evolved 5G

EXPERIMENTATION AND VALIDATION OPENNESS FOR LONGTERM EVOLUTION OF VERTICAL INDUSTRIES IN 5G ERA AND BEYOND

[H2020 - Grant Agreement No.101016608]

Deliverable D4.7

Network Apps for Production Line Infrastructures

Editors T.Peyrucain (PAL Robotics), B. Bendris (UMS)

Version 1.0

Date August 31st, 2023

Distribution PUBLIC (PU)

DISCLAIMER

REVISION HISTORY

Revision	*Date*	*Responsible*	*Comment*
0.1	*June, 23rd , 2023*	*G.Makropoulos*	*TOC*
0.3	*July, 12th , 2023*	*Thomas Peyrucain, Bianca Bendris*	*Initial contribution*
0.5	*July, 31st , 2023*	*George Makropoulos*	*First internal review*
0.7	*August, 18th , 2023*	*Javier Garcia*	*Internal review*
0.9	*August, 24th , 2023*	*Thomas Peyrucain, Bianca Bendris*	*Comments addressed*
1.0	*August, 29th 2023*	*Thomas Peyrucain, Bianca Bendris*	*Final document*

LIST OF AUTHORS

Partner ACRONYM	Partner FULL NAME	Name & Surname
PAL	PAL Robotics	Thomas Peyrucain
UMS	Unmanned Life	Bianca Bendris

GLOSSARY

Abbreviations/Acronym	*Description*
CAPIF	*Common API Framework*
NEF	*Network Exposure Function*
POI	*Point of Interest*
ROS	*Robot Operating System*
UE	*User Equipment*
UMA	*Universidad de Málaga*
vApp	*Vertical Application*
QoS	*Quality of Service*
SLAM	Simultaneous Localization and Mapping

EXECUTIVE SUMMARY

The objective of this deliverable is to present in detail the **final prototypes** and the **two integration rounds for testing and validating the use cases** that have been followed for each of the two Network Applications by the two SMEs participating in Task 4.5.

- Initially, the deliverable describes in detail the **final prototypes of the Network Apps** developed within the Production Line Infrastructure (PLI) in the EVOLVED-5G context, driven by Task 4.5:
    - The Teleoperation Network App by PAL Robotics.
    - The Localization Network App lead by UMS with the contribution of PAL as well.
    - Next, the **two cycles of integration activities and use cases testing** that have been followed for each of two Network Applications, are described. The first round of integrations has been carried out with the aim at ensuring seamless and reliable communication between various components within the system, including Network Apps, Vertical Apps (vApp), NEF, CAPIF and 5G network connectivity, on top of the cloud infrastructure provided by the Malaga platform. **The connectivity of 5G with the cloud infrastructure has been verified, specifically the connection between vApps and the 5G network.**
    - The purpose of the second integration round was to validate the use-cases utilizing the final components of the EVOLVED-5G project. On the one hand, NEF, CAPIF and the SDK were enriched with additional features, as described in D3.3 and D3.4. On the other hand, SMEs finalized their Network Apps by enhancing the 3.0 version and using the last versions of NEF, CAPIF and SDK, until the latest version of the Network Apps was finally developed: 4.1. This version 4.1 of the Network Apps also exploited the validation pipeline before the integration test took place. Finally, the Network Apps were deployed in Kubernetes clusters in Malaga premises instead of using Docker containers running locally. With the second round of integration tests, the Networks Apps of the pillar have reached their final stage, interacting with the last versions of NEF and CAPIF through the SDK and communicating with their respective vApp(s). **The three SME use-cases have also been validated** and such results highlight the fact that the Network Apps reached a mature enough state to be used by other SMEs through the EVOLVED-5G Marketplace.

As a final point, in the context of EVOLVED-5G, it is essential to highlight that a terminology update has been implemented. Specifically, the term "Network App" is now being used instead of "NetApp," as initially selected in the first period of the project. This update reflects the shortened form of "Network Application" and has been applied consistently across all project's documents and materials.

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

The current report describes the final prototype of the two Network Apps, namely the Teleoperation and Localization, that have been developed within the Production Line Infrastructure (PLI) pillar, focusing to support the agile production line infrastructure using robotics and is driven by Task 4.5. The report provides details on the development of the final prototype (version 4.1) while utilising the final version of the tools (SDK, NEF, CAPIF) developed within the EVOLVED-5G framework. Moreover, the report contributes to the testing and evaluation of the use cases, described in the previous deliverable of WP4 (D4.2), through the integration activities that took place in Malaga's infrastructure focusing on the iterative validation of 5G connectivity and communication between components (5G network <–> Network Applications <-> Vertical Applications).

1.2 STRUCTURE OF THE DOCUMENT

The core part of the document is divided into the following sections:

Section 2 presents the overall Production Line Infrastructure (PLI) pilar framework, focusing on goals, challenges and specificities.

Section 3 describes the finalized version of the PLI Network Apps (version 4.1). It starts with a reminder of the Network App use-case(s), providing a brief overview of the scenarios to be tested. Following that, the section delves into the technical architecture, features, and dependencies of each Network App.

Section 4 provides an overview of the two rounds of integration activities that took place, along with the results and takeaways. The first reported test was performed with intermediate version of Network Apps and components (NEF, CAPIF and SDK) while the second test was performed with final versions of Network Apps and components.

Finally, chapter 5 discusses the conclusion and next steps.

1.3 TARGET AUDIENCE

The release of the deliverable is public, intending to share the details of the final prototypes of the Network Apps, among a wide variety of research individuals and communities.
Different target audiences for D4.7 are identified as detailed below:

- **Project Consortium**: To validate that all objectives and proposed technological advancements have been analysed and to establish a common understanding among the consortium with regards to:
    - The final development of the Network Apps within Task 4.7 and the results derived from the implementation of the uses cases.
- **Industry 4.0 and FoF (factories of the future) vertical groups:** To crystallise a common understanding of technologies, and tools that were used for the development of the Network Apps. A non-exhaustive list of Industry 4.0-related groups is as follows:
    - Manufacturing industries (including both large and SMEs) and IIoT (Industrial Internet of Things) technology providers.

  - European, national, and regional manufacturing initiatives, including funding programs, 5G-related research projects, public bodies and policy makers.
  - Technology transfer organizations and market-uptake experts, researchers, and individuals.
  - Standardisation Bodies and Open-Source Communities.
  - Industry 4.0 professionals and researchers with technical knowledge and expertise, who have an industrial professional background and work on industry 4.0 areas that leverage robots and advanced production line infrastructure for enhanced efficiency and innovation
  - Industry 4.0 Investors and business angels.
- **Other vertical industries and groups**: To seek impact on other 5G-enabled vertical industries and groups in the long run. Indeed, all the architectural components of the facility are designed to secure interoperability beyond vendor specific implementation and across multiple domains. The same categorization as the above but beyond Industry 4.0 can be of application.
- **The scientific audience, general public and the funding EC Organisation:** To document the work performed and justify the effort reported for the relevant activities. The scientific audience can also get an insight of the progress towards the final prototype of the Network Apps.

2 Context of the PLI Pillar

The aim of the robotic pillar is to use the 5G technologies and the Network Applications (Network Apps) alongside mobile robots to support “Factory Automation and Indoor Logistics” in an agile production line. Two aspects of a production line are highlighted in this pillar: the teleoperation and tele-maintenance tasks using the TIAGo robot, the mobile manipulator provided by PAL Robotics; the orchestration of a fleet of mobile robots to enable the centralized control of autonomous mobile robots to perform logistics tasks in the agile production line. Before going into details about the two cases highlighted in the production line, when we talk about indoor mobile robots, one has to consider that indoor localization and mapping is a key enabler for pervasive use of robotic solutions. Simultaneous Localization and Mapping (SLAM) is the standard mathematical framework for iteratively optimizing 1) the trajectory (sequence of poses) or dynamics of a robot based on the predictions of its motion model as well as on the observations such as laser range, visibility or position of landmarks, odometry information coming from the wheels and 2) the position of the landmarks and the map itself. But sometimes the localization mechanism fails, and the robot needs to use several strategies to try to be able to relocate itself.

The integration of 5G technology introduces a promising advancement in global localization, offering the potential to significantly enhance robot localization accuracy, achieving levels of 1 meter or even higher precision. Such technological progress holds immense value for global localization of robots within industrial buildings. Accurate robot localization and environment awareness are crucial aspects that must be taken into consideration for all mobile robots operating indoors in a production line, so it is a common need for the whole robotic pillar.

The aim of the teleoperation use case applied to the TIAGo mobile manipulator of PAL Robotics is to develop an industrial internet telecontrol architecture for robots in a production line. The main objective is to realize teleoperation and tele-maintenance tasks, which on the one hand meet user needs of the industry partners and on the other hand can be performed over the 5G communication infrastructure. While teleoperation of technical highly sophisticated systems has already been a wide field of development, especially for space and robotics applications, the automation industry has not yet benefited from its results. Besides the established fields of application, remote accessibility is becoming crucial for production lines equipped with industrial robots and the surrounding facilities. This is especially critical for maintenance or if an unexpected problem can’t be solved by the local specialists. This problem was stressed even more during the current COVID-19 pandemic situation. Special machine manufacturers, especially robotics companies, sell their technology worldwide. Some factories, for example in emerging economies, lack qualified personnel for repair and maintenance tasks. When a failure occurs, an expert of the manufacturer needs to fly there, which leads to long down times of the machine or even the whole production line. With the development of data networks, a huge part of those travels can be omitted, if appropriate teleoperation equipment is provided. But, to enable data transmission over the network for teleoperation, an infrastructure to guarantee some specific constraints of bandwidth, security and service priorities, is required. The 5G Non-Public Networks seem to be the ideal candidate technology to fulfil this challenge.

For the Production Line Infrastructure (PLI) pillar, the EVOLVED-5G project represents the opportunity to address the current limitations related to network capacities.

The two Network Apps developed during the project's lifetime, aim at addressing the challenges mentioned above and facilitate the adoption of 5G for other stakeholders interested in Industry 4.0 and robotics.

3 FINAL PROTOTYPE OF NETWORK APPLICATIONS

3.1 TELEOPERATION NETWORK APPLICATION

3.1.1 Use case description

The Teleop Network App developed by PAL Robotics focuses on the Quality of Service (QoS) of the network during a teleoperation task where a remote robot (TIAGo) needs to execute a grab and relocate operation, hence allowing for the remote management of robot's connectivity to 5G. In particular, the use case reflects the functionality of the final prototype of the Network App is a teleoperation task where a TIAGo robot needs to perform a pick and place task while being teleoperated remotely due to the risks of the environment or of the objects to be manipulated.

Indeed, TIAGo is equipped with a force torque sensor on the wrist to provide haptic feedback to the user via a haptic device. This use case requires a connection that is stable, well performing and that can be always guaranteed during teleoperation.

With 5G, we can achieve incredibly low latency, which means our robots can respond in real-time, enabling precise and immediate actions. The high bandwidth of 5G empowers us to transmit vast amounts of data seamlessly, allowing our robots to process and analyse information faster than ever before. And, of course, the reliability of 5G ensures a consistent and stable connection, which is required for the seamless teleoperation of our robots.

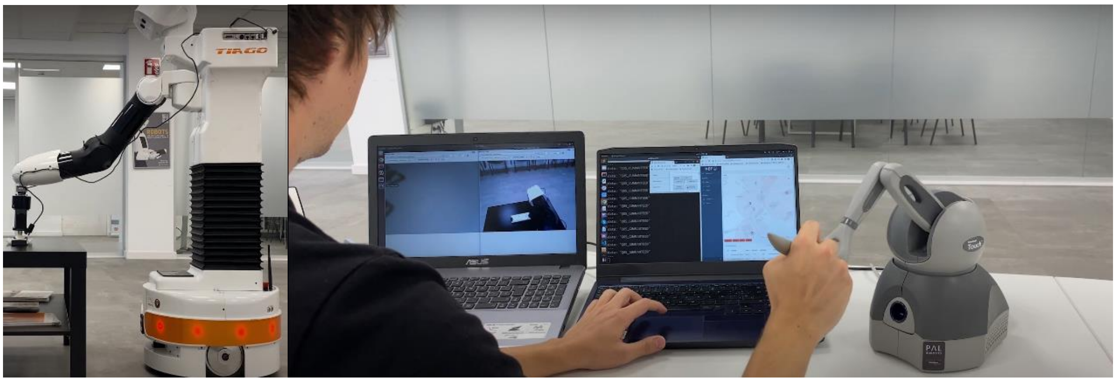

Figure 1 PAL robotics vertical application

With the Network App, Quality of Service (QoS) monitoring and additionally the request of customised connectivity performance to guarantee a seamless user experience in teleoperation can be achieved. The Network App empowers the robot with an enhanced level of safety and reliability during teleoperation. The latter are achieved by enabling the robot to proactively halt its operations whenever the quality of connectivity is compromised. This action effectively prevents any behaviour that could potentially pose risks to the environment due to issues like latency or lack of force feedback.

3.1.2 Detailed Architecture

The latest iteration of the architecture introduces several additions that significantly elevate the robot's capabilities. Among these enhancements is the seamless integration of the latest versions of NEF and CAPIF tools and the TSN APIs.

- From one side a computer is connected to a haptic device and a video stream of the different cameras of the TIAGo is shown (head camera and endoscopic camera) This cockpit allows the user to interact with the environment through the robot. This computer was then connected the UMA's private 5G thanks to a provided 5G modem with fixed IP and path through enabled.
- On the other side the robot was also equipped with a provided 5G modem with fixed IP and path through enabled. That allowed for both modems to be able to exchange messages in both ways as required by the vertical application
- On the Kubernetes server the customized CAPIF and NEF was deployed together with the Teleoperation Network App. The output rostopic of the Teleoperation Network app that shows the QoS can then be accessed by the robot.
- This new version of the Teleoperation Network App can also request a TSN profile at startup. This profile is set up based on the requirements for a proper video feed and a latency that allows seamless teleoperation

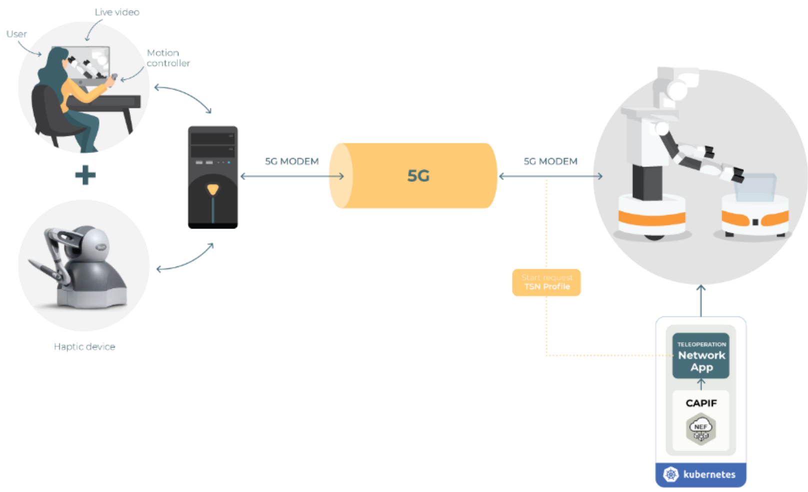

Figure 2 Architecture of the Teleoperation Network Application

3.2 Localization Network Application

The localization Network app, combined with a 5G network deployed in an indoor environment offers many advantages for safe and adaptive robot navigation in industrial-like environments. By utilizing the high-speed data transmission and low-latency communication of 5G, the application ensures real-time and accurate position updates for robots operating in production lines.

One key advantage of the localization Network app is its ability to enhance the robot's behaviour based on its position within the environment. By leveraging the capabilities of a 5G network, the application enables the robot to determine to which 5G cell it is connected. This feature allows the robot to adapt its behaviour based on the specific zone it is operating in. It can be used to tailor the robot's navigation in complex industrial environments, optimizing path planning, and avoiding collisions with obstacles or human workers. Additionally, the integration of a 5G cell network provides extensive coverage, ensuring a reliable and continuous connection between the robot and the network. This eliminates potential blind spots and guarantees uninterrupted communication, enhancing the reliability and effectiveness of the localization network application.

Two different use cases have been set-up to test the localization Network App:

3.2.1 Use case description (I): Adaptative Speed Control

1. The first use case consists of one Tiago robot which autonomously navigates in an indoor environment. The robot changes its speed depending on the area it is in (Free area or Crowded area). A lower speed is used when the robot finds itself in an area defined as crowded, while a higher speed is being used in an area defined as free. Thus, the robot traverses the indoor environment, switching from one area to the other. Each time a change of area is detected, the robot moves at the predefined velocity for each zone.

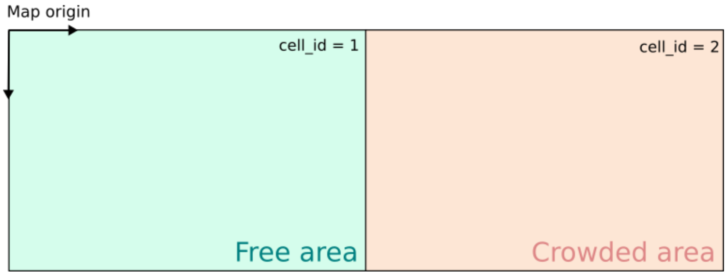

Figure 3. Cell ID configuration for the Adaptive Speed Control use case

3.2.2 Use case description (II): Autonomous Package Delivery

The second use case consists of one Tiago robot and one MiR250 robot which autonomously navigate through an indoor environment. In this use case, the Tiago delivers one item on top of the MiR250. Three distinct areas (identified as cell IDs) are defined as can be seen in the figure below:

- <u>Intake</u>: in this area the Tiago robot starts the mission and collects the package that needs to be delivered on top of the Mir250
- <u>Transition</u>: in this area the package is passed from the Tiago robot to the MiR250
- <u>Delivery point</u>: in this area the Mir250 starts the mission as well as deliver the package

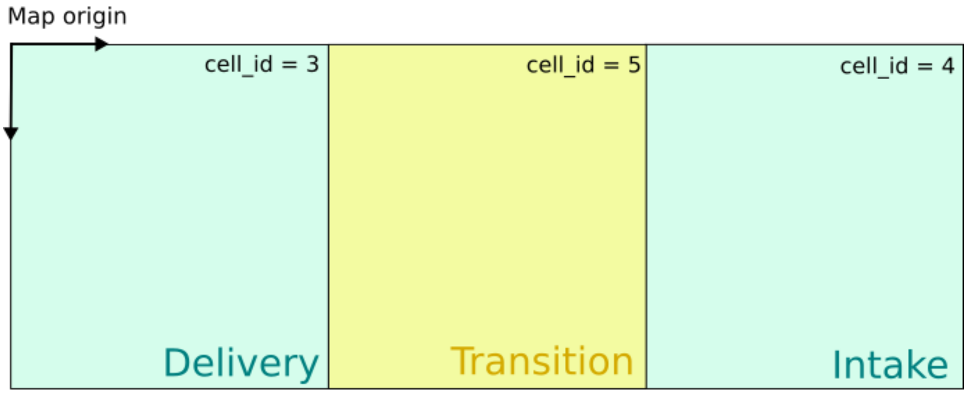

Figure 4. Cell ID configuration for the Autonomous Package Delivery

The mission starts with the MiR250 robot going from its start location in the *Delivery* area to a predefined point in the *Transition* area. Once the MiR250 is connected to the cell 5, the Tiago robot starts its mission. It grabs a package and delivers it to a predefined location where the MiR is located. It then drops the package on the Mir and returns to its initial location. Then the MiR robot delivers the package to a predefined point in the *Delivery* area.

The Tiago robot is aware of the area in which it is and the task it needs to perform in each area. This information is retrieved from the cell id of each zone.

3.2.3 Detailed Architecture

With respect to the architecture detailed in Deliverable D4.2, the Localization Network App has maintained its foundational elements while incorporating necessary adjustments to accommodate the changes introduced in the latest versions of the EVOLVED-5G SDK (v1.0.8).

The communication process between the Network App and the NEF Emulator for retrieving location information remains largely unchanged. The Localization Network App and the NEF Emulator utilize REST API calls to establish communication between them. However, there is a difference in the authentication procedure when the Network App connects to the NEF. Instead of utilizing a security token provided by the NEF, the Network App now employs the token provided by the CAPIF. To make this possible, the CAPIF on-boarding and registration process has been added to on-board the Network App on the CAPIF.

Furthermore, the Network App has been enhanced to retrieve location information for multiple User Equipment (UE) devices. Although the current use cases involve two robots (two UEs), as outlined in the previous section, this capability can be easily scaled to accommodate any desired number of robots.

The location information obtained from the NEF is then transmitted to the Vertical App, represented in this context by the Orchestration Platform and the two robots involved in the use cases. The Localization Network App utilizes ROS 2 to transmit the cell ID information to the robots. For a visual representation of the architecture, please refer to Figure 5, which provides an overview of the system's components and their interactions.

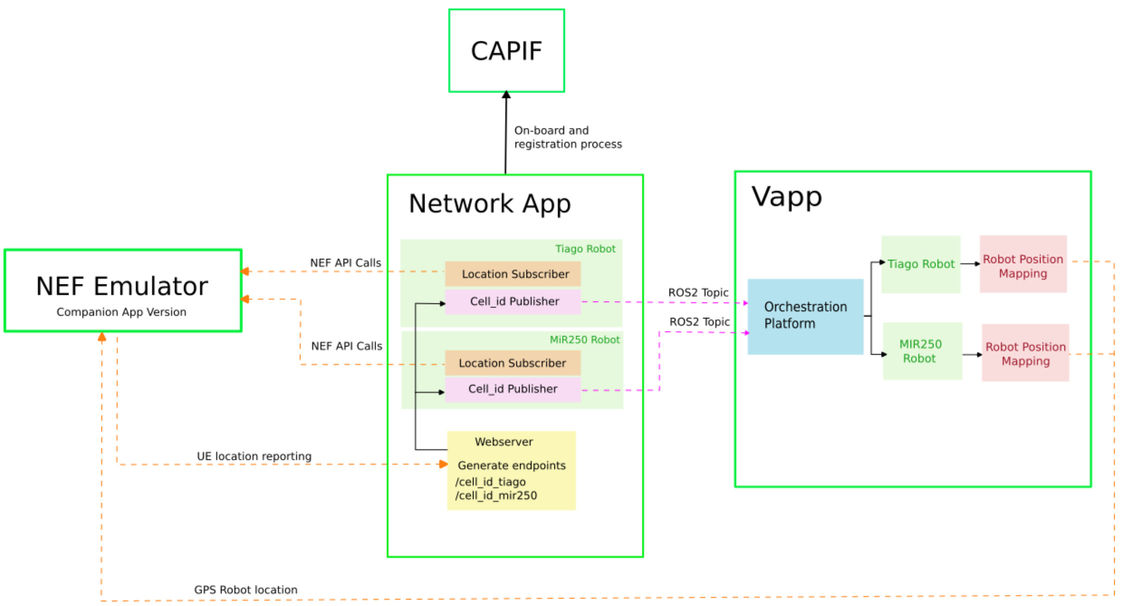

Figure 5. Architecture of the set-up showing main connections among CAPIF, NEF, Network App and vApp

To be able to test the Localization Network App with real robots, the NEF Emulator deployed is the enhanced version developed by the partners at the National Centre for Scientific Research “Demokritos" (NCSRD). This version enables the transmission of external GPS positions to govern the movement of the User Equipment (UE) within the simulator via a companion application developed by INFOLYSIS. The companion app provides the GPS coordinates of the UE to the NEF emulator, which allows for dynamic movement of the UE. It has been specifically designed for Android devices and requires GPS availability (outdoors) as well as connectivity to the NEF emulator via either Wi-Fi or a mobile network. However, in this case, this feature is used to send the real robots' positions to the NEF Emulator. To achieve that, the local robot positions are mapped to GPS coordinates and conveyed to the NEF Emulator. Consequently, each robot is treated as an individual UE, resulting in the emulation of two UEs within the NEF Emulator, mimicking the real robots' behaviour within the indoor environment. This piece of software was connected to each robot as shown in Figure 5. On the NEF Emulator’s web interface this position can be visualized as depicted in the figure below (Figure 6).

Figure 6. NEF Emulator view of defined 5G Cells. The positions of the two UEs are also represented by the grey marker

4 INTEGRATION ACTIVITIES AND USE CASE TESTING

4.1 PURPOSE OF THE INTEGRATION TESTS (1ST ROUND)

The primary objective of these integration tests was threefold:

- to verify the connectivity of 5G, specifically the connection between vApps and UMA's 5G network.
- To assess the overall communication among CAPIF, NEF, the two Network Apps, and their corresponding vApp, as well as the 5G connectivity with the cloud infrastructure.
- To enable conducting real-world testing of the EVOLVED-5G use cases and validating the communication across all components.

In the initial phase of the integration testing, the overall setup was implemented within the cloud infrastructure of the Malaga platform at UMA premises and the following components were utilized:

- Network Applications v3
- NEF v1.6.2

- CAPIF v2
- SDK v0.8.7

4.2 Topology and Setup

4.2.1 Teleoperation Network Application

The set up used involved two routers connected in a way that both can ping each other so that ROS topic that contains the Quality-of-Service message can be read from the robot. The Geomagic device was connected to a computer. The other computer was running locally the NEF, CAPIF and the simulation of the robots.

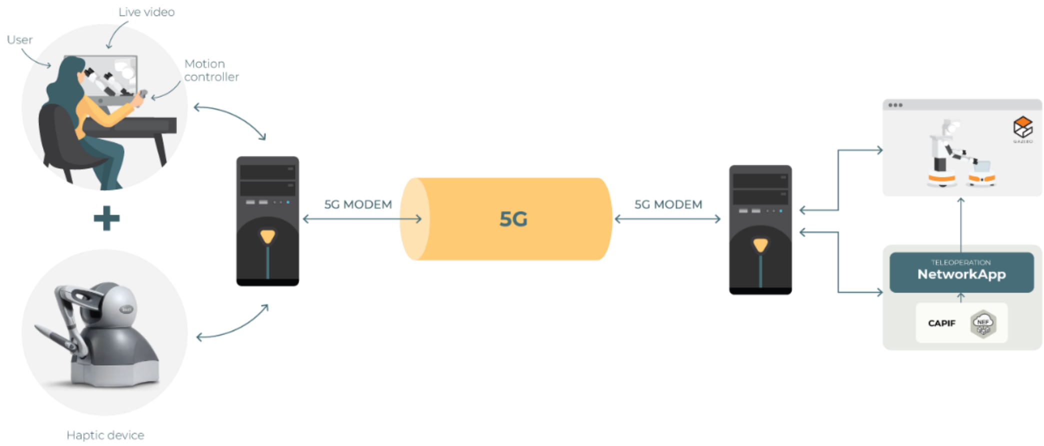

Figure 7 Topology and Setup of Teleoperation Network Application

The NEF was onboarded to CAPIF and 3 UEs were created to simulate the loss of the QoS when 2 UEs arrive on the same cell.

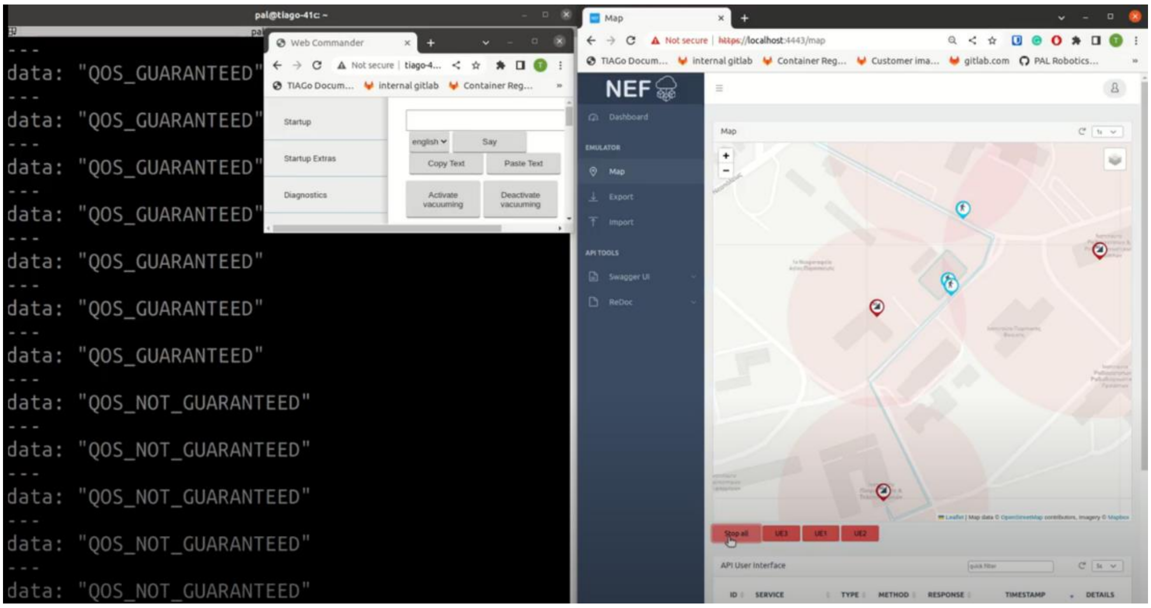

Figure 8 NEF onboarding to CAPIF and tested scenario in NEF emulator

4.2.2 Localization Network Application

The CAPIF, NEF Emulator and Localization Network App were manually deployed on the UMA Servers. The server was connected to the UMA 5G core. On the other hand, the software that would run on-board the robots were running on a mini-PC recreating the Vertical App. The embedded 5G modem allowed the connection of the PC with the 5G core via the dedicated SIM card provided by UMA. A schematic view of this set-up is shown in Figure 9.

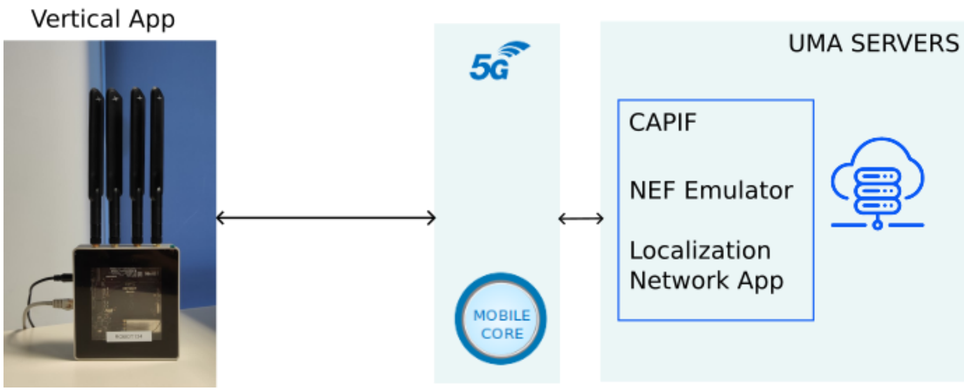

Figure 9. First integration tests set-up.

4.3 Results and Takeways

4.3.1 Teleoperation Network Application

To evaluate teleoperation performance in the context of the EVOLVED-5G project, we dispatched the haptic device to Malaga alongside a computer for simulating the robot. The connectivity between the Vertical Application, NEF and CAPIF was tested. The results were conclusive.

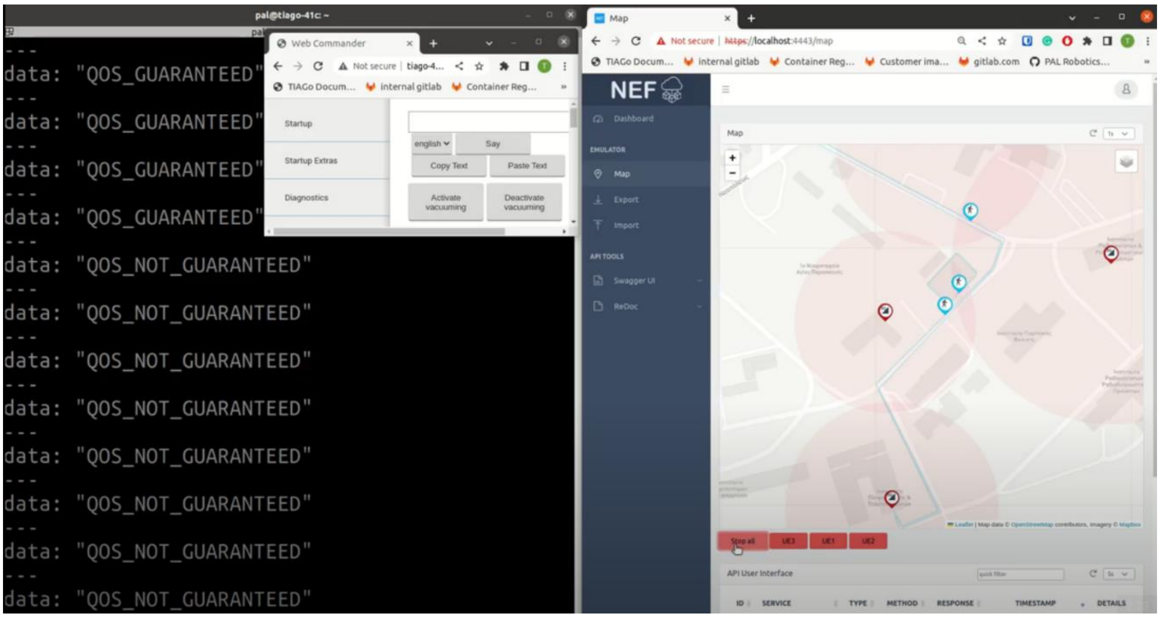

Figure 10 Teleoperation Network App performance

The successful teleoperation experience can be attributed to the collaborative efforts of EVOLVED-5G's components, including CAPIF and NEF, along with the effective deployment of UMA's private 5G network. This achievement was made possible by the combination of low latency and high bandwidth inherent in 5G technology, particularly in the seamless connectivity established between the virtual application (vApp) and UMA's private 5G deployment. Dedicated teleoperation assessments were carried out to ensure that user experience aligned with predetermined criteria and that the Quality-of-Service message transmission was reliable, enabling precise control and stopping of the robot whenever the QoS was not guaranteed.

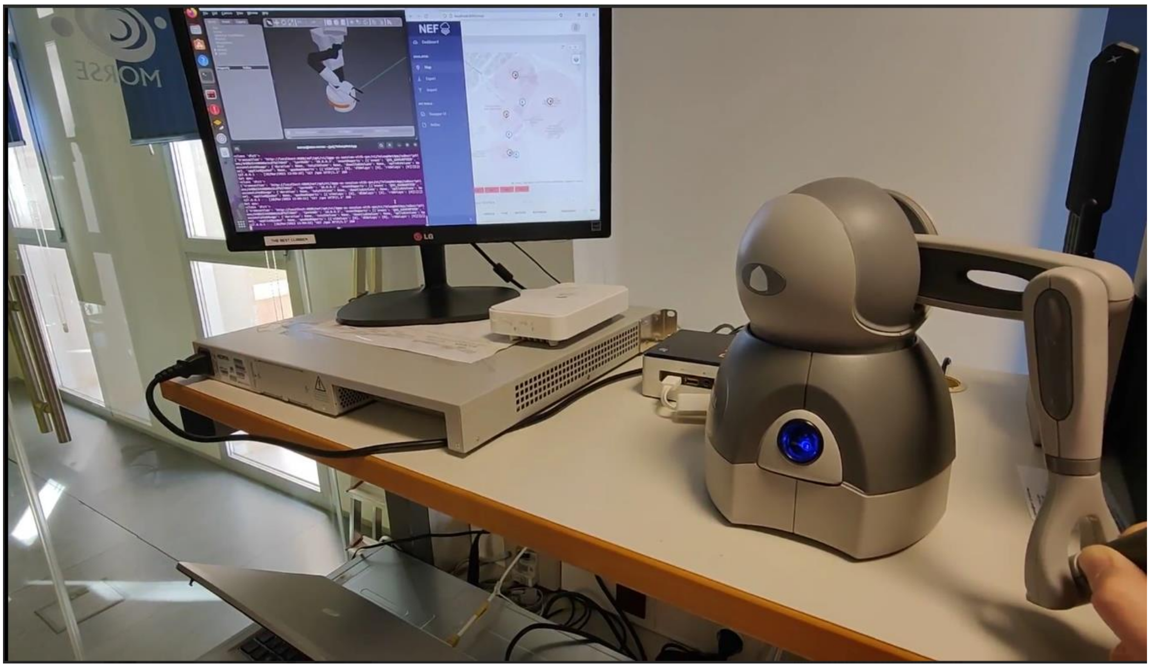

Figure 11 Geomatic device in Malaga premises

4.3.2 Localization Network App

In order to evaluate the Localization Network App, two different tests were conducted using the setup described in the previous section. These tests focused on the connectivity between the vApp and the UMA Servers, as well as the communication between ROS 2 nodes.

1) **Connectivity test between vApp and UMA Servers**

The objective of this test was to validate the connectivity and data exchange between the vApp running on the mini-PC and the UMA Servers. The following steps were executed:

a) *Test Configuration*: The 5G modem onboard the mini-PC was configured to connect to the 5G core. A local IP address was assigned to the PC:

- Mini-PC IP: 10.11.65.65
- UMA Servers IP: 10.11.23.138

b) *Connection Establishment*: The connection and communication between both devices was checked as follows:

Figure 12. Latency results gathered by testing connectivity from vApp to UMA Servers

The vApp was able to reach the UMA servers through the embedded 5G modem. The connection was uninterrupted showing an average latency of 20 ms.

2) ROS 2 node communication

The second test aimed to validate the communication between different ROS 2 nodes within the system; one node was running on the vApp while the other one was running on the Localization Network App.

a) *ROS 2 Network Setup*: The ROS 2 network was configured, ensuring that all nodes were connected and capable of communicating with each other. The necessary ROS 2 configurations, such as node discovery and message serialization, were implemented.

b) *Node Interaction*: Once the Network App and the vApp were up and running, the message exchange was checked. The Network App contains a simple ROS 2 publisher which continuously monitors and publishes the cell id to which a certain user in the NEF is connected. The vApp has a ROS 2 subscriber node which reads the value of that cell id.

As seen in Figure 13, the communication between these ROS nodes was correctly established.

Figure 13. ROS 2 nodes communication results. On the left, the data sent by the publisher node is shown. On the right, the data reaching to the subscriber node is shown.

4.4 Purpose Of the Integration Tests (2nd Round)

The purpose of the second round of integration tests was to validate the use-cases with the final components of EVOLVED-5G. On the one hand, NEF CAPIF and the SDK had been enriched with additional features. On the other hand, the two SMEs involved in the PLI pillar, namely PAL and UMS, had also finalized their Network Apps by expanding the 3.0 version and using the final versions of NEF, CAPIF and SDK. The final prototype (v4.1) of the Network Apps was also completed and used the validation pipeline before the integration test. As a change from the previous approach, the Networks Apps were deployed in the Kubernetes cluster of UMA's premises instead of using the cloud infrastructure.

It's worth noting that until the end of WP3, it was deemed necessary for the SDK to undergo some minor improvements, primarily aimed at enhancing functionality and addressing specific bugs. During this second integration round, the final version of components was utilized:

- Network Applications v4.1
- NEF v2.2.2 (Companion App Version)
- CAPIF v3.1.2
- SDK v1.0.8
- TSN 1.2.1

4.5 Topology and Setup

In this pillar, both vApps had to be physically deployed at the University of Málaga (UMA) as real robots were part of the use case. The tests took place on the ground floor of the building, where a part of the corridor was reserved for the testing of the use cases (see Figure 14).

Figure 14. Testing area at UMA (Malaga)

4.5.1 Teleoperation Network Application

For the second round of test the TSN was integrated in the Network app to request a certain profile to match the requirement for a seamless teleoperation.

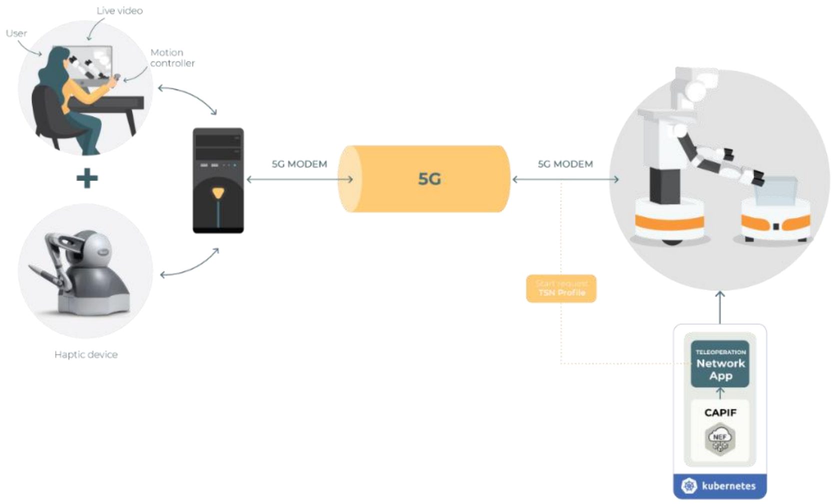

Figure 15 Topology and setup of Teleoperation Network App during the second round of integration activities

During the second set of integration tests, the Teleoperation Network App was operational alongside the NEF Emulator and the CAPIF within a Kubernetes cluster located at UMA premises. The Teleoperation Network App was hosted within a Kubernetes pod, which had an external IP address made accessible to facilitate interaction with other services.

Thanks to this set-up TIAGo was able to access the Quality of Service through the ROS topic /qos and react to the change.

The TSN SDK was also added to the Network App in order to request a certain profile to perform seamless teleoperation.

4.5.2 Localization Network Application

For the 2nd round of integration tests the Localization Network App together with the NEF Emulator and the CAPIF were running on a Kubernetes cluster at UMA premises. The Kubernetes pod where the Network App was running had an external IP exposed so that other services could access it.

The connection between the vApp and the 5G core was established using a Zyxel 5G modem, which was equipped with a 5G SIM card provided by UMA. In this case, the vApp consists of one laptop acting as the orchestrator plus the Tiago and MiR250 robot. The laptop is directly connected to the 5G modem through a wired connection, while the two robots are linked via Wi-Fi to a hotspot generated by the laptop. This configuration was selected due to the relatively short distance the two robots needed to cover from the laptop, making a Wi-Fi connection suitable for meeting the required connectivity demands.

Figure 16 illustrates the complete connection scheme employed for this use case. As can be seen, the laptop serves as the central hub, running all the essential software required to control and orchestrate the two robots. In this case, there is an additional complexity as one of the robots uses ROS 1 while the other one uses ROS 2. To facilitate seamless communication between the two ROS versions, a bridge module is incorporated.

For each robot, a Hardware Abstraction Layer (HAL) is employed, enabling the transmission of commands to the robots and the reception of vital data, such as their position and state. All these modules interact with a Mission Handler layer, which acts as a centralized information hub, managing the missions assigned to the robots. Additionally, this layer receives the cell id information from the Localization Network App.

Simultaneously, the Robot Position Mapping takes the Cartesian position of the robots and converts it into a GPS position, which is then fed into the NEF Emulator, allowing the UEs to traverse the same path as the real robots. Using this set-up, both the Adaptive Speed Control use case, as well as the Autonomous Robot Delivery use case have been demonstrated.

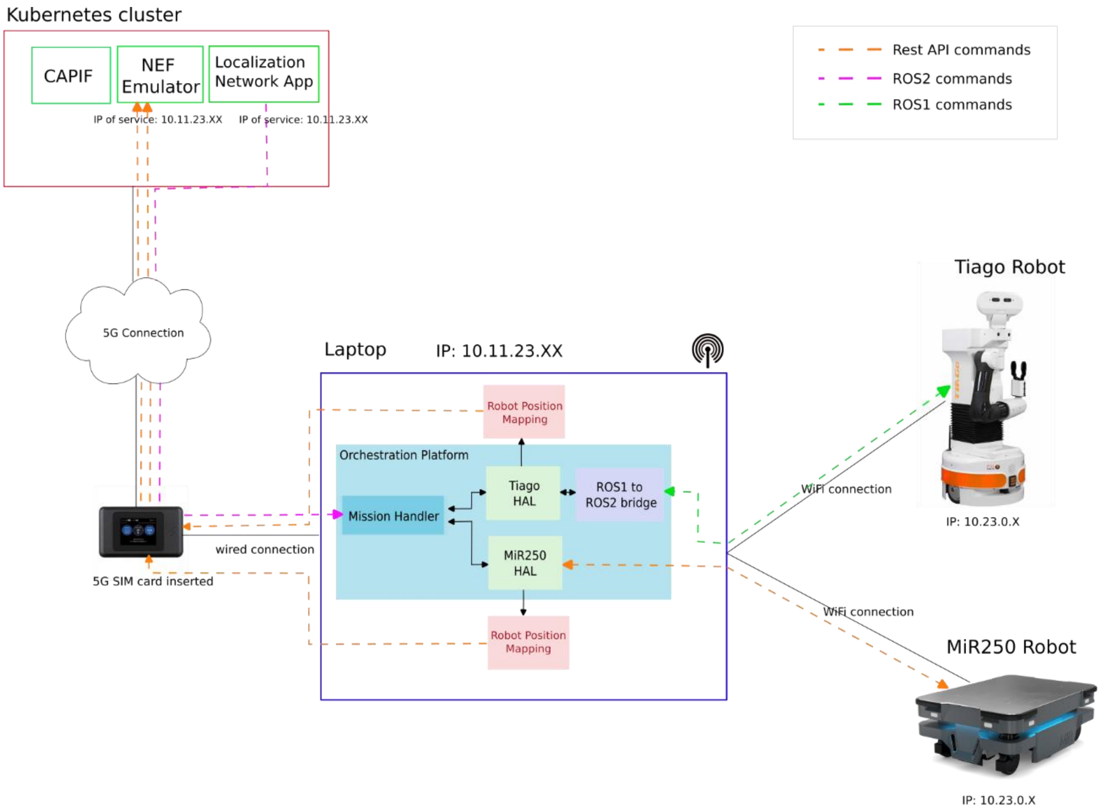

Figure 16. Final architecture and set-up for the second integration tests

4.6 Results and Takeaways

4.6.1 Teleoperation Network Application

In the picture in section 4.2.1, you can see how the computer and the robot are connected using two 5G modems.

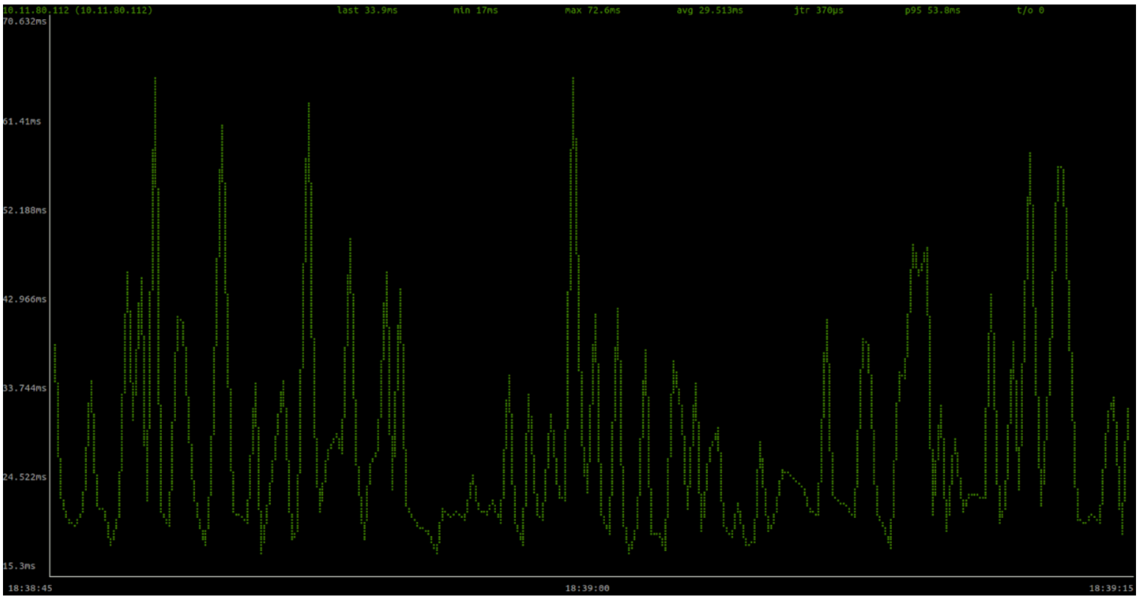

Figure 17 Connection between the computer and the robot

During a 30-second evaluation of this connection's performance, an average latency of 17 milliseconds was observed. Sometimes, there were short moments when the latency increased. The longest latency was 72.6 milliseconds, but this didn't happen too often. Most of the time, the latency was around 29 milliseconds.

Examining the consistency of latency over time, it remained within a 370-microsecond range of variance. This observation highlights the reliability of communication between the computer and the robot.

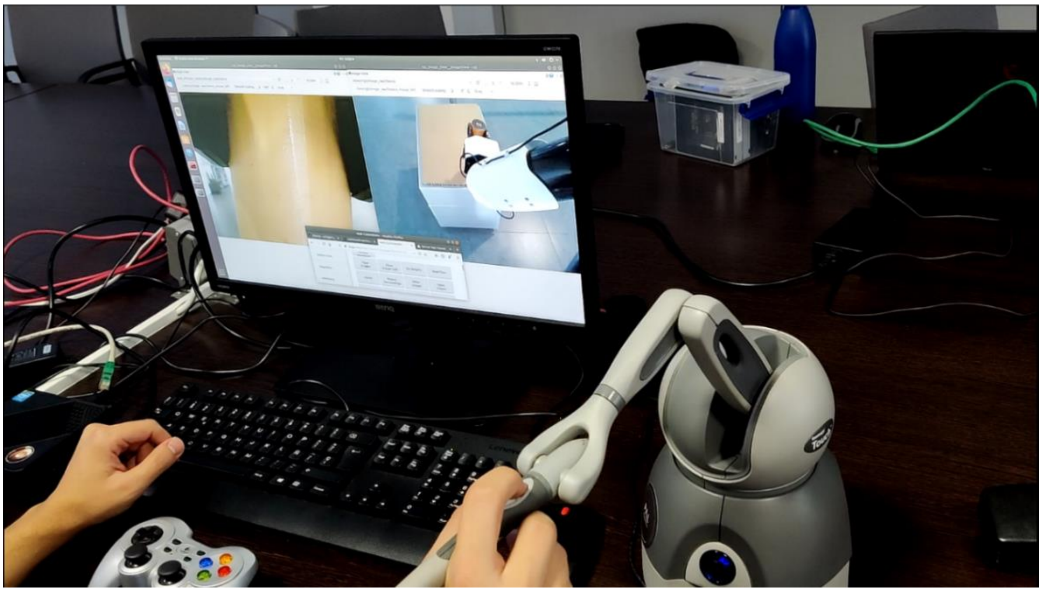

Figure 18 Teleoperation of the robot (Cockpit side)

This illustration depicts the cockpit side of the teleoperation, presenting the visual input from both the camera head and the endoscopic camera attached to the gripper. Accompanied by the employment of a haptic device (Geomagic Touch), this setup enables favourable viewing angles. With some training, it facilitates effortless object manipulation and grasping.

Figure 19 Teleoperation of the robot (Robot side) at UMA premises

The test done shown a seamless teleoperation of the robot and the robot stopped accordingly when the quality of service was not guaranteed.

Testing of the full TSN functionality was hindered by the specific configuration of the vertical application. To ensure accurate testing, separate TSN computers were required for the computer and robot connection. However, the current setup didn't allow successful pinging from the teleoperation laptop to the robot.

Furthermore, the final IP pass-through from the second TSN computer encountered difficulties in correctly redirecting traffic from the haptic device to the robot.

This situation provides valuable insights for potential enhancements, encouraging iterative testing and refinement. By addressing these challenges, we can pave the way for a more effective TSN setup in the future. The TSN server will nevertheless be tested with the bandwidth that the vertical app is transferring with the video feed and haptic feedback messages.

4.6.2 Localization Network Application

The Localization Network App was tested successfully at UMAs premises. Once all the modules were deployed, the connection between the vApp and the Network App was correctly established, allowing both robots to receive the ID of the simulated 5G cell to which each was connected. Bandwidth and latency tests have been performed between the vApp and the Network App to check the quality of the 5G connection. The results are shown in the table below.

Table 1. Latency and Bandwidth measured between Network App and vApp

	Bandwidth (MBytes)	Latency (ms)
Uplink	10.86 ± 0.1	38.28 ± 13
Downlink	12.11 ± 4.6	42.78 ± 17

The data shown above reflects the reliability of the 5G core set-up by the partners in UMA. The minimum requirements for the entire system to function properly are at least 5 Mbits/s or bandwidth and approximately 50 ms of latency. The measured values fulfil the necessary criteria for a successful deployment. Adaptive Speed Control

In this use case, the Tiago robot received instructions to move from one end of the testing area to the opposite end and return (refer to Figure 14). The NEF Emulator was set up with two 5G cells positioned at each end of the testing area, causing a cell shift as the Tiago robot traversed the space. Simultaneously, the robot position was mapped to GPS coordinates and sent to the NEF Emulator as seen in Figure 20.

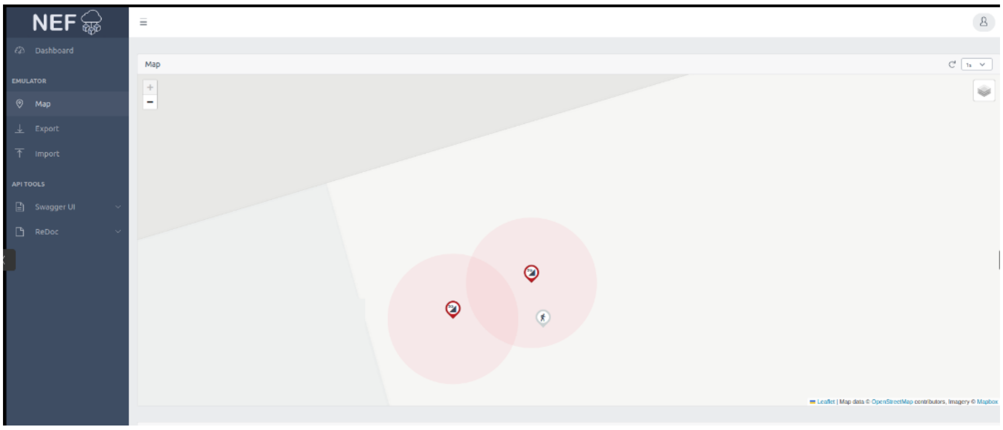

Figure 20. NEF Emulator view of 5G cells set-up and the UE representing the Tiago robot.

Figure 21 a) depicts the Tiago robot under Cell ID 1 which was considered a free area. The robot then moved towards the other side of the testing area (Figure 21 b) where Cell ID 2, signifying a crowded area, was located. Subsequently, the robot returned to the free area (Figure 21 c – d).

As described in previous sections, Cell ID number 1 indicated a free area where the robot could travel at a faster speed (~ 0.5 m/s), while Cell ID number 2 denoted a crowded area necessitating a slower speed (~ 0.25 m/s).

Figure 21. Adaptive Speed Control deployment. a) Tiago starts at initial point under Cell ID 4. b) Navigates towards end point at high speed (free area). c) Slows down as it reaches the end point under Cell 5 (crowded area). d) Navigates back to the start point moving slower until it shifts back to Cell 4 (free area)

This initial use case exemplifies the smooth connection and integration of all pertinent components (vApp, Network App, NEF, CAPIF, and SDK), showcasing the utilization of the latest versions and advancements of each tool in development. The successful speed adaptation of the Tiago robot is evident from Figure 22. Initially starting under Cell ID 1, the robot accelerated up to a consistent speed of around 0.4 m/s. However, upon the shift in cell ID, the robot adjusted its speed, limiting it to approximately 0.25 m/s. This ensured the robot maintained a safe and slower speed, given that the area was deemed crowded.

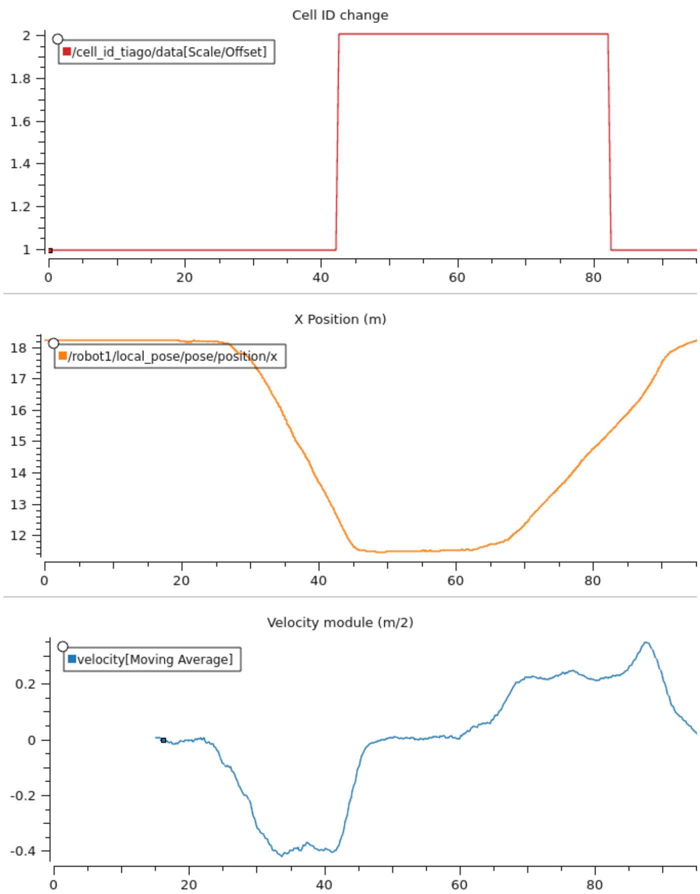

Figure 22. Graphs showing the Cell ID shift, the X position of the robot while it was crossing from one area to the other as well as its change in velocity due to the Cell ID shift.

4.6.2.1 Autonomous Package Delivery

In order to implement this use case, the robots were required to autonomously navigate through the indoor environment, reaching specific predefined Points of Interest (POIs). To accomplish this, the environment was initially mapped by both the MiR and the Tiago robots. The maps generated by each robot, along with their respective POIs, are depicted in the figure below.

Figure 23 a) shows the map of the MiR250 robot, highlighting the defined path containing the following POIs:

- *Charging point*: location where the robot can go and recharge in case of low battery
- *Delivery point*: location where the robot needs to take the package once it has been collected
- *Intake point:* location where the robot must go and await Tiago's delivery of the package

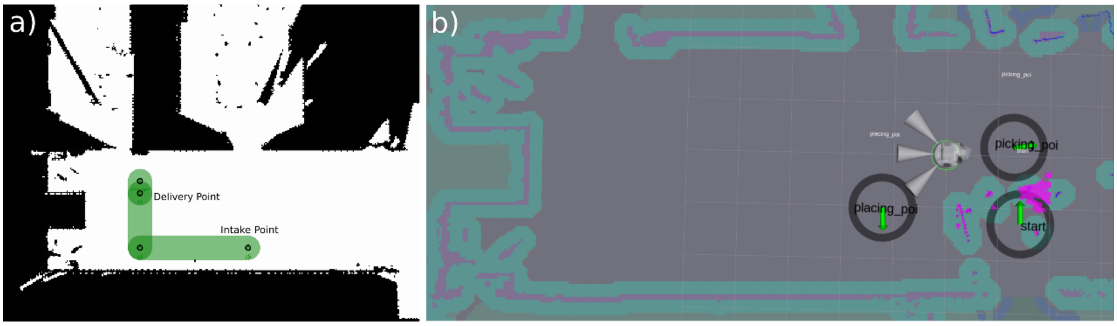

Figure 23. Environment maps. a) Map generated by the MiR robot along with the defined path for the autonomous package delivery. b) Map loaded on the Tiago robot along with the three main POIs defined

Figure 23 b displays the map of the Tiago robot, presenting its specific POIs:

- *Start point:* this serves as the initial location of the Tiago robot
- *Pick-up point*: location where the robot needs to go and pick up the object that must be delivered
- *Placing point:* location where the robot must travel and carefully place the object onto the box located atop the MiR robot

Using this configuration, several automated package deliveries have been successfully executed. Figure 24 provides an overview of the different stages involved in this use case.

1. Figure 24 a) illustrates the MiR robot navigating towards the designed Intake point (notice the blue light of the robot meaning that the robot is navigating towards a point)
2. Figure 24 b) illustrates the MiR robot having reached the Intake point, indicated by the green light displayed on the robot. Meanwhile, the Tiago robot remains at its starting point.
3. Figure 24 c) depicts the Tiago robot reaching the Pick-up point and positioning itself to pick up the designated object.
4. Figure 24 d) shows the Tiago robot successfully grasping the object.
5. In Figure 24 e), the Tiago robot is seen navigating towards the MiR robot, carrying the object for delivery.
6. Figure 24 f)-g) showcases how the Tiago robot aligns itself with the MiR robot and places the object securely within the box.
7. In Figure 24 h) the Tiago robot returns to the Pick-up place, preparing for another delivery, while the MiR robot begins its navigation towards the Delivery point.
8. Finally, Figure 24 i) illustrates the MiR robot reaching the Delivery point, where a human operator is expected to retrieve the package.

Figure 24. Autonomous package delivery deployment. Images from a) to i) show the different stages of the delivery.

The robot's trajectories as well as the cell ID shifts that the robots experimented while performing this use case are shown in Figure 25. The information regarding the connected cell ID provided valuable insights and awareness regarding the specific tasks the robots were assigned in different areas.

For instance, when Tiago was connected to cell ID 5, it marked the moment when it had to place the object on the MiR. On the other hand, for the MiR, being connected to cell ID 5 indicated the need to wait for the Tiago robot to deliver the object. This level of awareness was effortlessly attained by monitoring the cell ID to which each robot was connected at various points during the operation.

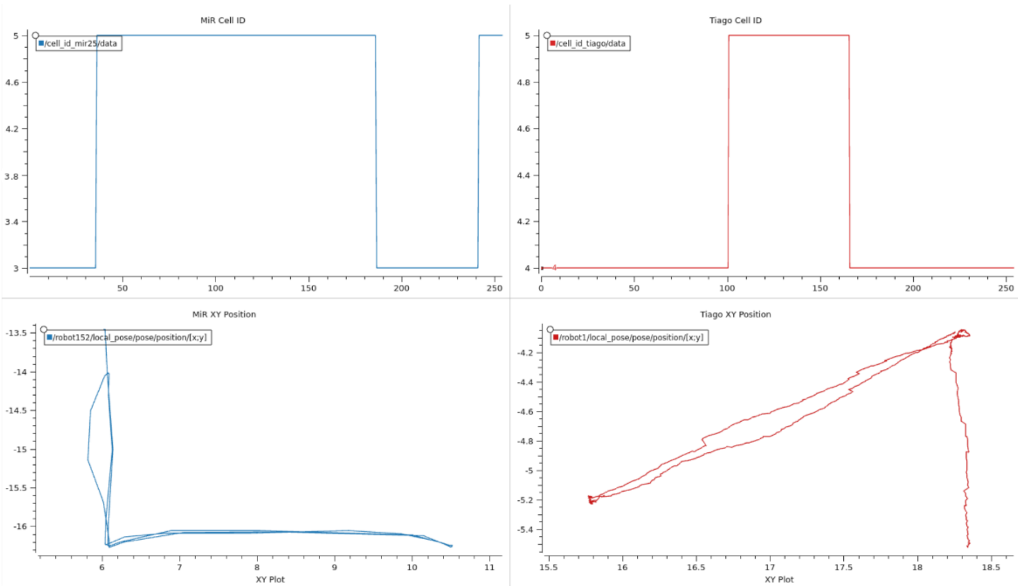

Figure 25. Cell ID shift and XY trajectories for both MiR (in blue) and Tiago (in red) robots

5 Conclusion and Next Steps

The work presented in this deliverable describes in detail the final prototype of the Network Apps (Teleoperation and Localization) developed within the PLI pilar in the EVOLVED-5G context, driven by Task 4.5. Moreover, detailed descriptions of the two iterations of integration tests that the Network Apps have undergone on top of the EVOLVED-5G infrastructure, in Malaga platform at UMA premises, are provided. Both rounds of integration activities aimed to test the functionality of the Network App when seamlessly connected with the vApp as well as evaluating use case for each Network App, with the components deployed in different environments (Openstack in the first round and K8s in the second round, respectively). With the second round of integration tests, the Networks Apps of the PLI pillar have reached their final stage, interacting with the last versions of NEF and CAPIF through the SDK and communicating with their respective vApps. The three use-cases (Teleoperation task use case, Adaptive speed control and Autonomous package delivery) have been validated on a real 5G network provided by the infrastructure of UMA.

The results obtained from the Localization Network App provide compelling evidence of how 5G cell information can significantly enhance robot navigation in indoor environments. By utilizing the Cell ID information, the robots' awareness of their surroundings is notably augmented. Although the distance information to a specific 5G cell was not available in this case, the knowledge of the cell ID alone proved to be highly valuable.

This level of awareness could play an important role specially in industrial environments, where multiple agents need to navigate through a vast space. The Cell ID information serves a simple means of space segregation, allowing robots to identify and distinguish different areas within the environment. As a result, the robots can intelligently adapt their behaviour and movement patterns based on the characteristics of each area. This can lead to improved efficiency, optimized task allocation, and enhanced safety in industrial settings.

The next steps will take place within the scope of WP5. Both SMEs have already started to use the validation pipeline to check their Network Apps. When they pass the final validation and certification steps, the Network Apps will be ready to be made publicly available through the EVOLVED-5G Marketplace.