AR-based access to industrial robots and their operational status. Deliverable D2.1 specifies the overall design for the 5G-based testbed, also defining main robotics-related functional blocks and their communication interactions. D2.2 presents the industrial robotics use cases' main design and implementation specifics. This includes a functional view of the testbed components, focusing on the needed aspects of robot control and supervision, and data-exchange interactions among the related functional blocks. The prototype of each use case is described, also documenting how the associated software is used in the 5G-based testbed. D2.2 also outlines the 5G network solution on the trial site, including how its mm wave radio connectivity is integrated into the robotics-related equipment.

1.3 Structure of the report

The rest of this document is structured as follows. Section 2 summarizes use cases, while Section 3 introduces the evaluation methodology and criteria. Section 4 explains the network characteristics of the 5G connectivity solution. Sections 5-9 introduce the different use cases, their respective industry goals, and validation results. For each use case, the impact of the connectivity network is discussed. Section 10 summarizes the overall findings and learnings and draws some conclusions.

2 Use case introduction

Industrial robots are envisioned to play an important role in manufacturing as the Industry 4.0 ecosystem evolves. As a result, industrial robots and other machines will need to operate more autonomously and allow human workers to interact with them in new ways [EGG+20]. One important paradigm shift is to enable humans to work side-by-side with robots in a safe way. This will remove the need for fencing in robots and greatly improve the shopfloor utilization.

The 5G-SMART project implemented and deployed a testbed for 5G-enhanced industrial robotics to evaluate these new capabilities. The testbed is used to evaluate two important technical trends that may disrupt the way industrial robots are deployed and used, namely 5G wireless communication and edge-cloud computing.

The following use cases have been evaluated:

- Use case 1 on 5G-connected robots and their collaboration
- Use case 2 on vision-supported real-time human-robot interaction
- Use case 3 on advanced visualization for the factory floor

The selected use cases showcase several advantages of 5G connected robots: The hardware of industrial robots can be simplified, become cheaper, and occupy less space on the shopfloor. This is achieved by moving control functionality into an edge-cloud – a local computing infrastructure located, e.g., in a control room of the factory, rather than in today's design where the control is placed in an embedded processor on the industry robot or in dedicated control hardware that is in the proximity of the robot and connected to it via cable. By removing cabling, the flexibility when redesigning process chains on the shopfloor is improved. Wireless connectivity allows for increasing the number of mobile robots on the shopfloor, taking over more tasks in a flexible production process. A key component of the testbed is the vision system used to identify objects and support the mobile robot navigation. A functional overview of the testbed is shown in Figure 1.

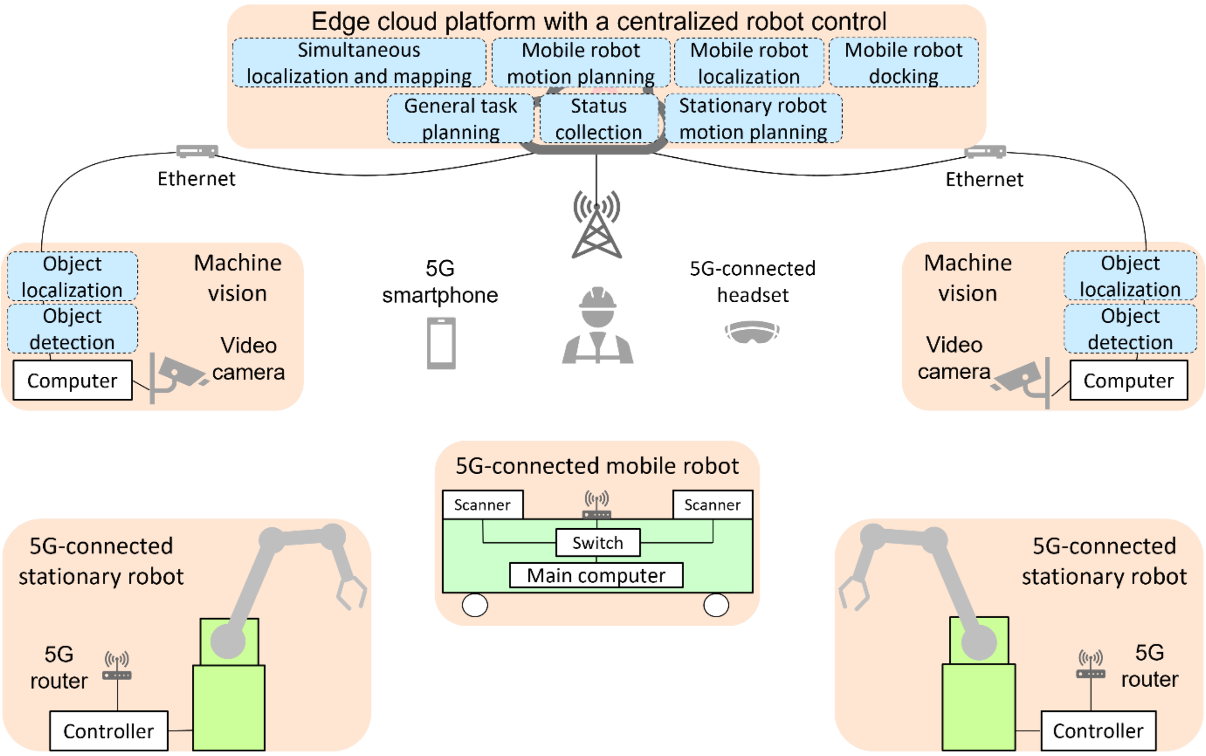

Figure 1: Functional overview of the testbed

To better understand the different steps used in the testbed, an overview of the workflow is shown in Figure 2.

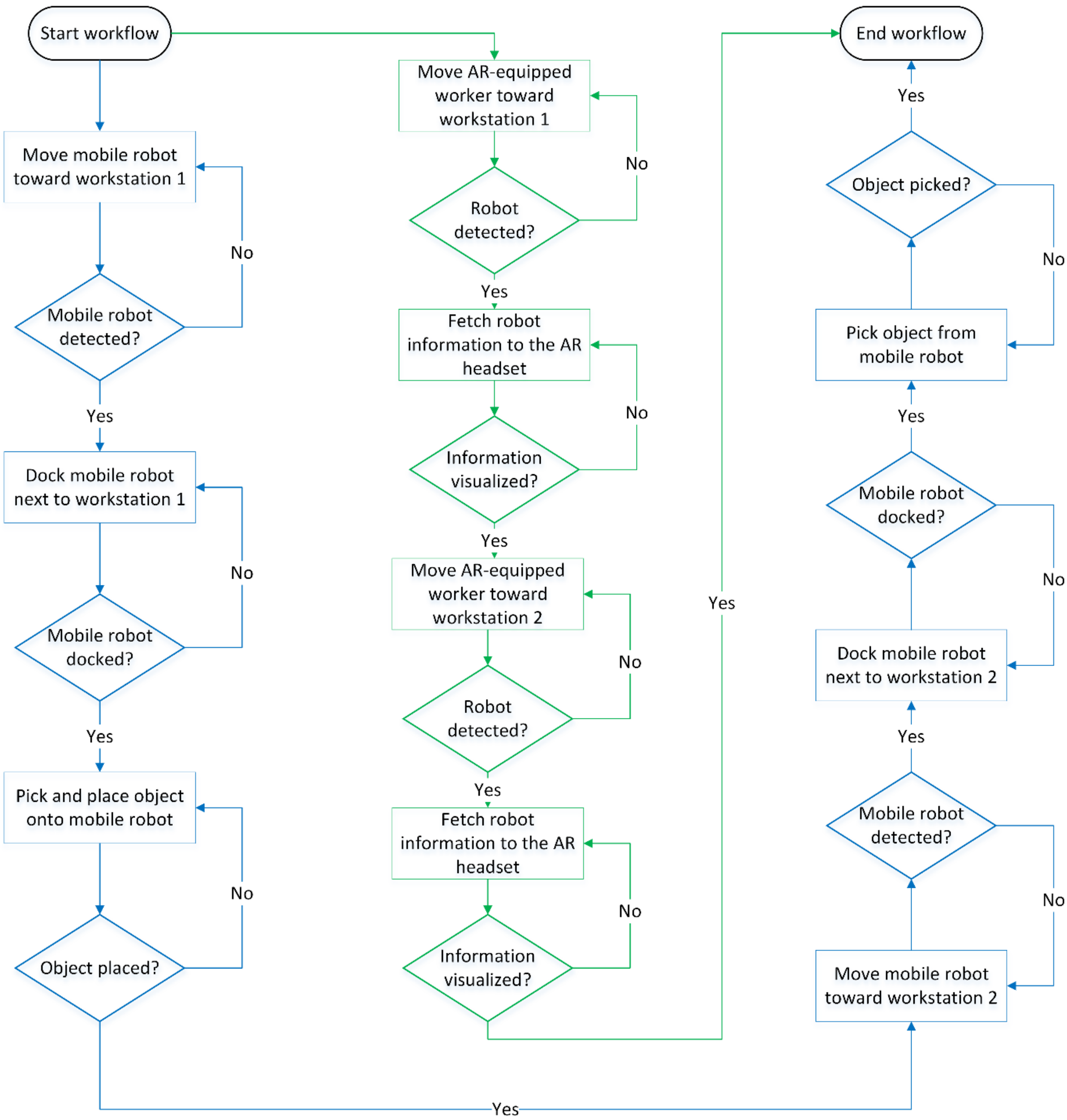

Figure 2: A common workflow for the testbed components

The workflow shown in Figure 2 consists of two independent sequences of operations: mobile robot transfer of an object between production workstations with stationary robots and inspection of stationary robot status by a human worker equipped with an AR headset (noted in the figure with the blue and green coloring, respectively). More detailed information on the implementation aspects can be found in [5GS20-D21].

2.1 Use case 1: 5G-connected robots and their collaboration

This use case focuses on a very common task in manufacturing, namely the scenario of autonomously transferring materials between production lines. The task has been realized by relying on the collaboration between different types of robots. The project has implemented a setup where a mobile robot transfers an object, navigating the mobile robot between workstations with stationary robots and having the stationary robots grasp and move the object. Two distinctive features of the use case instantiation are machine vision-assisted docking of the mobile robot to a precise location next to the robot workstation and vision-assisted execution of the object pick-and-place operation by each stationary robot.

2.2 Use case 2: Vision-supported real-time human-robot interaction

Workers in a factory need to have safe and efficient ways of interacting with machines and robots, and in this use case, we explored and implemented a novel approach to robot programming. The use case is instantiated by a human worker (e.g., commissioning engineer) programming a stationary robot to autonomously execute the object pick-and-place operation through the means of demonstration. Instead of writing a robot program, the worker mimics grasping and moving the object through the application on a mobile device, which the stationary robot then executes. In order to get good application performance a 5G smart phone was used in this use case[1].

The robot needs to learn two tasks to perform the operation: trajectory generation and object pick/drop. In the trajectory generation task, the human worker manipulates the robot by contactless lead-through using the smartphone. The pick/drop task is taught by opening and closing the robot gripper.

2.3 Use case 3: Advanced visualization for the factory floor

This use case is characterized by using AR-based means to visualize operational robot information efficiently. It also illustrates how novel technologies can be exploited to create new ways for human workers to access factory-floor machinery. Like the other two use cases, machine vision support detects and distinguishes between different objects. In this case, information retrieval is started by reading a marker tag located near the robot.

[1] The procedure can be seen in this video: https://www.youtube.com/watch?v=MBbaPKw27QU.

3 Demonstration, validation, and evaluation of 5G capabilities

The activities described in this document target the evaluation of 5G capabilities, such as connectivity support, to validate their conformance to the requirements of the testbed at the Kista trial site.

3.1 Validation and evaluation methodology

Methodologies to validate and evaluate the different use cases concerning the industry goals are described for each use case section.

The common methodology for all trialed use cases consists of the following steps:

1. Use case characterization and identification of relevant industry goals
2. Radio planning and 5G deployment at the trial site
3. Use case implementation and use case integration
4. Identification of validation scenarios and relevant KPIs for evaluation
5. Validation, evaluation, and demonstration

Detailed information on use case characterization (step 1) and steps 2-3 can be found in [5GS20-D11] and [5GS20-D22]. The focus of this report is on steps 4 and 5 concerning the relevant industry goals, which will be further explained in the following.

3.2 Industry goals

Industry KPIs are essential metrics to evaluate business success. In the 5G-SMART project, several KPIs or industry goals have been identified [5GS20-D12]. These goals are productivity, quality, mobility, flexibility, safety, and sustainability, as seen in Figure 3.

Figure 3: Industry goals for the use cases in the 5G-based testbed for industrial robotics

In Table 1, the different industry goals are shown for each use case being evaluated. Note that not all industry goals are considered relevant for each use case.

Use cases	Industry goals					
	Flexibility	Mobility	Productivity	Quality	Safety	Sustainability
Use Case 1	X	X	X	X	X	X
Use Case 2	X	X		X	X	
Use Case 3	X		X	X		X

Table 1: Industry goals per use case

3.2.1 Flexibility

Improving flexibility in production is an important industry goal. This enables a factory or production facility to adapt more easily to changes in demand. Shorter production cycles and a higher need for customization are key drivers for this need. Mobile robots transport material between workstations and allow for easier re-configuration on the factory floor. A high-performance wireless 5G network is key to introducing mobile robots while maintaining high productivity.

5G can also enable novel and more flexible ways for human workers to interact with industrial robots. This is explored both in use case 2, where the robot is programmed using a 5G smartphone, and in use case 3, where the human worker can visualize robot information using a 5G-enabled AR headset.

3.2.2 Mobility

Mobility is another industry goal that is targeted by all three use cases. 5G technology enables mobile robots to transport material from different factory areas. However, the technology is also used to allow workers to perform essential tasks while moving around in the production area. Getting a holistic view of the factory floor and identifying potential issues is extremely valuable in production. Having the possibility to move around while obtaining information using an AR headset freely is very beneficial for this purpose.

3.2.3 Productivity

Optimizing productivity is a crucial challenge in all production. The 5G testbed explored in use case 1 includes both stationary and mobile robots. This setup enables a 24/7 operation, including both transportation and pick-and-place operations. A mobile robot can also easily be re-assigned to different work areas in the factory, depending on the current need. This reduces the risk of material getting stuck along a production chain.

Off-loading robot control software to the 5G Edge can also improve productivity since path planning optimization can be performed in a high computing node resulting in faster or better optimized paths. This becomes even more important when multiple robots are being deployed.

A critical aspect of productivity is to optimize production across the entire production chain. Having a 5G-enabled AR headset that can visualize factory floor information in real-time is beneficial for making accurate decisions. For example, the AR visualization enables an operator to more easily get a holistic view on the production and more quickly identify any disturbances in the process.

3.2.4 Quality

Quality is an industry goal that encompasses many things. For use case 1, the goal is to provide high-quality robot operation. The mobile robot and robot arms movement should be consistent across operation cycles. Furthermore, jerkiness or sudden stops must be avoided. This requires the 5G communication network to perform well in latency, jitter, and reliability.

In the use case where the human worker visualizes robot information, quality is more related to the quality of the production process. Identifying and remedying potential problems with a robot early is essential to ensure good quality production.

3.2.5 Safety

Safety is a critical industry goal for any production facility. Mobile robots will move around the production area, and they must not hit any humans or machinery. Different safety measures are typically implemented onboard the robots to prevent this. However, utilizing a high-performance 5G network and edge technology can enable new safety concepts. Investigating the breaking distance of the mobile robot is explored for use case 1.

For use case 2, safety can be improved since the technician is performing the movement of the robot arm using a 5G phone. This minimizes the risk of the robot arm hitting any object nearby.

Safety can also be improved by having a 5G-enabled AR headset to visualize factory floor information in real-time. This enables a human worker to identify any issues quickly and prevent a potentially dangerous situation.

3.2.6 Sustainability

Sustainability is another important industry goal where minimizing losses and waste is key. Off-loading control functionality to the edge will reduce the hardware complexity and cost of the robots. As a result, the power consumption of the robots will also decrease. Software maintenance will also become more efficient, e.g., by simplifying remote software updates reducing the need for travel.

Minimizing losses can be achieved by early identifying issues causing the robot not to perform optimally. Use case 3 explores if a 5G-enabled AR headset can be used to visualize information about the robot's performance more easily.

4 Network characteristics at the trial site

In this section, the network characteristics at the trial site are explained. Network solution and floorplan are also detailed in Deliverable D2.1 [5GS20-D21]. This report focuses on the evaluated throughput, coverage, and latency performance.

Performance of the connectivity network was evaluated before executing the different use cases to ensure that the performance and capacity in the network, considering the available spectrum resources, were sufficient. Uplink (communication from devices to the network side) and downlink (communication from the network to the device/UE side) were evaluated separately. Latency performance for different packet sizes and packet arrival interval times was evaluated using a packet generator transmitting these packets over the air and measuring the end-to-end packet delay. Bit rate performance, or cell capacity, was measured using a packet generator to generate traffic to maximize the resource utilization in the cell and measure the resulting bit rate, or throughput, in relation to the radio quality at a given position in the factory environment.

4.1 5G network at Kista trial site

The 5G network at the Kista trial site is deployed on mmWave spectrum, also referred to as high band (HB) or frequency range 2 (FR2). One reason for such a design decision is the belief that HB could be an interesting option for indoor industrial deployments and connectivity solutions. Its short wavelength does not penetrate walls very well, so the network could be kept well isolated, and the available bandwidth on these frequencies is relatively wide to support future applications with (very) high requirements on throughput and capacity. The selection of HB spectrum suggests the networking characterization measurements are rather unique and important.

The network deployed is a so-called 5G non-standalone (NSA) solution. The solution requires a 4G LTE connectivity leg for the control plane communication, while the user plane communication, or data traffic, is primarily sent over the 5G NR leg.

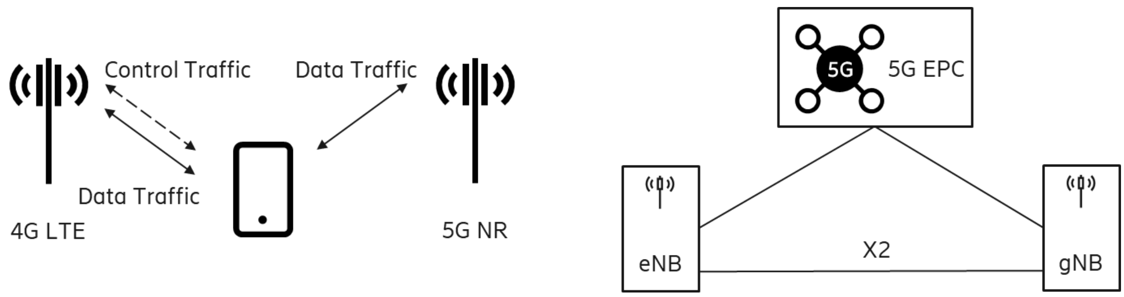

Figure 4: Illustration of the 5G Non-standalone architecture (source: Ericsson)

In summary, the following characteristics are important for the resulting network characteristics.

- Frequency band: 28 GHz
- Radio bandwidth: 200 MHz (2 Component Carriers, 100 MHz each)
- TDD frame structure: DDDDU (4 slots downlink and 1 slot uplink)
- Sub-carrier spacing (SCS): 120 kHz
    - Transmission time interval (TTI): 125 µs

- TDD pattern cycle time: 0.625 ms (5 * 125 µs)

Please refer to [5GS20-D21] and [5GS20-D22] for further details of the 5G connectivity solution.

4.2 Network characterization

The network in place at the trial site was characterized by two main user data performance metrics: throughput and one-way latency. Two different measurement methodologies were employed to ascertain these two metrics. In all cases, the network was unloaded, i.e., the mobile devices involved in the measurements were the only contributors to radio resource usage and traffic generated in the entire network. This would then give a 'best-case' result or upper limit of what performance the network could provide.

Throughput characterization

For throughput measurements, a custom-built cart with measurement equipment was used to represent a mobile device, and measurements were carried out continuously as the cart was moved to cover the entire floorspace where the 5G-SMART use case would run.

Test traffic was exchanged between a server on the edge of the 5G Core Network and the UE under test on the cart. The *iperf* application running on both these devices was used to generate a high rate of UDP traffic in the downlink and uplink directions simultaneously, stressing the capacity limits of the connection. Simultaneously, the Qualcomm QXDM software running on the UE recorded the actual data rate flowing through the modem, reflecting the maximum channel throughput.

Finally, as the cart was moved, custom-built onboard positioning equipment correlated the measured throughput with the cart's physical position within the floorspace to produce a throughput or coverage heatmap of the 5G-SMART trial site.

Figure 5 below shows the setup of the measurement cart, and Figure 6 shows the network diagram of the configuration used for the throughput measurements.

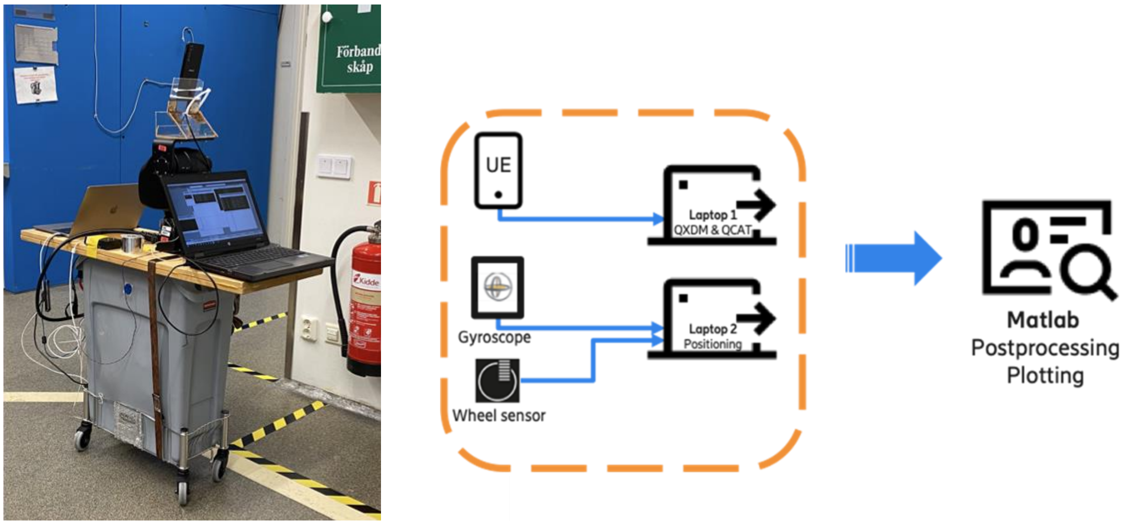

Figure 5 Throughput measurement cart setup

Figure 6 Throughput characteristics network diagram

Once it was ascertained that there was good and consistent radio coverage over the entire test floorspace, which would not contribute to the latency variations, one-way latency measurements were carried out only at a single stationary point at the center of the room.

Latency characterization

One-way latency measurements were made using an in-house custom-built traffic generation application capable of producing unidirectional traffic streams with configurable characteristics, e.g., packet sizes and inter-packet times. These UDP-based packets were exchanged between a server at the edge of the 5G core network and a laptop connected to the UE/modem under test.

By employing an Ethernet switch with port-mirroring capabilities and judicious choice of networking connectivity, it was possible for the server node equipped with a second wired Ethernet networking interface to also tap into packets seen at the UE end. In this way, the server was able to timestamp a packet at both the UE end and the server's end and subsequently determine the one-way latency of this packet as it traveled between these two endpoints. With this method, one-way latency calculations of traffic were made, both in the uplink and downlink directions through the 5G network.

Figure 7 shows the network diagram used to determine one-way latency.

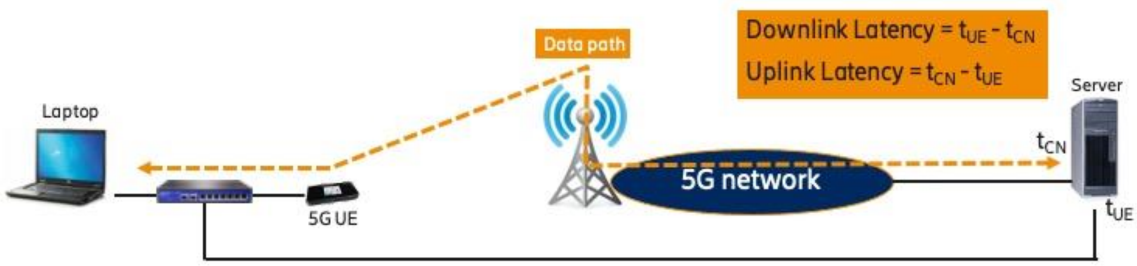

Figure 7 Latency characteristics network diagram

4.2.1 Throughput characteristics results

Maximum bit rate, or throughput, was measured across the shopfloor in the test area. The signal strength varies depending on the distance between the base station and the device, resulting in varying bit rates. It should be noted that the evaluation was made with a single 100 MHz carrier, and the resulting throughput is very close to the theoretical maximum (due to the short distance between base station radio and UE). For the use case validations, the complete available 200MHz bandwidth was used (two so-called component carriers (CC) of 100MHz each), and in this case, the capacity is doubled (as well as the throughput performance if the UE supports aggregating CCs). The throughput characteristics provide insights regarding the cell capacity and how many devices could be connected in a single cell.

So-called coverage heatmaps were created to understand the throughput variation over the shop floor. As shown in Figure 8, the downlink (DL) coverage is excellent over the entire test area, with some variations in signal strength, but due to the generally good signal strength, the variation in throughput is minor. The blue dots indicate that the measured throughput is very close to the theoretical maximum over the test area.

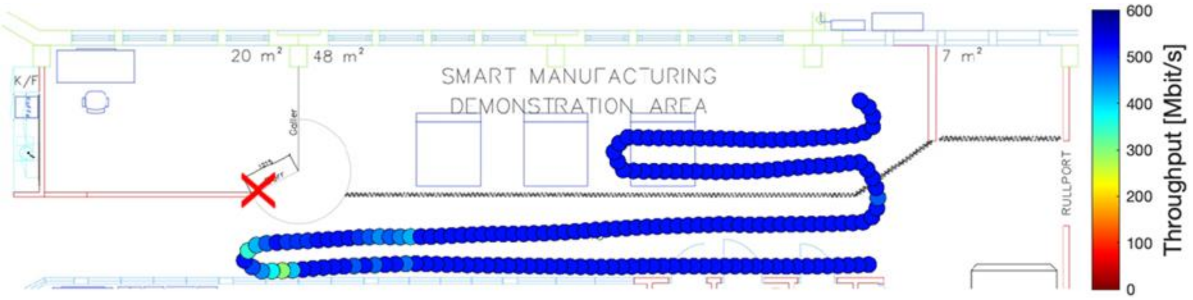

Figure 8 Coverage heatmap over the test area, illustrated by DL throughput performance with UE A. The red cross indicates the location of the base station antenna.

The same test was performed with a different UE with a different antenna configuration, as shown in Figure 9. The walk test was repeated in two directions, clockwise (upper part of the figure) and counterclockwise (lower), with the result that different sides of the UE were directed towards the base station radio at different locations. The results clearly illustrate that the UE B used in the second test (Figure 9) has antenna characteristics that are much more sensitive to the orientation of the UE than the UE A that was used in the first test (Figure 8). Generally, a UE with good antenna characteristics in all directions (like UE A) is most suitable for use cases involving mobility, while a UE with more directional antenna characteristics (like UE B) may still be suitable for e.g., stationary use cases, where the UE can be positioned to perform at its best.

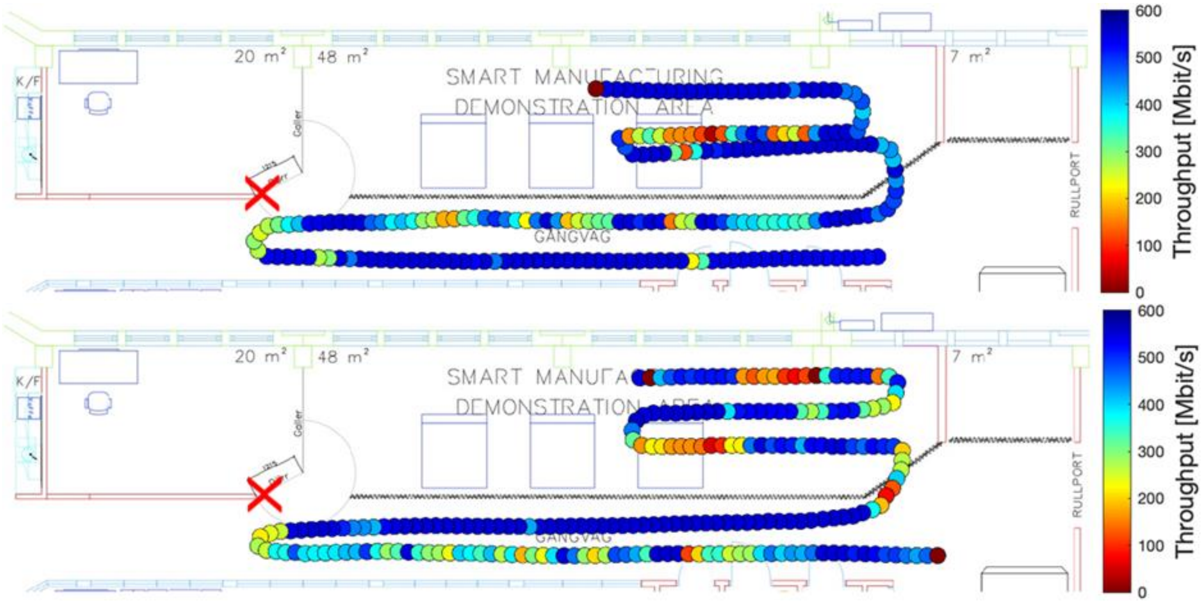

Figure 9 Coverage heatmaps over the test area, illustrated by DL throughput performance with UE B. In this case, throughput performance is substantially dependent on UE orientation. The red cross indicates the location of the base station antenna.

Coverage heatmaps for uplink (UL) throughput were also measured in the same test area for both UEs, as shown in Figure 10. Also, in this case, the measured peak throughput is at the theoretical maximum level. However, in UL, we can see rather large differences between UE A and UE B. The same behavior with orientation-dependent performance observed in DL is also seen for UL.

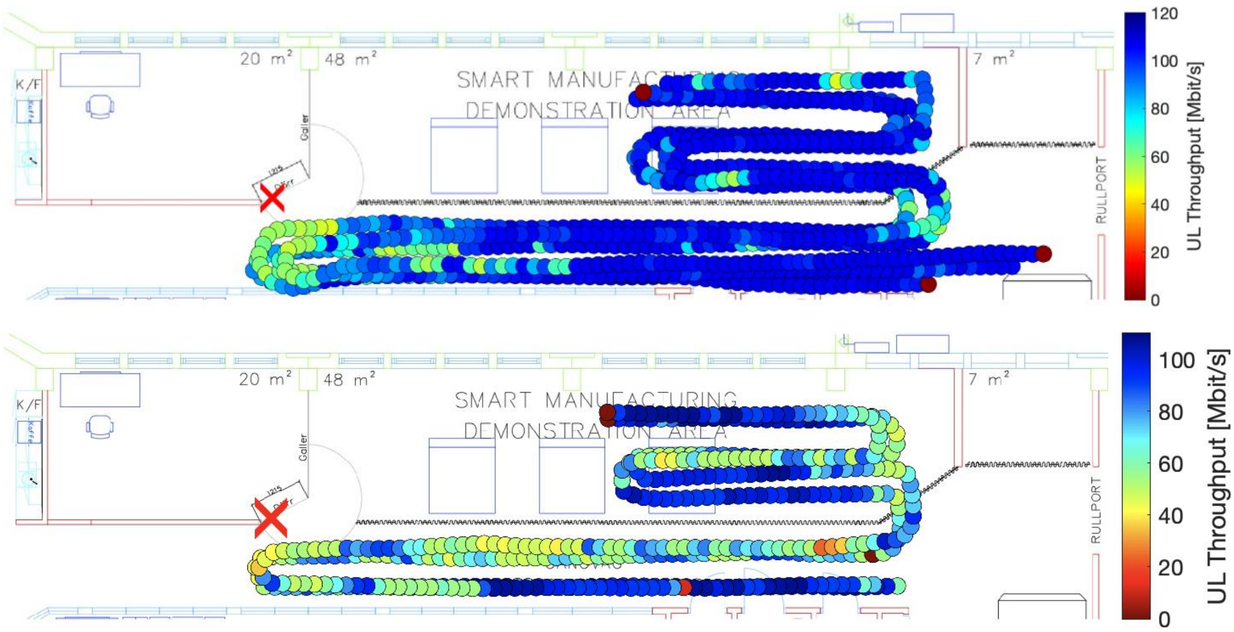

Figure 10 Coverage heatmaps over the test area, illustrated by UL throughput performance for UE A (top) and UE B (bottom). Similar differences in throughput performance between UE A and UE B can be seen. The red cross indicates the location of the base station antenna.

We also note that the somewhat lower performance in the lower-left corner of the maps, close to the red cross in the figures above, for both UL and DL and both UEs, is because this area is outside the service sector of the base station antenna.

UL and DL throughput performance over the entire test area is summarized in Figure 11. As can be seen, the variations across the test area for UE B are significant. While almost 90% of the area results in DL throughput near the theoretical maximum for UE A, UE B provides this performance for less than 50% of the area. For UL throughput, the difference between UE A and UE B is, in fact, even more emphasized. While the UL throughput for UE A is close to the theoretical maximum for around 60% of the measurements/area, UE B reaches maximum throughput only for a few locations in the test area. The main reason for this is the difference in antenna configurations between the two UEs (with a more directional antenna configuration for UE B). That said, the UL throughput performance is better than 40Mbps in all the test area, including all effects of non-optimal UE orientation.

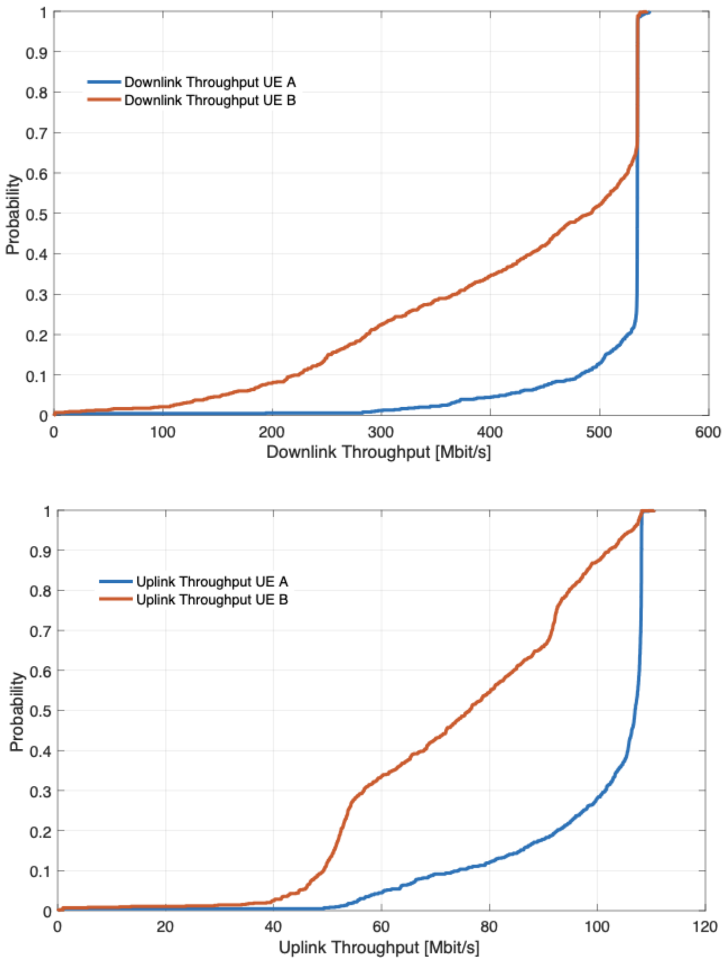

Figure 11 Throughput distributions over the test area for DL (top) and UL (bottom) for the two different UEs tested

4.2.2 Latency characteristics results

The latency measurements were performed separately for UL and DL latency since some principal differences between the two directions and some performance differences are expected. Furthermore, the measurements were performed for two different UEs to evaluate potential differences due to the impact of different UE implementations. Unfortunately, the measurement method, in combination with the design of the different UEs, did not support measuring UL latency separately for UE B. The following combinations of packet sizes and packet arrival intervals, deemed representative for the evaluated use cases and general industrial applications, were evaluated.

- Packet sizes: 100B, 512B, 1024B
- Packet interarrival times: 4 ms, 32 ms
- Directions: UL (UE A and UE B) and DL (UE A only)

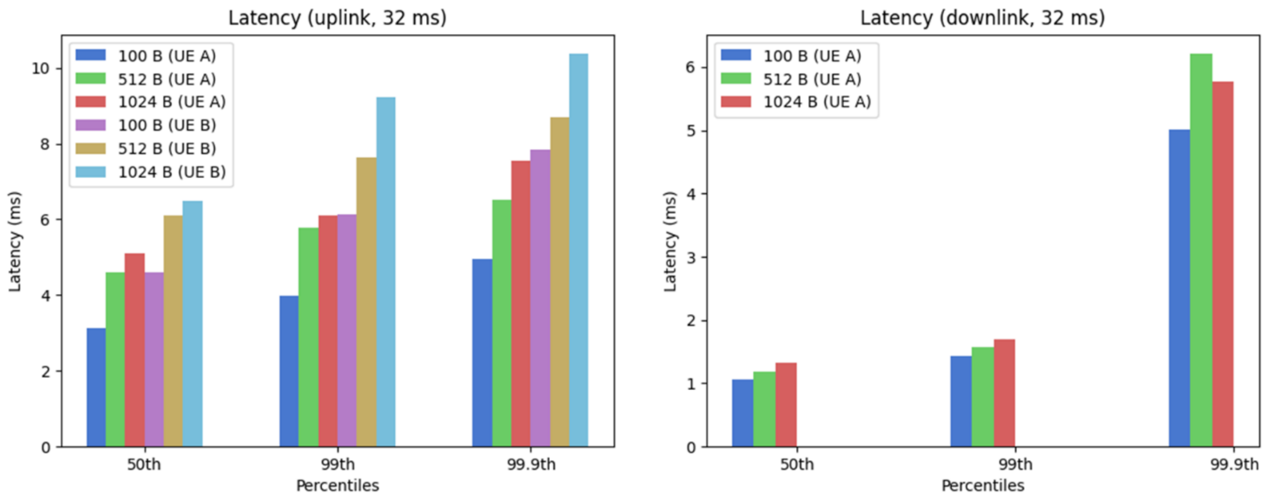

Figure 12 Latency measurement results – illustrating the differences due to varying packet sizes, for both UL and DL transmissions, with packet interarrival time of 32 ms

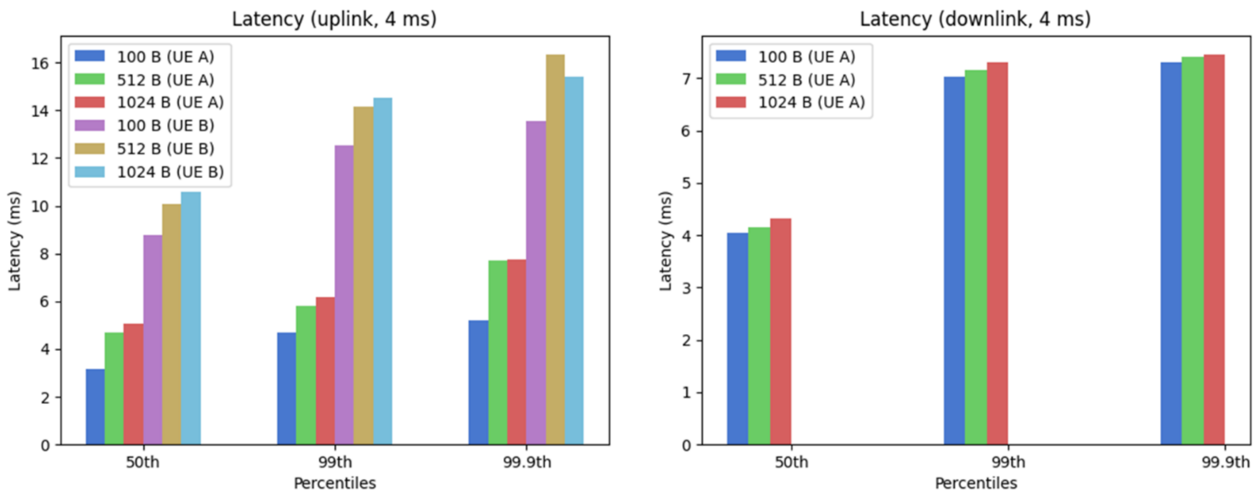

Figure 13 Latency measurement results – illustrating the differences due to varying packet sizes, for both UL and DL transmissions, with packet interarrival time of 4 ms

As shown in the above results, increasing packet size gives, as expected, a higher resulting packet delay. A possible reason for this is the need for using less robust coding to fit more payload bits in the transmission and the, thereby, slightly increased risk for HARQ re-transmission. The difference in DL is less prominent than for UL due to the network configuration with more resources allocated for DL. It can also be seen that the uplink delay is higher than the downlink delay, and the main reason for this is that the uplink is scheduled from the base station, on request from the UE. Furthermore, the TDD frame structure employed (4 slots downlink and 1 slot uplink) has fewer and more infrequent resources in UL, which also impacts the latency. Shorter inter-packet arrival time has limited impact on the UL latency performance for UE A, but still not as much impact as the varying packet sizes. The shorter packet interarrival time results in higher latency for the DL latency performance. A possible explanation for this is (counterintuitively) the more resources available. With a longer packet interarrival time, packets can be sent immediately, while with a shorter interval, the system has the opportunity to combine several incoming packets into simultaneous transmissions, thereby causing more delay. This behavior is not preferred or suitable for typical industrial applications but is beneficial for the resource utilization for typical MBB services, for which the current 5G system is primarily designed.

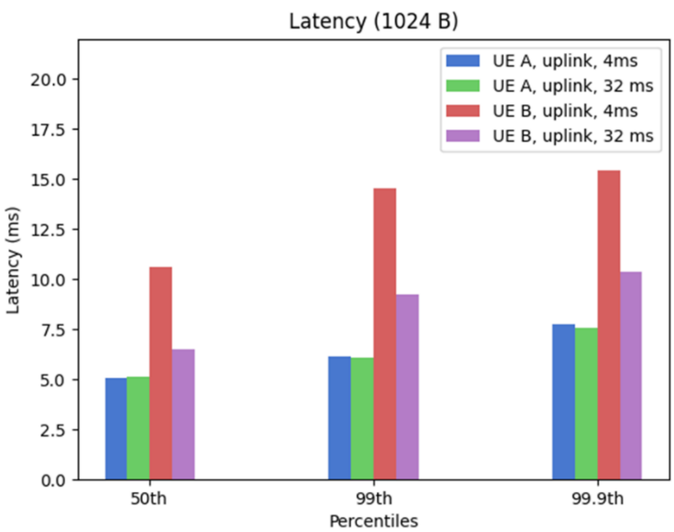

Figure 14 Comparison of the impact of different packet interarrival times (with fixed packet size, 1024B)

Figure 14 above compares different packet interarrival times for the largest packet size (1024B) for both UEs in UL. This plot clearly shows the limited difference in UL for UE A, while the performance difference for UE B is significant. The reason for the difference between the different UEs is unknown, but it is important to note that different UEs have significantly different performance, even if they, as in this case, are built on the same chipset. There are many design choices and implementation specifics that are not regulated in the 3GPP standard, so the performance may vary. The variation between UEs may be even more significant for throughput, where the difference in antenna solutions may have a large impact.

4.3 Conclusions, learnings and insights – Network characterization

The general conclusion is that the 5G network coverage is excellent, and the performance is very stable over the shopfloor. The network performance is expected to support all the use cases being validated at the Kista trial site.

Despite being built on the same chipset, UEs may differ significantly in performance due to technical implementations, particularly related to antenna configurations and impact on throughput. Both packet size and packet interarrival time impact the resulting latency performance. Based on practical measurements, similar behavior has also been reported in [AAB+22], where primarily operation on lower frequency bands was investigated (5G frequency band n78, 3.7GHz, also referred to as mid-band, MB or FR1).

For future 5G deployments in industrial environments, antenna configuration on the device should be carefully considered and planned in line with the network deployment.

5 Mobile robot navigation

5.1 Introduction

Mobile robots play a crucial role in factories and other production facilities, supporting transportation and handling of materials, they are necessary to automate manufacturing processes. Mobile robots may be assigned tasks like transferring production parts within a facility as well as sorting goods and other production items. There are different technical solutions for mobile robots, but unlike moving platforms which rely on, e.g., magnetic floor-stripes to follow a needed trajectory, we use an autonomous mobile robot (AMR) in use case 1 and use case 2. An AMR uses onboard sensors to perceive and dynamically adapt to its environment. This adaptation capability is crucial for a factory floor with, for instance, hundreds of such robots but also for the safety of human workers, who commonly share the floor and some tasks with robots. Navigation is the main component that plans the movement of mobile robots, including how to avoid collisions with dynamically appearing obstacles in their paths.

This section first puts mobile robot navigation in a wider industrial context by giving examples of how it is relevant to achieving industry goals. It then defines KPIs used to validate the feasibility of off-loading navigation from a mobile robot and executing it over 5G, then analyzes collected KPI measurements and presentation of key-related insights.

5.2 Industry goals

Mobile robots are essential to achieving industry goals of improving the flexibility and productivity of manufacturing processes. As an illustration, extra mobile robots can be added into a production workflow to shorten its execution cycle, or their roles can be changed to transport different types of material if customization of a production line needs to be performed. Flexibility is especially important to support mass customization, i.e., production for large markets which meets individual customer requirements. Navigation can govern the movement of a single or a group of AMRs (which, for example, share a common task). In the latter case, navigation can be realized as a centralized system that coordinates the mobile robots.

5.2.1 Mobility and safety

With this type of robot, mobility must inherently be supported across a whole factory floor. This is especially important for AMRs, which can be navigated along different possible paths on the floor. The variety in selecting an AMR path also needs to be carefully considered by navigation with respect to potential obstacles, which re-emphasizes safety in production facilities as a critical objective. While inter-connected industrial subsystems can coordinate their actions to avoid, e.g., an AMR hitting other moving machinery, human workers freely move in the same production facility. The safety of humans, thus, becomes a new challenge to solve.

5.2.2 Flexibility and productivity

A high-performance 5G network can be seen as an enabler for production facilities to increase their flexibility and productivity. 5G supports mobility of connected devices, and a cellular network based on the associated standards can be planned to accommodate communication ranges required even by large factories. This would allow AMRs to reach, for example, all production lines, robot cells, and storage space. Combining 5G with edge computing technologies can facilitate the realization of navigation off-loaded from mobile robots, which plans and controls paths for a group of AMRs such that chances for inter-collision are minimized. Having mobile robots in full operation also supports improving manufacturing output and productivity. A centralized view of the robot fleet further allows to make necessary adjustments and re-assign, in an automated fashion, certain AMRs to work in a different factory area. With 5G improving reliability and latency of cellular communication, navigation of mobile robots over wireless has another means to make them safe for human workers and either bypass the workers in proximity or stop at a sufficient distance.

5.3 Validation KPIs

In order to validate, evaluate and demonstrate that robot navigation is feasible via 5G, three different validation scenarios have been defined, and the relevant KPIs for evaluation have been determined. Table 2 summarizes the KPIs used for the validation regarding mobile robot navigation and the industry goal category that they correspond to. Each of the KPIs is explained below in more detail, while a selection of KPI measurement results and their analysis are given in the subsections of the corresponding validation scenarios. In use case 1 and use case 2, navigation is off-loaded from the AMR to an edge server, and related communication runs wirelessly over the 5G network. Typically, all functions related to navigation run on-board AMR, which give it capabilities to determine its own position (and orientation) on a map of the environment and plan how to reach a navigation goal. For the validation purposes, path planning, mobile robot localization and collision avoidance functions were off-loaded, while other related functions, such as inverse kinematics and wheels control, remained on the used AMR platform.

KPI name	Industry goal category	KPI short definition
Completion time	Productivity, mobility	The time it takes navigation to plan and control the motion of a mobile robot between start and goal positions on the factory floor. The KPI is measured and expressed in seconds ([s]).
Stopping margin	Safety	The distance from an obstacle that a mobile robot needs to stop at. The KPI is measured and expressed in meters ([m]).
Application-level latency for downlink	-	The time it takes to transfer navigation-related application data from the navigation engine to the mobile robot. The KPI is measured and expressed in milliseconds ([ms]).
Application-level latency for uplink	-	The time it takes to transfer navigation-related application data from the mobile robot to the navigation engine. The KPI is measured and expressed in milliseconds ([ms]).

Table 2 A summary of the KPIs for mobile robot navigation

Completion time measures the time it takes a navigation engine to plan and control the motion of a mobile robot along a desired path between start and goal positions. This indicator depends on various parameters, such as the type of task that AMR is assigned and the robot's target speed, the load it carries, and the quality of communication. In general, the objective would be to minimize the completion time, as it would positively contribute to productivity. Stopping margin relates to safety and specifies the desired distance from an obstacle that a mobile robot needs to stop at in case of an emergency. To avoid a potential collision, crashing into other machinery, and/or harming human workers, the larger that distance is, the better. Like completion time, different factors may impact the actual distance for a mobile robot, e.g., its moving speed, braking system, and the carried material load.

Each of the two latency KPIs relates to a total delay in transferring navigation data, from the moment it is transmitted (at the application level) by the source to the moment it is successfully received at the destination (i.e., its application level) [5GS20-R]. Since navigation runs over wireless, the two KPIs distinguish direction of navigation-related communication. The latency for downlink assumes the navigation engine as the source node and the mobile robot as its destination, while in the latency for uplink it is inverse. Contrary to completion time of mobile robot navigation and stopping margin, which relate to industry goals of productivity and mobility, and safety, respectively, the latency KPIs have not been "mapped" to a specific such goal. While they can be seen as impact factors for the industry goals, the latter KPIs are introduced to analyze and reflect on quality of communication over networked infrastructure.

5.4 Validation scenario 1: completion time

5.4.1 Description of the scenario

Values for the completion time validated in these tests are obtained by navigation guiding an AMR platform between two pre-defined positions in the Kista testing area. The mobile robot is configured with a dedicated 5G router/UE, while the edge server hosting the navigation engine is connected over Gigabit Ethernet (GbE) to the core part of the 5G network. While navigation is being run, all other use-case features (e.g., mobile robot docking and vision-assisted pick and place by the robot arm) are suspended. That makes sure that only navigation-related communication and network traffic which it causes are present in the testbed.

The navigation is tasked to plan and control motion of the AMR between start and goal positions, which are 6.6 meters apart. Given that there are no obstacles, the navigation algorithm plans a straight-line path between the two positions and, thus, allows a shortest possible completion time. The validation testing comprises consecutive executions of navigation between the two points, i.e., the AMR goes from start to goal position, then returns from goal to start position, and so forth. Each such traveled path (either from start to goal or vice versa) is considered one navigation execution.

One parameter being changed between different runs of this validation testing is the target speed of the AMR: 0.5 m/s and 1.0 m/s (the latter is the maximum possible speed by the robot). The reference value for the completion time is measured with no wireless connectivity between the AMR and the navigation-engine node. (Only for the purposes of these reference validations and collecting relevant insights, a sufficiently long unshielded twisted pair (UTP) cable and a GbE switch have been used to interconnect the robot and its navigation node.)

To bring the Kista testbed a bit closer to a more realistic factory setting, multiple AMR units would require sharing the test-area floor. With one physical mobile robot in the testbed, others needed to be emulated and that was achieved by generating traffic over separate UEs, which resembles the actual one for navigation. One extra 5G UE unit was available at the time of validation testing, thus allowing to "emulate" one more AMR. Tests with only one actual mobile robot are referred to as "5G with actual navigation traffic", while those where additional AMR is emulated by means of generating extra navigation-related traffic over the separate UE as "5G with actual + emulated navigation traffic".

5.4.2 Validation results

Results for the completion time are presented in a table form (Table 3) and report the median and maximum of the measured values. Mean and median are representative data values, while the maximum is to illustrate the "upper bound" of the measured values. A total number of ten test runs have been performed.

Network conditions	**Completion time** [s]					
	Target AMR speed = 0.5 m/s			Target AMR speed = 1.0 m/s		
	Mean	Median	Maximum	Mean	Median	Maximum
Reference navigation values	14.97	15.11	15.51	11.77	11.72	12.11
5G with actual navigation traffic	15.34	15.28	15.68	11.87	11.89	12.35
5G with actual + emulated navigation traffic	15.36	15.38	15.86	11.94	11.97	12.28

Table 3 Completion time values for mobile robot navigation

5.4.3 Discussion

The AMR employed is a 135-kg heavy platform, supports a maximum speed of 1.1 m/s, and allows a maximum payload of 100 kg. The robot payload was negligible in weight. Start and goal positions for this validation test are around 6.6 meters apart, which corresponds to a maximum available distance of the testing area at the Kista trial site. Having the start and goal positions this close did not allow the mobile robot to accelerate enough to achieve a speed near the 1.0 m/s target. This is a major contributor to measured values and why targeting double AMR speed, with all other conditions unchanged, did not result in the completion time dropping by a factor of 2 as compared to the 0.5 m/s speed. (Technical details about the whole testbed, including the AMR and navigation stack running on an edge server, can be found in 5G-SMART deliverable D2.2 [5GS22-22].)

The values presented here do not quantitively evaluate performance of 5G-based communication for navigation but serve to validate feasibility of off-loading the navigation engine from the mobile robot to a close-proximity edge computing node and executing it over a 5G wireless link. Since completion times over 5G for a single AMR come close to the reference values (Table 3), with medians differing by approximately 170 ms for a single navigation execution at both AMR speeds, the feasibility in that case is confirmed.

One can notice a further increase in the completion time when additional mobile robot is emulated by adding navigation-like traffic over a separate 5G UE. While studying scalability aspects were not possible due to the limited number of available AMRs and UEs, this remains an interesting study to perform in future research work.

5.5 Validation scenario 2: stopping margin

5.5.1 Description of the scenario

For stopping margin measurements, the same mobile robot with a dedicated 5G UE and edge navigation connected over GbE to the core part of the 5G network are employed. A special-purpose navigation planner is used for the testing, while all other use-case features – including regular navigation engine – are suspended. An obstacle is placed on the factory floor and kept at the same position throughout this validation. The AMR is tasked by the navigation planner to move in a straight line from its start position. When the robot is 0.6 m away from the obstacle, the planner sends a command to the AMR to start breaking (another distance could be configured for sending out this command). The stopping margin is then the remaining distance between the AMR and the obstacle after the robot completely stops.

The validation testing involves repetitions of executing that special navigation for the mobile robot from its start position and then commanding it to break. A total number of ten test runs have been performed. As with the previous validation scenario, the target speed of the AMR is modified between different test runs: 0.5 m/s and 1.0 m/s. The reference value for the stopping margin is also measured with wired connectivity between the mobile robot and the navigation node. Again, one extra UE is employed, over which mimicking traffic is added, to emulate an additional mobile robot unit.

5.5.2 Validation results

Table 4 reports results for this KPI based on the values measured within the Kista testbed.

Network conditions	**Stopping margin** [m]					
	Target AMR speed = 0.5 m/s			Target AMR speed = 1.0 m/s		
	Mean	Median	Maximum	Mean	Median	Maximum
Reference navigation values	0.492	0.491	0.502	0.246	0.239	0.272
5G with actual navigation traffic	0.463	0.468	0.487	0.213	0.227	0.236
5G with actual + emulated navigation traffic	0.469	0.471	0.478	0.206	0.206	0.250

Table 4 Stopping margin values

5.5.3 Discussion

A specific stopping-margin value depends on several important factors. Technical factors include the load that a mobile robot is carrying, its type of brakes, and state of the wheels. The heavier the robot is, the larger this margin should be, also if it is programmed for higher target speed. Other, context-related factors also need to be considered, for instance, what kind of tasks the mobile robot is involved in, especially if those tasks involve collaboration with and proximity to human workers.

During the stopping margin tests three different target AMR speeds were employed, with 1.0 m/s almost being the maximum supported by the given AMR platform. Load carried by the mobile robot was negligible, resulting in the total weight of around 135 kg. Reference values for the 0.5 m/s speed note that the mobile robot stopped at almost 0.5 m from the obstacle (Table 4, median of 0.49 m). That implies it needed around 0.1 m to stop after receiving the corresponding command from the planner. With 5G communication, the median stopping margin for that AMR speed decreased to around 0.47 m, i.e., the measured margin was 2-2.5 cm less. When the target robot speed was increased to 1.0 m/s, the stopping margin reduces in total below 0.24 m for the reference and 1 cm less with 5G.

As this KPI focuses on safety in production facilities which employ mobile robots, most importantly toward human workers, it must be carefully considered. The reference median value for the 1.0 m/s speed and the one obtained over 5G differ by around 1 cm. This could lead to a conclusion that communication itself may have a lesser impact than for the 0.5 m/s speed. However, it must be noted that a high-performing wireless communication becomes even more important then, since a higher speed increases inertia and extends stopping distance of a mobile robot. One could argue that increasing the stopping margin is the "safest" way to accommodate requirements of a factory floor with human workers but extending that margin must also be done with a trade-off not to cause AMRs to stop too often and negatively impact the overall productivity.

5.6 Validation scenario 3: application-level latencies for downlink and uplink

5.6.1 Description of the scenario

Navigation relies on Robot Operating System (ROS) messages to convey motion control data to and from the AMR. That ROS communication is based on publish-subscribe principles, wherein certain nodes publish relevant data and others subscribe to it. Two key so-called ROS topics for navigation are "/fscan" and "/cmd_vel". Topic "/fscan" refers to LiDAR data collected based on front scanner readings of physical environment around the AMR and sent to the navigation engine [5GS22-D22]. The other topic, "/cmd_vel" represents motion velocity commands sent by the navigation for the mobile robot to execute. With the given configuration of the Kista testbed, communication from the edge server hosting the navigation engine to the AMR is in the downlink direction ("/cmd_vel") and the opposite in the uplink direction ("/fscan").

The measurements for these two KPIs were performed in parallel to the completion time tests for navigation. The ambition was to capture insights into the time it takes to transfer navigation-related application data from the navigation engine to the mobile robot ("/cmd_vel") and also in the opposite direction ("/fscan"). That latency calculation is based on two mechanisms: timestamping performed at the application-level by ROS and keeping clocks between the edge server and the AMR in-sync. For the latter part, Network Time Protocol (NTP) and an NTP tool commonly used by ROS community, chrony [Chrony], were exploited. Since both mechanisms were implemented in the testbed during the corresponding realization activity, measurements of the 1-way downlink and uplink latencies relied on unobtrusively collecting timestamp values from respective ROS messages. Collection of latency values was performed continuously while executing navigation for the AMR.

5.6.2 Validation results

Results for the measured application-level latencies are presented in Figure 15 and Figure 16, reporting mean values as well as values for the 90th and 95th percentiles. Figures present results obtained for the AMR speed of 0.5 m/s.

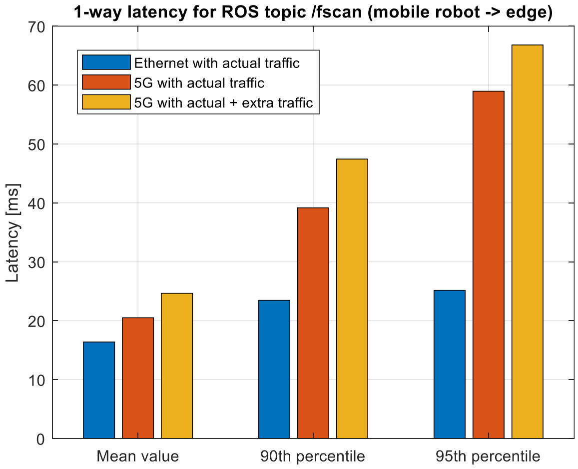

Figure 15 One-way latency for ROS topic "/fscan" (uplink) during mobile robot navigation

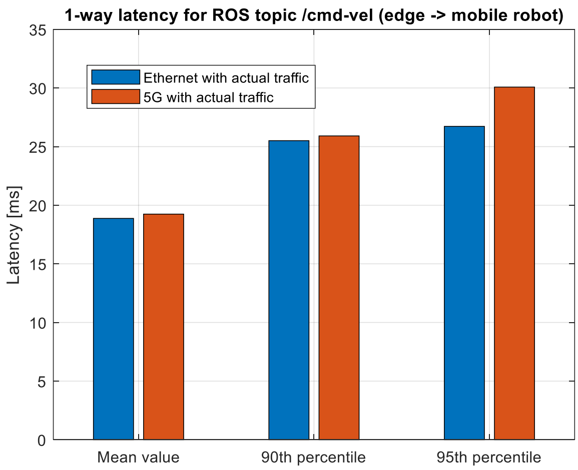

Figure 16 One-way latency for ROS topic "/cmd_vel" (downlink) during mobile robot navigation

5.6.3 Discussion

The measured latency results are based on timestamps in exchanged ROS messages, which rely on clocks of the communicating nodes to be in-sync. Before sending related ROS data, it is first timestamped at the source node, serialized at the ROS level, and then further processed "down" the protocol stack. After being transmitted over a 5G network, the destination node receives the corresponding message, processes it, and timestamps it. Difference between the two timestamp values corresponds to one-way latency. ROS topic "/fscan" is published periodically with f = 40 Hz and a typical data size of around 8000 bytes, while "/cmd_vel" is being continuously sent with f = 20 Hz and a typical data size of around 40 bytes. Both topics are sent by employing the TCP protocol at the transport layer.

Mean values of the one-way latency references for mobile robot navigation and of the downlink and uplink latencies measured over 5G in the Kista testbed show differences of a few milliseconds or less. The difference is more evident for ROS topic "/fscan" in the uplink direction (around 4 ms) than for "/cmd_vel" in the downlink direction (below 1 ms). The presented percentile values show that for the higher percentiles of 90% and 95% the one-way latency of the ROS topics increase over both wired Ethernet and wireless 5G. In particular for the large "/fscan" topic, the latency of ROS over 5G becomes substantially larger than over wired Ethernet. It should be noted that for both of these ROS topics, ROS uses TCP transport as default, in contrast to the network performance evaluations of section 4.2.2 that were performed with UDP traffic. This shows the need for continued research to try and analyze contributing factors to observed variations of the one-way latencies.

One likely source for the unexpected latency increase are possible interactions of large ROS messages being transmitted over TCP. TCP is a transport protocol for reliable data transmission, which is a crucial aspect of communication performance for mobile robot navigation. However, it is not well suited for real-time communication. TCP comprises connection establishment procedures prior to data transfer and connection release after an idle period. It also applies an adaptive congestion control mechanism that controls sending packets at the transmitter according to an estimated congestion state of the network, which in turn is based on a default value at session setup and then adapted over longer data transfers according to network round-trip time measurements and observed packet losses. In addition, TCP applies retransmissions that can be triggered by packet losses or large latency variations and modify the estimation of the network congestion state. In total, there can be many sources for added latencies in TCP-based transmissions, and a further understanding would require more in-depth analysis. It can be noted that the next generation of ROS, i.e., ROS 2, aims at using UDP as default transport protocol for data transfer. UDP is the common protocol for real-time communication in IP networks. Another potential source for added latencies are variations of computing processing in the edge server for the frequent large data sizes of the ROS topic "/fscan".

While in validation scenario 1 it was demonstrated that the completion time of robot navigation via 5G was very close to the reference case, it can be seen here that on application level, when ROS commands are being exchanged over TCP, the interworking is not optimal with wireless transmission.

5.7 Conclusions, learnings, insights: mobile robot navigation

Performed tests and measurements in the Kista testbed around the implementation of mobile robot navigation (Use Case 1 and Use Case 2) validate the feasibility of off-loading navigation from an AMR onto a close-proximity edge computing node and executing it with 5G-based communication in place. As previously noted, the off-loaded navigation engine comprises functions for path planning, mobile robot localization and collision avoidance, wherein the planning was running with the 20 Hz periodicity. Other robot control functions, such as inverse kinematics and wheels control, remained on-board the used robot platform.

Several learnings have been collected when integrating, testing, and evaluating the navigation over 5G. A careful on-board placement of 5G UE when integrating it with the mobile robot platform is required. Placing a 5G UE with internal antennas on the platform's base, which is some 30 cm high, would impact motion smoothness and cause a slight jerk. This was observed when the AMR would approach one of the robot workstations, in which case the workstation and its metal-made stand came in-between the UE and antenna system of the base station. In addition, the UE would be hidden by the mobile robot's transportation plate and its legs. Instead, the UE was placed onto the transportation plate during the validation tests. This confirms the need to consider the requirements of such mobile robot platforms when selecting UEs but also wireless technology and radio propagation specifics when producing blueprints of commercial robots.

Before starting navigation execution, the AMR would need to localize itself on the virtual map of the physical environment around it. To achieve that, time-stamped LiDAR data is sent from the mobile robot to the edge server through ROS topic "/fscan". If clocks between the edge server and the AMR would not be synchronized within a given tolerance, the robot localization would fail, and the navigation could not be started at all. As a pre-requisite to guiding mobile robots with ROS-based navigation, traffic of time-synchronization protocols running between end-devices would need to be prioritized in the network and, as a supporting feature, 5G networks could provide the required synchronization.

The usage of TCP for transmitting large ROS messages over the wireless 5G network is likely a significant contributor to the latency variations. In the currently developed ROS 2, UDP is the transport alternative to TCP, being the preferred choice for real-time communication in IP networks. We would expect significantly improved latency behavior for ROS-based interactions over UDP.

In a future-step validation, a pilot with multiple mobile robots communicating over 5G, as well as more wireless friendly protocol solutions, should be established.

6 Mobile robot docking

6.1 Introduction

Another important role of a mobile robot in manufacturing facilities is assisting in tasks of picking material and general inventory. Such tasks rely on collaboration between fixed robot arms and mobile robots, since a picking operation includes detecting an object in an a-priori not known position, grasping it, and then moving it to a target position (e.g., onto a mobile robot). This operation becomes even more challenging when an AMR is involved, which first needs to be precisely positioned next to, e.g., a workstation with a robot arm. Positioning an AMR is referred to as mobile robot docking and, due to required precision, involves support from a machine vision system. Implementation of Use Case 1 brings unique features since the docking engine is offloaded to an edge server and a mobile robot does not need to have an on-board camera. Instead, video cameras are fixed onto workstations with a robot arm and assist the docking procedure.

This section first specifies KPIs which are used to validate feasibility of running a docking control from an edge computing node and executing it over 5G, followed by analysis of collected KPI measurements and presentation of key related insights. Since docking can be considered as a type of mobile robot navigation, similar considerations regarding industry goals apply herein. For the discussion on relevant industry goals, the reader is therefore referred to Section 5.2.

6.2 Validation KPIs

In order to validate, evaluate and demonstrate that robot docking is feasible via 5G, three different validation scenarios have been defined and the relevant KPIs for evaluation have been determined. Table 5 presents the key KPIs used in the validation for mobile robot docking together with the industry goal category that they correspond to. Each KPI is elaborated below the table, while a selection of associated measurement results and their analysis are provided in the subsections of the corresponding validation scenarios. In use case 1, mobile robot docking is running in an edge server and related communication is established over 5G.

KPI name	Industry goal category	KPI short definition
Completion time	Productivity, quality	The time it takes docking to move a mobile robot from an initial to goal pose next to a robot-arm workstation. The KPI is measured and expressed in seconds ([s]).
Control error	Productivity, safety	The difference between the actual and the goal pose of the mobile robot. The KPI is measured and expressed in meters ([m]).
Application-level latency for downlink	-	The time it takes to transfer docking-related application data from the docking control engine to the mobile robot. The KPI is measured and expressed in milliseconds ([ms]).

Application-level latency for uplink	-	The time it takes to transfer docking-related application data from the mobile robot to the docking control engine. The KPI is measured and expressed in milliseconds ([ms]).

Table 5 A summary of the KPIs for mobile robot docking

Completion time measures the time that it takes a docking control engine to plan and control motion of a mobile robot from initial to the goal pose. This indicator depends on variety of parameters, such as maximum allowed speed of the robot, quality of communication, but also robustness and precision of the supporting machine vision. As with navigation, the objective would be to minimize completion time of the docking, as it would contribute to increasing productivity. Since mobile robot docking implemented for Use Case 1 is an example of classical closed-loop control, its control error is measured. Control error represents the difference between actual pose of the mobile robot being docked and its goal pose for the docking to finish. Docking should over time “converge” to the goal pose, making the control error equal to zero (or a small value greater than zero, which suffices precision requirements). Like completion time, different factors may impact if control error “steadily” decreases during the docking procedure, e.g., communication performance but also object detection precision by machine vision. If communication messages get delayed, this might lead to the control error value not converging to a zero threshold.

The other two KPIs represent a total delay in transferring docking data, from the moment it is transmitted (at the application level) by the source to the moment it is successfully received at the destination (i.e., its application level). Since docking is executed over wireless, the two KPIs distinguish direction of the communication. In this case, the latency for downlink assumes docking engine as the source node and the mobile robot as its destination, and vice versa for the uplink latency.

6.3 Validation scenario 1: completion time

6.3.1 Description of the scenario

As for navigation validations, the mobile robot is equipped with a dedicated 5G UE, while the edge server hosting the docking control algorithm is connected over GbE to core part of the 5G network. While docking is executed, all other use-case features (e.g., mobile robot navigation and vision-assisted pick and place by robot arm) are suspended. The docking engine is assisted by a machine vision system, which tracks the robot and sends its pose to the docking control. The machine vision system is running on a separate computing node, which is directly connected to the edge server over a wired GbE link.

Docking is tasked to control motion of the AMR between the initial (“start docking”) and docking goal pose. Based on robot tracking performed by the machine vision system, the control algorithm is provided with the current pose of the AMR during execution. The docking engine uses the current pose to calculate required motion of the robot and then sends it in a motion velocity command. Since there are no obstacles between the AMR and workstation where it docks at, the completion time depends on the pose tracking precision of the machine vision and communication performance. The validation testing consists of consecutive executions of docking (and undocking) between a pre-defined, initial robot pose and the desired docking pose. A single docking execution encompasses the mobile robot being moved from the initial to the desired pose.

The initial AMR position in this validation was around 35 cm from the robot workstation used for docking. A parameter being varied between different runs of this validation test is the maximum allowed speed of the AMR: 0.2 m/s, 0.5 m/s, and 0.8 m/s. A reference value for the completion time is measured with no wireless connectivity between the mobile robot and the docking-engine node. (Only for the purposes of these reference tests, a UTP cable and a GbE switch have been used to interconnect the AMR and its docking control.)

Similar to navigation, a more realistic scenario with multiple mobile robots being docked was emulated by generating docking-like network traffic over separate UEs. Two extra 5G UE units were available at the time of docking tests, thus allowing to “emulate” two more AMRs next to the actual one. Tests with only one, actual mobile robot is referred to as “5G with actual navigation traffic”, while those wherein two additional AMRs are emulated by means of generating extra docking-related traffic as “5G with actual + emulated navigation traffic”.

A total number of ten test runs has been performed.

6.3.2 Validation results

Results for the completion time are summarized in Table 6.

Network conditions	**Completion time** [s]					
	Max. allowed AMR speed = 0.2 m/s			Max. allowed AMR speed = 0.8 m/s		
	Mean	Median	Maximum	Mean	Median	Maximum
Reference navigation values	6.29	6.26	6.48	6.33	6.27	6.48
5G with actual navigation traffic	6.51	6.48	6.72	6.51	6.46	6.74
5G with actual + emulated navigation traffic	6.53	6.50	6.64	6.52	6.52	6.66

Table 6 Completion time values for mobile robot docking

6.3.3 Discussion

The mobile robot payload was negligible in weight during the tests. The initial AMR position in this validation was around 35 cm from the robot workstation used for docking. Increasing maximum allowed AMR speed from 0.2 m/s to 0.5 m/s or 0.8 m/s did not show any effect in the end, as the control algorithm always resorted to the 0.2 m/s speed.

Docking completion times over 5G for the AMR were slightly longer as compared to the reference values (Table 6), with medians differing by approximately 0.2s for a single docking run. However, the feasibility of closing this kind of control loop for a single mobile robot is confirmed, also since all testing instances of docking execution ended up with the AMR successfully reaching the desired pose.

6.4 Validation scenario 2: control error

6.4.1 Description of the scenario

While running validation executions of mobile robot docking, control error values were collected for later analysis. The control error is the difference between the actual and the goal pose of the mobile robot.

6.4.2 Validation results

Results for this KPI are summarized in Figure 17, showing how the control error changes over time when several consecutive docking procedures are executed. The plotted graph relates to the maximum allowed AMR speed of 0.8 m/s. Only "x" dimension of the robot pose, corresponding to the main direction of the mobile robot moving closer to the workstation, is depicted. The starting position of the mobile robot is around 33cm from the target position, which is around 2cm from the stationary robot.

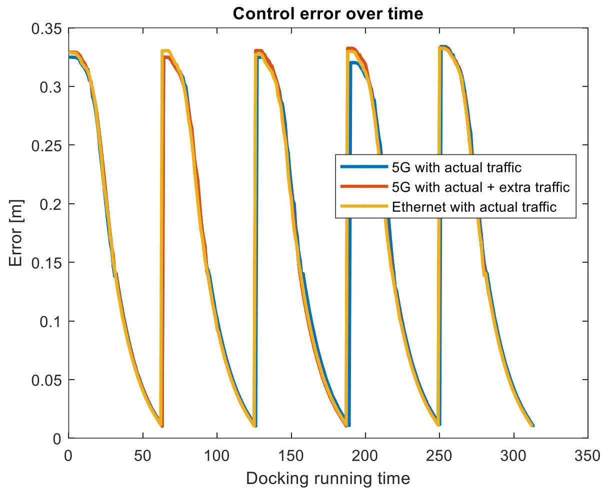

Figure 17 Control error measured over consecutive docking executions, separated by the sudden error changes

6.4.3 Discussion

The measured control error follows a "saw tooth" trend. In Figure 17, each "tooth" corresponds to one docking execution. Initially, the control error value is almost 0.33 m, which means the AMR is in its initial position. The control error then steadily decreases to approximately 2 cm (the distance between the AMR and the stationary robot workstation), which is configured as the desired docking target. Before starting the next docking execution, the AMR returns to its initial/starting pose, which is depicted by the vertical "jump" of the control error value.

As can be seen in the figure, control error plots for all three network configurations and conditions almost completely overlap. This indicates that for the prototyped control loop for the docking procedure, similar precision is achieved over the 5G network as when the AMR is connected over a GbE cable.

6.5 Validation scenario 3: application-level latencies for downlink and uplink

6.5.1 Description of the scenario

As in navigation, see 5.6, the docking relies on ROS messages to convey motion control data to and from the mobile robot. Two of the same ROS topics are used therein, “/fscan” and “/cmd_vel”. Communication from the edge server hosting the docking algorithm to the AMR (“/cmd_vel”) corresponds to the downlink direction and communication based on “/fscan” to the uplink direction.

The measurements for these two KPIs were performed in parallel to the completion time tests for docking. Same measurement principles and mechanisms from the navigation tests were applied, with the goal to understand what time it takes to transfer docking-related application data from the docking engine to the mobile robot and then in the opposite direction. Collection of latency values was performed continuously while the docking was running.

6.5.2 Validation results

Measured values for these two KPIs were similar to the values obtained during the navigation tests in section 5.6.2.

6.5.3 Discussion

Although supporting a different robotics application, the docking imposed same requirements on the underlying ROS communication and respective settings therein as for the mobile robot navigation. It is interesting to note that executing mobile robot docking with a lower AMR speed than in the navigation tests, and also in a smaller area next to a robot workstation, as compared to the AMR being guided between two locations almost 7 m apart, yielded similar results as for the navigation. This would imply that a dominant impact comes from ROS communication being established over 5G.

6.6 Conclusions, learnings, insights: mobile robot docking

Tests and measurements around the docking prototype for Use Case 1 validate the feasibility of docking a single AMR by the edge-hosted control engine and over 5G. The docking control algorithm tested relies on assistance of machine vision to track pose of the mobile robot and then plans motion for it to reach the goal docking pose. Motion planning in this case was running with a 20 Hz periodicity.

No issues were come across during docking executions in the Kista testbed and each such execution was successfully finalized with the AMR reaching a pose approximately 2 cm away from robot workstation. Furthermore, docking appeared to be smooth with no mobile robot jerkiness observed, also based on good tracking performance of machine vision. One important aspect to note, however, is that successful docking depends on calibration of cameras in the machine vision system. Since the cameras that specifically support the docking have a wide field-of-view, they are not too sensitive if a camera is unintentionally moved due to, e.g., maintenance work around the robot station which it is fixed at.

7 Lead-through teaching of robot pick and place

7.1 Introduction

This section describes an intuitive and safe way to program an industrial robot by contactless teaching, learning a behavior from observing the motion executed by the human demonstrator. If a non-expert wants to program, e.g., a robotic arm, this person needs a natural and intuitive interface that does not require rigorous robot programming skills. Programming-by-demonstration is an approach which enables the user to program a robot by simply showing the robot how to perform a desired task. In this approach, the robot recognizes what task it should perform and learns how to perform it by imitating the teacher.

7.2 Industry goals

Manufacturing organizations must adapt to market changes, and they need to reprogram their robots frequently and quickly to achieve the routing flexibility: the ability to produce different products by using the same system. Besides the fact that the robotics market has expanded, it also addresses non-expert users (e.g., medical assistants, craftsmen, etc.). For this reason, there is a need for simplifying both programming interfaces and methods to program robots.

7.3 Validation KPIs

In order to validate, evaluate and demonstrate the feasibility of lead-through teaching via 5G, a validation scenario has been defined and the relevant KPIs for evaluation have been determined. For the lead-through teaching of a robotic arm, a key feature of Use Case 2, the following KPIs are defined, and then described in the table below. As compared to the previous validation scenarios and KPIs, for this use case, also a Quality of Experience (QoE) related KPI is defined.

KPI name	Industry goal category	KPI short definition
Two-way latency	Quality	Two-way latency measured at the edge server, by probing smart phone used for the teaching
User experience	Flexibility, safety	Subjective experience by the user while jogging the robot

Table 5: Summary of the KPIs for lead-through teaching

7.4 Validation scenario 1: two-way latency

In this scenario, active packet probing was executed while performing contactless lead-through teaching by demonstration.

7.4.1 Description of the scenario

In this scenario the robot learns a behavior from observing the motion executed by human demonstrator while jogging the robot contactlessly. Good communication with low latency is important for a real-time synchronized motion between the teaching smart phone and gripper on the robot arm. Figure 18 illustrates lead-through teaching.

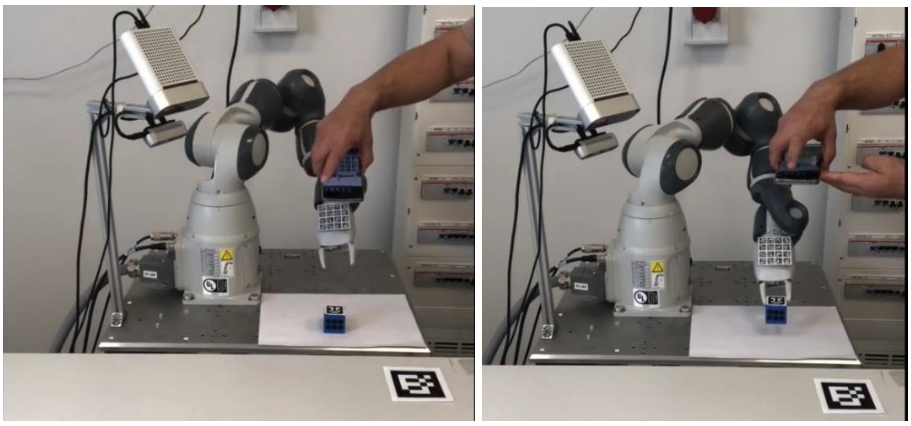

Figure 18 Lead-through teaching

7.4.2 Validation results

The two-way latency between the application in the smartphone and the motion planning in the edge node was measured. The latency statistics values are summarized in Figure 19.

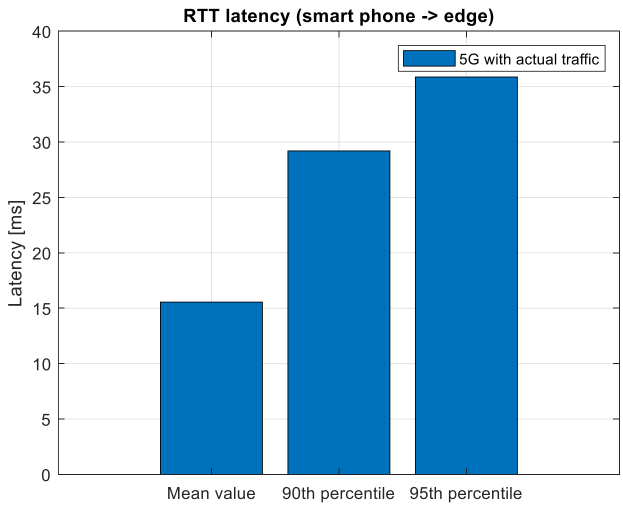

Figure 19 Two-way latency statistics for lead-through teaching

7.4.3 Discussion

As can be seen in Figure 19, the measured two-way latency varies. The variations are due to different amounts of data sent from the smartphone and its transmission speed, likely also due to different angles of holding the smartphone camera towards the marker on the robot arm, different actions performed by the teacher, etc. However, the overall experience is that the lead-through programming works well.

The user experience aspect was not measured in a systematic way during the tests, since the application is still at prototype level. The overall impression from an experienced user performing multiple programming cycles during the development and evaluation was that the 5G network supported the application well.

7.5 Conclusions, learnings, insights: lead-through teaching of robot pick and place

Intuitive programming of a stationary robot by lead-through teaching, using a 5G-enabled smartphone with the developed teaching application prototype, works well. The teaching application offers its user to program a robotic arm to perform several tasks, without needing to write a single line of program code. Moreover, the teacher does not have to be an expert in the robotics domain to use the application. That way, it has a substantial impact on the efficiency of programming robots and flexibility to re-configure them for different tasks. Good 5G communication is essential, as the teacher needs to assess the quality of the task performed by the robot, which is executed during the teaching process.

8 Robot manipulation for pick and place

8.1 Introduction

To respond to a rapidly increasing demand for high levels of flexibility in manufacturing and production facilities, industrial robots are endowed with the ability to react and adapt to their environments. Capabilities of reacting to the surrounding environment rely on the robots being able to perceive the environment through different types of sensors and vision being in focus. For Use Case 1, a prototype of vision-assisted manipulation by a robot arm was developed, targeting the task of picking an object and placing it to a desired position. This use-case feature supports collaboration of 5G-connected robots and complements mobile robot docking, which precedes execution of robot manipulation and having the robot arm grasp an object and place it onto the AMR platform. Similar to other use-case features, robot manipulation is planned in the edge computing node and controlled based on UDP communication with a controller of the robot arm.

8.2 Industry goals

Industrial robots and associated control methods are continuously developing. With the recent progress in the field of artificial intelligence, new perspectives in industrial robot control strategies have emerged, and prospects toward cognitive robots have arisen. AI-based robotic systems are strongly becoming one of the main areas of focus, as flexibility and deep understanding of complex manufacturing processes are becoming the key advantage to raise competitiveness.

8.3 Validation KPIs

In order to validate, evaluate and demonstrate that robot manipulation for pick and place is feasible via 5G, a validation scenario has been defined and the relevant KPIs for evaluation have been determined. Table 7 summarizes KPIs for validation of vision-assisted robot manipulation in the Kista testbed, together with their industry goal category

KPI name	Industry goal category	KPI short definition
Completion time	Flexibility, productivity, quality	The time for manipulation to execute a manipulation, pick and place task.
Receiving frequency	Quality	Receiving frequencies of ROS topics /tcp_pose and /joint_state at the edge server

Table 7 Summary of KPIs for manipulation

8.4 Validation scenario 1: completion time and receiving frequency

In this scenario the time required to execute the pick and place task, previously learned through lead-through teaching, is measured.

8.4.1 Description of the scenario

This section describes the manipulation phase for pick and place operation of the stationary robot, where the learned task is executed by the single-arm robot. This execution is trigged by the state-machine, after the docking action is completed. The state-machine calls two services, the first service is to pick the cube from the mobile robot platform, while the second service is to bring the robot back to the home position. The state-machine calls the execution service, where the cube is recognized both with point clouds and a marker tag to estimate the pose and orientation of the cube. The execution service produces a linear interpolated trajectory to pick the object according to the learned task of picking. After that the cube is placed onto the fixed station workstation. The manipulation process is depicted in Figure 20.

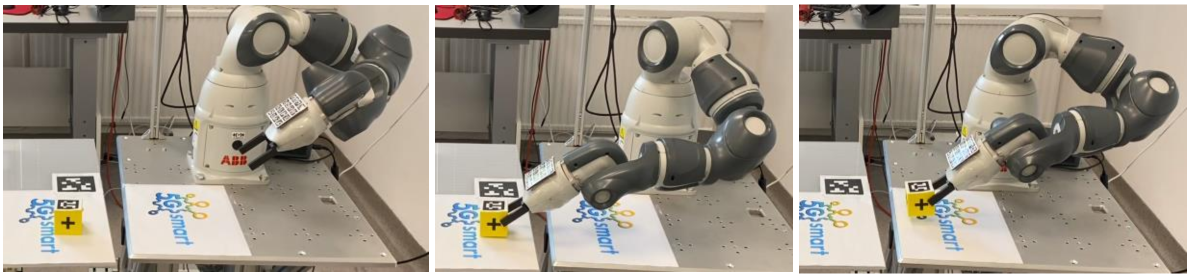

Figure 20 Execution service for the pick action, (a) home pose, cube pose estimated, (b) cube picked from the mobile robot platform, (c) cube dropped onto the fixed workstation

After the first Pick action is executed by placing the cube on the stationary table, the mobile robot platform undocks and docks again, and then the execution service is called again. The cube is then picked from the stationary workstation and dropped onto the mobile robot platform. The execution sequence is shown in Figure 21.

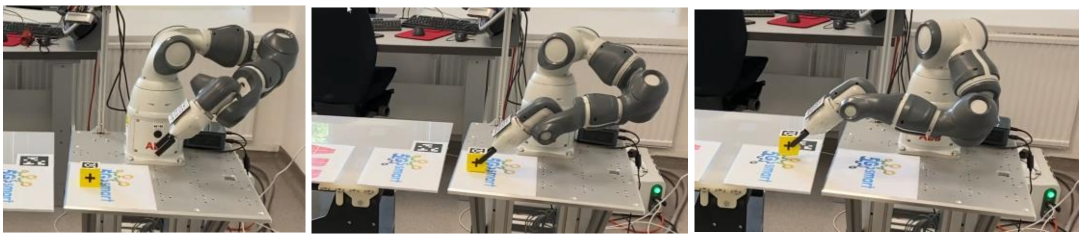

Figure 21 Execution service for the drop action, (a) home pose, cube pose estimated, (b) cube picked from the workstation, (c) cube dropped onto the mobile robot platform

8.4.2 Validation results

Table 8 and Figure 22 summarize results for this validation scenario: the completion time for the manipulation operation and receiving frequencies of the two ROS topics measured at the edge-server side. The completion time refers to one manipulation cycle, i.e., a single pick and place operation.

Network conditions	**Completion time** [s]			
	Min	Mean	Max	Std
Reference manipulation values	9.37	10.01	10.60	0.37
5G with actual manipulation traffic	12.18	13.14	13.45	0.37
5G with actual + emulated manipulation traffic	13.16	13.27	13.36	0.07

Table 8 Completion time values for robot manipulation

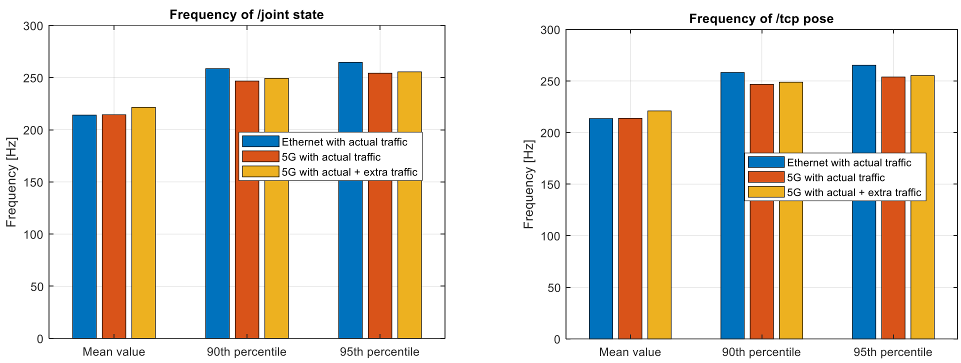

Figure 22 Receiving frequency of ROS topics /joint_state and /tcp_pose

8.4.3 Discussion

The completion times for robot manipulation show a difference between the reference values and those measured over 5G. The different contributions to the completion time include processing motion feedback from the robot arm (e.g., /joint_state) and computing motion commands in the edge server, latency of communication from the edge server to the controller of the robot arm (and vice versa), processing motion commands in the robot arm controller, mechanical execution of requested robot motion, and computing motion feedback in the controller. Both motion commands and motion feedback messages are sent with default periodicity of around 250 Hz, i.e., an interval of 4 ms, with UDP being used as transport protocol. Since adding a probe on the robot controller to measure the receiving frequency of motion commands was not feasible, only the receiving frequency for the motion feedback was measured, at the edge-server side.

One possible reason for the additional delay with the wireless communication is the high number of motion commands and feedbacks sent – around 250 per second in each direction. Accumulation of the communication delay, even of small values, over frequently sent messages might not be negligible. However, no perceivable issues with the manipulation execution over 5G were observed, like jerkiness, so an elaborate evaluation methodology to analyze over-the-air latencies is required to draw solid conclusions. Another possible reason for the discrepancy could be that a slightly different trajectory toward the picking object was calculated by the execution service for validation testing over 5G as compared to the reference execution.

8.5 Conclusions, learnings, insights: robot manipulation

Tests for the robot manipulation (use case 1 and use case 2) validate the feasibility of planning robot manipulation from an edge-hosted engine and with 5G communication. The maintained control loop frequency in Figure 22, irrespective of communicating over cable or 5G, confirms that the control loop works well.

Although completion time measurements over 5G imply a longer completion time than the reference values (with wired communication), the manipulation execution was perceived as smooth, and no observable issues were noticed. Further investigations are needed to understand the cause of the additional delay when transmitting over 5G.

As with mobile robot docking, successful pick-and-place operation relies on calibrated cameras for machine vision and object detection. To avoid possible impact on the measurement results, grasping of an actual object was suspended during the manipulation tests. The cameras are quite sensitive if their view direction is changed so if that happens, cameras need to be recalibrated, which is quite time-consuming.

9 AR Visualization of Robots

9.1 Introduction

With increased levels of automation and robotization, simple and fast access to information from robot units on the shop floor is required. This use case is characterized by employing AR-based means to visualize operational robot information in an efficient way. It also illustrates how novel technologies can be exploited to create new ways for human workers to access factory-floor machinery. Like in the other two use cases, machine vision support is used to detect and distinguish between different objects.

9.2 Industry goals

The AR visualization of robot status shows the potential of AR technology to supervise industrial robots and their every-day operation, to increase the work efficiency of human technicians on the factory floor, to make human-machine interaction simpler. It also showcases the usability of 5G networks to enable low latency exchange of data and commands between mobile AR-using technicians and industrial robots.

General industry goals that are expected to be benefited are listed below:

- Productivity: manufacturing process output per unit of input, over a specified period
    - Labor: decrease in plant maintenance labor due to higher engineering efficiency i.e., faster completion time and lower task difficulty for maintenance and monitoring tasks when comparing traditional and AR visualization-enabled methods of working in the factory floor.
- Sustainability: Conservation of energy and natural resources
    - Travel costs: reduction of times vendors have to be flown in for repairs by providing factory teams with virtual guidance from experts to troubleshoot and repair equipment.
- Utilization: actual time the machine is used compared to the theoretically available time
    - Equipment downtime: decrease in equipment downtime because of more time-efficient troubleshooting.
- Flexibility: ability to process many different parts within the manufacturing system with minimum engineering effort and changeover time
    - AR over 5G can enable novel and more flexible ways for human workers to configure and interact with industry robots.
- Quality: rates the degree to which output of the production process meets the requirement.
    - Early and intuitive identification and remedy of potential problems is essential to ensure good quality production, supported by AR visualization over 5G.

Flexibility and Quality goals are explored and validated in this AR use case as shown in the next chapters.

9.3 Validation KPIs

In order to validate, evaluate and demonstrate that AR visualization of robots is feasible via 5G, three different validation scenarios have been defined. As opposed to the other use cases, for the evaluation of the AR visualization of the robot, only parameters related to the Quality of Experience (QoE) have been evaluated.

The Use Case AR Visualization is expected to impact the following KPIs as described in the table below.

KPI name	Industry goal category	KPI short definition
Information retrieval	Quality/Flexibility	Subjective ease of operability to retrieve information from robots via the AR application

Table 9: Summary of the KPIs

Below we describe the KPI validation methodology adopted for 5G SMART in more detail.

Subjective Measurements: Subjective measurements are used to characterize the quality of experience and perceived lag/network stability of the AR Visualization app over 5G. Validation scenarios are created to evaluate the performance indicators. A form is created with a questionnaire to capture and evaluate the test user experience in each validation scenario.

Evaluation Form	Specification
General Questions	Collect some general data about the users participating in the test: age, experience with AR/VR, knowledge about 5G and/or Robotics. The target is to check if there is any influence of this knowledge background on the results.
Questionary	Participants were asked to score the specific validation scenario questions with responses that range from Strongly agree to Strongly disagree**.** 15 testers participated in each validation scenario.
Scale Range	6-points scale to capture the subjective participant response - (1) Strongly agree; (2) Agree; (3) Somewhat agree (4) Somewhat disagree; (5) Disagree; (6) Strongly disagree.
Score Calculation	Each question ranked from 1 to 6, overall score is the sum of all question scores, normalized to 0-100.

Table 10 Evaluation form specification

The following questions are part of the evaluation form to be filled in by each test participant.

Question [Tag]	Description
Q1 [AGE]	General: What is your Age?
Q2 [Experience AR/VR]	General: What is your experience with Augmented / Virtual Reality?
Q3 [Experience 5G/Robotics]	General: What is your experience with 5G and / or Robotics?
Q4 [Connection Stable]	The connection was stable during the entire experience.

Q5 [No impact due to time interval	The time interval between detecting a robot and receiving data didn't negatively impact my experience.
Q6 [Time interval not noticeable]	The time interval between detecting a robot and receiving data wasn't noticeable.
Q7	The time interval between pressing a button and the robot moving did not negatively affect my experience
Q8	The time interval between pressing a button and the robot moving wasn't noticeable.
Q9 [Overall Experience]	The overall experience was smooth.
Q10 [Recommend Technology]	I would recommend this technology to others.
Q11	Any final comments or suggestions?

Table 11 Question list, part of the Evaluation Form

Questions 1, 2 and 3 are meant to identify the test participant profile. Questions 4, 5, 6, 7 and 8 are subjective measurements related to the validation scenarios. Questions 9, 10 and 11 measures the overall experience and related technology.

9.4 Validation scenario 1: Reading of AR robot data from one robot over 5G

9.4.1 Description of the scenario

The validation scenario 1 is related to reading of AR robot data from one robot over 5G in applicable activities like maintenance and monitoring at factory floor. The test environment set-up is shown in Figure 23.

After the test environment set-up, the tests will be executed by the participants following the Instructions described below:

[1] Play AR app in the Unity project at the notebook.
[2] Look at stationary robot 1 located in the testbed. Robot 1 is detected by reading a unique marker tag (see Figure 24, left) which is assigned to and fixed onto each of the robots.
[3] Start Monitoring Panel at the AR app.
[4] Position of Monitoring Panel can be moved by holding both thumbs up in front of the user for 5s.
[5] Start reading of robot data 1 (CPU, Health, etc) in the AR app - Monitoring Panel (see Figure 25).
[6] Check if any lag was perceived when starting the data reading.

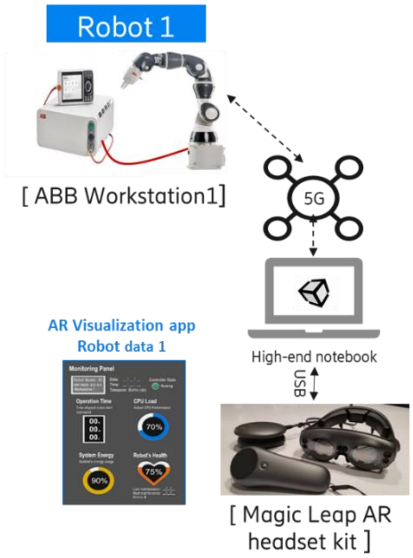

Figure 23 Test set-up for the validation scenario 1

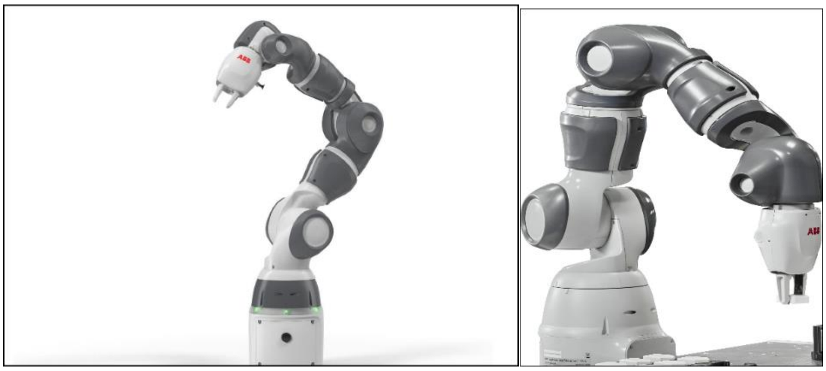

Figure 24 Unique marker tags for robots 1 and 2 respectively.

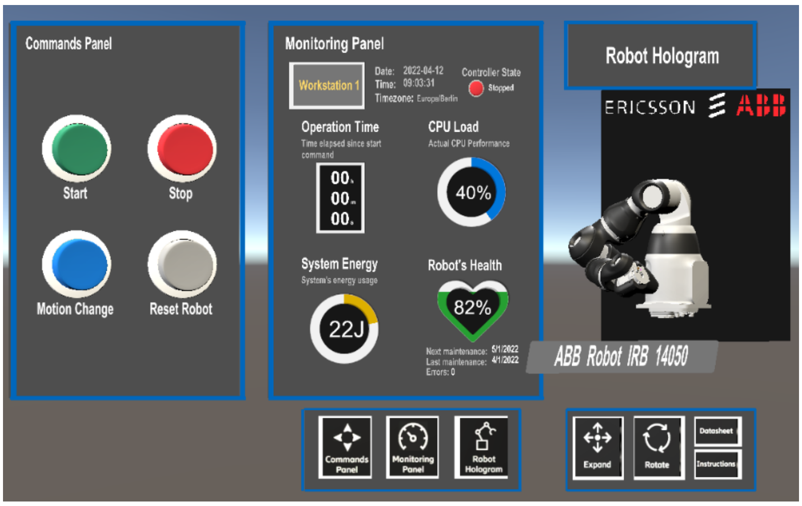

Figure 25 The three panels of the AR Visualization application: Commands, Monitoring and Hologram.

9.4.2 Validation results

Results for the test participant profile (questions 1, 2 and 3) are summarized in Figure 26. Results for the subjective measurements related to the validation scenario and overall experience (questions 4, 5, 6, 9 and 10) are summarized in Figure 27. Graphics refers to measurements of 15 participants.

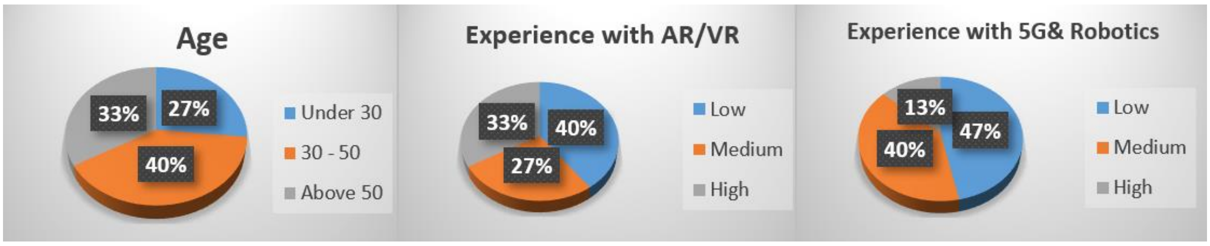

Figure 26 Test participant profile

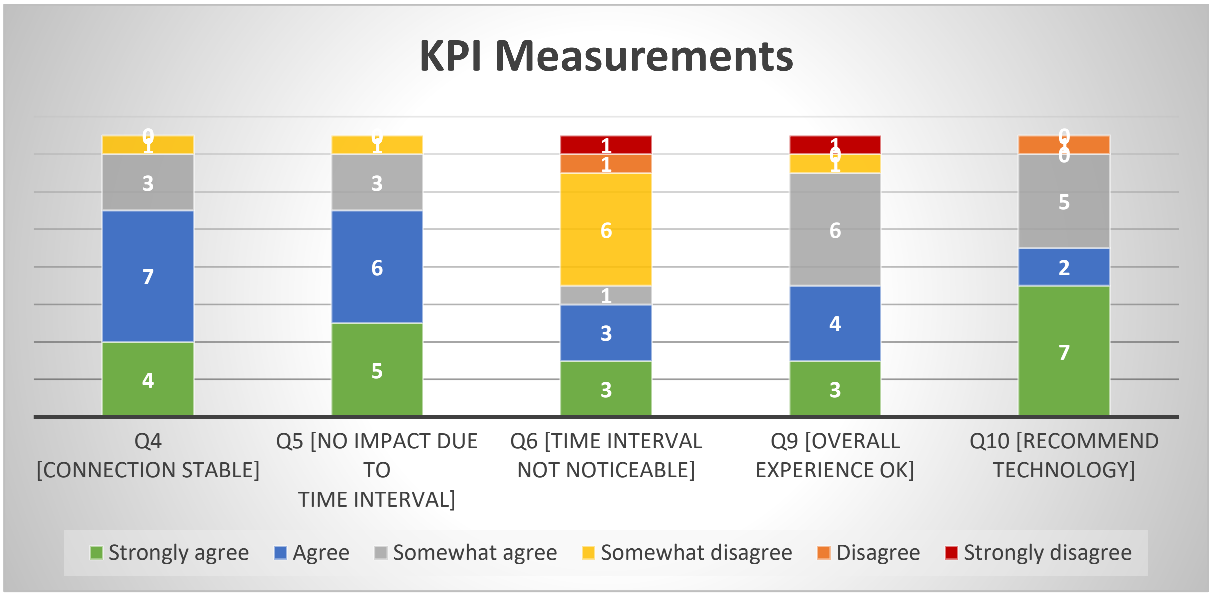

Figure 27 Subjective measurements for the validation scenario

Cross-analysis between test participant profiles and the quality of experience and recommended technology is included in Figure 28, Figure 29, Figure 30 and Figure 31.

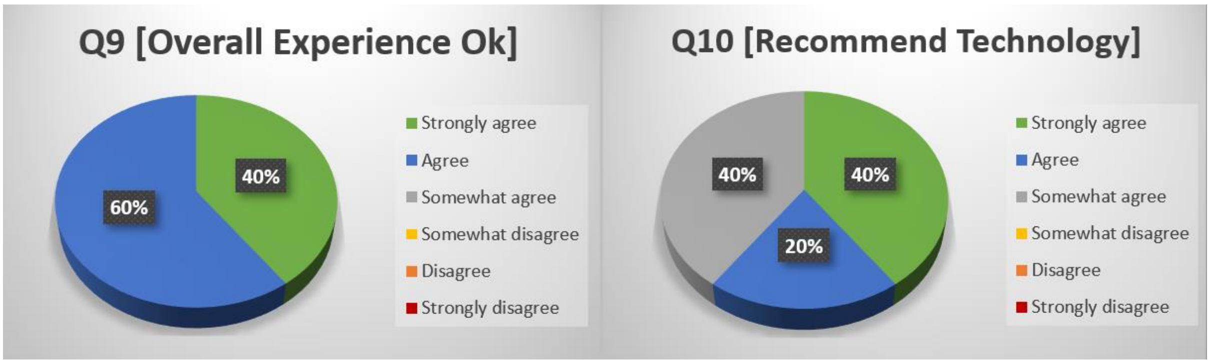

Figure 28 Cross-analysis between participant profile Age above 50 and quality of experience

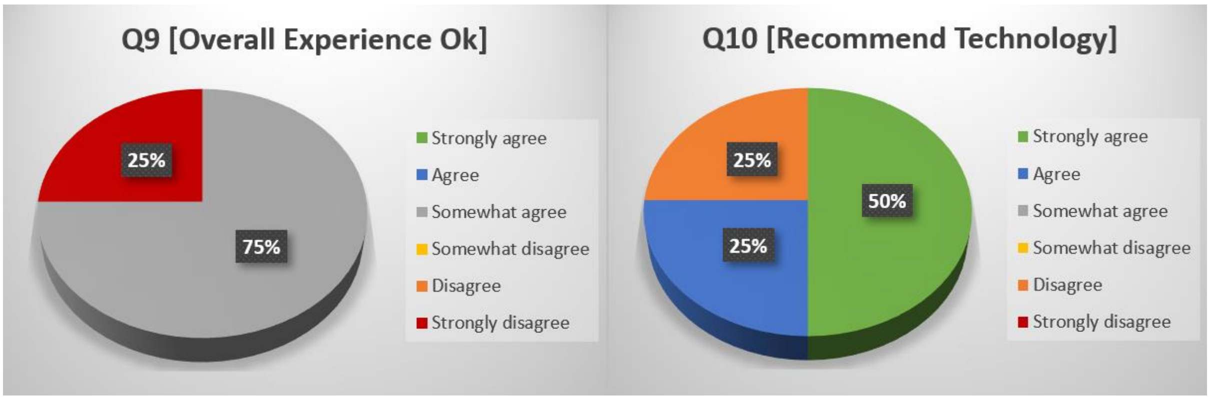

Figure 29 Cross-analysis between participant profile Age below 30 and quality of experience

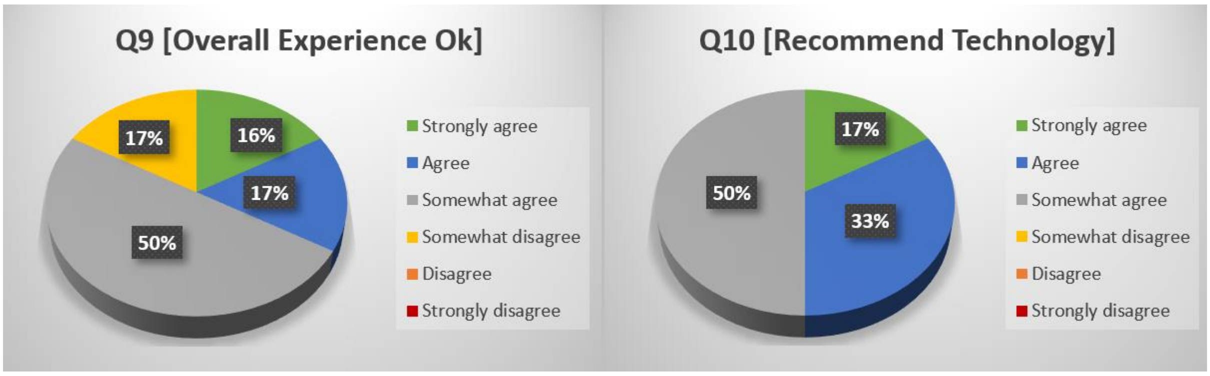

Figure 30 Cross-analysis between participant profile Low Experience in AR/VR and quality of experience

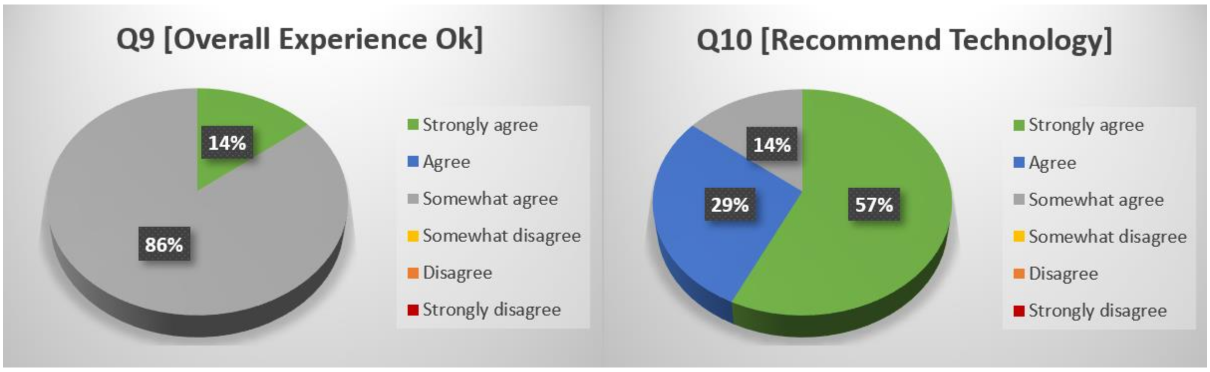

Figure 31 Cross-analysis between participant profile Low Experience in 5G / Robotics and quality of experience

9.4.3 Discussion

The 5G connection between AR user and robot was perceived and evaluated as stable during the entire experience by more than 90% of the test participants. It should be noted that the test setup presents two 5G communication legs over the air: both the AR solution and the robot controller are connected via a 5G UE.

The majority of the test participants agree or strongly agree that the time interval between detecting a robot and receiving data did not negatively impact the experience. This means the 5G communication network performed well in terms of reliability.

Almost 50% of the test participants evaluated the time interval between detecting a robot and receiving data was not noticeable. The other part of the testers had a contrary opinion. Somewhat similarly, the perception of the overall experience split the test participants in different opinions. From the cross-analysis, it can be seen that in the group aged above 50, 100% of the participants evaluated the experience as good, while in the group aged below 30 the majority were not as positive and 25% even strongly disagreed. Nevertheless, a total of almost 90% of the test participants evaluated the overall experience as good.

Finally, more than 90% would recommend this technology to others. In the group with low experience in AR/VR, the majority noted a reasonably good experience and 100% agreed to recommend the technology to others. Similarly, in the group with low experience in 5G/Robotics the majority perceived the AR application as good and all of them could recommend the technology to others

9.5 Validation scenario 2: Reading of AR robot data from two robots over 5G

9.5.1 Description of the scenario

The validation scenario 2 is related to reading of AR robot data from two robots over 5G in applicable activities like maintenance and monitoring at factory floor. The test environment set-up is shown in Figure 32.

After the test environment set-up, the tests will be executed by the participants following the Instructions described below:

[1] Play AR app in the Unity project at the notebook.
[2] Look at stationary robot 1 located in the testbed. Robot 1 is detected by reading a unique marker tag (see Figure 24, left) which is assigned to and fixed onto each of the robots.
[3] Start Monitoring Panel at the AR app.
[4] Position of Monitoring Panel can be moved by holding both thumbs up in front of the user for 5s.
[7] Start reading of robot data 1 (CPU, Health, etc.) in the in the AR app - Monitoring Panel (see Figure 25)
[5] Look at stationary robot 2 located in the testbed. Robot 2 is detected by reading a unique marker tag (see Figure 24, right) which is assigned to and fixed onto each of the robots
[6] Start reading of robot data 2 (CPU, Health, etc.) in the AR app.
[7] Shift the AR data view from robot 1 to 2 and vice-versa.
[8] Check if any lag is perceived when shifting the which robot’s data is being accessed in the visualization.

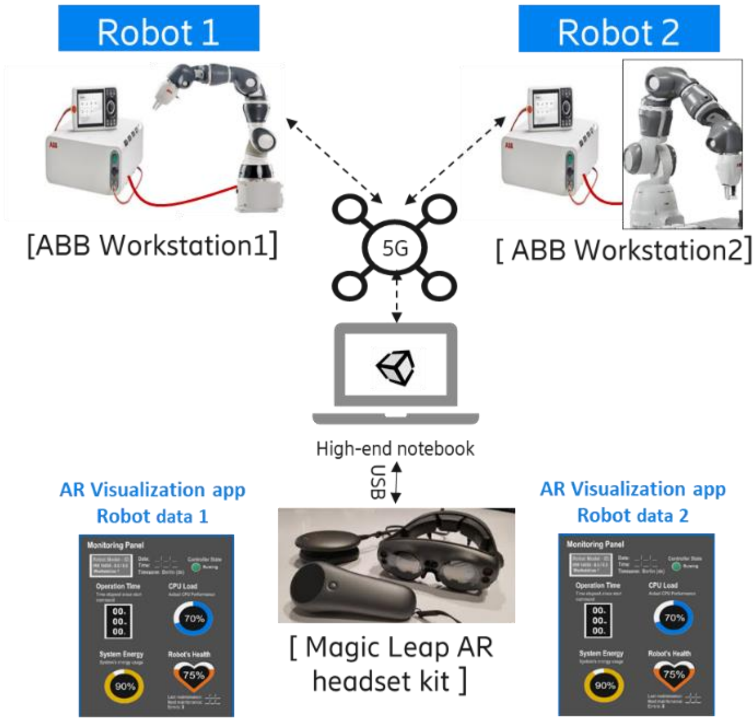

Figure 32 Test set-up for validation scenario 2

9.5.2 Validation results

Measured values for this validation scenario 2 are very similar to the values obtained during the validation scenario 1 in section 5.6.2.

9.5.3 Discussion

Discussions raised for validation scenario 1 in section 9.4.3 are also applicable to validation scenario 2. It should be noted that the time interval in this scenario refers to the time it takes to get information from the first robot and then switch to the second and retrieve the information from this. Thus, considering that the time interval in this scenario is longer, it appears that the expectations from the test persons are adjusted accordingly.

9.6 Conclusions, learnings, insights – AR Visualization of Robots

It has previously been concluded that the 5G network coverage is excellent in the test area, see section 4.2., and the subjective tests performed for use case 3 shows that the perceived performance is very stable over the 5G-based testbed at the Kista trial site. No issues with the 5G connections between AR user and the robots were experienced.

Several learnings have been collected regarding the AR technology applied to robotics over 5G. Measurements around the applicable scenarios validate the feasibility of the use case applied to maintenance and monitoring in the factory floor. Although a time interval between the detection of the robot and reading of robot data was observed, it did not impact the overall experience. Thus, latency performance can be considered sufficient for the applicable scenarios.

One important aspect to note is the fact that low knowledge on related AR technology and/or 5G does not affect the overall quality of experience. Moreover, people with age above 50 did not have issues regarding the quality of experience and technology as well. However, it was observed that young people (below 30) seem to be more critical in terms of the quality and experience and if the technology is ready to be applied to the applicable scenarios. These findings may impact the way new technology is introduced on the shop floor.

9.6.1 Future Work

For future work, it is recommended to explore overall benefits of AR for learning related to use cases remote training and support in the factory floor as it could bring additional benefits as follows:

- Effectiveness: AR learning allows to train employees faster than in the traditional classroom on average.
  - It enables immersive and “learning by doing”, which leads to a substantially faster learning process.
- Improved attention: AR learners are more focused than e-learners.
  - Virtual training that is supported by AR learning minimizes the physical distance and increases learner engagement.
- Confidence building: AR learners are more confident to act on what they learned after training.
  - The 3D holograms help learners to interact with a simulated robot environment which will help them to have first trials in an immersive and low risky environment and thus be prepared effectively for real-world situations.
- Higher information retention: AR learners are more emotionally connected to the content than classroom learners.
  - It offers learners an opportunity to move beyond paper manuals and watching videos to interacting with the robot holograms they will use on the job.
- Sustainable and cost-effective training:
  - Training classes without travel and with faster learning curves.

10 Summary and outlook

This deliverable summarizes the results of the validation and evaluation of the use cases in the 5G-based testbed at the Kista trial site. The most important industry goals have been identified per use case, showing the relevance of the use cases and benefits 5G-enhancement can bring to industrial robotics with respect to productivity, mobility, flexibility, quality, and safety. Different validation scenarios and related KPIs have been defined in order to broadly validate and evaluate the use cases.

The network characterization activity at the trial site showed that network coverage is excellent, and the performance is very stable over the entire shopfloor. This activity also revealed that a careful selection and testing of UE are important, and further development of UEs for industrial usage is expected.

The use case validation showed that mobile robot navigation, mobile robot docking and stationary robot arm's pick-and-place planning are feasible to implement from an edge cloud and with communication over 5G. Also, the lead-through teaching use case was successfully executed over 5G. The AR visualization use case was also validated to work well over 5G, with subjective evaluations only.

It is to be noted that all test results and measured KPIs should be seen in the light that the functional design and implementation for the industrial robotics use cases were prototyped, and the 5G network was based on MBB services, without functionality for, e.g., bounded latency. Despite this, the overall conclusion is that 5G supports the implemented use cases and remains a leading wireless-communication candidate for industrial robotics, which is also an important learning of the project. Furthermore, evaluations at the use-case level and observed variations of communication performance motivate continuation of research around design of robotics systems to be run over wireless networks.

Other important findings for the future are that

- Quality of Service (QoS) functionality was not used in this network for the investigated use cases. It is expected that traffic differentiation would be beneficial when communication load increases, in a larger deployment.
- Bounded latency will likely be beneficial or even required in the future. Even if the overall latency performance is good, occasional packets can be delayed, which is likely related to the fact that bounded latency is not yet supported in the network. In the future operational environment such glitches would not be acceptable, but on the other hand the industry applications may be more adapted to wireless communication, so the issue will be less in the future. Nevertheless, bounded latency functionality is needed for some applications.
- UE selection for commercial deployments/solutions will be critical, both regarding general UE performance and integration aspects, including physical antenna arrangements.
- Synchronization, i.e., using a common time reference in the complete system, including the communication, as well as support for time-synchronization protocols, would enhance performance and efficiency.
- For future applications, communication protocol solutions that are more adapted for use over wireless networks should be considered.

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Appendix

List of abbreviations

3GPP	The 3rd Generation Partnership Project
4G	The Fourth Generation (of cellular network technologies)
5G	The Fifth Generation (of cellular network technologies)
API	Application programming interface
AMR	Autonomous mobile robot
AR	Augmented Reality
BS	Base station
CN	Core network
DL	Downlink
EGM	External Guided Motion
FR2	Frequency range 2
GbE	Gigabit Ethernet
HB	High band
IMU	Inertial measurement unit
LiDAR	Light Detection and Ranging
LTE	Long-Term Evolution
MBB	Mobile broadband
mmWave	Millimeter Wave
NR	New Radio
NSA	Non-standalone Architecture
NTP	Network Time Protocol
OS	Operating System
P&P	Pick and place (operation)
RAN	Radio Access Network
RGB	Red, green, and blue (color model)
ROS	Robot Operating System
RWS	Robot Web Services
SCS	Subcarrier spacing
SLAM	Simultaneous Localization and Mapping
TDD	Time-division duplexing
UE	User Equipment
UL	Uplink

Table 9: List of abbreviations