# Using 5G URLLC Protocol to Establish IMS Safety Zones for Industry 4.0: A Case Study With an Autonomous Robotic System

Thiago Silva de Benedito, Murilo Araujo Romero

*Abstract*— **The adoption of wireless technologies in industrial environments has been a highly relevant topic of investigation, considering both the interplay between automation and industrial data communication systems as well as the goal to meet the stringent communication requirements of Industry 4.0, where network reliability and resilience are critical considerations. In such Integrated Manufacturing Systems (IMS), where people and machines interact in an industrial environment, safety aspects also play a fundamental role. In this context, this work investigates a new application framework for 5G URLLC communications in Industry 4.0, taking advantage of the low latency provided by the 5G infrastructure, through the integration of automation safety systems into an IMS architecture. In our setup, an Industrial Internet of Things, IIoT, device uses 5G connectivity to send an emergency stop command to an Industrial Autonomous Mobile Robot. Our experiment achieved a maximum latency below 1 ms with a block error rate (BLER) below $10^{-5}$ on the air interface, including scenarios of high consumption of Physical Resource Blocks (PRBs). The results reinforce the great potential for using 5G networks for worker safety systems and automation elements in industrial environments.**

*Index Terms— Terms—* **Terms—5G, 5G URLLC, IMS, Industry 4.0, Autonomous Robots, IoT, Low latency communication, wireless communication for factory automation, BLER, reliability, Time Sensitive Networks.**

## I. INTRODUCTION

THE fifth generation of mobile networks, referred to as 5G NR, was developed by the 3GPP (3rd Generation Partnership Project), to meet various new application scenarios for wireless connectivity beyond cellular broadband, with higher data transfer speeds and reduced latency, when compared to previous network protocols, such as LTE [1]. Connections based on URLLC (Ultra Reliable Low Latency Communication), open up a new range of possibilities for the integration of 5G networks into new contexts, such as serving as a communication medium for different elements in industrial automation, thereby replacing protocols based on wired media, such as Profinet, which is widely used in industrial environments [2].

5G URLLC data communications are characterized by connections with latency up to 1 ms and high reliability in data packet transmission [3]. These characteristics enable 5G network architectures as wireless communication platforms, in applications requiring high levels of reliability and minimal latency in data transmission, such as in the operation and supervision of robotic systems [4] and [1], as well as in the creation of safety zones for IMS systems, as it will be demonstrated here, to our knowledge, for the first time in the literature. In short, the proposed scheme involves sending IIoT sensor data through the 5G network to an autonomous robotic system, by means of edge processing. The goal is to evaluate the 5G network performance in the creation of safe operational zones in IMS.

The use of the cloud in an edge computing configuration offers a significant advantage by enabling a single appliance to seamlessly serve multiple manufacturing facilities. This centralized approach enhances scalability and operational efficiency, reducing the need for site-specific infrastructure and streamlining management processes across units. While this configuration might introduce a slight increase in latency outside the transport network, our experiment achieved a maximum latency always below 1 ms with a block error rate (BLER) below $10^{-5}$ on the air interface, even in scenarios of high consumption of Physical Resource Blocks (PRBs). Also, any eventual trade-off is outweighed by the improved resource utilization and the ability to standardize operations across geographically distributed sites, providing a reduction in the investment to implement the same technical solution in different factory facilities.

The work is structured as follows: Section II provides a literature overview and places our work in the context of the previous advances of this field of investigation. Section III describes the technological testbed architecture, and the methodology adopted in the experiments. Section IV describes the results obtained for use of URLLC in the autonomous robotic testbed integrated with operational safety systems and Section V outline our conclusions regarding the use of the 5G

Thiago Silva de Benedito (ORCID: 0009-0007-7874-6450; e-mail: thiago.benedito@usp.br), and Murilo Araujo Romero (ORCID: 0000-0002-2312-7253, e-mail: murilo.romero@usp.br) are with the Department of Electrical and Computer Engineering, Sao Carlos School of Engineering - Universidade de Sao Paulo (EESC-USP), Sao Carlos, São Paulo, Brazil.

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network in this low-latency application.

## II. LITERATURE OVERVIEW

In a bird´s eye view of these aspects in the technical literature, the work described in [5] and [6] focused on performance testing of 5G networks for the transmission of Profinet and Profisafe data. These protocols are of traditional use in industrial automation, ensuring real-time communication and safety in environments where equipment and human operators must coexist. The study focused on the potential of 5G networks to replace these traditional wired solutions, demonstrating that the URLLC feature of 5G could meet the stringent latency and reliability requirements needed for critical industrial operations. Specifically, the study showed that 5G could handle data traffic originating from these protocols while still maintaining the necessary safety standards, indicating a viable path forward for wireless industrial automation systems.

Similarly, [7] focused on the use of 5G to support time-sensitive networks (TSN) in industrial automation. The study explored the integration of 5G with existing Ethernet-based protocols, such as Fieldbus and Profinet. Key 5G features, such as packet duplication and redundancy in the user plane were highlighted as essential to achieve the reliability and low latency requirements of industrial systems. In addition, the concept of network slicing was discussed as a mechanism to establish different levels of service to various industrial applications, providing flexibility and efficiency in resource allocation.

In another study [8], the authors conducted a detailed evaluation of URLLC in industrial automation systems, particularly in environments requiring low-latency and high-reliability communications. Their work highlighted how URLLC can meet the demanding needs of industrial control systems, such as closed loop control, where cycle times can range from as low as 0.25ms to 50ms. The study demonstrated that URLLC could deliver the required performance with packet error rates as low as 10´9, making it suitable for safety critical applications. This research serves as a foundational reference for implementing 5G in high-performance industrial environments.

On the other hand, the work described in [9] explored the service-based architecture (SBA) of 5G networks and its implications for Industrial IoT applications. The study investigated how the 5G architecture can support the integration of AI and ML driven automation systems and discussed the challenges involved in transitioning from traditional industrial network protocols to wireless solutions, such as 5G NR. By using network slicing, edge computing and URLLC, the authors outlined how 5G could cater to different levels of service requirements in industrial environments, offering tailored solutions based on the specific demands of IIoT devices. This architecture allows for greater scalability and flexibility; a crucial feature found in modern industrial automation systems.

The survey by [10] offers a comprehensive review of network automation protocols for industrial IoT, highlighting the critical role 5G and, eventually, 6G networks will play in the future of Industry 5.0. As industries evolve toward more sophisticated automation, the demands for bandwidth, low latency, and reliability increase exponentially. The study underscored the importance of these emerging network technologies in supporting complex, data-intensive applications like Digital Twins, which require large-scale data processing and real-time communication. The research emphasized the importance of 5G for connecting numerous devices and sensors in large industrial environments, preparing the ground for the upcoming 6G developments.

In the study presented [11], the focus was on the use of short block-length codes in URLLC for Ultra-Reliable communication in low-latency environments. This work addressed one of the key challenges in wireless communications for industrial automation: maintaining extremely high reliability while reducing latency to the millisecond level. The authors discussed the trade-offs between latency, reliability, and throughput and proposed coding techniques that enable faster and more reliable data transmission in critical industrial systems.

The study in [12], [13] [14] extensively examine the use of 5G URLLC for AGVs and autonomous mobile robots, demonstrating how low-latency communication supports safe navigation, real-time computing offloading, and efficient autonomous operation in industrial environments. However, these works focus primarily on mobility, perception, and edge-computing integration, without addressing how 5G communication performance can be directly coupled with industrial safety mechanisms. In contrast, the contribution of the present work lies in explicitly integrating 5G URLLC communication with IMS-based safety zones, enabling the network latency and reliability characteristics to directly trigger and govern safety-critical actions such as emergency-stop procedures. This represents a novel perspective relative to existing literature, as none of the referenced studies incorporate safety zoning as part of the communication loop or evaluate how deterministic wireless performance interacts with safety-certified industrial workflows. By demonstrating this interplay, the proposed approach extends the role of 5G beyond high-performance connectivity, leading to a functional component within industrial safety architectures, highlighting a gap not yet explored in recent related research.

The investigations described in [15], [16] and [17] focus on the development of energy-efficient and cost-effective transmission systems for Industrial IoT. Specifically, the study [15] detailed in explores a two-stage wireless transmission strategy for industrial systems, which is designed to balance energy consumption and estimation accuracy. These studies aim to optimize network performance by reducing energy usage while ensuring reliability and low latency.

Research papers [18], [19], [20] and [21] emphasize the integration of 5G technology with robotics, particularly for applications requiring ultra-low latency. In particular, [18] examines how 5G can enable precise control of distributed robotic systems, providing improved performance for automated guided vehicles (AGVs) in smart manufacturing environments. Overall, these papers highlight the challenges of real-time control and coordination in industrial robotics, exploring how 5G capabilities, such as ultra-reliable low-latency communication (URLLC), support more resilient and efficient operations.

The papers [22], [23], [24], [25] and [26] review the advancements in Industrial IoT (IIoT) and network automation as the technology moves towards Industry 5.0 into the 5G network context. These works focus on how 5G networks can enhance industrial connectivity by integrating automation and intelligent systems into factory environments. The integration of AI with industrial networks allows for improved decision-making and autonomous operation, placing 5G as a key enabler for next-generation smart manufacturing.

Taken together, all the studies discussed in this section provide a rich understanding of the various applications of 5G URLLC in industrial environments, from safety-critical systems to real-time automation, including the integration of advanced technologies like AI and Digital Twins. In this context, our work addresses a much less explored safety aspect of these systems, aiming to evaluate the performance of a 5G network as a means of low-latency and high-reliability communication in motion detection zones within IMS automation environments.

These IMS zones can be defined in [27] [28] as areas where electro-sensitive protective equipment can detect movements or interventions in places where the presence of people may pose a risk to their physical integrity. In response, this protective equipment will trigger an emergency stop. However, if latency is too high, danger to people is still a possibility. In addition, machinery damage and long interruptions to the production line may result.

In order to overcome these shortcomings, we deployed a testbed emulating the operational areas of an autonomous robotic system, in order to design and test an IoT device consisting of a reflective infrared sensor associated with an edge computing element and specific programming software. The goal was to detect movements or intrusions in the operational areas of the autonomous robotic system and trigger an emergency stop with the lowest available latency, through and 5G wireless network using URLLC. The devices and emulated scenarios follow the main safety practices for IMS systems, as described in [28], and make use of an indoor 5G standalone network (3GPP Release 16) [3] [29].

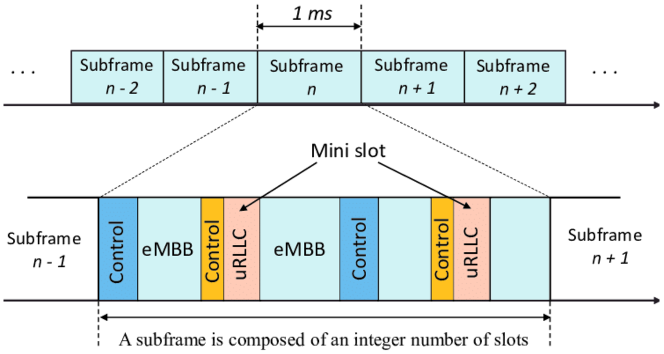

Fig. 1. 5G frame structure, showing the presence of mini slots for reduced latency communication.

## III. NETWORK AND IMS TEST SETUP

In the 5G standalone architecture, the URLLC data transmission frame structure leverages the NR network architecture ability to operate with different sub carrier spacing, SCS, allowing for shorter subframe allocations to enable significant reductions in latency when routing data to the destination IP. The distribution of resource blocks allocated to URLLC packets within the 5G architecture frame is illustrated in Fig. 1. The 5G frame structure plays a crucial role in the efficient temporal resource allocation for different types of services and applications, with URLLC mini-slots being an integral part of this system. This capability to operate with flexible subcarrier spacing accordingly to the criticality classification allows the transmission of data packets with extremely low latency, considering both the air interface and data routing after processing in the network core.

Fig. 2. Indoor 5G AS architecture utilized to connect the industrial devices during the tests.

The infrastructure used in this study comprises a private 5G network operating on the N78 band, with an NR carrier of 100 MHz, from 3.7 GHz up to 3.8 GHz. The choice of this specific range is associated with the allocation of this band for private limited service by Anatel, the local regulator for telecommunications systems based on licensed bands in Brazil. The access equipment includes Nokia components such as the AirScale Baseband Unit, ASOE, IXR 7250 interconnect router, Juniper SRX 300 firewall, AirScale PRRH with 4x4 MIMO with 1W for EIRP, connected to a standalone 5GC core implemented on an HP DL110 edge server. The experimental arrangement can be seen in detail on Fig. 2.

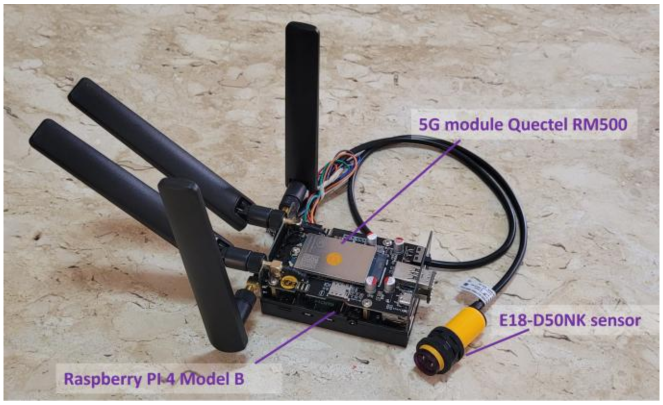

Fig. 3. 5G IIoT module developed based on a Raspberry Pi 4B and Quectel 5G chipset RM500U.

The IoT element used for emergency stop activation in IMS system's operating range consists of a Raspberry Pi Model 4B board programmed specifically to read the E18-D50NK infrared detection sensor and communicate with the control system of the automation element via a Quectel RM500Q 5G serial module. The setup can be seen on Fig. 3.

For the autonomous robotic system, a MiR250 shelf transporter model was used, featuring an onboard control and movement system. This system can transport items up to 250 kg and includes a built-in Lidar system for obstacle avoidance along its path. To enable connectivity with the 5G network, an industrial gateway model, the Nokia Fieldrouter FRRx502e, was integrated, which transmits local control information from the MiR to the management system, the Fleet Manager, implemented on virtualized servers in Azure. Implementing the Fleet Manager for route control in the cloud offers a significant advantage by seamlessly enabling a single appliance to serve multiple manufacturing facilities. This centralized approach enhances scalability and operational efficiency, reducing the need for site-specific infrastructure and streamlining management processes across units. While this configuration might introduce a slight increase in latency outside the transport network, the drawback is outweighed by the improved resource utilization and the ability to standardize operations across geographically distributed sites, which means a reduced CAPEX to implement the solution in different factory facilities. This gateway has an industrial-grade classification and 2x2 MIMO for operation in the N78 band (3.75 GHz as the central frequency). The system integration is presented in Fig. 5, highlighting the implementation of the MiR 250 route management service virtualized in the cloud, with Express Route integration for maximum data transmission efficiency.

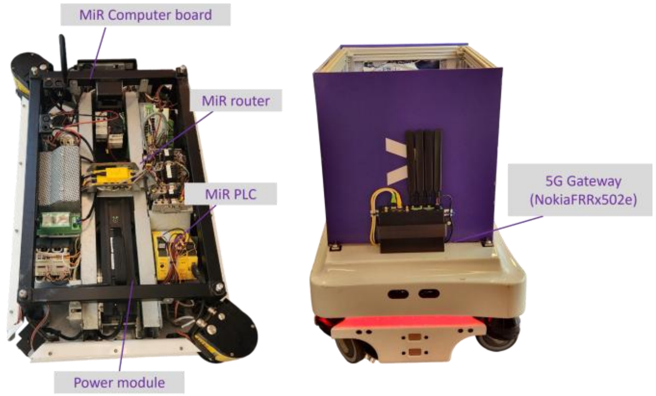

Fig. 4. 5G industrial gateway with Autonomous Mobile Robot MIR250 connected with the private 5G network.

The logical network topology of the setup is highlighted in Fig. 5, where the integration of elements through the 5G network can be observed. In this case, the edge element continuously monitors the safe operating area limits of the IMS system. Upon detecting movement in the security perimeter though IoT sensor readings, the edge element sends the emergency stop command through the 5G network to the IP of the automation system's control host. This cycle involves the uplink of the stop command via a 5G connection with URLLC and the downlink of the command to the control system's host, which ultimately triggers the system's emergency stop. The system integration is achieved through the interconnection of a Palo Alto 3430 Firewall, which receives the network core information and securely directs it via a site-to-site VPN connection to the virtualized machines deployed in Azure's cloud.

## IV. EXPERIMENTAL METHODOLOGY

To assess the performance impact of URLLC connectivity over the private 5G network, multiple evaluations were conducted in which the MiR250 navigated from location A to a pre-mapped location B, following a route predefined in the fleet manager. Throughout these experiments, communication data between the MiR250 and the Fleet Manager were continuously collected by accessing the network's equipment (Baseband Unit). In these scenarios, the MiR assured stable communication with its control module and the cloud-based route manager, with displacement data transmitted continuously. This approach enabled the collection and subsequent analysis of statistical data regarding data packet transmission. During data collection, the MiR250 was programmed to carry out a pre-defined operation, including transitioning trough different environments changes with obstacles, to closely simulate an industrial environment characterized by the natural presence of people and dynamic equipment, like other robots and machines.

To better exemplify the sequence of actions within the security system. Fig. 5 illustrates the interaction between different components of the set-up. Notably, both the sensor reading information, as well as the stop command to the MiR250, transit through the 5G network twice. In both cases, transmission via the URLLC frame is used to ensure the minimal latency and maximum transmission reliability for the operation. In short, the IoT device is continuously monitoring the sensor data and processing it. When motion is detected, configuring a protected area invasion, the sensor conveys the information through the 5G network to the fleet manager, who sends the stop command to the MiR250 by the 5G network as well by means of the DL PRB.

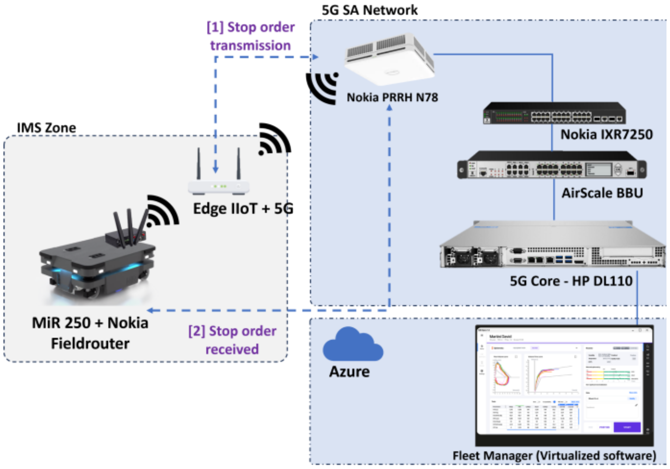

Fig. 5. Test setup topology utilized to emulate an industrial process with AMR connected to the 5G Network.

Performance indicators for industrial networks usually differ from those used in general-purpose networks due to the distinct application areas and purposes. Metrics commonly prioritized in general-purpose networks, such as data rate, are of secondary relevance in industrial settings. The IEC 61784 International Standard, [30], introduces several key performance indicators for industrial networks, such as delivery time, latency, throughput RT, and non-RT bandwidth mainly [31].

An indicator explored in this work is the total latency, a measure for the precision in performing periodic operations. The overall latency of the system can be estimated through the following equation:

$$L_t = l_i + l_w + l_c + l_r \qquad (1)$$

where $L_t$ represents the total latency of the system, encompassing the sum of the latency induced by the IoT device, $l_i$, the latency of the air interface, $l_w$, the latency induced by the network core, $l_c$ and, finally, the latency associated with receiving the data packets and the consequent stop command for the system, $l_r$.

The data packets collected through the different emulations scenarios were analyzed, and the results are presented in the next section. The distribution of packet size, one-way latency, and total system latency were used to evaluate the performance of the 5G URLLC connection for control operations of the AMR within IMS zones. Fig. 6 represents the flow chart for the tests integrating the IoT and 5G network. infrastructure.

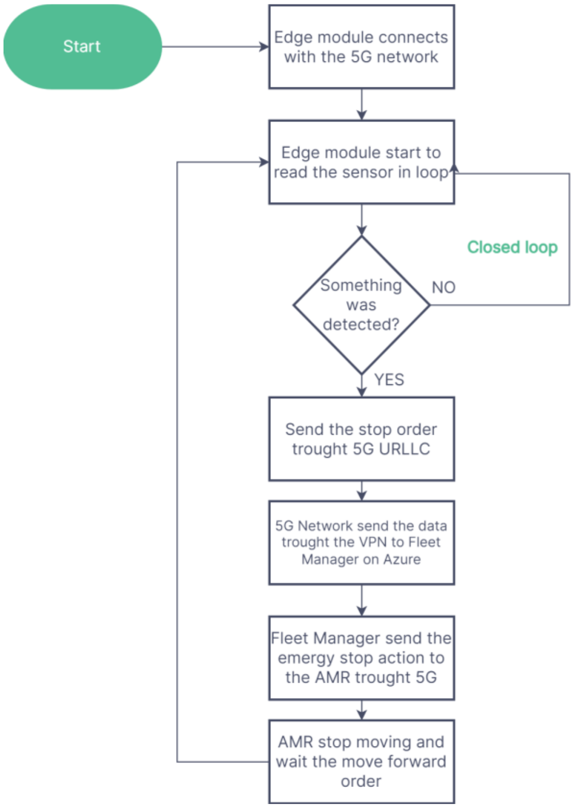

Fig. 6. Flowchart of IMS system actions integrated with the 5G network connected with the private 5G network.

This study relied on datasets collected from two primary sources: the Nokia base station unit and a network sniffer running on the IIoT device through Wireshark. The experimental procedure involved capturing all uplink and downlink packets directly at the device level, enabling precise timestamping, protocol-level inspection, and validation of URLLC frame behavior during the emulated industrial operation. Wireshark Statistics was used to extract latency distributions, retransmission events, and radio interface indicators. Complementary data processing was performed for handling SQL-formatted datasets and to generate analytical visualizations. This methodology ensured a transparent, reproducible, and fine-grained characterization of the communication performance under the tested conditions.

## V. RESULTS

This section presents the data collected from the functional tests conducted to evaluate the performance of 5G URLLC in industrial applications. The experiments were designed to evaluate critical metrics such as latency, reliability, and network availability in advanced automation scenarios. The obtained results provide a detailed insight into the capability of 5G URLLC to meet the industry's stringent requirements, highlighting both the benefits and the challenges observed during the operation of our test-bed.

The results were obtained by analyzing data collected from the Nokia base-station unit and the Wireshark network sniffer on the IIoT device, emulating an industrial operation setting. Data processing and analysis leveraged tools such as Wireshark statistics and Matplotlib python library.

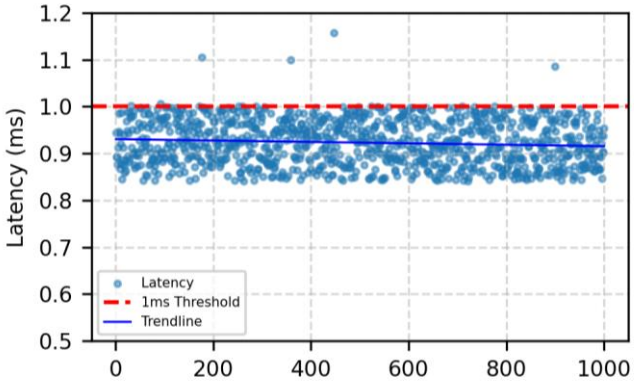

Fig. 7. Dispersion of the URLLC frame captured during the tests and data acquisition..

Latency in control and sensing systems is a critical feature for operational safety, particularly in IMS zones, directly impacting the well-being of personnel and equipment. Figure 7 depicts the latency distribution observed during tests with the MIR250, where the Nokia Fieldrouter gateway traffic was prioritized with the highest possible CQI, even with other applications concurrently using the 5G network. The data indicates that most frames exhibit inbound latency below 1 ms, meeting the URLLC requirements defined by 3GPP. Outliers exceeding 1 ms may be attributed to high PRB utilization or management frames that are non-operational for the IIoT system and the Fleet Manager.

The Signal-to-Noise Ratio (SNR) is another critical factor in telecommunications network performance, influencing the reliability and transmission quality for the link between the gNodeB and the industrial gateway. Tests involved creating a path for the MIR250 to move away from the 5G access point, degrading the Radio Signal Radio Power (RSRP) and potentially increasing frame retransmission rates via Hybrid Automatic Repeat reQuest (HARQ). HARQ and preemptive scheduling are key techniques to reduce the final latency experienced by the industrial gateway by adjusting ACK/NACK wait times based on channel quality. Fig. 6 illustrates the correlation between SNR and retransmission rate across three scenarios with the AMR.

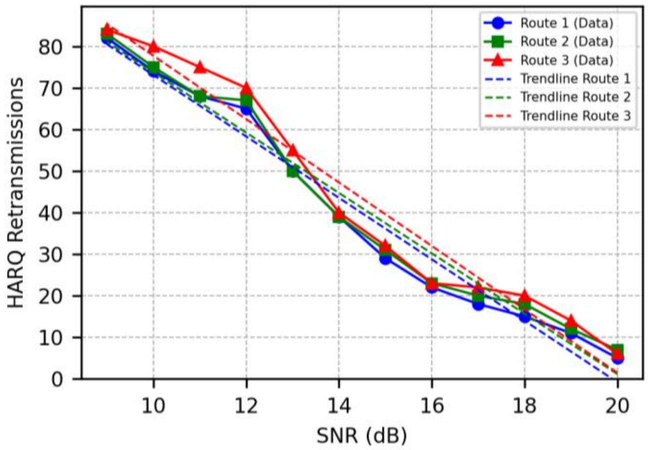

Fig. 8. Relationship between SNR measurements captured at the industrial gateway and 5G access layer HARQ retransmissions. The retransmission rate represents the average frequency of recovery attempts per 10.000 transmitted packets.

Under low SNR conditions, HARQ performance is affected due to difficulties in correctly decoding transmitted data, leading to increased frame retransmission rates and higher average latency. HARQ relies on the receiver capability to detect and correct errors, which is hindered by low SNR, resulting in retransmissions and reduced data throughput. The MiR robot travelled the assigned path in three instances, yielding similar results, reinforcing that a higher SNR correlates with better radio interface quality and fewer retransmissions due to modulation failures. The trend line in Fig. 8, derived from linear regression, supports this conclusion.

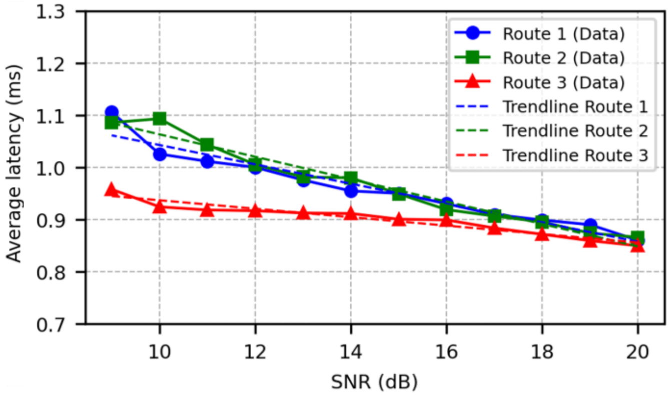

Fig. 9. Impact of SNR measured at the industrial gateway on system latency. The reported latency represents the average of total duration from the 5G access infrastructure perspective, incorporating the processing time of cumulative HARQ retransmission cycles.

Latency was also observed and collected for the specific routes executed by the AMR within a facility designed to emulate an industrial environment. The latency measurements were evaluated as a function of the received SNR and are presented in Fig. 9, highlighting the impact of radio link conditions on user plane performance. According to 3GPP TR 38.913 [32], user plane latency for URLLC is defined as the time required to successfully deliver an application-layer packet between the ingress and egress points of the radio protocol layer, explicitly accounting for retransmission mechanisms such as HARQ. In this context, the higher latency values observed under lower SNR conditions can be attributed to retransmission events triggered by decoding failures, which are further intensified by the propagation characteristics of the industrial scenario considered in this study. It is worth noting that the same AMR routes and trajectories used in the previous experimental evaluations were preserved, ensuring consistency across latency, reliability, and radio performance analyses.

The results presented in Fig. 9 show a clear inverse relationship between SNR and end-to-end latency at the industrial gateway. As the SNR increases, latency consistently decreases across all three evaluated routes, indicating improved radio link reliability and reduced need for retransmissions. The similar behavior observed among the routes demonstrates the stability and repeatability of the measurements, while the linear regression trend lines further confirm that higher SNR levels contribute to lower and more predictable latency in the 5G air interface.

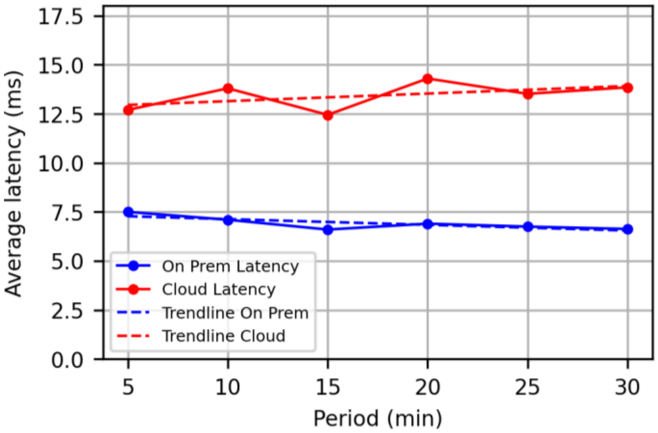

Fig. 10. Latency comparison between on-premises and cloud implementations. The total system latency was captured via network sniffing performed at the local access infrastructure.

In another test scenario, the Fleet Manager, which governs the operational actions of the MIR250, was deployed in the Azure public cloud (South Brazil region). The goal was to evaluate the performance of the centralized configuration using the cloud, to provide high availability, and cost effectiveness by serving multiple factories from a single virtualized instance. A series of tests were performed over a continuous 30-minute period with average latency readings stored in 5-minute intervals. The Innovation HUB's Express Route connection to the Azure data center reduced latency relatively to typical Internet connections. The edge server hosting the core SA was used for on-premises latency capture.

Fig. 10 compares the average latency for each scenario, revealing that Azure infrastructure latency is nearly twice the value of the on-premises setup, adding approximately 12ms for a roundtrip. Given the MIR250's maximum speed of 2 m/s, this 12ms latency could increase stopping distance by up to 2.5cm compared to the on-premises scenario. While this is acceptable for most AMR systems, it may eventually be an issue for high-precision manufacturing environments.

## VI. CONCLUSION

The utilization of 5G in Industry 4.0 environments, particularly by means of URLLC, shows great potential in enabling applications and systems with stringent latency and reliability requirements, or those needing high mobility and positioning precision. Test results offer valuable parameters on 5G URLLC performance in a manufacturing setting, utilizing an AMR (MIR250) connected to the 5G network and a Fleet Manager solution for centralized control. Analysis of latency measured on the IIoT device for URLLC frames demonstrated 5G ability to meet the low-latency requirements established by 3GPP for 5G SA architecture. The large majority of frames showed latency below 1 ms, confirming 5G URLLC's potential for latency-restricted control applications.

The influence of Signal-to-Noise Ratio (SNR) on HARQ retransmission rate was also investigated, revealing the correlation between signal quality and communication reliability. Low SNR increased retransmission rates, impacting the average latency observed at the industrial gateway. These results reinforce the need for careful 5G network infrastructure planning, ensuring adequate coverage and high signal quality.

The N78 band (3.3-3.8 GHz) is standardized for 5G use and it is the most widely deployed FR 1 band for 5G Standalone networks worldwide. In our study, this band was selected because there is a 100 MHz bandwidth allocated by the Brazilian regulator, Anatel, for private networks usage in this spectral range. Although public commercial networks could be used for the same purpose, performance degradation is likely to occur due to contention with other users on the air interface. Additionally, depending on the geographical location and the density of active users, the use of Physical Resource Blocks (PRBs) on the air interface may increase significantly, potentially leading to reduced throughput, higher latency, and overall degradation of network performance.

If needed, carrier aggregation using two or more operational bands could mitigate traffic congestion due to high radio resource utilization. Millimeter-wave bands (FR2) are strong candidates due to their high bandwidth and minimal signal degradation in indoor environments common in Industry 4.0.

The comparison between on-premises and public cloud (Azure) performance revealed that cloud infrastructure latency is approximately twice the corresponding value of on-premises, adding an average of 12 ms for a roundtrip. This latency increase is generally acceptable but can impact some applications demanding high precision and ultra-fast response times. Therefore, network optimization, infrastructure planning, choice of operating bands, and the implementation architecture (on-premises vs. cloud) are critical issues to assure consistent and reliable 5G URLLC performance in industrial environments.

It is relevant to compare our results with alternative wireless technologies such as industrial Wi-Fi. Although 5G provides clear advantages in deterministic latency, reliability, and resource scheduling, Wi-Fi remains attractive due to its lower cost and simpler deployment. While both technologies can operate with similar EIRP levels in indoor scenarios, 3GPP-based systems offer a broader set of reliability-oriented features compared to Wi-Fi specially in a 5G Standalone network. However, these capabilities are generally associated with higher implementation costs, a factor that frequently plays a decisive role in industrial investment decisions. On a final note, it should be pointed out that a strong emerging trend for the near future may be the interplay between safety-critical systems and AI-driven edge computing for intelligent automation [33].

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**Thiago Silva de Benedito** (Student Member, IEEE) received the M.Sc. degree in Electrical Engineering from the University of São Paulo (USP), São Carlos, Brazil, in 2025, and the B.Sc. degree in Mechatronics Engineering from the University of São Paulo (USP), São Carlos, Brazil, in 2016, with a specialization in Automotive Engineering. He is currently a Senior Manager at VIVO, São Paulo, Brazil, where he leads initiatives related to telecommunications networks and digital infrastructure. Prior to this role, he worked as a Technology Manager at Accenture, São Paulo, Brazil, leading private network solutions for multiple industries across Brazil and Latin America. His research and professional interests include wireless communications, 5G private networks, URLLC, IoT devices, and industrial wireless gateways.

**Murilo A. Romero** (Senior Member, IEEE) was born in Rio de Janeiro, Brazil, in 1965. He received the B.Sc. and M.Sc. degrees from the Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil, in 1988 and 1991, respectively, and the Ph.D. degree from Drexel University, Philadelphia, PA, USA, in 1995. After his return to Brazil in 1995, he joined the University of Sao Paulo, Sao Carlos, as a faculty member. At the University of Sao Paulo (USP), he became an Associate Professor in 2001 and a Full Professor in 2008.

He was then Head of the Electrical Engineering Department, EESC-USP, from 2009 to 2013, and was the Chair of the Electrical and Biomedical Engineering Committee of the Brazilian Research Council (CNPq, from 2011 to 2013) as well as Head of the Electrical Engineering area at CAPES from 2014 to 2017, an accreditation agency of the Brazilian government, established to carry out quality assurance of graduate studies in Brazil, both at the master and doctoral levels.

His research interests span over a large variety of topics in electrical engineering. Prof. Romero holds two patents and has published about 200 journal and conference papers, including manuscripts at IEEE Transactions on Microwave Theory and Techniques, IEEE Journal of Quantum Electronics, IEEE Photonics Technology Letters, IEEE Transactions on Circuits and Systems, IEEE Transactions on Electron Devices, IEEE Transactions on Nanotechnology, IEEE/OSA Journal of Lightwave Technology, IEEE Sensors, IEEE Access and IEEE Transactions on Information Forensics and Security, among other top-ranked journals.