Next-Gen Industrial Networking: 5G and WiFi 6's Role in MES Deployment

Samuel Costa, Gabriel Fré, Andre Souza, and Alessandro Luz

***Abstract*— This paper presents a practical study on the feasibility of private 5G and Wifi 6 technologies for executing applications employed in discrete manufacturing processes, which is of great interest for the digital transformation of the industry, investigating future technologies to figure the next generations of industrial networks. The study utilizes typical manufacturing operations on two identical systems, one operated on 5G technology and the other on Wifi 6. Based on this setup, results are collected and analyzed, providing important quantitative indicators on the applicability of each technology in the context of the next generations of industrial networks, considering the requirements of reliability, availability, and the ability of the analyzed systems to ensure nominal parameters over critical operations recurrent in the industry.**

***Keywords*— Industry 4.0, 5G, Wifi 6, Private Network, Manufacture Execution System.**

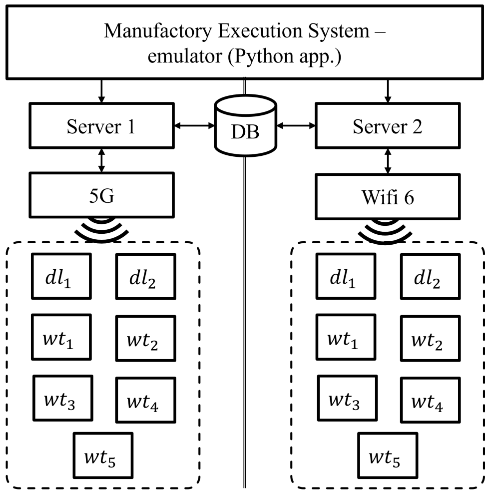

Fig. 1. Representation of the setup utilized for the experiments in this work. 5G communication (left) and Wifi 6 (right) operate, individually, the same Manufacturing Execution System (MES), reporting performance data records to a common database.

I. Introduction

Since the fifth generation of mobile communication technologies, 5G, entered the private network market by the early 2020s, it has facilitated numerous advancements in industrial digital transformation. The resilience, reliability, and capability for managing high densities of communicating devices provided by 5G have been pivotal in this progress. Additionally, the high data rates and low latency offered by 5G are crucial for supporting critical mission operations, which are commonplace in the Industry 4.0 reality [1]–[3].

In this context, as highlighted by Aijaz et al. [4] and Selvam et al. [5], there exists a lack of models that fully satisfy the typical industry requirements for reliable data transfer in private network environments. For instance, in discrete manufacturing, as discussed in these studies, there is a specific need for short packet exchanges to operate the Manufacturing Execution System (MES) concurrently with multiple data streams for commissioning and programming devices in the final steps of assembly lines. It's imperative that all these services adhere to high availability, reliability, and security Service Level Agreements (SLAs).

Furthermore, a notable aspect driving industry transformation is the flexibility afforded by a comprehensive wireless connectivity system, which currently relies on 4G/5G and Wifi (IEEE 802.11) networks. [6] This work presents a practical approach to investigating the operation of a typical MES system over a 5G private network and compares its performance with that provided by Wifi 6. The overarching objective is to quantify the performance gains in terms of manufacturing execution time, latency, and throughput when conventional factory plants deploy 5G technology to manage operations.

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A. Related Works

In their study, Cao et al. [7] conduct an analysis of several Key Performance Indicators (KPIs) essential for enabling the scenarios of the new generations of Industry 4.0 in high-capacity wireless networks. The study highlights that beyond 5G technology (B5G) stands out as one of the most promising solutions for deploying applications such as augmented/virtual reality (AR/VR), industrial Internet of Things (IIoT), and Digital Twins (DT), as well as real-time precise control. This connectivity technology fulfills time-sensitive requirements, offering 1 millisecond latency, enhancements for high effective throughput of short-packet exchanges, and reliability values of about 99.999% [8]. Based on the research conducted by Mertes et al. [9], there exists a deficiency in experimental evidence quantifying the potential of 5G technology to address challenges prevalent in real-world manufacturing environments. Within their study, Mertes and colleagues executed a digital twin application utilizing a 5G network, analyzing its implications on manufacturing operations. Furthermore, they conducted a comparative assessment of the overall performance metrics, particularly latency, between 5G and Wifi 6 networks. Their investigation indicates that 5G stands out as the most adaptable wireless communication technology suitable for a diverse range of industrial communication applications within the manufacturing sector.

Thus, combining the potential offered by current 5G network with applications that provides industry retrofitting, IIoT, non-intrusive sensing and actuation capabilities [2], [4], indicates that 5G is indeed the future of industry 4.0 for wireless connectivity as stated by Selvam et al. [5].

II. Industry 4.0 Use Case

As stated on previous section, this work aims to quantify the performance gain in terms of Manufacturing Execution System metrics, time required per operation, which is related to the end-to-end latency and throughput. In this case, metrics such as miss operation rate, yielding and system failure probability was not considered for results. For data extraction, it was developed a MES application for client and server, capable of emulating the long production processes across two assembly lines, each one provided by a different connectivity technology: Wifi 6 and private 5G network, as depicted in Fig. 1. In a real manufacturing environment, each operation across the assembly process is recorded by scanning a unique barcode generated when a production order is created. Whenever an item passes through a workstation, the serial number is read, indicating to the MES that the specific item within the current production order has completed the operation. In this work, there is no physical barcode reading. Instead, an orchestrating application generates the production order and serial numbers based on the total quantity of items, and sends each item, sequentially, to all the workstations attached to the process. Each station, upon receiving the serial number, responds with an acknowledgment, thus simulating the human operator in a real case.

The MES used to emulate manufacturing operations functions similarly to a real MES in discrete manufacturing, but in this case, it just emulates the assembly line running. Essentially, it organizes the assembly line, which comprises a sequence of workstations. Each piece progresses through the line, passing station by station until it reaches the final operation. Subsequently, the MES increments the count of assembled units. Once the total number of processed units matches the quantity specified in the production order, the MES considers the production complete. Hence, each workstation must communicate continuously to the MES running on a local server, that inserts a new serial number on the first workstation every Δ_t seconds. The information in this case consists of short data packets, which primarily include a timestamp, the piece identifier (also referred to as the Serial Number), the station identifier, and the production order to which the current process pertains.

Figure 2 shows the production flow adopted for the analysis in this work. Continuous download processes occur in parallel, thus representing a workload for both networks to operate the MES. At the same time, the influence of MES execution on the download process is also analyzed. The operation time, T_{op} is defined as the interval between the insertion of a serial number at a specific workstation and the time required for that station to respond with an acknowledgment. Thus, equation below brings the operation time evaluated for the i-th serial number processes by the j-th workstation

$$T_{op}(sn_i, wt_j) = t\left[\text{ack}(sn_i, wt_j)\right] - t(sn_i, wt_j) \quad (1)$$

An acknowledgment must be computed for each serial number at every station assigned to the process. Considering a produtcion order with a total itens identified by $sn_{\max}$, the mean operation time per workstation, is

$$\overline{T}_{op}(wt_j) = \frac{1}{sn_{\max}} \sum_{i=1}^{sn_{\max}} t\left[\text{ack}(sn_i, wt_j)\right] - t(sn_i, wt_j) \quad (2)$$

Thus, considering that all assembly line was composed by five workstation, as shown in Figure 1, the finally the total elapsed time for the production order, T_{PO}, is,

$$T_{PO} = \sum_{j=1}^{5} \sum_{i=1}^{sn_{\max}} t\left[\text{ack}(sn_i, wt_j)\right] - t(sn_i, wt_j) \quad (3)$$

The value of T_{PO}, in a real context, will depend most on the characteristics of the product engineering on the assembly line and the resources available on factory. It is utilized a configurable cycle time (1 second, by default), that emulates the time required for a single station to process each device a long the assembly flow. The objective on this work, is to understand how the network could affect T_{PO}, in function of the workload. For that, it was placed two station consuming data streaming from the server(dl_1 and dl_2, on Figure 1). As the download station share the same radio resource as the assembly line, it could be verified the influence of the continuous data streaming on the MES process.

III. The setup specifications

The previous section described the discrete manufacturing execution processes that emulate the operation of two assembly lines sequentially operated through two different wireless networks. This section provides technical specifications (hardware and software) about the components used to realize this system, including the manufacturing execution system mockup and test setup for data acquisition.

A. The Networks

In this work two local wireless networks were addressed to the MES implementation. For 5G, it was utilized a Nokia nDAC solution for private network. It operates at band n78, in frequencies between 3700 and 3800 MHz. The radio access is implemented by an indoor picocell, with maximum transmission power of 200 mW. The application server is connected to the VLAN by a 10 Gbps optical interface. For Wifi 6, an off-the-shelf router with an internal controller was used, featuring a maximum transmission power of 250 mW and channel bonding capability. The Wifi 6 access point was directly connected to the application server through a 10 Gbps Ethernet interface. The overall topology is depicted in Figure 3. It can be observed that each assembly line is provided with a single server that runs the applications for MES emulation in isolation.

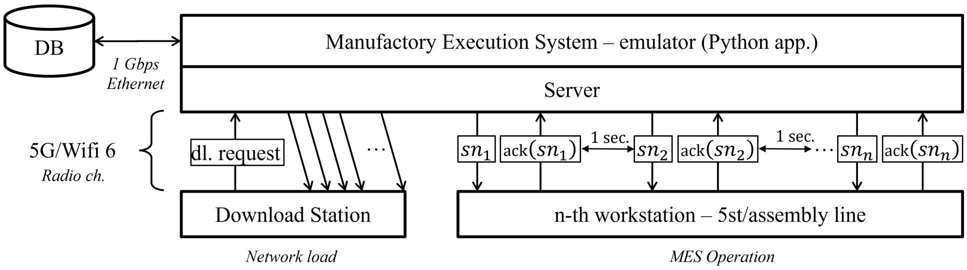

Fig. 2. Developed application that emulates the Manufacturing Execution System (MES) operated from a local server that communicates with workstations through the high-capacity wireless network (5G or Wifi 6), concurrently with the firmware downloads process as a load generator for the analyses in this study

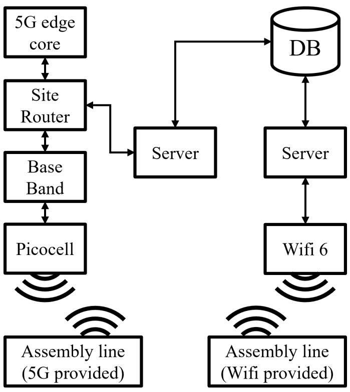

Fig. 3. Overall topology of the networks utilized for the tests.

B. The workstations

In order to normalize the tests, the workstations assigned on both assembly lines was implemented with same models of notebooks, featuring an Intel Core i5 8550U, 16 GB of DDR4 RAM and USB 3.0 connectivity. For the application servers, it was utilized the desktop featuring an Intel Xeon E5-1650 V3, 32 GB ECC RAM DDR4. Additionally, for Wifi 6 provisioning, it was attached to the notebooks a USB 3.0 network interface card Fenvi AX1800 [10], thus keeping both, access point and user device, compatible to the IEEE 802.11/ax protocol. [11] Similarly, for ensure connectivity to the private 5G network, an network interface card was utilized on the notebooks, in this case, it was based on Quectel RM500Q connectivity module with an M.2 to USB 3.0 adapter. [12]

C. The application

During the test, the server sends a set of data in JSON format to all stations nearly simultaneously, considering processing time. The primary information transmitted is the timestamp of the exact moment the message was sent. On the client side, the receipt timestamp of the message is recorded, which is then stored in the database along with values for RSSI and latency. The next transmission occurs only after all stations have written the information to the database. All the applications, including download and MES emulation was implement in Python. The analysis of the collected data was conducted within the Jupyter Notebook interface for the VSCode IDE, starting with the retrieval of the MES system database and the download stations data.

The same station responsible for generating network load simultaneously conducted downloads for the technologies studied in this article. This was achieved through synchronization by threads in Python, ensuring that both functions within the same script were initiated concurrently. The process involved downloading and saving a 2.7 GB file, that consists in a Raspberry Pi Linux customizing image. Also, it register the timestamps referring to the start and finish of each downloaded file, as well as, it is save the progress log in time. This data was saved locally in a excel file, and a plot is shown in Figure 5.

IV. Results

This section presents the resulting performance of the MES when executed over the two networks in tests, considering two workload scenarios on the connectivity system. Initially, the MES was executed without any load or concurrent data traffic, and subsequently, it was conducted in the presence of data streaming, sharing network resources with the MES.

Figure 4 presents a time analysis for both latency (Lat) and operation time delay (OT) under different workload conditions. The statistical values of mean ($\mu(OT)$ and $\mu(Lat)$) and standard deviation ($\sigma(OT)$ and $\sigma(Lat)$) are presented in Table I. It is evident that the latency of the 5G system is minimally affected by the workload imposed during tests, maintaining an average of less than 20 milliseconds regardless of the load, as shown in Figure 4.a (no load) and Figure 4.c (load applied with data streaming). While both connectivity technologies proved acceptable when latency measurements were taken without load, the same cannot be said for stress situations in the Wifi 6 network. The latency results in the Figure 4 demonstrate a considerable increase in packet retry

TABLE I
Empirical statistical values derived from time analysis for both studied systems.

statistic values	$\mu(OT)$ [s]	$\sigma(OT)$ [s]	$\mu(Lat)$ [ms]	$\sigma(Lat)$ [ms]
5G load	0.094	0.083	24.250	10.750
5G no load	0.011	0.001	16.010	4.910
Wifi 6 load	1.890	0.127	44.761	38.080
Wifi 6 no load	0.154	0.204	31.790	24.547

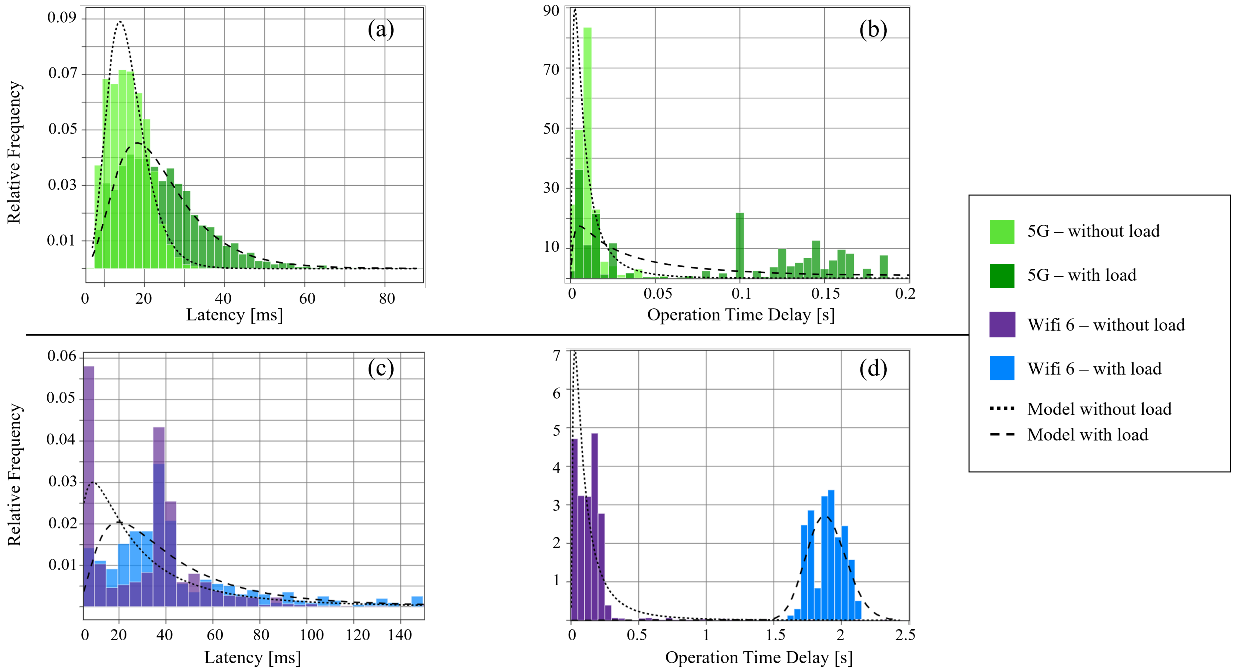

Fig. 4. Results from time analysis obtained from the manufacturing execution system considering the download operation as a network load generator are presented as follows: (a) 5G Latency (b) 5G Operation Time Delay, (c) Wifi 6 Latency (d) Wifi 6 Operation Time Delay.

occurrences when the network is subjected to high traffic load. Although, on average, both technologies exhibit latency values below 100 ms, the Wifi network showed a significant recurrence of average latencies between 250 and 400 ms under load conditions.

In terms of operation time delay, both networks exhibited similar retention of their nominal values, with the operating time window stretching from less than 1 second (with no load, as seen in Figure 4.b) to an average of 1.5 seconds when the network resources are shared with data streaming downloads (Figure 4.d). Figure 4 presents the histogram of the operation time delays.

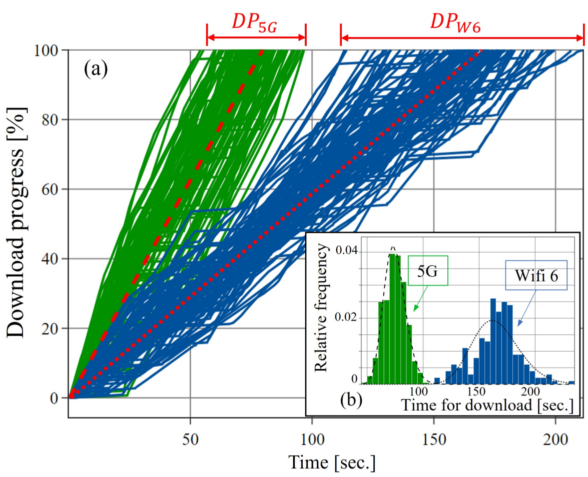

Fig. 5. Download progress recorded during manufacturing operations for the two tested technologies. (a) Download progress over time, and (b) statistical distribution of the total elapsed time for downloads across the technologies.

The Figure 5 depicts the analysis of the download process concurrently with the manufacturing execution flow. It illustrates the time required to complete 100% of each download executed over 5G and Wifi 6 technology. Notably, for 5G, the task is fulfilled in approximately half the time required for the Wifi 6 system. Furthermore, there is a notable disparity in download completion times between the Wifi 6 and 5G systems. Based on the acquired data, all downloads executed by the Wifi 6 system were completed within 110 and 210 seconds, with a mean time approximately equal to 165 seconds. Conversely, for the 5G system, the window for download completion is notably narrower, with values observed between 52 and 95 seconds, and the mean time in this case is approximately 74 seconds. The Figure 5.b presents the histogram of the download progress time (DP), indicating a normal distribution whose parameters are provided in Table II. The overall performance in terms of download rate is present in Figure 6 and Table III, with the dispersion of realized throughput along the tests taken with Wifi 6 and 5G setup, it yields an average throughput of 320 Mbps for Wifi 6 and 400 Mbps for 5G.

TABLE II
STATISTICAL PARAMETERS OF THE DOWNLOAD PROGRESS TIME DISTRIBUTION.

statistic val.	5G	Wifi 6
$\mu(DP)$[s]	74.90	165.49
$\sigma(DP)$[s]	9.49	20.46

V. Conclusions and Further Works

The results obtained in this work enable a detailed understanding of how the data download operation can affect the

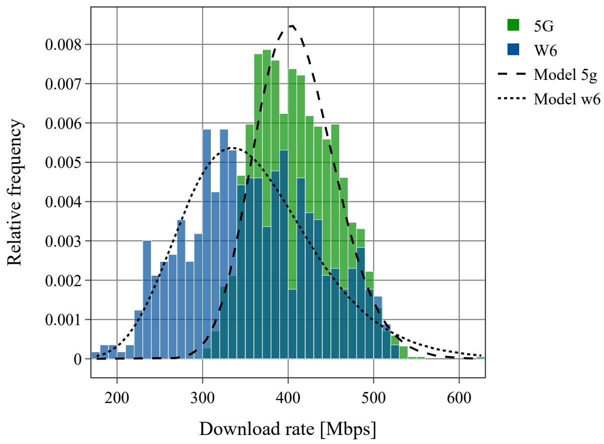

Fig. 6. Download rate for all data transferred along the tests for both connectivity technologies, Wifi 6 and 5G.

TABLE III
STATISTICAL PARAMETERS OF THE DOWNLOAD EXECUTION.

statistic val.	5G	Wifi 6
$\mu(DP)$[s]	410.03	359.23
$\sigma(DP)$[s]	47.83	75.30

performance of a manufacturing execution system. Analyzing the results, one may conclude that regardless of the load applied to the network, there is an acceptable level of nominal retention for both technologies, Wifi 6 and 5G. Regarding cycle time on assembly lines commonly utilized for handheld operation in Industry 4.0 environments, the Operation Time delay (OP) has been stretched, but it remains acceptable even when the workload is distributed across networks. The results show that, despite both systems being influenced by network congestion resulting from contention for radio resources in the access network, both systems could theoretically be applied for solutions in the context of Industry 4.0.

However, there are quantitative evidences endorsing the use of 5G private networks for time-sensitive operations and critical mission applications. The results demonstrate excellent retention of network nominal parameters even under stressed radio access channels, with enhanced capability for handling multiple tasks simultaneously. This includes continuous data streaming download processes and the requirements of the manufacturing execution system. Although the WiFi 6-based system demonstrated its capability to handle both types of tasks tested in this work individually (MES and download), the same was not observed regarding its capacity to run these activities simultaneously. Significant performance degradation was observed for both use cases when stressed in parallel.

For future work, it is essential to evaluate the performance metrics of the systems used in this study when applied to other types of applications relevant to Industry 4.0. These may include the operation of autonomous vehicles, collaborative robotics, intelligent surveillance and monitoring systems, as well as the integration of all these demands simultaneously with manufacturing management and execution processes, inspection systems through augmented reality and virtual reality. Other characteristics of these networks should also be studied, such as cybersecurity aspects, mean time between failures, rejection rates, and retransmission rates, providing important insights for the SLA requirements that may define or restrict the use of these connectivity technologies in the next generations of enabling technologies for Industry 4.0.

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