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RESEARCH ARTICLE

An Empirical Study of 5G, Wi-Fi 6, and Multi-Connectivity Scalability in an Indoor Industrial Scenario

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ABSTRACT Industry 4.0 is being adopted by the manufacturing sector to improve the flexibility and reduce installation costs by the use of wireless connectivity. There is an open question of which wireless technology deployment should be used in the factory to fulfil the requirements for next-generation applications such as autonomous mobile robots. Wi-Fi technology is the most extended and easy to deploy, while the fifth generation of mobile networks (5G) has been designed to support these industrial needs. Therefore, it is important to compare both technologies from a performance point of view, especially under different load conditions and number of devices. The use of multi-connectivity between 5G and Wi-Fi can also be an option to fulfil the requirements for the most critical real-time applications. In this paper, we empirically measure the scalability of 5G, Wi-Fi and multi-connectivity in the ‘‘Aalborg University 5G Smart Production Lab’’ and compare them in terms of latency and packet loss with different packet sizes. We found that in general Wi-Fi obtains lower latencies but large tails in the distribution, with a higher packet loss compared to 5G. On the other hand, 5G latency is very consistent with bounded tails, and low packet loss is obtained. In terms of scalability, 5G scales better than Wi-Fi, the latter being very affected by the number of devices transmitting data. Finally, multi-connectivity showed an improved reliability and lower latencies in all evaluated cases.

INDEX TERMS 5G, Wi-Fi, Industry 4.0, multi-connectivity, latency, scalability, packet loss.

I. INTRODUCTION

Currently, the industrial sector is facing its fourth revolution known as Industry 4.0 [1]. This new era aims to improve the efficiency and productivity of the factories with the use of novel technologies such as Artificial Intelligence (AI), Big Data, cyber-physical systems (CPS), and the Internet of Things (IoT). Industry 4.0 is characterized by the interconnection of numerous machines involved in manufacturing to collect data, control the production and manage the machinery. One important step of Industry 4.0 is to establish reliable and ubiquitous stationary and mobile networks for this type of communications, especially for the most critical applications involved in the factory.

Traditionally, wired connections have been used in industrial networks to connect different elements such as Programmable Logic Controllers (PLC), due to their reliability and determinism. However, wired communications are costly in terms of installation and maintenance and cannot cover new use cases, such as mobility in factories. Moreover, Industry 4.0 focuses on flexibility, re-configurable modules and the use of Autonomous Mobile Robots (AMRs) [2]. As a result, the industrial sector is starting to adopt wireless networks such as Wi-Fi and the fifth generation of mobile networks (5G) to achieve automation and flexibility on the factories [3]. In 2023, wireless deployments have experienced

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a growth of 22% [4] and accounts for 8% of new connected devices in industry. Although Wi-Fi is still the most extended wireless technology in factories, due to its simplicity and easy deployment, factories can also take advantage of cellular networks. With the arrival of 5G, one of the main focus on the design of this technology has been to support industrial communications requirements. This can be achieved thanks to the handover and Quality of Service (QoS) support, and the use of new 5G features such as numerology [5], network slicing [6] or Packet Duplication (PD) [7].

The use of multi-connectivity [8] between different technologies can also be an option to fulfil the requirements for the most critical real-time applications in the factories by improving the reliability and reducing the latency for the users.

Many of the applications present in Industry 4.0 have very strict requirements in terms of QoS. Therefore, there is a need for an assessment of the performance of the main network access technologies and commercial equipment present in such scenarios, with a special focus on applications such as AMRs and PLCs, where critical communications often take place. The aim of this paper is to compare the performance of 5G, Wi-Fi and multi-connectivity in an indoor industrial scenario. For this, we empirically measure the scalability performance of these technologies and multi-connectivity in the "Aalborg University 5G Smart Production Lab" [2] and compare them in terms of high percentile round-trip time (RTT) latency and packet loss. Moreover, two different scenarios have been considered, one with stationary terminals and another one with mobile terminals with different packet sizes.

We expect that the results of all of these measurements will provide a global vision of which technology suits better the manufacturing sector, depending on the type of applications and use cases involved in their factories.

The remainder of this paper is organized as follows. In Section II, an overview of the related works assessing the network in an industrial scenario is presented. Section III explains the methodology along with the scenario, setup and metrics to evaluate the performance of the network. Results are shown in Section IV, along with an overview of the system limitations. Finally, conclusions are drawn in Section V.

II. RELATED WORK

Evaluating the network performance with commercial equipment is very important since it provides a clear vision of the real performance obtained. Mostly, simulators are used to test the network performance under different conditions. However, the performance obtained via simulators sometimes is far from reality, as the wireless channel may not be accurate (e.g., with the standard) or some processes may be simplified. In this Section different works in the literature are analyzed where measurement campaigns have been performed in industrial scenarios with wireless technologies.

The latency performance has been one of the most addressed topics in the literature. In fact, since the adoption of wireless connectivity in the industrial sector and the emergence of new use cases with low latency requirements and high reliability, this topic has gained a high importance to determine which wireless technology is the most appropriate in industrial environments and if they can fulfil these requirements. In [9] and [10], 5G Non-Public Network (NPN) solutions are evaluated in terms of baseline Key Performance Indicators (KPIs). A comparison between 5G NPN and Public Network (PN) is performed in [11], where the network performance was evaluated in terms of latency, throughput and packet loss using one device. A framework for the integration of 5G in industry was proposed in [12], where the authors also evaluated the control-loop latency performance for the use case of controlling an AMR in the mobility case. These measurements were performed with Wi-Fi and 5G with only one device attached to the network. In [13], the latency performance of the 5G network was evaluated. Specifically, the uplink and downlink latency was measured with different packet sizes and inter-packet arrivals, with one user equipment. The authors of [14] evaluated the handover performance of Wi-Fi 6 in an indoor industrial environment; the 802.11r roaming functionality was evaluated for a mobility use case, using an AMR with some stationary background devices that transmitted traffic to load the network. The quality of experience (QoE) and throughput of the 5G network was evaluated in [15]. The results obtained by the authors indicate that the relationship between network performance and QoE in industrial settings is complex, due to a time-variant dependency. In [16] and [17], the authors compared the performance between Wi-Fi and Citizenship Broadband Radio System (CBRS) on the unlicensed spectrum of the USA using the Long-Term Evolution (LTE) radio network. In particular, they focused on the evaluation of different KPIs such as the average latency, the throughput and the packet loss under different loads.

Multi-connectivity consists in establishing two or more links between a user and two or more radio access nodes, which are typically uncorrelated links. For instance, the two links can use different channels, different networks or even different network access technologies, such as cellular and Wi-Fi. Multi-connectivity is often adopted for improving communication aspects such as latency, reliability and throughput. In the literature, different multi-connectivity schemes have been tested in industrial scenarios [8], [18], [19], [20]. In [18], the authors studied multi-connectivity for Ultra-Reliable and Low Latency Communications (URLLC) and the cost in throughput for other services such as Enhanced Mobile BroadBand (eMBB) services. A comparison between LTE and Wi-Fi technologies was done in [8], where different multi-connectivity schemes were evaluated (load balancing, PD and packet splitting). A multi-connectivity solution for Wi-Fi was evaluated in [19], where a device is composed of two Wi-Fi cards, each of them connected to different Access Points (APs) and coordinated by a smart Layer-4 scheduling mechanism. This work focused on the latency performance for the mobility case when using the PD and best path switching solutions in an indoor factory. On the other hand, the authors of [20] presented a novel multi-connectivity solution that takes into account the QoS to dynamically select the links for PD. This scheme was evaluated with Wi-Fi 6 in terms of latency and throughput. Finally, the authors of [21] compares the performance of multi-Radio Access Technology (RAT) with Wi-Fi 6, LiFi and 5G. In particular, their multi-connectivity approach used was Multi-Path Transmission Control Protocol (MPTCP), which consists of splitting data flows into small flows and sending them over different interfaces to improve throughput. However, the scalability of the network was not considered (measurements were performed with one device) and the evaluated scenario was a museum.

Despite the different empirical measurements performed in the literature in industrial scenarios, we have not found any paper that takes into account the scalability of the network in terms of latency and packet loss. In fact, previous works usually take into account the performance of the network with only one device attached to the network. Also, multi-connectivity performance with a PD approach between 5G and Wi-Fi has not been addressed yet with a real implementation. Therefore, this paper tries to fill this gap by assessing the scalability of 5G, Wi-Fi and multi-connectivity between both technologies in an indoor industrial scenario in terms of latency and packet loss. For this, we used different packet sizes and use cases (stationary and mobility).

III. METHODOLOGY

A. SCENARIO AND NETWORK CONFIGURATION

The different measurements have been performed inside the "Aalborg University 5G Smart Production Lab" [2]. This lab consists of a small-scale industrial factory environment of approximately 1250 m^2 composed of two halls (see Figure 1) and a wide range of industrial manufacturing and production equipment, such as welding machines, robotics arms, production lines, etc. The dimensions of the halls are as follows: one measures 40 × 15 × 6 cubic meters, while the other measures 32 × 20 × 6 cubic meters. Approximately, 20% of the entire area is occupied by clutter, with a clutter height ranging from 1 to 3 meters. The lab is also equipped with different network technologies such as NPN 5G Stand-Alone (SA) and PN 5G Non-Stand-Alone (NSA), Wi-Fi 6, LTE and ultra-wide band (UWB). In this paper, the focus is set on 5G SA and Wi-Fi 6 technologies.

The 5G SA network is operated in collaboration with Telenor Denmark using Nokia equipment, more specifically, it is equipped with an in-house Nokia Mxie 5G SA core, a Nokia AirScale baseband unit and 3 Nokia AirScale indoor Radio (ASiR). The network operates in band N78 (3.7 GHz) with a bandwidth of 100 MHz and is configured as Time Division Duplex (TDD) with an UL/DL slot ratio of 3/7. In this deployment, all base stations (BS) transmit with a maximum power of 23 dBm and have the same configuration (i.e., emit the same cell), therefore, handovers will not occur during mobility.

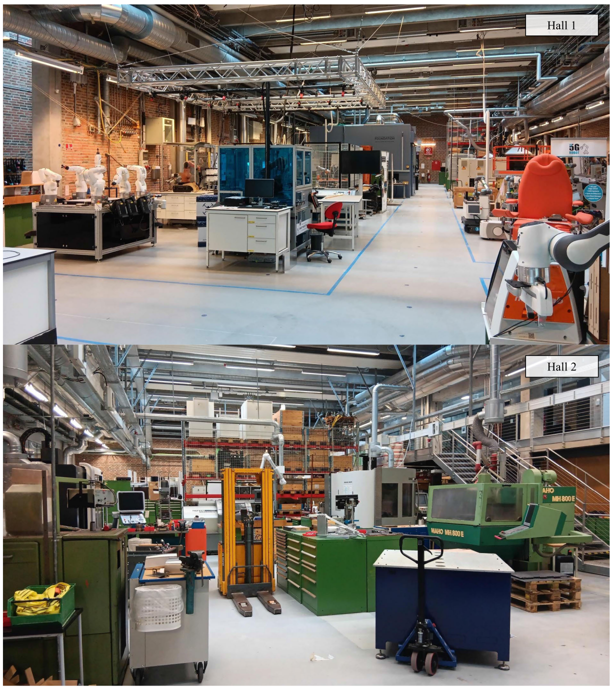

FIGURE 1. Overview of the Aalborg University 5G Smart Production Lab, including details on the two industrial halls.

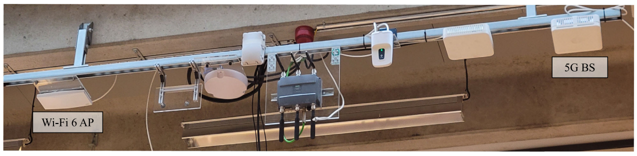

FIGURE 2. Overview of the different operational wireless network deployments.

The Wi-Fi 6 network is composed of three CISCO MR36 AP [22], distributed within the lab and operating in the 5 GHz band. The CISCO MR36 AP supports 2 × 2 Multi-User Multiple-Input Multiple-Output (MU-MIMO) and uplink/downlink Orthogonal Frequency Division Multiple Access (OFDMA) for more efficient transmission to multiple clients with up to 1024-Quadrature Amplitude Modulation (QAM) coding support. It also supports Basic Service Set (BSS) coloring which enables spatial reuse and reduces co-channel interference. Each AP transmits with a power of 20 dBm and is configured with a bandwidth of 20 MHz. To ensure that they do not interfere with each other, a dedicated channel is used on each AP (channels 132, 136 and 140), therefore, BSS coloring feature is not used. For roaming between APs when mobility, we enabled and used the IEEE 802.11r roaming functionality [23].

For both networks, the ASiRs/APs are mounted in the ceiling, approximately 6 meters above the ground and they are positioned to cover roughly 1/3 of the factory floor, as shown in Figure 2.

B. SETUP

The User Equipment (UE) used to perform the measurements is shown in Figure 3. It is composed of an Intel

FIGURE 3. Picture of the equipment used to evaluate the network performance.

NUC5i3MYHE [24], equipped with an Intel M2 Wi-Fi 6 AX200 card, running Arch Linux with kernel version 6.2.2. The Wi-Fi 6 adapter has been configured with the following features: uplink/downlink OFDMA, up to 1024 QAM coding and Target Wake Time (TWT) [25]. Regarding the 5G connection, a Simcom SIM8202G-M2 5G modem has been used [26] configured with 4 antennas, with MIMO 2 × 2. This modem is connected to the NUC through a M2 to USB3 adapter.

Two different scenarios have been considered: stationary and mobility. The stationary scenario represents the connectivity of a PLC in a production line. On the other hand, the mobility scenario represents a use case of an AMR that moves within the factory floor to transport goods/pallets.

To evaluate the scalability of the network, the number of devices is increased from 1 up to 10 in steps of 3 devices. One device was used to transmit data and measure the network performance, whereas the rest of the devices acted as background devices. All background devices were stationary and transmitted a constant bit rate.

Regarding data transmission, two different packet sizes have been considered in this study: 64 and 1250 bytes. The small packet size represents short control messages exchanged in the network, whereas the high packet size represents use cases such as video-operated remote control [27].

The measurement campaigns were performed for single connectivity with 5G SA and Wi-Fi 6, and multi-connectivity between both technologies. In this case, we used the PD [7] solution which consists on duplicating the data and sending it through each available link. This could improve the reliability and also reduce the latency when one of the links experiences poor channel conditions, and the data could be successfully transmitted through the other link. To test this feature in our setup, we used a multi-connectivity tunneling tool [28], developed at Aalborg University. This tool duplicates the packets at Layer 3 and sends it over Internet Protocol (IP) in Layer 4 (User Datagram Protocol, UDP) packets through 5G SA and Wi-Fi 6.

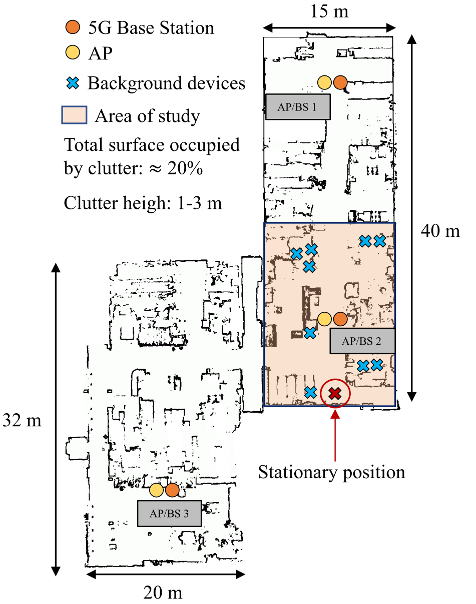

FIGURE 4. LiDAR floor plan of the lab and stationary setup. 5G BS and AP locations are marked with an orange and yellow circle. Background devices location are marked with a blue cross while the measuring device location is marked with a red cross.

The detailed information about the stationary and mobility setup is described below.

1) STATIONARY

Figure 4 shows the Light Detection and Ranging (LiDAR) floor plan of the lab and the stationary setup, where the location of the 5G BSs/APs are highlighted in circular markers. For the stationary case, the focus was set on the light orange area depicted in the figure, where all devices were placed and connected to AP/BS 2. Wi-Fi devices were forced to be connected to AP 2 by configuring the BSS Identifier (BSSID) in the connection profile.

The stationary position for the measuring device is marked with a red cross, while stationary background devices are marked with a blue cross. The mean distance from the devices to the AP/BS 2 is approximately 10 meters (in the range of 5 to 15 meters). Furthermore, regarding the density, up to ten devices were deployed in an area of 20 × 15 squared meters. At the beginning, only the measuring device was connected to the 5G SA and Wi-Fi 6 network. Then, background devices were added to the network to increase the number of devices for the different measurements.

2) MOBILITY

The mobility setup is depicted in Figure 5. Unlike the stationary setup, here background devices are placed throughout the factory floor. The maximum number of background devices per AP/BS was set to 3 to maintain consistency in the number of devices during the movement path. Similar to the stationary case, background devices were forced to be connected to the specific AP located where they were placed by configuring the BSSID in the connection profile. The

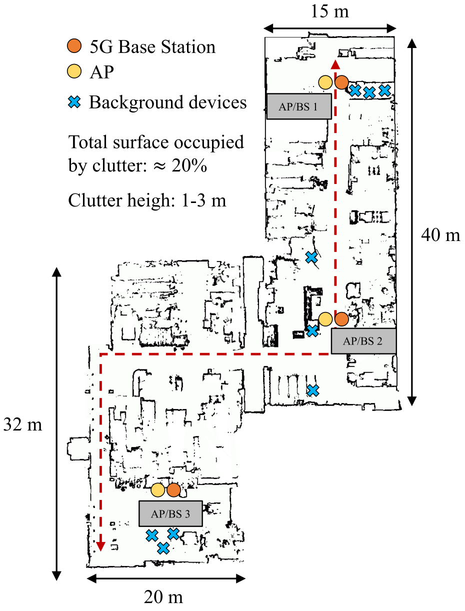

FIGURE 5. LiDAR floor plan of the lab and mobility setup. 5G BS and AP locations are marked with an orange and yellow circle. Background devices location are marked with a blue cross. AMR route is marked as a red dashed line.

mean distance from the stationary background devices to the corresponding AP/BS is approximately 8 meters (in the range of 5 to 12 meters). Furthermore, regarding the density, up to six devices were stationary deployed in an area of 40 × 15 squared meters (hall 1) and up to three devices in an area of 32 × 20 squared meters (hall 2).

Mobility measurements were performed using a MiR200 AMR [29], with the 5G modem and Intel NUC placed on top, as shown in Figure 6. The MiR200 is designed for smaller transport tasks within the industry and logistics, such as transport of goods. The robot navigates using LiDAR, encoders and inertial measurement units with a payload of up to 200 kg. The use of this robot allowed to perform different reproducible mobility tests, which guarantees a consistency on the measurements. During the measurements, the AMR navigates within the 5G Smart Production Lab following the path marked with a red dashed line in Figure 5, with a speed of 1 m/s in a loop.

Similar to the stationary case, at the beginning only the measuring device was connected to the 5G SA and Wi-Fi 6 network. Then, background devices were added to the network to increase the number of devices for the different measurements. However, in this case, they were added proportionally to the APs/BSs, that is, the number of devices was increased by one on each AP/BS.

C. METRICS

In this study, the following metrics have been considered:

- **Latency**: The ping tool was used to measure the RTT of a packet sent from the UE to our edge-cloud server, and back. A diagram of the path of the packets is shown in Figure 7. This tool was configured to transmit Internet Control Message Protocol (ICMP) packets with a periodicity of 10 ms, with packet sizes of 64 and 1250 bytes, and a preload of 100 packets. The preload helps to maintain the transmission periodicity when long delays occur. The periodicity of 10 ms ensures that the modem does not enter power saving mode between requests, which could negatively impact the measurement campaigns. To obtain statistic results, we run ping until it transmits more than one million packets. For a real-time application in a factory scenario, the RTT latency should be less than 100 ms [27].
- **Packet loss**: Based on the packet statistics from the latency results, the number of lost packets is counted for each measurement campaign. This is done by reading the output of the ping tool after a completed measurement, which includes the number of ICMP packets transmitted (request) and received (replies).

FIGURE 6. MiR200 AMR within the 5G Smart Production Lab.

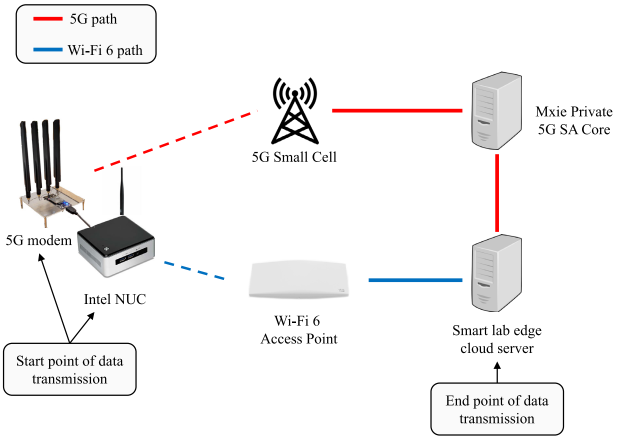

FIGURE 7. Diagram showing the data path between the measuring device and the Smart lab edge cloud server.

Then, based on the difference, the packet loss is obtained.

IV. RESULTS AND DISCUSSION

In this section, the results obtained throughout the different measurement campaigns for the stationary and mobility cases are presented. Latency results are shown as a Complementary Cumulative Distribution Function (CCDF), whereas packet loss statistics are summarized in a table.

A. STATIONARY

1) 64 BYTES

Figure 8 shows CCDF plots of the latency measurements when using a packet size of 64 bytes and Table 1 summarizes the key values.

As it can be seen, the latency distribution with 5G SA is very stable, not exceeding 14.8 ms with 1 device. Obviously, when adding more devices to the network, the latency is increased as expected. In this case, the network needs to manage different data traffic and this is done in 5G by assigning different resources (time slots) to the users. This can be observed on the median values, which suffer an increase in the range of 0.3 ms to 0.8 ms. However, a similar trend is observed in the tails, obtaining a 99.99%-ile (10^{-4}) value of 12.6 ms, 17.5 ms, 19.8 ms and 23.8 ms with 1, 4, 7 and 10 devices, respectively.

When using Wi-Fi 6, it is observed that in general the latency is lower compared to 5G SA. This can be seen on the median values obtained, which ranges from 3.1 ms to 5.3 ms when increasing the number of devices. Another aspect observed is that higher latency tails are obtained compared to 5G SA, even with only one device connected. In terms of network scalability, contrary to 5G SA, the latency with Wi-Fi 6 is clearly affected when adding more devices, especially with 7 and 10 devices, obtaining latency values above 100 ms. The high values on the latency are expected when increasing the number of devices, since with Wi-Fi the devices compete for the channel to transmit data, using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) at the Medium Access Control (MAC) layer. Therefore, whenever a device wants to transmit data, it first needs to listen and ensure that nobody is transmitting data. Otherwise, it will wait for a random period of time (backoff time) and check again if the channel is clear. As the number of devices increases, the probability of waiting to transmit data is also increased. In this case, a 99.99%-ile (10^{-4}) value of 21.1 ms, 24.1 ms, 88 ms and 127 ms is obtained with 1, 4, 7 and 10 devices, respectively.

When multi-connectivity is applied, it is observed that the tails are reduced and the trend is similar to 5G SA. This reduction is due to the fact that the packet is always sent duplicated via two radio links (5G SA and Wi-Fi 6) and the latency obtained will be the best of these two links. For the same reason, the CCDFs on the first part of the distribution are similar to Wi-Fi 6 with a slight offset. This offset is due to the multi-connectivity tool, that adds an extra overhead on the packets. In general, multi-connectivity takes advantage of both networks and reduces the latency values in all cases evaluated, as it can be seen in the maximum and 99.99%-ile (10^{-4}) values in Table 1.

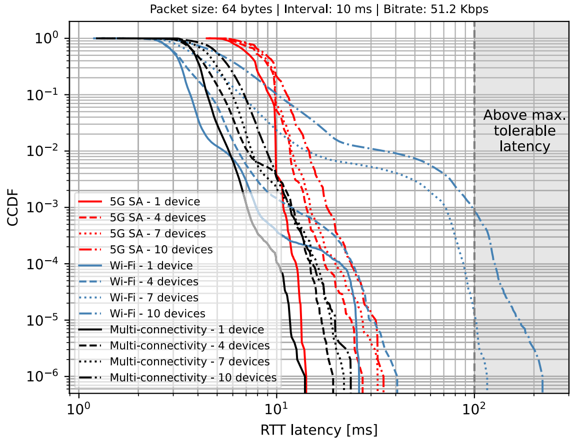

FIGURE 8. Latency CCDF obtained for the stationary case with a packet size of 64 bytes.

TABLE 1. Latency [ms] obtained for the stationary case with a packet size of 64 bytes.

Deployment	Median	Max.	99.9%-ile	99.99%-ile
5G SA - 1 device	7.3	14.8	10.9	12.6
5G SA - 4 devices	8.1	31.6	14.2	17.5
5G SA - 7 devices	8.6	34.2	14.8	19.8
5G SA - 10 devices	8.9	42.2	18	23.8
Wi-Fi 6 - 1 device	3.1	26.2	7.9	21.1
Wi-Fi 6 - 4 devices	3.2	51.8	11.9	24.1
Wi-Fi 6 - 7 devices	3.9	133	71.3	88
Wi-Fi 6 - 10 devices	5.3	231	97.6	127
Multi-connectivity - 1 device	3.9	14.6	7.1	10.2
Multi-connectivity - 4 devices	4	19.8	12	14.8
Multi-connectivity - 7 devices	4.5	22.7	11.9	15.9
Multi-connectivity - 10 devices	5.1	25.7	11.7	15.2

Table 2 summarizes the packet statistics, which include the number of packets sent, received and lost. In general, a low packet loss is obtained with both technologies in all cases. In 5G SA only 1 or 2 packets are lost, whereas Wi-Fi 6 suffers a slightly higher packet loss, reaching 5 in some cases. As expected, multi-connectivity reduces the packet loss to 0.

2) 1250 BYTES

Figure 9 shows CCDF plots of the latency measurements when using a packet size of 1250 bytes and Table 3 summarizes the key values.

In this case, a higher latency is noticeable when using 5G SA, with the CCDFs shifted to the right in comparison to the previous case with a smaller packet size. This clearly indicates that the packet size has a high influence on the latency values. Since the packet size is higher, more resources are necessary to transmit all data, that is, more slots need to be assigned to the users in the scheduler. Consequently, the

TABLE 2. Packet statistics for the stationary case with a packet size of 64 bytes.

Deployment	Sent	Received	Lost (%)
5G SA - 1 device	1001000	1000999	0.0001
5G SA - 4 devices	1001000	1000999	0.0001
5G SA - 7 devices	1001000	1000998	0.0002
5G SA - 10 devices	1001000	1000999	0.0001
Wi-Fi 6 - 1 device	1001000	1000995	0.0005
Wi-Fi 6 - 4 devices	1001000	1000995	0.0005
Wi-Fi 6 - 7 devices	1001000	1000997	0.0003
Wi-Fi 6 - 10 devices	1001000	1000995	0.0005
Multi-connectivity - 1 device	1001000	1001000	0
Multi-connectivity - 4 devices	1001000	1001000	0
Multi-connectivity - 7 devices	1001000	1001000	0
Multi-connectivity - 10 devices	1001000	1001000	0

TABLE 3. Latency [ms] obtained for the stationary case with a packet size of 1250 bytes.

Deployment	Median	Max.	99.9%-ile	99.99%-ile
5G SA - 1 device	12.9	44.7	25.7	27.6
5G SA - 4 devices	14.7	44.7	25.8	29.5
5G SA - 7 devices	15	41.6	27.2	31.3
5G SA - 10 devices	17.2	53.3	29.8	34.4
Wi-Fi 6 - 1 device	2.2	29.6	8.8	20.8
Wi-Fi 6 - 4 devices	2.4	61.1	16.5	30.1
Wi-Fi 6 - 7 devices	3	111	68.3	85.2
Wi-Fi 6 - 10 devices	5.8	231	99.7	128
Multi-connectivity - 1 device	2.4	26.8	6.7	14.1
Multi-connectivity - 4 devices	2.6	28.8	11.7	18.9
Multi-connectivity - 7 devices	3.2	32.7	14.9	22
Multi-connectivity - 10 devices	5.3	35.8	22.4	25.9

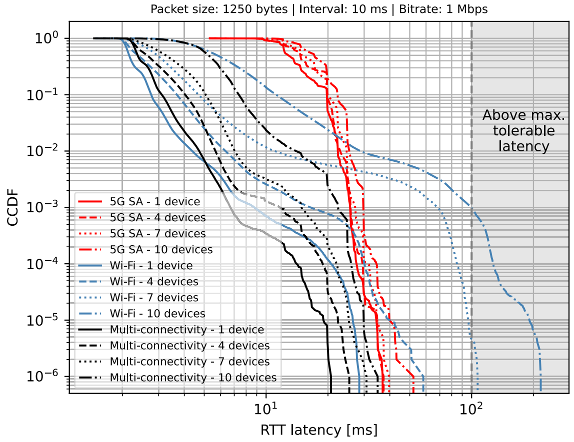

FIGURE 9. Latency CCDF obtained for the stationary case with a packet size of 1250 bytes.

TABLE 4. Packet statistics for the stationary case with a packet size of 1250 bytes.

Deployment	Sent	Received	Lost (%)
5G SA - 1 device	1001000	1000997	0.0003
5G SA - 4 devices	1001000	1001000	0
5G SA - 7 devices	1001000	1000996	0.0004
5G SA - 10 devices	1001000	1001000	0
Wi-Fi 6 - 1 device	1001000	1000994	0.0006
Wi-Fi 6 - 4 devices	1001000	1000992	0.0008
Wi-Fi 6 - 7 devices	1001000	1000984	0.0016
Wi-Fi 6 - 10 devices	1001000	1000981	0.0019
Multi-connectivity - 1 device	1001000	1001000	0
Multi-connectivity - 4 devices	1001000	1001000	0
Multi-connectivity - 7 devices	1001000	1001000	0
Multi-connectivity - 10 devices	1001000	1001000	0

latency will increase. Taking a look on the median values, an increment of more than 6 ms is obtained. Despite that, a similar trend in the tails is observed when connecting more devices to the network, obtaining a 99.99%-ile (10^{-4}) value of 27.6 ms, 29.5 ms, 31.3 ms and 34.4 ms with 1, 4, 7 and 10 devices, respectively.

On the other hand, with Wi-Fi 6, a similar behaviour to case with a small packet size is observed. This occurs due to Wi-Fi trying to send all data from the buffer on each transmission opportunity. Therefore, the packet size is not clearly affected but the number of devices is. Moreover, a slight reduction in the median values is observed in all cases except with 10 devices and this is because of using a more efficient Modulation Coding Scheme (MCS) coding on the data transmission. In this case, similar tails are obtained with a 99.99%-ile (10^{-4}) value of 20.8 ms 30.1 ms 85.2 ms and 128 ms with 1, 4, 7 and 10 devices, respectively.

When using multi-connectivity, we observed a similar trend on the CCDFs. The main change is that large tails are obtained, but this is due to the fact that the latency with 5G SA is higher because of the packet size. Therefore, the potential gains of multi-connectivity in terms of the tails are reduced in this case. Moreover, it is observed that multi-connectivity obtains lower tails in all cases (even with 10 devices) than 5G SA with only one device.

Taking a look at the packet statistics in Table 4, a similar packet loss is obtained with the 5G SA network. On the other hand, with Wi-Fi 6, a slight increase on the packet loss is obtained and this can be related to the packet size, since it is higher and the time transmitting data over the channel is also higher, so the probability of failure (i.e., having bit errors) increases. Another aspect observed with Wi-Fi 6 is that as the number of devices increases, the packet loss is also increased. Finally, when applying multi-connectivity, no packet loss is obtained in any of the evaluated cases.

B. MOBILITY

1) 64 BYTES

Figure 10 shows CCDF plots of the latency measurements when using a packet size of 64 bytes and Table 5 summarizes the key values.

When mobility is introduced, a higher variation on the latency distribution is observed. This is expected, since the channel varies during the movement on the path, with changing reflections and propagation loss. This also causes the use of different MCS during data transmission, which may have an impact on the latency if a more robust MCS is selected.

In the case of 5G SA, a similar trend is observed on the CCDFs with respect to the stationary case when increasing the number of devices. In this particular case, a similar latency distribution is observed with 1 and 4 devices, whereas there is a gap in the latency tails with 7 and 10 devices. The median

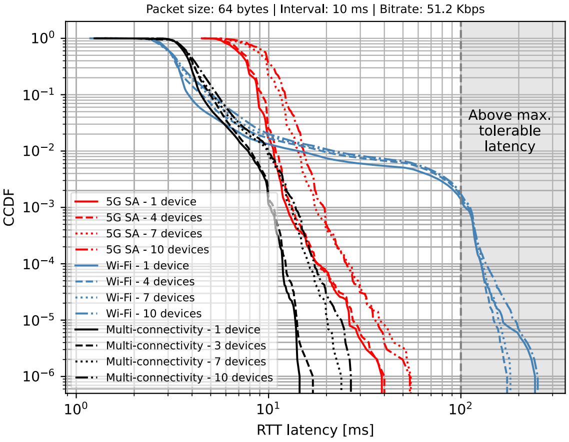

FIGURE 10. Latency CCDF obtained for the mobility case with a packet size of 64 bytes.

TABLE 5. Latency [ms] obtained for the mobility case with a packet size of 64 bytes.

Deployment	Median	Max.	99.9%-ile	99.99%-ile
5G SA - 1 device	7.3	43.2	12.5	17.9
5G SA - 4 devices	7.6	41.9	13.3	18.1
5G SA - 7 devices	9.2	63.7	17.4	26.2
5G SA - 10 devices	9.8	64.2	19.4	25.4
Wi-Fi 6 - 1 device	3.2	259	106	128
Wi-Fi 6 - 4 devices	3.1	182	110	128
Wi-Fi 6 - 7 devices	3.2	197	112	130
Wi-Fi 6 - 10 devices	3.2	266	112	135.2
Multi-connectivity - 1 device	3.7	14.6	10.3	11.9
Multi-connectivity - 4 devices	3.9	21.2	10.7	12.3
Multi-connectivity - 7 devices	3.8	31.8	13.1	16.2
Multi-connectivity - 10 devices	3.9	27.3	13.9	17.4

values obtained are slightly higher compared to the stationary case, which is expected due to the varying channel conditions during the path. Moreover, the tails on the distribution are also higher, obtaining a 99.99%-ile (10^{-4}) value of 17.9 ms, 18.1 ms, 26.2 ms and 25.4 ms with 1, 4, 7 and 10 devices, respectively.

On the other hand, with Wi-Fi 6 a clear difference in the tails of the latency distribution is observed. The high increase on the latency is caused due to Wi-Fi roaming between the APs along the movement of the AMR in the scenario. Consequently, latencies above 100 ms are obtained. In this case, although Wi-Fi 6 obtains a lower median value than 5G SA, the tails in the distribution are higher, with a 99.99%-ile (10^{-4}) value above 120 ms in all cases evaluated.

Finally, when using multi-connectivity, the tails are reduced and they converge to a similar trend respect to 5G SA, since when Wi-Fi 6 signal drops, it experiences higher latencies than 5G SA, especially in the roaming case between APs. A 99.99%-ile value of 11.9 ms, 12.3 ms, 16.2 ms and 17.4 ms is obtained with 1, 4, 7 and 10 devices.

In terms of packet loss statistics (see Table 6), the 5G SA network obtains a low packet loss, similar to the stationary case. On the other hand, Wi-Fi 6 obtains a high number of packet losses. Again, with multi-connectivity, the packet losses are reduced to 0, since the packet is sent duplicated over both interfaces and the reliability is increased (i.e., when Wi-Fi 6 AP roaming).

TABLE 6. Packet statistics for the mobility case with a packet size of 64 bytes.

Deployment	Sent	Received	Lost (%)
5G SA - 1 device	1000002	999999	0.0003
5G SA - 4 devices	1001000	1000999	0.0001
5G SA - 7 devices	1001000	1000998	0.0002
5G SA - 10 devices	1001000	1000998	0.0002
Wi-Fi 6 - 1 device	1001000	999136	0.18621
Wi-Fi 6 - 4 devices	1001000	999047	0.1951
Wi-Fi 6 - 7 devices	1001000	999049	0.19491
Wi-Fi 6 - 10 devices	1001000	999008	0.199
Multi-connectivity - 1 device	1001000	1001000	0
Multi-connectivity - 4 devices	1001000	1001000	0
Multi-connectivity - 7 devices	1001000	1001000	0
Multi-connectivity - 10 devices	1001000	1001000	0

2) 1250 BYTES

Figure 11 shows CCDF plots of the latency measurements when using a packet size of 1250 bytes and Table 7 summarizes the key values.

When a high packet size is used in the mobility case, again, a higher variation on the latency values is obtained in all cases evaluated, which makes sense due to signal reflections and multi-path propagation.

A similar trend is observed in 5G-SA when increasing the number of devices, however, same as in the previous case with a small packet size, there is a higher step in the CCDF when increasing the number of devices from 4 to 7. In general, it is observed that 5G SA latency is very stable, particularly in the tails of the distribution. In this case, as expected, the 99.99%-ile (10^{-4}) value of the tails has increased, being 26.4 ms, 28.7 ms, 37.4 ms and 40.7 ms with 1, 4, 7 and 10 devices, respectively.

A similar latency distribution is observed with Wi-Fi 6 compared to when using a packet size of 64 bytes. As previously mentioned, this occurs due to Wi-Fi trying to send all available data in the buffer whenever the device has a transmission opportunity. Therefore, the packet size does not have a high impact on the latency if it does not exceed the Maximum Transmission Unit (MTU), configured as 1500 bytes, in which case packet fragmentation will occur. Again, the median values are lower when using a high packet size, since a more efficient MCS is used when transmitting data.

Finally, same as in the previous cases, the use of multi-connectivity reduces drastically the latency tails in the distribution, obtaining median values similar to Wi-Fi 6 and a 99.99%-ile values lower than 5G SA, as shown in Table 7.

Looking at Table 8, which contains the packet statistics, a slight packet loss is observed with 5G SA. In the case of Wi-Fi 6, higher packet loss were obtained, with values above 1800, due to roaming between APs and by the fact that the

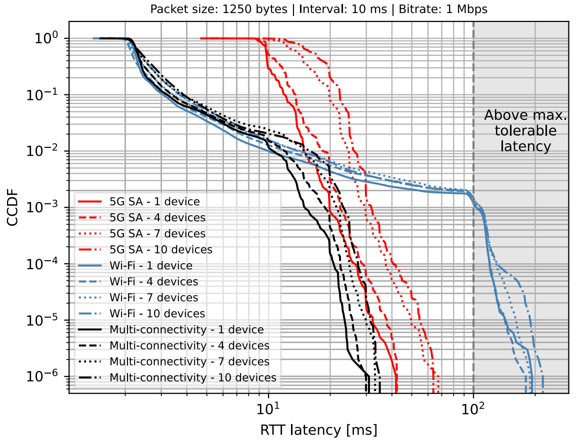

FIGURE 11. Latency CCDF obtained for the mobility case with a packet size of 1250 bytes.

TABLE 7. Latency [ms] obtained for the mobility case with a packet size of 1250 bytes.

Deployment	Median	Max.	99.9%-ile	99.99%-ile
5G SA - 1 device	9.8	42.3	19.9	26.4
5G SA - 4 devices	10.3	44.7	22.4	28.7
5G SA - 7 devices	14.6	75.7	29.7	37.4
5G SA - 10 devices	17.2	64.8	31.8	40.7
Wi-Fi 6 - 1 device	2.2	197	103	120
Wi-Fi 6 - 4 devices	2.2	193	106	121
Wi-Fi 6 - 7 devices	2.2	197	109	129.2
Wi-Fi 6 - 10 devices	2.4	226	109	130.2
Multi-connectivity - 1 device	2.3	33.6	15.1	20.8
Multi-connectivity - 4 devices	2.3	34.9	18.9	22.4
Multi-connectivity - 7 devices	2.4	33.3	21.6	24.8
Multi-connectivity - 10 devices	2.4	36.8	23.2	27.3

TABLE 8. Packet statistics for the mobility case with a packet size of 1250 bytes.

Deployment	Sent	Received	Lost (%)
5G SA - 1 device	1001000	1000991	0.0009
5G SA - 4 devices	1001000	1000992	0.0008
5G SA - 7 devices	1001000	1000988	0.0012
5G SA - 10 devices	1001000	1000997	0.0003
Wi-Fi 6 - 1 device	1001000	999166	0.18322
Wi-Fi 6 - 4 devices	1001000	999053	0.19451
Wi-Fi 6 - 7 devices	1001000	998753	0.22448
Wi-Fi 6 - 10 devices	1001000	998685	0.23127
Multi-connectivity - 1 device	1001000	1001000	0
Multi-connectivity - 4 devices	1001000	1001000	0
Multi-connectivity - 7 devices	1001000	1001000	0
Multi-connectivity - 10 devices	1001000	1001000	0

time transmitting data is longer, and therefore, the probability of having errors during the transmission is also increased.

C. SYSTEM LIMITATIONS

This study does not consider the impact of interfering devices on network performance. This will be addressed in subsequent steps, and the work carried out in this paper will serve as a baseline for comparison of network performance with and without interference.

For this reason, as the factory scenario is surrounded by multiple laboratories with different Wi-Fi networks deployed, a bandwidth of 20 MHz was used on each AP, since we have 60 MHz of spectrum dedicated for our APs. In particular, we have available channels 132, 136 and 140. Nevertheless, the results should not be significantly altered when using a higher bandwidth on each AP, as the maximum bitrate of each device is 1 Mbps and it is far from the measured capacity limit on each AP with this configuration (200 Mbps).

Conversely, in this study, up to 10 devices were employed due to the availability of commercial equipment for both technologies, rather than due to network/capacity limitations.

Finally, the multi-connectivity solution evaluated in this paper duplicates and transmits all packets over Wi-Fi 6 and 5G interfaces. As a future step, we will implement a dynamic duplication process that based on network metrics, will determine whether to duplicate or not the packet in order to improve network efficiency and reduce resource wastage.

V. CONCLUSION

In this paper, an empirical comparison of 5G SA, Wi-Fi 6 and multi-connectivity between both technologies have been performed in an indoor industrial scenario. Particularly, the focus of this paper has been to study the latency performance and packet loss with different packet sizes for stationary and mobility cases in terms of network scalability.

From the measurement campaign performed in this paper, the following conclusions can be derived:

- In general, Wi-Fi 6 produces lower latencies but large tails in the distribution, particularly in the mobility case due to APs roaming. On the other hand, with 5G-SA, the latency distribution is very stable with bounded tails for stationary and mobility cases.
- The packet size has an impact on the latency with 5G SA, obtaining higher latencies and tails when increasing the value. No impact on the latency is observed with Wi-Fi 6. Moreover, the packet size has a noticeable impact on packet losses with Wi-Fi 6, whereas with 5G SA the impact is negligible.
- In terms of network scalability, 5G SA performs better than Wi-Fi 6. An offset to higher values on the latency distribution is observed with 5G SA, whereas Wi-Fi 6 increments the tails as the number of devices increases.
- Multi-connectivity improves the latency distribution in all evaluated cases. This feature is specially useful in the mobility case, due to Wi-Fi 6 APs roaming. As the number of devices increases, multi-connectivity becomes necessary to reduce the latency tails.
- 5G SA is more reliable than Wi-Fi 6 in terms of packet losses, particularly in the mobility case. When increasing the number of devices, packet losses are also increased with Wi-Fi 6 while for 5G SA it does not seem to be affected. Multi-connectivity improves the reliability, with no packet losses obtained in any of the cases evaluated in this study.

The selected technology will vary by industrial sector and business use case. Companies should base their decision on a trade-off between the expected performance for their use cases and the economic cost. Some companies may opt for a low-cost Wi-Fi 6 technology, even if it comes at the expense of performance; or for a reliable technology such as 5G at the expense of a higher cost. However, for the most rigorous latency and reliability requirements, we recommend the multi-connectivity solution, as it can guarantee a low latency and high reliability, although this implies a higher cost.

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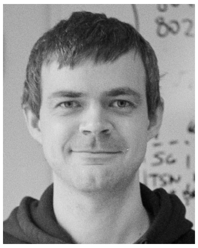

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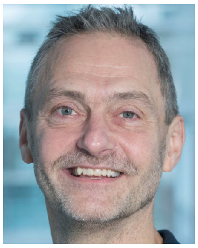

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