Remote Control of a Collaborative Robot with Virtual Reality and Joystick in a 5G Network

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Abstract*—This study focuses on the retrofitting of a collaborative robot to operate in different 5G networks using joysticks and virtual reality glasses. The aim is to provide small and medium-sized enterprises (SMEs) with insights into retrofitting robots for 5G networks and enable them to make informed decisions about developing 5G products and services. The paper includes an overview of related work, a description of the retrofit robot, measurements in different networks to evaluate latency, and a discussion of the impact on SMEs. The results show that a private 5G campus network provides significant advantages in terms of low latency, making processes more efficient and increasing productivity. Future work could explore the potential of 5G in different industries and application areas, as well as integrating AI and machine learning into 5G networks to improve performance and efficiency, as well as identifying and exploiting synergies with other emerging technologies such as blockchain and IoT. Overall, this research highlights the benefits of 5G for SMEs and provides a practical example of how to retrofit robots for 5G networks. By leveraging the power of 5G, SMEs can improve their business and remain competitive in today's rapidly evolving digital landscape.

Keywords*—5G, mobile communication, retrofit collaborate robot, virtual reality, test bed, remotely controlled, real-time, comparison of networks.

I. Introduction

The introduction of the 5G standard has transformed the way data is transmitted, offering faster and more reliable connectivity than ever before. This offers numerous benefits for industrial companies, especially small and medium-sized enterprises (SMEs), which can leverage the power of 5G to improve their business and remain competitive.

To support SMEs in developing 5G products and services, the Chamber of Crafts of Lower Bavaria-Upper Palatinate and the Deggendorf Institute of Technology (DIT) have jointly developed demonstrators at the Technology Campus Freyung (TCF). This partnership offers SMEs the opportunity to develop and test their 5G products and services in a controlled environment to offset competitive disadvantages and take advantage of new technologies.

One such demonstrator is a retrofittable robot that can operate in different 5G networks using joysticks and virtual reality (VR) glasses. This research project will investigate how an existing robot can be retrofitted to operate in different 5G networks and how latency affects the operation of the robot in different test setups. The project aims to provide SMEs with insights into retrofitting robots for 5G networks and enable them to make informed decisions about developing 5G products and services.

The paper first provides an overview of related work. The second part describes the retrofit robot and explains its technical specifications and integration into different networks. The third part includes measurements in three different net- works, evaluating the behavior of latency in each network and comparing the different test setups. The results of the tests are presented and their impact on SMEs is discussed. Finally, a conclusion is given and an outlook on future work is given.

II. Related Work

The combination of 5G, virtual reality (VR) and robotics has many applications in various fields. The publications listed here show the diverse requirements for these applications. One example is the paper "BakeryRobot: 5G connected robot for SMEs", which can relieve employees from monotonous tasks. The BakeryRobot can produce bread dough fully automatically by mixing ingredients, portioning pieces of dough and placing them on a conveyor belt. One of the most common problems with this process is repeatability due to the different positions of the dough pieces. To ensure a reliable process, the robot is equipped with a camera that integrates 5G to increase efficiency and accuracy while reducing production costs [1].

Telesurgery is a prime example of a time-critical application that requires fast and reliable communication networks. With the development of 5G technology, there are no longer any spatial limits to performing telesurgery, as any location can now be connected. A recent Department of Medicine publication, "5G robotic telesurgery: remote transoral laser microsurgeries on a cadaver", describes a difficult transoral laser microsurgery on the vocal cords of an adult cadaver with robotic assistance. The surgeon was able to perform the robotic telesurgery from a distance of 15 km using a 5G connection. The success of the telesurgery was due to the low latency and high data bandwidth of 5G. Control commands were monitored via video stream in VR goggles, illustrating the use of 5G in a time-critical scenario combined with virtual reality and robotics [2].The introduction of 5G in industry and SMEs is proving difficult due to the lack of availability of industrial 5G devices. One solution could be to implement a standalone 5G system in the manufacturing environment. A study titled "Private 5G Solutions for Mobile Industrial Robots: A Feasibility Study" examined the performance of a modern standalone 5G system in a manufacturing environment. This involved packet-based measurements to investigate 3GPP requirements for through- put, packet rate, packet size and latency. The measurements showed that the 5G links can meet the delay, and reliability requirements as long as there is no cross traffic. However, when cross traffic occurs, especially in the uplink, it leads to a significant increase in delay and it is impossible to meet the reliability requirements. To improve the performance of the overall system, solutions such as network slicing and priority-based scheduling are important to distinguish different types of traffic. To verify the applicability of the standalone 5G setup, extensive measurement campaigns were conducted. The latency limit of 10 ms can be met 99.9 percent of the time for typical use cases, as long as no bandwidth-intensive applications are running. However, the number of devices and the influence of cross-traffic have a significant impact on the performance of the overall system. Future measurements will focus on the implementation of these concepts and investigate the application of 5G in other areas of automotive production [3].

The article ”Performance Analysis of Local 5G Operator Architectures for Industrial Internet” [4] exemplifies how a network architecture for a local 5G operator in industrial environments could be implemented according to Industry 4.0 standards. The proposed architecture is based on collaboration between the local 5G operator and mobile network operators (MNOs) in building the core network. The focus is on network functions (NFs) and operational units for the core and radio access network in smart factory environments. The paper shows simulation results for various use cases such as augmented reality, massive wireless sensor networks, and mobile robots to measure latency. The experiments show that a locally deployed 5G network inside the factory floor can achieve lower end-to end latency compared to a 5G network operated by a mobile network operator outside the factory. The decision to deploy network functions locally depends on the requirements of the use case, and analysis of past usage data can help optimize latency.

Network communication is becoming increasingly important in globally networked markets. Therefore, information about the reliability of computer networks is critical. In the article ”One-Way Delay Measurement: State of the Art” by DeVito, Rapuano and Tomaciello, the evaluation of performance measurement in computer networks is a central topic. The authors identify one-way delay (OWD) as one of the most important network performance parameters for the quality of service of network communications. Accurate estimation of OWD is necessary to guarantee or improve network communication performance in real-time applications. The authors emphasize the importance of accurate OWD estimation because several parameters can affect the measurement. They mention operating systems, especially threads, as they run concurrently with the measurement application. Future research aims to reduce the uncertainties of networks and use network synchronization and conventional networks for accurate OWD estimation. In summary, accurate measurement of OWD is critical for maintaining reliable network communications, especially for real-time applications. The paper provides valuable insights into the evaluation of performance measurement in computer networks, focusing on OWD as a critical network performance parameter [5].

An example of how the real-time management of a network can be improved is given in the paper ”Adaptive network reliability for human-robot interaction in beyond 5G industrial applications”. Here, a novel technique for dynamic real-time management of radio transmission redundancy based on the mutual positions of humans and robots in smart industrial environments is described. The technique aims to improve network availability and reliability to ensure safe mobility. Simulation results suggest that the current number of radio bearers supported by 5G may not be sufficient to meet the stringent reliability requirements of critical applications. The proposed model introduces adaptive reliability control that dynamically increases the number of active radio bearers for each user equipment (UE) to meet the reliability requirements. Simulation results show the need for a higher number of bearers, possibly up to 5, for 125-byte user data. Such control mechanisms optimize resource consumption by enforcing reliability requirements only when needed [6].

III. Retrofitting of Existing Robot

SMEs often face challenges in acquiring 5G-capable machines, either because there are no suitable solutions or because the cost of replacing existing machines is too high. Retrofitting existing robots can be a practical solution for these companies. The test setup shown in Figure 1 consists of a Universal Robots (UR) robot and associated components.

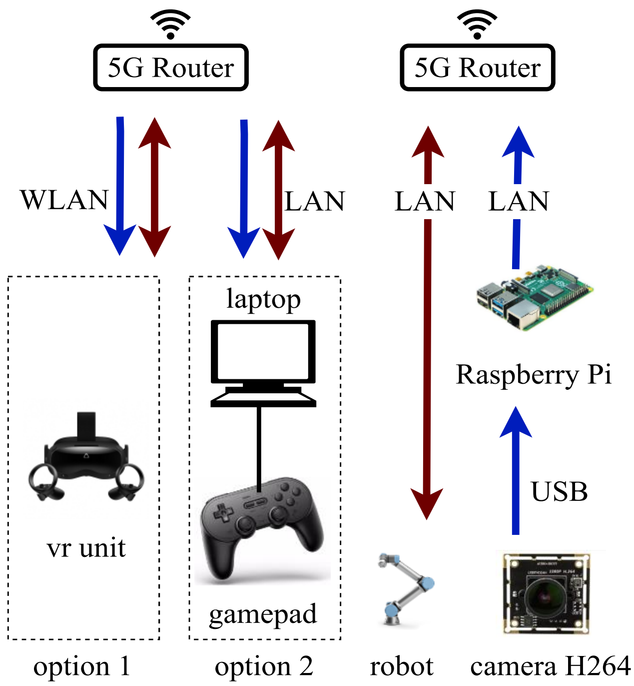

Fig. 1. Test setup UR robot

There are two possible options for controlling the robot

Option 1: In this approach, the control signals from the VR goggles are transmitted directly to the robot via the network. A Raspberry Pi with an USB camera provides the video signal, and the video transmission is done in the reverse direction. A 5G standalone (SA) compatible router is used for this purpose.

Option 2: The control is realized with a laptop and a gamepad. The video stream is displayed on the screen of the laptop so that the user can follow the movement of the robot. The control signals are transmitted as TCP packets from the connected gamepad to the robot over the 5G network. By using a 5G network, control and feedback of the robot can be provided in near real-time, resulting in more precise control and a better user experience.

The implementation of the collaborative robot is divided into hardware and software components:

Commercially available hardware will be used for the test setup, including an UR5 series collaborative robot, a Robustel R5020 5G router, a HTC Focus 3 VR headset, a USB camera for video streaming, a standard Linux laptop, and a gamepad. A 5G campus network will be used to ensure a suitable 5G environment.

The software aspect involves investigating possible methods of controlling the robot, such as Modbus, Real Time Data Exchange (RTDE), and TCP/IP. TCP/IP is chosen for implementation due to its low latency. The control tests were performed over LAN and 5G networks successfully.

The video stream is implemented over the HTC Vive glasses using VLC media player plugin. To enable playback in the VR goggles, a USB camera is used to directly encode and provide the video signal in H264 format. This provides the ability to control the robot while playing back the video stream in the VR goggles. This retrofit approach effectively integrates 5G technology into existing robot systems, providing enhanced control and user experience.

IV. COMPARISION OF DIFFERENT NETWORK SETUPS

A. Concept

This chapter compares different use cases for connecting a retrofitted robot to a 5G network. These use cases are selected based on whether the robot and controller are in the same location, two different locations, or any location. In addition, a technical comparison will be made between campus networks and public networks to determine if the high capital cost and bureaucracy would be worth it for campus networks.

In order to evaluate the quality of network connections, network latency is measured using the ping command [6]. The ping command is a tool for testing the reachability of network devices and is an important factor in evaluating the quality of a connection.

To measure network latency, the ping command is sent from a Raspberry Pi representing the robot to a 5G router representing the device to which the controller can connect. In this way, the delay caused by 5G can be measured and evaluated.

For each use case, 12,000 measurements are taken, and the ping results are written to a log file for further analysis. The three use cases selected for evaluation are a private single 5G campus network, tunneled private 5G campus networks, and a public 5G network. They are based on different scenarios and requirements and provide a comprehensive comparison of the different connectivity options for retrofitting robots with 5G. Using a 5G network on a private single campus (figure 2) offers some advantages and disadvantages. All components are connected to the same network, which means that the robot and the controller are restricted to the same location. However, for many applications, this is not a problem. A major advantage is the high level of security, as no data leaves the private network. In addition, network load can be controlled.

Frequency bandwidth, subcarrier spacing and time division multiplexing can be adjusted according to the application, making the network very flexible and adaptable. It manages itself and can be adapted according to the requirements.

However, using such a campus network is expensive because it requires its own network infrastructure. To test the network, a Raspberry Pi is connected to a 5G router via LAN, which forwards the ping request to gNodeB 2 via Router 2, then to gNodeB 1 over the 5G core network, and finally to Router 1. Router 1 is a Robustel R5020 router that has RS232/RS485, Wi-Fi, and Ethernet interfaces and is of interest for various applications, including research. Router 2 is a commercially available standard 5G router, an AVM Fritzbox 6850 5G.

The TCF test-bed is an open 5G standalone campus network with a usable frequency bandwidth between 3.7 GHz and 3.8 GHz allocated by the German Federal Network Agency for private campus networks [7]. It has a modern network infrastructure with 5G core, gNodeB and 5G router. The gNodeB is a 3GPP-compliant implementation of the 5G SA base station [8] and serves as an interface in a cellular network between the UE and the 5G core. The gNodeB corresponds to the radio units (RU) and consists of several independent network functions, the 3GPP-compliant new radio (NR) radio access network (RAN) protocols. The 5G core consists of a centralized unit (CU) and a distributed unit (DU), each supporting higher and lower protocol levels.

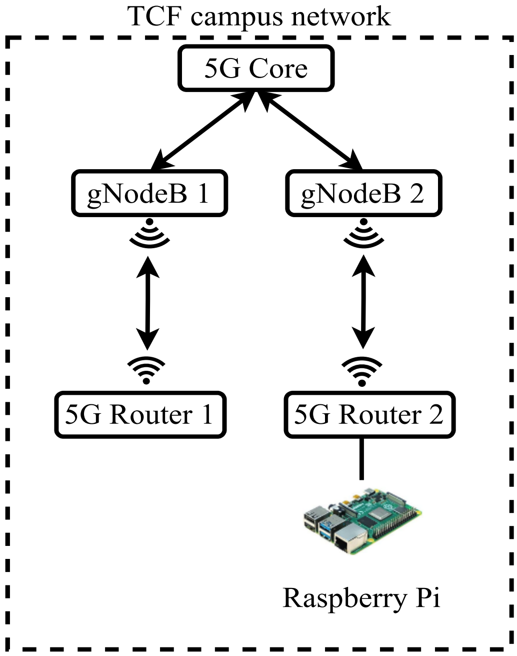

Fig. 2. Test setup for the private 5G network

This scenario is about evaluating the latency and connectivity quality of two separate tunneled private 5G campus networks connected via a VPN tunnel. This is to ensure that a robot can be controlled from another site, such as a second enterprise site, without compromising security or network load.

For this test (Figure 3), two private self-managed networks are connected through a VPN tunnel. The robot resides on one network and the other network contains the controller.

A Raspberry Pi is used to send the ping, and the same routers are used as in the previous test. Instead of forwarding the ping from the core network, to a second gNodeB, it is sent through a VPN tunnel to the core network of the second private campus network. A publicly available VPN server is used to connect the TCF campus network to that of the H5G project partner in the Chamber of crafts for testing purposes.

The Chamber of crafts campus network, is a closed system provided by Nokia. The purpose of this test is to ensure that the quality of connectivity between the two separates private 5G campus networks is at least satisfactory so that the robot can be controlled from another location without latency issues. Overall, using a VPN tunnel to connect the two campus networks provides a secure solution for remote control of the robot.

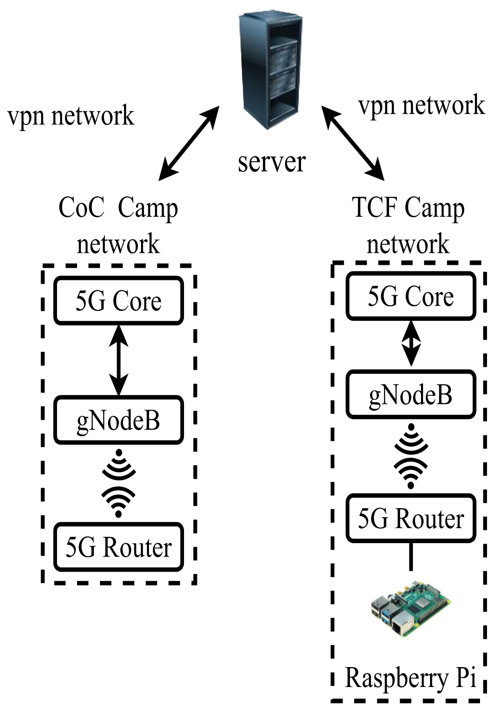

Fig. 3. Test setup for the private tunneled 5G campus networks

A public 5G network (fig. 4) is used to test the functionality and reliability of network communications under realistic conditions and to ensure that craft businesses can use reliable and stable network communications. All components are connected to the public 5G network, and SIM cards from the provider are required for all devices. The setup is simple, as no network infrastructure needs to be built, but the public network is used. This setup method is very flexible, as it does not matter where the devices are located as long as they have network coverage. For example, a robot can be controlled from a mobile device, or the robot itself can be mobile, such as on a construction site. The cost of a cellular contract is negligible compared to the cost of a private 5G campus network. The test setup uses a public 5G core managed by a commercial provider, and commercial SIM cards from the public provider are used. Signal transmission is passed from the Raspberry Pi to 5G router 2, then to gNodeB 2, to the public 5G core network, to gNodeB 1, to 5G router 1, and vice versa. The same components (Pi and router) are used again. The Telekom network is used for the measurement.

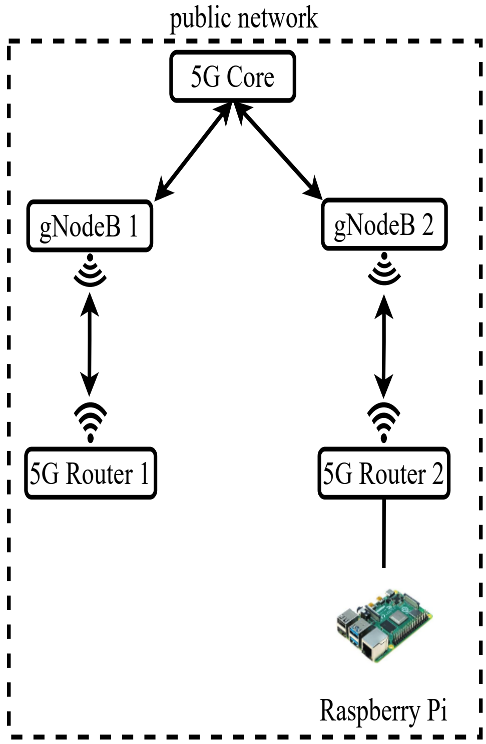

Fig. 4. Test setup for the public network

B. *Measurement and Results*

In order to investigate factors that influence the latency of 5G, it is important to define influencing variables. A histogram can be used to show distribution and frequency, but comparability is crucial. Therefore, factors affecting 5G latency were identified, including network congestion, signal strength, user location, network topology, devices used, and processing capacity of servers. To ensure comparability of graphs, scaling bins were set to 1 ms, and the x-axis represents milliseconds while the y-axis shows the number of measured values. The data sources include 12,000 measurements, and a logarithmic representation is used for better visibility of measurement results. The measurement results are summarized in table I, which shows the 80, 90, and 99 percent probabilities that the ping time would be lower than the given values. Overall, the investigation of these factors and the use of standardized comparison features will enable a better understanding of 5G latency and improve its performance in the future.

TABLE I. MEASUREMENT RESULTS OF THREE TEST SETUPS

Measurements (results in milliseconds)	***Single private 5G network***	***Tunneled private 5G network***	***Public 5G network***
minimum	20 ms	41 ms	50 ms
maximum	90 ms	326 ms	558 ms
average	40 ms	57 ms	128 ms
80 percent	40 ms	62 ms	175 ms
90 percent	48 ms	64 ms	198 ms
99 percent	54 ms	90 ms	347 ms

The presented diagram (Figure 5) depicts the measurement results of a private campus network connection. The evaluation of the histogram shows that the data is not symmetrically distributed, but rather exhibits a right skewness.

The measurement data is presented in the range of 20 ms to 90 ms, possibly due to interference in the network connection.

The peak of the data is located to the left of the mean value, and the median is smaller than the arithmetic mean. The diagram also shows multimodal data, possibly due to parallel hardware processes.

Despite this, it can be observed that the network provides a stable connection, with no visible network overload, as the measured values are in the range of 30 ms to 60 ms. The network is self-configurable and self-manageable. Additionally, a high level of security is ensured as the know-how remains within the company.

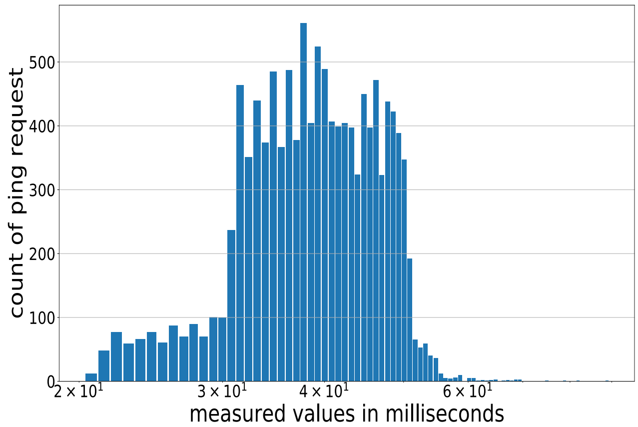

Fig. 5. Ping test private 5G networks

The results of the ping measurements in private tunneled 5G campus networks are presented in Figure 6. The evaluation histogram shows that the data is left-skewed. The measurement outliers range from 66 ms to 326 ms, which could be due to possible errors in the VPN connection, as well as hardware and connection processes in the background. The highest value in the diagram is to the right of the mean value, and the scatter width of the diagram is 286 ms. Despite the measurement outliers, the histogram indicates a high-performance connection quality. The tunneled campus network is self-configurable and offers highly secure options that ensure the company's expertise remains in-house while providing reliable and stable latencies. However, a major drawback is the high capital cost. Setting up two private tunneled 5G networks requires a campus network at each location.

In today's world, 5G networks have become an essential part of our lives and are being used by more and more people. Public 5G networks play a special role in this regard. To evaluate the quality of these networks, measurements were carried out and presented in a diagram (Figure 7).

The evaluation of the results shows that the data is right-skewed and has outliers, possibly due to interference from background processes. Additionally, the graph is widely scattered due to the high number of users and dependence on commercial providers. However, connectivity is satisfactory and strongly depends on the number of users in the public 5G network.

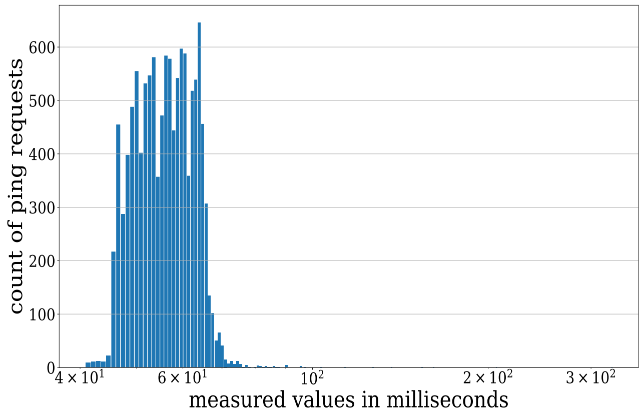

Fig. 6. Ping test private single 5G networks

Nevertheless, there are also some disadvantages in using these networks, such as dependence on network coverage and number of users, and high latency due to high network utilization. However, the advantages are not to be overlooked: fast deployment and low-cost solution with a 5G router and a commercially available SIM card make the use of public 5G networks attractive.

In summary, public 5G networks play an important role in today's digital age. Although there is still room for improvement, these networks are a promising option for many users due to their fast deployment and low cost.

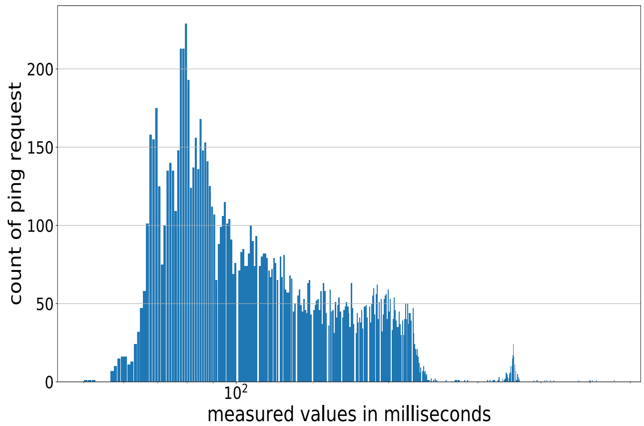

Fig. 7. Ping test public 5G network

In the conducted study on network performance, it was found out that the private single campus network performed the best without internet traffic. Therefore, the study focused on two types of 5G networks: a private tunneled campus network and a public network. The tunneled campus network showed good connection quality despite the VPN connection over the public network, while the public 5G network had satisfactory connection quality, but with fluctuating ping requests due to high user load. The dispersion values were lowest in the tunneled campus network and highest in the public 5G network, with both networks displaying asymmetric graphs indicating latency issues. The scatter range was 286 ms in the tunneled campus network and 476 ms in the public 5G network, with both networks showing measurement outliers, suggesting potential link interference due to user load. Both networks exhibited multimodal data due to possible background processes, leading to several high measurement values in the graphs. The private tunneled 5G campus networks had a higher median than the mean, while the public 5G network had a lower median and a very large scatter range, indicating latency variations. Overall, the tunneled campus network had better connection quality than the public 5G network. The performance of the public 5G network heavily depends on the provider's network coverage and user load.

The diagram (Figure 8) shows clear differences in speed between the two networks. A private, tunneled campus network offers lower latency and higher quality, but is more expensive and has limited network coverage. On the other hand, a public 5G network has higher latency variation, is slower, but less expensive and quickly deployable. However, it is dependent on the number of users and the network coverage of the provider. It is important to note that a latency of 500 ms is not suitable for time-critical applications. The test has shown that a latency of up to 500 ms is feasible for the operation of the robot. For more stable and faster latency, it is recommended to implement a private 5G campus network. However, this may come with higher costs, but offers higher quality and better network coverage. Ultimately, the choice of network depends on specific requirements and budgets.

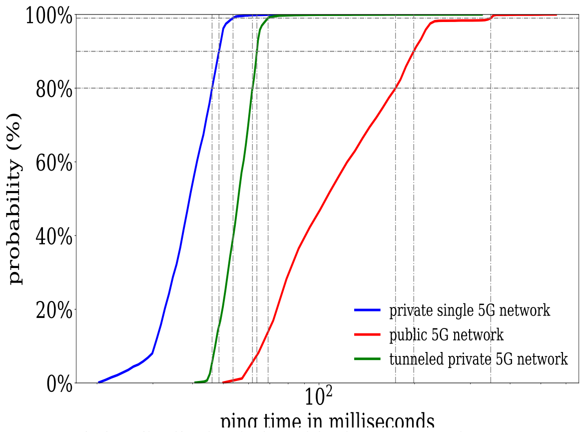

Fig. 8. Cumulative distribution in logarithmic representation

V. CONLUSSION AND FUTURE WORK

This work focused on retrofitting a remotely controlled collaborative robot in different 5G communication networks using VR and joysticks. The focus was on implementing the robot in different 5G networks and using remote control to solve problems for SMEs while ensuring enterprise security. Measurements were taken to demonstrate the benefits of 5G in terms of flexibility, interactivity, data transmission speed and latency. A comparative analysis of the measurements showed significant advantages in using a private 5G network in terms of fast latency. When fast latencies are of great importance, it makes sense to implement a private 5G campus network. This measure can make processes more efficient and increase productivity. The goal of this work was to show SMEs how they can benefit from integrating 5G into their products. As for future work, there is potential for further research and development of 5G implementations in SMEs. One focus could be to implement 5G in different industries and application areas to explore the potential of 5G. The integration of artificial intelligence and machine learning into 5G networks is also an area that could be explored to further improve the performance and efficiency of robots and other applications. In addition, expanding the study to include the use of 5G in conjunction with other emerging technologies such as blockchain or IoT could help identify and exploit the benefits of synergies.

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