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Performance Benchmarking of 5G Non-Public Networks for Industrial Use Cases

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Abstract

This paper presents the deployment and evaluation of a private 5G network designed to support Industry 4.0 applications in a Factory-of-the-Future environment. Using open-source components such as Open5GS, srsRAN, and USRP-based radios, we built an end-to-end testbed and benchmarked throughput, latency, and jitter across three industrially relevant topologies. Our results show TCP throughput of up to 66 Mbps and UDP throughput of up to 75 Mbps in multi-device setups, with latency ranging from 7 to 28ms. Direct 5G connectivity achieves downlink rates of up to 950 Mbps. The findings demonstrate that private 5G networks can meet the performance requirements of real-time automation, remote monitoring, and advanced human–machine interaction, thereby confirming their suitability as a communication backbone for Industry 4.0.

Index Terms: Industry 4.0, 5G Non-Public Networks,

INTRODUCTION

The worldwide rollout of Fifth-Generation (5G) mobile systems has accelerated over the past few years, marking a significant milestone in the evolution of wireless communication, specifically. Beyond simply extending the capabilities of earlier generations, 5G introduces an architecture designed to support extremely high data rates, ultra-reliable low-latency communication, and massive-scale device connectivity [1]. Together, these advancements form the technological foundation for a new class of applications, particularly those emerging from Industry 4.0 and the digitalization of industrial processes.

Public 5G networks are traditionally deployed and operated by mobile network operators (MNOs). While these networks provide broadband internet, multimedia services, and various enterprise solutions, their rollouts are primarily optimized for dense urban environments. However, low population density, challenging terrain, and high infrastructure costs often make rural deployments economically unattractive for operators, leaving many communities with limited connectivity options [2]. This digital divide impacts not only residents but also industries in rural regions, restricting automation, remote operations, and digital transformation.

Therefore, to increase deployment flexibility and enable tailored communication services, the 3rd Generation Partnership Project (3GPP) introduced the concept of 5G private networks, also known as non-public networks (NPNs) [3] [4]. These networks are implemented within the premises of specific organizations—such as factories, research labs, logistics hubs, or energy facilities—and are configured according to the operational and security requirements of the host. This management may be handled directly by the private entity or outsourced to a third party, such as an MNO or service integrator [8].

The ability to customize network behaviour, guarantee deterministic performance, and isolate critical traffic has made private 5G a central pillar of Industry 4.0 [6]. Industrial automation demands stringent communication characteristics such as high availability, reliable and bounded latency, and robust security. As a response, initiatives such as the 5G Alliance for Connected Industries and Automation (5G-ACIA) have categorized deployment models and guided the integration of 5G into manufacturing and process industries [7]. Numerous experimental deployments and feasibility studies have demonstrated the potential of private 5G for applications including robotic control, predictive maintenance, mobile edge computing, real-time monitoring, and augmented reality for human–machine interaction [5].

In the rest of the paper, section II contains Industry 4.0 use cases and their requirements, where section III provides the deployment of a private 5G network for the Industry 4.0 environment. Section IV contains the performance results, whereas Section V discusses the results. Finally, the conclusion is provided in Section V.

Industry 4.0: Factory of the Future

The Factory of the Future embodies the vision of fully digitized, automated, and interconnected manufacturing environments under Industry 4.0 [5]. In such facilities, cyber-physical systems, collaborative robots (cobots), autonomous guided vehicles (AGVs), smart machines, and distributed sensors communicate seamlessly over a 5G NPN forming a large-scale IoT ecosystem [13]. The ultra-low latency, high reliability, and massive connectivity features of 5G NPNs enable real-time coordination, predictive maintenance, and advanced human–machine interaction, laying the foundation for intelligent and adaptive production processes.

Several advanced applications can be realized within this context, including,

- **Remote Monitoring as a Service:** High-resolution video and sensor data from production lines and robotic stations can be streamed over the 5G network, with network orchestration ensuring that critical traffic is prioritized. Operators can monitor operations in real-time and make timely decisions remotely.
- **Remote Control with Real-Time Feedback:** Machinery, robots, and AGVs can be operated remotely, with instantaneous feedback supported by low-latency video and control signals. Time-Sensitive Networking (TSN) and precise localization services over 5G enable accurate coordination of multiple devices operating concurrently.
- **5G Integration and Adaptability in Industrial Environments:** The network continuously monitors connected devices, sensors, and controllers, dynamically adapting to the operational requirements of the factory. This ensures efficient resource allocation and sustained performance under changing conditions.

- **Process Control over 5G:** Large volumes of process data—simulated or live—can be transmitted to support automated decision-making, production scheduling, and quality management. The reliability and throughput of the 5G network make distributed process control seamless and efficient.
- **VR/AR Control over 5G:** Virtual and augmented reality technologies can be integrated to allow operators to interact with machinery, production lines, and digital twins using smart glasses or holographic displays. IoT sensors and actuators work in tandem with these devices to enable immersive, real-time operational management.

Thus, these applications illustrate how private 5G networks on NPNs can empower the Factory of the Future, driving autonomous, flexible, and highly efficient industrial operations while supporting the broader goals of Industry 4.0. Below, we provide some of the requirements, including the following, that could help realize these use cases.

Private 5G for Industry 4.0:

Industry 4.0 envisions highly automated, flexible, and self-optimizing manufacturing environments where cyber-physical systems, machines, robots, and humans collaborate in real-time. Specifically, this paradigm shift from rigid automation to adaptive production demands a communication infrastructure that is fundamentally different from best-effort Wi-Fi or consumer-centric public cellular networks. In the current circumstances, Private 5G networks, with their inherent design principles, are poised to be this backbone. To reliably support the mission-critical operations of a Factory-of-the-Future, these networks must fulfil a set of stringent and interconnected requirements [6].:

- **Ultra-Reliable Low-Latency Communication (URLLC):** URLLC guarantees packet delivery within a bounded, extremely short time frame (e.g., 1-10 ms) with very high reliability (e.g., 99.9999%). This capability is non-negotiable for applications such as closed-loop motion control of collaborative robots (cobots), synchronization of production-line actuators, and safe navigation of Autonomous Guided Vehicles (AGVs) where any delay or packet loss can lead to production defects, machine damage, or safety incidents.

- **Massive Connectivity:** A modern factory is populated by thousands of connected devices, from simple sensors monitoring temperature and vibration to complex actuators and mobile robots. Thus, Private 5G must support a connection density of up to 1 million devices per square kilometer. This massive connectivity allows for comprehensive asset tracking, pervasive condition monitoring, and the fine-grained data collection necessary for predictive maintenance and overall equipment effectiveness (OEE) optimization, without the network congestion typical of legacy wireless systems.
- **High Throughput:** While latency is critical for control, large bandwidth is essential for data-intensive applications. Therefore, high throughput is essential for data-intensive industrial applications. With potential speeds of multiple Gbps downlink and hundreds of Mbps uplink, it enables the streaming of high-definition video for quality inspection and immersive AR for maintenance, while also supporting the constant, high-volume data exchange needed to synchronize complex Digital Twins.
- **Network Slicing and Traffic Prioritization:** A single network must concurrently serve diverse applications with vastly different QoS requirements. In this case, Network slicing is a key 5G feature that allows a single physical network to be partitioned into multiple virtual, end-to-end networks. This capability enables operators to create a dedicated, logical "slice" with guaranteed resources for a critical application like AGV control (requiring URLLC), while another slice handles massive sensor data (mMTC) and a third supports high-speed video uploads for monitoring. Furthermore, traffic prioritization within and across slices ensures that a burst of non-critical data never interferes with a time-sensitive command.
- **Time-Sensitive Networking (TSN):** For industrial automation to fully transition to wireless, 5G must seamlessly integrate with the wired Ethernet standards used in operational technology (OT) networks. For this purpose, TSN provides deterministic latency and precise clock synchronization across a network. Thus, the convergence of 5G and TSN is crucial for replacing legacy fieldbuses and supporting distributed control systems where wired and wireless devices must

operate in perfect, synchronized harmony, such as in a coordinated multi-robot assembly cell.

- **Precise Localization and Positioning:** Beyond mere connectivity, knowing the precise location of assets is vital for factory efficiency and safety. Private 5G networks can provide indoor and outdoor positioning accuracy down to the sub-meter or even centimeter level using advanced techniques like angle-of-arrival (AoA) and time-difference-of-arrival (TDoA). This enables real-time tracking of AGVs, tools, and inventory, facilitates automated guided vehicle navigation without the need for magnetic tapes, and enables geofencing for worker safety.
- **Security:** Modern factories are high-value targets for cyber-attacks. Private 5G provides a robust security framework encompassing strong mutual authentication between devices and the network, end-to-end encryption of user and control plane data, and integrity protection. Furthermore, because it is a private network, all traffic remains within the organization's premises or is securely routed to a chosen cloud, ensuring isolation from public internet threats and protecting sensitive production data.
- **Flexibility and Integration:** The Factory-of-the-Future is a dynamic environment – nodes joining and leaving the network around the clock, depending on the factory operation and other factors. Therefore, the communication network must be highly flexible to support reconfigurable production lines and the addition of new equipment. Further, it must also offer seamless integration with existing industrial protocols (e.g., OPC UA, PROFINET, Modbus TCP) and legacy systems, often through industrial gateways, to protect previous investments and enable a gradual transition to a fully connected ecosystem.
- **Edge Computing:** To achieve the ultra-low latencies required for real-time control and to reduce the traffic load on the core network, processing power must be moved closer to the data source. Edge computing, integrated with the private 5G network, allows data from machines and sensors to be processed locally. This ability enables immediate decision-making for critical functions (e.g., instant anomaly

detection, real-time robot vision processing) and supports low-latency AR/VR applications, all while ensuring that sensitive data remains on-site.

In summary, it is the synergistic combination of these requirements—reliability, capacity, intelligence, and security—that enables private 5G to serve as a robust and future-proof communication backbone for the Factory of the Future. Significantly, by meeting these demands, private 5G empowers advanced automation, enables real-time monitoring and control, and ultimately supports the creation of efficient, responsive, and highly flexible industrial operations.

DEPLOYMENT METHODOLOGY

To evaluate the capabilities of a private 5G network in an Industry 4.0 environment, we deployed a complete end-to-end testbed using open-source components. The deployment aimed to benchmark key performance indicators (KPIs) such as *throughput, latency, and jitter*, which are critical for industrial applications, including real-time control, remote monitoring, and process automation.

Network Architecture and Components

The private 5G network was constructed using the following core components:

1. **Open5GS 5G Core**
   Open5GS is an open-source 5G core implementation that supports both 4G EPC and 5G SA/NSA architectures. It provides all the essential core network functions, including AMF (Access and Mobility Management Function), SMF (Session Management Function), UPF (User Plane Function), and AUSF/UDM for authentication and subscriber management. Open5GS is highly configurable, making it suitable for experimental and industrial test deployments where flexibility is critical. Specifically, in our setup, Open5GS handled user registration, session management, and traffic routing between the 5G radio network and external networks. The use of such open-source and SDR-based platforms provides a flexible and reproducible testbed for evaluating 5G performance, an approach also adopted in other recent research efforts [10].

2. **srsRAN 5G Radio Access Network**
   srsRAN is an open-source software radio suite that implements 5G NR gNB (next-generation NodeB) and UE (User Equipment) functionalities. It provides a flexible, fully software-defined radio (SDR) platform capable of operating on commercial and experimental frequency bands. Similarly, in our deployment, srsRAN was used to implement the 5G gNB, enabling connectivity with the core network and providing the radio interface for the industrial devices under test.
3. **USRP-based Radio Units**
   Universal Software Radio Peripherals (USRPs) were used as the physical radio units in our setting. These SDR platforms allowed us to transmit and receive 5G NR signals, bridging the software-defined radio implementation of srsRAN with real-world RF communication. Additionally, by configuring USRPs with appropriate frequency bands and bandwidth, we ensured realistic deployment conditions for performance evaluation.

Integration and Test Setup

The 5G core (Open5GS), the RAN (srsRAN), and the USRP radio units were fully integrated to form a standalone private 5G network. Industrial devices, like industrial 5G modems, were connected to this network to emulate a Factory-of-the-Future scenario. Traffic from these devices was routed through the Open5GS core, while the srsRAN gNB and USRPs provided the over-the-air connectivity. Figure 1 shows end-to-end 5G connectivity. For performance benchmarking, this paper focuses on the following key metrics.

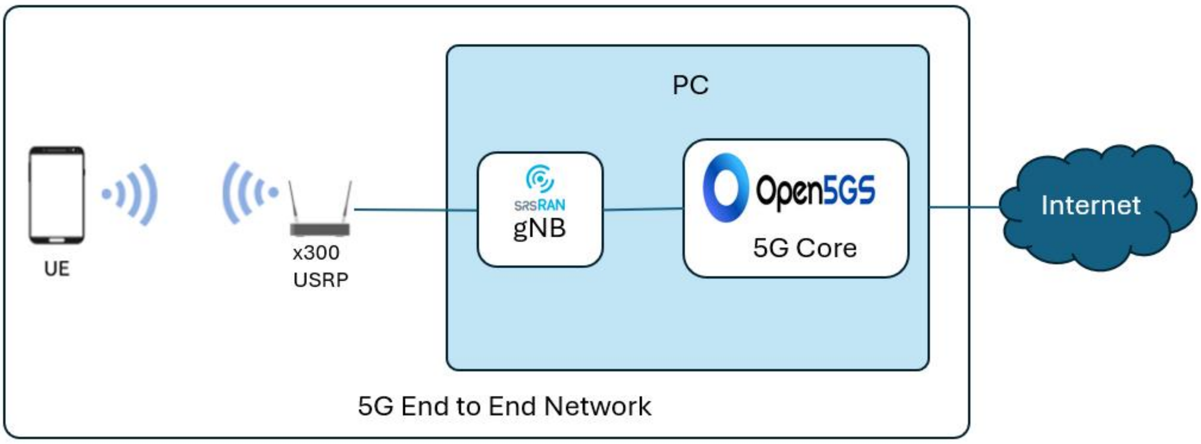

Figure 1: End to End 5G Connectivity Setup

- **Throughput:** Measured the maximum data rate achievable between devices and the core network under different traffic loads.
- **Latency:** Assessed the round-trip time for critical control and monitoring data, providing insight into the responsiveness of the network.
- **Jitter:** Evaluated the variability of latency over time, which is essential for real-time industrial applications requiring deterministic behavior.

Overall, this deployment allowed us to validate the suitability of private 5G networks for Industry 4.0 use cases and quantify their performance under realistic operational conditions. Furthermore, by leveraging open-source solutions such as Open5GS and srsRAN, combined with USRP hardware, we demonstrated a flexible and reproducible platform for testing advanced industrial applications.

Performance Benchmarking of Non-Public 5G Network

To evaluate the performance of the private 5G network for industrial applications, we defined three different topologies representing end-to-end system setups. These topologies incorporate both 5G-related delays and additional delays introduced by test PCs and associated wired networks. Key performance indicators (KPIs) measured include throughput, latency, and jitter, using both TCP and UDP traffic. Figure 2 shows an illustrative description of the tests where traffic from the client side starts and ends at the Server side. An iperf3 server is used for performance measurements. Subsequently, below, we will provide different topologies used and the corresponding performance measurements of those topologies. The topologies are selected based on usual scenarios that could be experienced in Industry 4.0 environments.

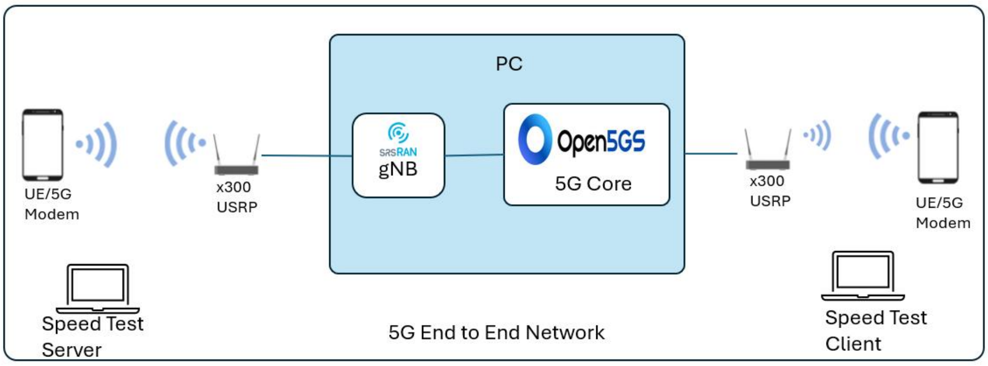

Figure 2: End to End test between Open Speed test server and the client

A. Topology 1

Topology 1 represents a complete end-to-end system setup, similar to how it would be deployed in an industrial environment. End application devices are connected via 5G modems, with all intermediate network hops included in the measurement.

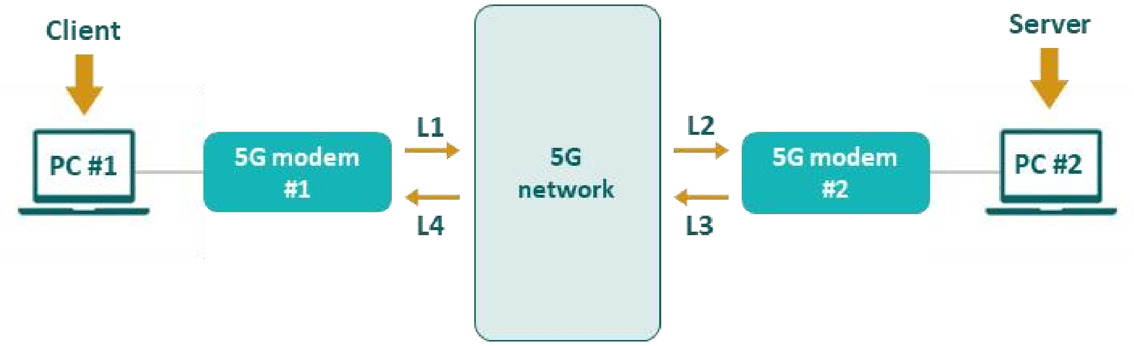

Figure 3: Topology 1 employed in the performance tests: client on PC #1, server on PC #2, connected via two 5G modems

Figure 3 shows a simplified representation of this topology, where the client resides on PC #1 and the server on PC #2, connected through two 5G modems. L1–L4 denote the different hops in the uplink (UL) and downlink (DL) paths used for end-to-end testing.

For Topology 1, the following KPIs were measured:

- Throughput using Transmission Control Protocol (TCP)
- Throughput and jitter using User Datagram Protocol (UDP)

Table 1 shows the results obtained for the first topology considered in the measurements.

Table 1: ***TCP Throughput Results, Topology 1***

Test	Traffic	Min. Throughput (Mbps)	Av. Throughput (Mbps)	Max. Throughput (Mbps)
#1	TCP	23.8	42.77	62.9
#2	TCP	18.7	39.81	57.8
#3	TCP	20.9	42.85	62.9

In this setup, the client is the sender, and the server is the receiver. It involves two UL and two DL paths, and the test was run for 300 seconds. The Table 1 shows a recorded throughput range of 18.7 to 62.9 Mbps.

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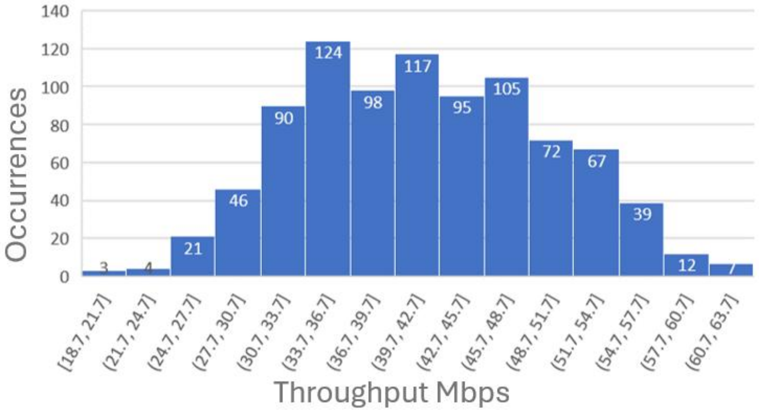

Figure 4. TCP throughput distribution over 5G, topology 1.

Notably, the recorded throughput in this case goes from PC 1 to PC 2, with throughput capability at PCs in the order of Gbps. Assuming a throughput (wired) capability on 5G modems, and that the 5G UL throughput is expected to be lower than DL throughput, hence the recorded throughput is associated with the UL (UL throughput is the bottleneck in this design). A similar behaviour can be observed with UDP packets. Figure 4 shows the distribution of the throughput, which is mainly concentrated around 42.7 Mbps.

Topology 2

However, Topology 2 is similar to Topology 1 in representing a complete end-to-end industrial system but differs in the location of the server. In this setup, the server is connected directly to a native 5G component, representing a scenario where industrial devices interface directly with the private 5G network.

Figure 5 illustrates this configuration, with the client on PC #1 and the server on 5G modem #2. For this topology, the following KPIs were measured:

- **Throughput** with TCP
- **Throughput and jitter** with UDP
- **End-to-end latency** (minimum, maximum, and average)

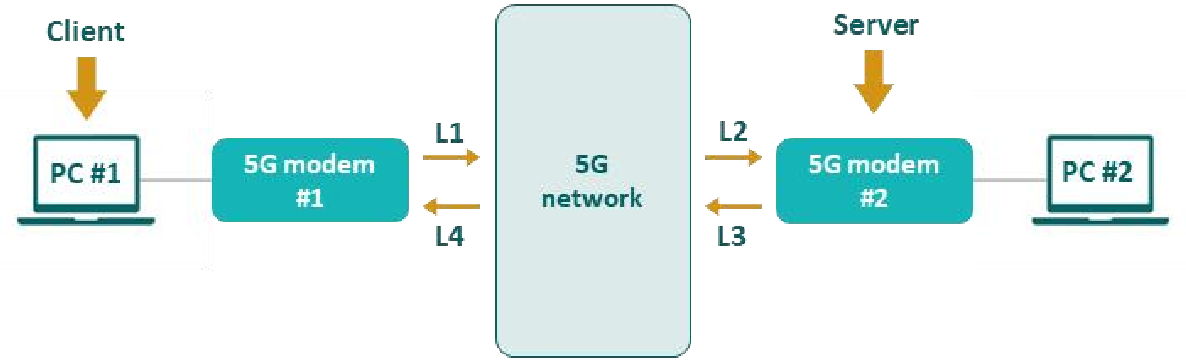

Figure 5: Topology 2 employed in the trials: client on PC #1, server connected directly to 5G modem #2.

The results obtained with the second topology are shown in Table 2 for TCP. In this case, we recorded an UL throughput range between 16.8Mbps and 66.2Mbps. It follows that, therefore, it can be observed that no major changes are observed when changing the server from PC #2 to the 5G modem.

Table 2: ***TCP throughput results, topology 2.***

Test	Traffic	Min. Throughput (Mbps)	Av. Throughput (Mbps)	Max. Throughput (Mbps)
#1	TCP	23.8	42.77	62.9
#2	TCP	18.7	39.81	57.8
#3	TCP	20.9	42.85	62.9

This behaviour is, however, slightly different when obtaining UDP results, as shown in Table 3. It is important to highlight that the jitter has been reduced drastically, from values ranging 2-3 ms to 0.05-0.02 ms, which represents 100 times lower values. Regarding the throughput, it has experienced a significant increase up to 75.7 Mbps.

Table 3: UDP throughput results, topology 2

Test	Traffic	Jitter (ms)	Min. Throughput (Mbps)	Av. Throughput (Mbps)	Max. Throughput (Mbps)
#1	UDP	0.101	26.3	55.31	74.1
#2	UDP	0.059	35.8	58.43	75.7
#3	UDP	0.242	28.3	47.12	67.8

Moreover, we additionally measured the 5G latency when using this topology. Table 4 and Figure 6 show the minimum, average and maximum values obtained, as well as the distribution, respectively. The results show an RTT 5G latency range from 7ms to 28ms.

Table 4: ***5G Latency Results, Topology 2***

Test	Min. Latency (Mbps)	Av. Latency (Mbps)	Max. Latency (Mbps)
#1	7	15	23
#2	9	18	26
#3	9	18	28

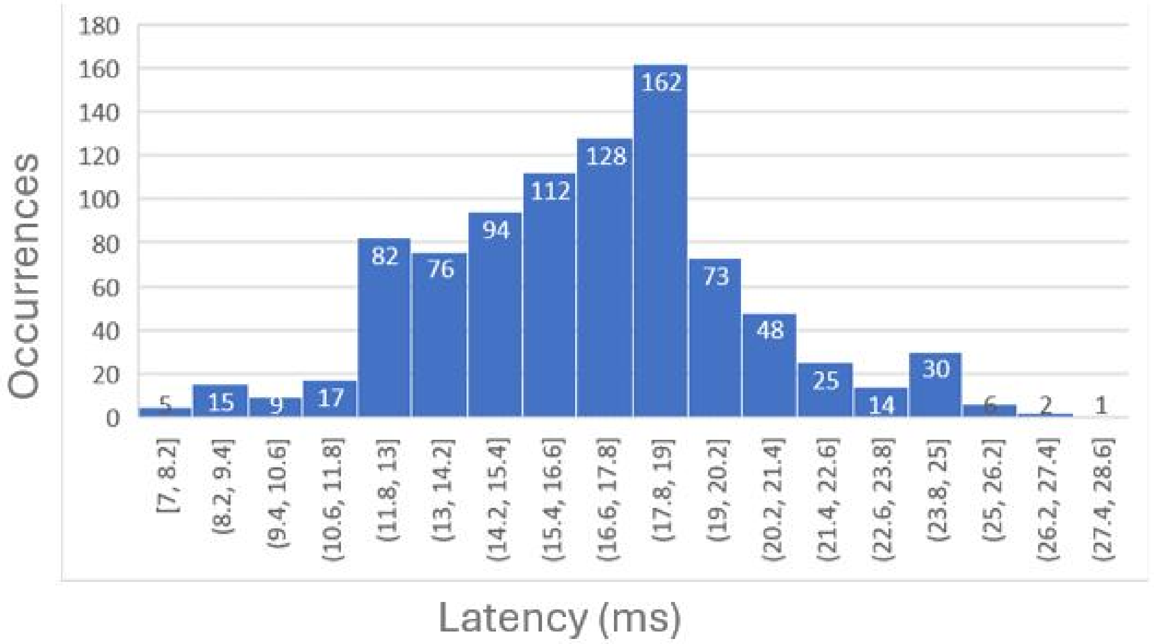

Figure 6. 5G latency distribution (ms) when using 5G, topology 2

Topology 3

In contrast, Topology 3 removes the second modem and connects the second PC directly to the 5G network via an edge router interfacing with the 5G core (5GC). The client is moved to the 5G modem connected to PC #1, representing a more integrated industrial deployment where devices connect directly through 5G endpoints. Figure 7shows a simplified representation of this setup.

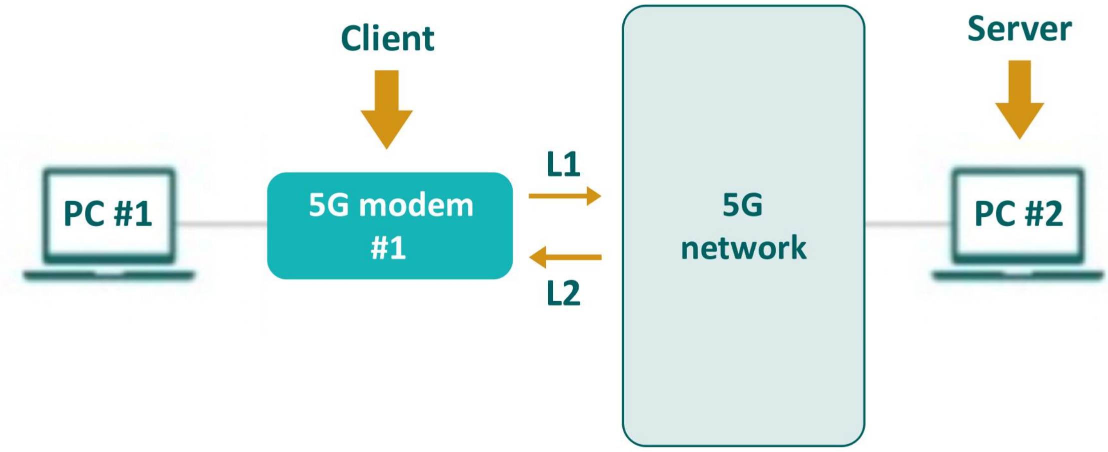

Figure 7: Topology 3 employed in the trials: client on 5G modem #1, server on 5G modem #2

The focus in topology #3 was the throughput, by using both UDP and TCP transmissions with a single 5G modem. This was done as the direct connectivity to the network allowed us to differentiate between the two links without having any UL bottlenecks because of the use of two 5G connected modems. Table 5 shows the summary of the results for Topology 3.

Table 5: Throughput obtained with TCP and UDP transmission, topology 3

Throughput (Mbps)			
TCP	Downlink	Sender	399
		Receiver	395
	Uplink	Sender	50.2
		Receive	42.9
UDP	Downlink	950	
	Uplink	43.8	

Consequently, as it can be observed, this topology permitted us to validate that, although the UL throughput values are still similar to the ones obtained in topologies 1 and 2, the DL throughput is clearly higher, obtaining an average value of 395-399 Mbps with TCP and 950 Mbps with UDP.

DISCUSSION

Overall, the performance measurements of the private 5G network demonstrate its potential to meet the demanding requirements of Industry 4.0 applications. Across the test scenarios, TCP throughput ranged from approximately 16.8 Mbps to 66 Mbps, while UDP throughput varied from 20 Mbps up to 75 Mbps in multi-device configurations, with jitter values as low as 0.02 ms in optimized setups. The observed latency ranged from 7 ms to 28 ms, confirming that the network can provide low-latency communication suitable for industrial automation tasks. Importantly, these results highlight the ability of private 5G networks to sustain high data rates and maintain minimal jitter, which are critical for time-sensitive operations such as coordinated robot control, autonomous guided vehicle (AGV) navigation, and real-time process monitoring.

Additionally, the benchmarking also revealed that uplink traffic can be a limiting factor in certain configurations, particularly when multiple devices share the network [11]. However, direct connectivity to the core significantly improves downlink throughput, enabling high-bandwidth applications like high-definition video streaming, augmented reality (AR) or virtual reality (VR) operator assistance, and real-time updates for digital twins [12]. The jitter reduction observed when devices are directly connected to the 5G network demonstrates the importance of optimizing network topology for deterministic communications, which are essential for precision tasks in industrial environments.

Overall, these findings indicate that private 5G networks provide the flexibility required to adapt to various industrial layouts and workloads. Specifically, their combination of high throughput, low latency, and low jitter supports critical Industry 4.0 use cases, including remote monitoring as a service, process control over 5G, real-time analytics, and immersive human–machine interaction [10] [14]. Furthermore, the results suggest that careful planning of network architecture and device placement can maximize performance, ensuring reliable operation for both uplink-intensive and downlink-intensive industrial applications. Overall, the experimental outcomes confirm that private 5G networks can serve as a robust backbone for the Factory of the Future, enabling efficient, responsive, and highly connected industrial operations [9].

CONCLUSION

In conclusion, this study demonstrates the feasibility and effectiveness of deploying a private 5G network to support Industry 4.0 applications in a Factory-of-the-Future environment. Notably, using open-source components, including Open5GS for the 5G core, srsRAN for the radio access network, and USRP-based software-defined radios, a fully integrated end-to-end testbed was realized. Performance benchmarking across multiple topologies highlighted the network's ability to provide high throughput, low latency, and minimal jitter—key requirements for industrial automation, real-time monitoring, process control, and immersive human–machine interaction.

Importantly, the results indicate that private 5G networks can reliably sustain the communication demands of advanced industrial applications, including remote monitoring, coordinated robotic control, AR/VR-assisted operations, and real-time analytics. However, observations such as uplink bottlenecks and the impact of network topology emphasize the importance of careful deployment planning to optimize network performance for specific industrial use cases.

In summary, this work confirms that private 5G networks offer a flexible, high-performance, and secure communication backbone for Industry 4.0, enabling factories to achieve greater automation, operational efficiency, and responsiveness. Lastly, these findings provide a foundation for further research into advanced applications, scalability, and optimization of private 5G networks in complex industrial environments.

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