Accepted for presentation in: 2025 IEEE 21st International Conference on Factory Communication Systems (WFCS)

Towards Future Industrial Connectivity: Evaluation of Private 5G and Wi-Fi Networks in Professional Industrial Environments

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***Abstract*—Various technologies are being evaluated for wireless and flexible connectivity in future production processes, with a key focus on the suitability of private 5G networks compared with industrial Wi-Fi networks. Current studies often derive technological advantages from isolated, idealized case studies, neglecting significant influences of the application environment and scalability. This paper proposes a locally distributed approach for comprehensive performance evaluation of relevant wireless technologies. The STING approach enables reproducible test procedures for evaluating environment-dependent system limits and application characteristics through integration into real operational processes. This approach was used in a case study at an operational washing machine production facility to compare a temporarily deployed 5G campus network and an existing Wi-Fi 6 infrastructure. The results demonstrated that 5G technology achieved 75 % higher reliability compared to Wi-Fi 6 for the analyzed AGV application in operational settings.**

***Index Terms*—Distributed Monitoring, Private 5G, Industrial Wi-Fi, Real Production Environment**

***Video Abstract*—Video abstract can be accessed on http://tiny.cc/industrialconnectivity**

I. Introduction

With the rise of Industry 4.0, the need for advanced connectivity solutions that can support the complex demands of modern industrial applications and complex environments has been driven. In this regard, many areas of modern production environments are already digitalized and connected via wireless and wired communication solutions. Today, a mix of complementary technologies (e.g. Wi-Fi, fibre optics, bus technologies) is often used to meet application-specific requirements. However, in this rapidly evolving landscape of industrial connectivity, the need for robust, reliable and powerful wireless communication systems is becoming increasingly critical. Especially low latency and high reliability are crucial for mission-critical applications in industrial settings. In this context, industrial companies are increasingly showing great interest in the new opportunities offered by private 5G networks, and expect significant benefits from the performance features tailored to industrial use that 5G promises and provides worldwide, particularly in exclusive and broadband frequency bands (e.g. 100 MHz at 3.7-3.8 GHz in Germany). With 5G, the performance feature of highly reliable real-time communication (Ultra-Reliable Low Latency Communication (URLLC)) is emphasized as a core innovation, although there is currently only limited experience with guaranteed Quality of Service (QoS) for mission-critical applications in real operational applications. While URLLC use cases in public spaces require a broad 5G rollout, mission-critical scenarios on company premises can be implemented significantly more efficiently and allow such 5G 'marketing claims' to be validated.

On the other hand, Wi-Fi continues to be a cornerstone of industrial connectivity, with advancements such as Wi-Fi 6 and 7 enhancing its speed, efficiency, and capacity. Wi-Fi's broad adoption and relatively lower cost make it a pragmatic choice for many industrial scenarios, providing flexible and scalable solutions that integrate well with existing infrastructure. In the realm of industrial connectivity, the true potential and performance of such wireless communication solutions can only be accurately assessed through their application in real-world industrial environments, which is the goal of this study as depicted in Fig. 1.

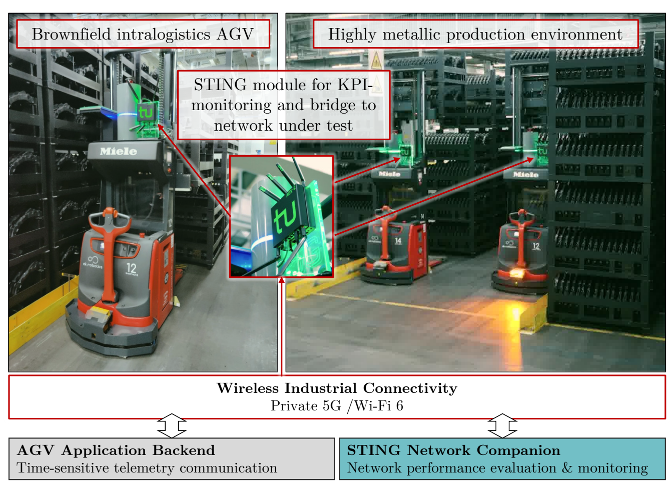

Fig. 1. Intralogistics AGV retrofit with STING unit for 5G and Wi-Fi 6 connectivity and performance evaluation

Industry pilots and marketing efforts often highlight the benefits of 5G through isolated case studies but fail to address the resources required for deploying professional local industry networks. Although 5G is hailed as a disruptive technology, its perceived potential largely stems from innovative use cases that have only recently become feasible. There is a significant gap in understanding how 5G enhances existing production systems and facilitates straightforward upgrades compared to brownfield solutions, such as industrial Wi-Fi. Discussions often overlook the complexities of supporting multiple applications and integrating them into established processes, adding to uncertainty regarding the advantages of 5G over Wi-Fi.

This study evaluates private 5G and Wi-Fi networks in industrial settings and analyzes their performance, scalability, and integration challenges. It demonstrates the Spatially Distributed Traffic and Interference Generation (STING) network companion [1] for real-time data collection, analytics, and automated control. STING provides scalable, flexible, and easy-to-deploy performance management across technologies and frequencies. Through reproducible tests, it delivers continuous, comparative evaluations of private 5G and industrial Wi-Fi 6, helping industries make informed connectivity decisions. Additionally, STING's integration into operational environments enables real-time demand-driven network control and configuration adjustments.

The remainder of the paper is structured as follows. First, the related state-of-the-art of KPI management and performance evaluation of industrial connectivity solutions is discussed in Sec. II. We then introduce our distributed STING network companion in Sec. III. To demonstrate the capabilities of our system, we conducted a case study within the professional and operational production environment of a large German manufacturing enterprise (Sec. IV). Sec. V gives an overview of the channel access mechanisms of Wi-Fi and 5G, and what Round Trip Time (RTT) is expected, before the performance evaluation in Sec. VI illustrates the technology comparison and improvements in the operational efficiency of our introduced and investigated reference application. Last, Sec. VII concludes with a summary and outlook for future research directions.

II. Related Work

The concept of private 5G networks with a focus on industrial applications is prominently discussed in [2]. The authors of [3] show the promising performance of a private 5G system in an industrial scenario with high throughput and low and stable latency; however, they focus on single-user scenarios in that analysis. A similar study is shown in [4] where different private 5G configurations were analyzed for single-user latency in an industrial environment. The authors show a similar range of latency results to our analysis with a sub-6 GHz Standalone (SA) network, while showing improved performance with a mmWave URLLC system. In [5], a systematic one-way latency analysis is conducted with an open-source 5G core and up to three active User Equipments (UEs), concluding with the impact of cross traffic, especially in the uplink direction. A study on latency and jitter of a camera based object recognition use case has been conducted in [6], concluding that a private 5G network is capable of retaining stable latency even under load. However, this analysis was limited to two UEs in the network. The authors of [7] analyzed RTT for a private 5G network, evaluating the feasibility for smart energy use cases. They also experienced a mean RTT of approximately 10 ms for a single-user setup. Similar results have been obtained in [8], where a private 5G system was deployed in a production facility of Bosch TT in Portugal, assessing validation tests with with one UE to verify coverage and sufficient performance for e.g. predictive maintenance Industrial Internet of Things (IIoT) use cases. Opposed to this work, their setup did not run in live production yet at the time of publication.

A comparison between Wi-Fi and 5G is drawn in [9], with a focus on the downlink focused firmware download use case. The authors show an advantage of 5G with regard to complying with a given Service Level Agreement (SLA)

This work uses the STING Key Performance Indicator (KPI) monitoring & control system introduced in [10] and [1], where the interference impact on a Wi-Fi enabled teleoperation use case and the systematic traffic congestion of a commercial private 5G system were analyzed. In [11], we used this system to explore the RTT stability of Wi-Fi 6 and private 5G in a lab environment, which in this work is brought into productive operation in a real-world manufacturing facility.

III. STING Network Companion

The STING system consists of distributed UE-based modules and a central network companion backend instance, as depicted in Fig. 2. This concept allows holistic KPI monitoring and network stress testing, by centrally orchestrating passive measurements and active traffic generation processes of the distributed units. The central STING network companion

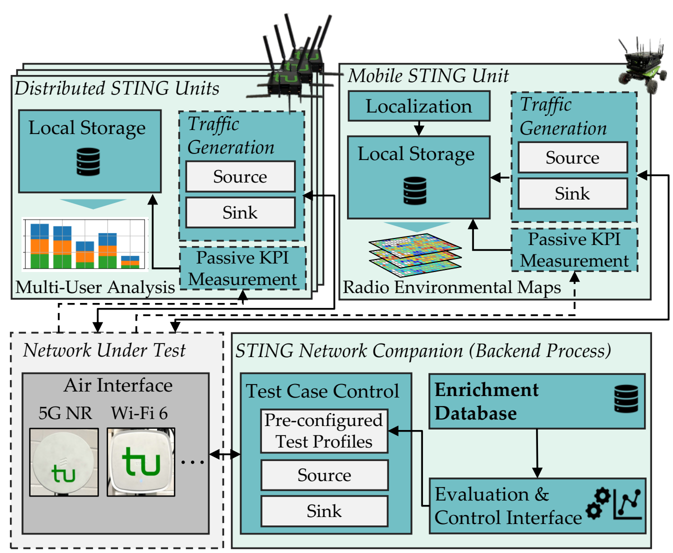

Fig. 2. Overview of STING system architecture

combines the counterpart for traffic generation and a database for KPI measurement data with an evaluation and control interface, enabling comprehensive insights on network performance to initiate mitigation strategies if necessary. The distributed STING units follow a modular approach allowing integration of multiple network interfaces and technologies, in this work private 5G and Wi-Fi 6 modems. This enables technology independent, demand based performance analysis and therefore a comparison of the suitability of different technologies for their respective application areas. Additionally, a mobile STING unit is introduced, which consists of a STING UE integrated in a mobile robotic platform. This allows the generation of Radio Environmental Maps (REMs), which give a spatial context to performance data, e.g. Reference Signal Received Power (RSRP) and data rate measurements, to estimate network performance over the whole area of interest. Fig. 3 shows the STING deployment at Miele.

In this work, the static STING modules are used to generate network load as contention for an application under test, as described in Sec. IV-A. To allow a fair comparison, network load is normalized with regard to the channel capacity of the network under test. This is done by at first measuring the maximum throughput achievable with a single active UE. The distributed STING units are then used to generate percentage steps of this maximum achievable throughput, equally distributed over all units.

IV. Real World Deployment Scenario

This work was conducted at a manufacturing facility of Miele & Cie. KG. This environment poses a challenge for wireless technologies, as it consist of highly metallic structures leading to intense shadowing and multipath effects. Nevertheless, wireless connectivity is crucial for manufacturing processes to allow flexible and dynamic operation. Therefore, a commercial private 5G system was deployed temporarily for this analysis in this facility in a brownfield approach, in addition to an already existing Wi-Fi 6 deployment. Fig. 4 depicts the scenario and the introduced use case for this work.

Within manufacturing applications, throughput is not a primary concern, as the focus is on reliability and low latency. This is why in this study, RTT is chosen as the main metric to evaluate the performance of the two networks. The main use case analyzed in this work is an AGV-based intralogistics application shown in Sec. IV-A, where intermediate products

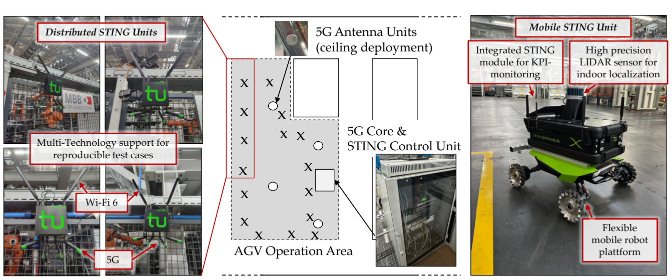

Fig. 3. STING system deployment at Miele production facility

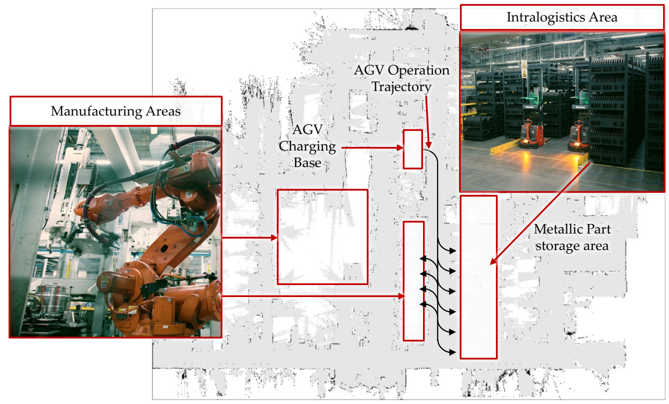

Fig. 4. Miele brownfield production environment

are autonomously transported to the next manufacturing step. The main operation area of the AGVs is depicted as trajectory in Fig. 4. This area was provided with 5G connectivity following an over-provisioning of antenna units in order to ensure good coverage within the critical area. Within the production facility, two networks under test are established. A Wi-Fi 6 system is deployed regularly in the facility for establishing the AGV use case described in Sec. IV-A. The Wi-Fi 6 network is used solely for the AGV application and is not shared with other applications. An additional Wi-Fi network is deployed for other applications in the facility, which is not part of this analysis and operates on different frequency channels. Furthermore, a commercial private 5G network was deployed for analyzing its suitability for industrial processes in this context. Both of these networks can therefore be analyzed in a fair comparison without interference from other applications. In addition to the 5G network components, our STING system was deployed in the area with 16 distributed UEs to measure and stress-test the network as well as the application for resilience against high network loads in the 5G network as well as the Wi-Fi 6 technology deployed in the facility (cf. Fig. 4, left). Furthermore, a mobile STING unit on a flexible robot platform equipped with a highly accurate Light Imaging, Detection and Ranging (LIDAR) sensor for localization is used to generate REMs for a holistic overview of the coverage within the main AGV operation area.

A. *Use Case: Intralogistics AGV*

In this work, the primary use case analyzed is a fleet of 5 AGVs, which autonomously transport goods between production steps at a factory of Miele. Fig. 1 introduced earlier gives an impression of the use case. STING units have been used to retrofit the AGVs into the 5G network and enable continuous monitoring of their network connectivity and performance. This intralogistic system uses a centralized path planning entity, which sends waypoints to the AGVs to navigate through the production facility. At every waypoint, the AGVs receive an acknowledgement indicating that they are allowed to move to the next waypoint without obstacle. For safety reasons, local sensors on the AGVs are used to detect obstacles and stop the vehicle if necessary, independent of the central management. Additionally, a heartbeat is transmitted periodically to ensure backend connectivity. If either a waypoint confirmation is missing before the AGVs reaches the previous waypoint, or a heartbeat is not received back within one second, the AGV will stop. Therefore, RTT and especially its stability is crucial for the application to be beneficial for production processes.

V. Expected Round Trip Delays

The defining factor for the minimum possible RTT of both technologies lies within their channel access methods. Wi-Fi is active in unlicensed frequency bands like the Industrial, Scientific and Medical (ISM) band at 2.4 GHz, 5 GHz and with Wi-Fi 6E 6 GHz. The license free nature of these bands comes with the need for a decentralized channel access, as the medium could be shared by multiple systems not knowing about each other. Therefore, Wi-Fi uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) channel access scheme, where the channel has to be sensed idle before a Station (STA) can attempt to access it.

When a STA senses the channel as idle, it waits for a DCF Inter-Frame Space (DIFS), which is defined as $DIFS = SIFS + 2 \cdot T_{slot}$, where T_{slot} is the slot duration depending on the frequency band and standard version in use. If the channel is still idle after the DIFS, the STA waits a random number of slots between 0 and its current Contention Window (CW). The possible size of the CW depends on the channel congestion and doubles with every collision on the channel. After the contention period, the STA sends an Ready to Send (RTS) packet, telling the Access Point (AP) that it wants to transmit data. If successful, a Short Inter-Frame Space (SIFS) later the AP responds with a Clear to Send (CTS) packet, indicating a transmission to other STAs, before the actual data can be transmitted again after a SIFS. The uplink data transmission is finished with reception of an acknowledgement packet, indicating correct reception at the AP. The downlink transmission process then follows the same rules, as the AP needs to do the same contention for the channel as the STAs. RTT on the application layer is measured from sending the packet to lower layers to successful reception of the STA, therefore leaving out the acknowledgement packet of the STA to the AP, as it is irrelevant to the STA's application layer.

It can then be calculated as follows (derived from [12]):

$$t_{\text{Wi-Fi}} = 2 \cdot \left(DIFS + \frac{CW_{\text{min}} \cdot t_{\text{slot}}}{2} + t_{\text{RTS}} + SIFS + t_{\text{CTS}} + SIFS + t_{\text{data}} \right) + SIFS + t_{\text{Ack}} + \sum_{i=1}^{n} \left[DIFS + \frac{(CW_{\text{min}} \cdot 2^{\min(i,6)} - 1) \cdot t_{\text{slot}}}{2} + t_{\text{RTS}} \right]$$

where the sum denotes n possible retransmissions due to packet collisions caused by the decentralized channel access. The parameters based on the system in use are depicted in Tab. I.

TABLE I
Wi-Fi channel access parameters [12]

Parameter	Value
$SIFS$	16 µs
T_{slot}	9 µs
CW_{min}	15
$DIFS$	$SIFS + 2 \cdot T_{slot} = 34\,\mu s$
T_{RTS}	$\frac{20\,\mathrm{B}}{1\,\mathrm{Mbit/s}} = 160\,\mu s$
T_{CTS}	$\frac{14\,\mathrm{B}}{1\,\mathrm{Mbit/s}} = 112\,\mu s$
T_{Ack}	$\frac{14\,\mathrm{B}}{1\,\mathrm{Mbit/s}} = 112\,\mu s$
T_{data}	$\frac{54\,\mathrm{B}}{162.5\,\mathrm{Mbit/s}} = 2.7\,\mu s$

With these parameters and an assumed MCS 7 (64-QAM), resulting in 162.5 Mbit/s for a 20 MHz channel, this results in a medium RTT of around 930 µs, depending on the actual CW chosen and assuming no retransmissions. This depiction does not take Orthogonal Frequency Division Multiple Access (OFDMA) into account, which was introduced with Wi-Fi 6, however the underlying general channel access remains the same, as the multi-user capabilities are built on top of that.

For 5G, the channel access follows a centralized scheduling approach, assuming all UEs are already attached to the network. The private 5G system is a Time Division Duplex (TDD) system with a DDSU slot pattern. The process for an uplink initiated RTT is depicted in Fig. 5.

To indicate a transmission, a UE needs to send a Scheduling Request (SR) during an uplink slot on the Physical Uplink Control Channel (PUCCH). SRs can be sent only during SR occasions, which are defined periodically with a vendor-specific periodicity. When the SR is processed by the Next-Generation Node B (gNB), it sends a Downlink Control Information (DCI) on the Physical Downlink Control Channel (PDCCH) during a downlink slot with the uplink resource allocation for the UE. After the implementation-specific slot delay K_2 and during an uplink slot, the UE can send its data packet on the Physical Uplink Shared Channel (PUSCH). This parameter can have a significant impact on end-to-end delay, as shown in [13]. Again after processing the data, the gNB sends a downlink resource allocation within a DCI on the PDCCH, before sending the actual downlink data after the slot delay K_0, which can be 0 and therefore use the same downlink slot, or higher and therefore another downlink slot would be used for the actual downlink data. This process can be approximated as follows:

$$t_{5\text{G}} = (\Delta_{\text{SR}} + \Delta_{\text{UL}} + K_2 + \Delta_{\text{DL}} + K_0 + 1) \cdot t_{\text{slot}}$$

Where Δ_{UL} and Δ_{DL} denote the processing time and the difference of slots to the next valid uplink or downlink slot, respectively, to align with the utilized TDD pattern. In this exemplary case depicted in Fig. 5, with a DDSU pattern, and $K_2 = 2$, $\Delta_{\text{UL}} = 2$, $K_0 = 0$ and $\Delta_{\text{DL}} = 1$. The additional slot added corresponds to the slot where the response is actually transmitted. The SR occasion periodicity in this deployment is set to be 12 slots, resulting in the additional delay Δ_{SR} of 0 to 12 slots. With numerology 1, resulting in 30 kHz Subcarrier Spacing (SCS), the duration of a slot t_{slot} is 0.5 ms.

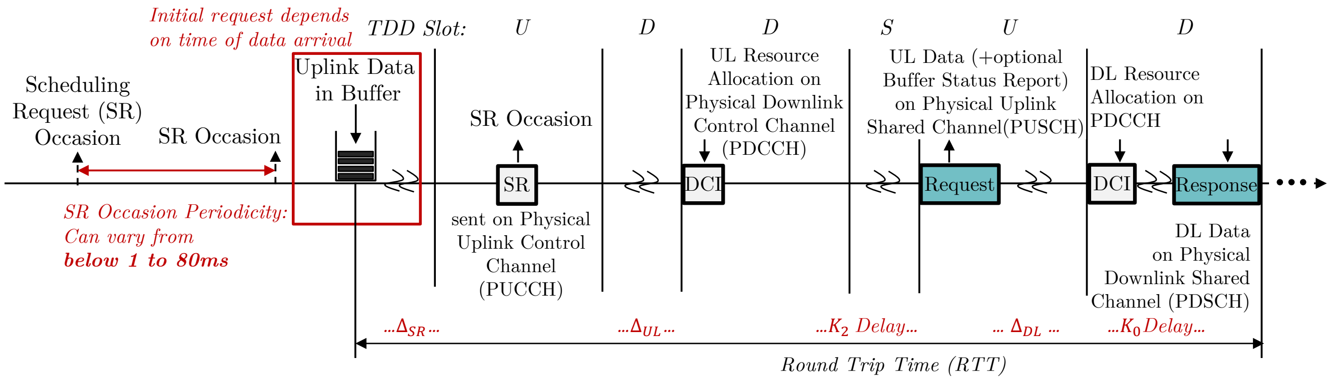

Fig. 5. Minimum Round Trip Time for Request/Response application type in 5G TDD networks

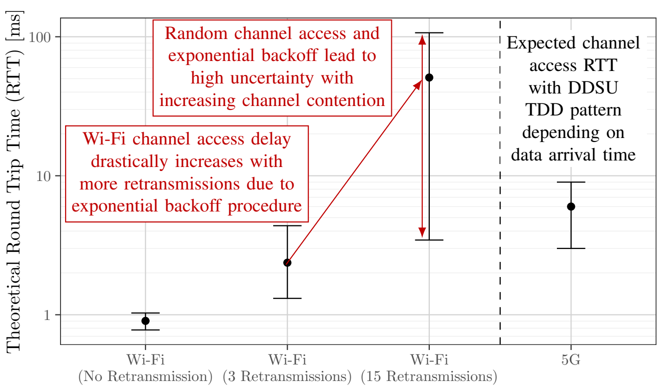

Fig. 6. Theoretical RTT for different number of retransmissions in Wi-Fi compared to channel access RTT in 5G (not considering processing delays)

TABLE II
CONFIGURATION OF NETWORKS UNDER TEST

	Parameter	5G	Wi-Fi 6
Cell Configuration	System	Ericsson Private 5G (EP5G)	Cisco Catalyst 9120
	Frequency Band	5G NR n78 (TDD)	5 GHz
	Center Frequency	3.775 GHz	5.68 GHz
	TDD Pattern	DDSU	-
	TDD Special Slot Pattern	10:2:2	-
	Bandwidth	50 MHz	20 MHz
	Subcarrier Spacing	30 kHz	-
	Number of Radios	4	6
UEs	Number of Active Devices	16 UEs	16 STAs
	Device Model	Quectel RM500Q-GL	Intel AX200
	MIMO Capabilities	DL 4×4, UL 2×2	2×2

The theoretical minimum RTT is therefore 3 ms, when all delays and processing time are nearly 0, data occurs right before the next SR and there are no retransmissions in the Hybrid Automatic Repeat Request (HARQ) process. With data occuring right after the last SR, the expected delay raises to 9 ms, accordingly, as there are max. 6 ms between consecutive SRs.

A similar analysis with another TDD configuration has been conducted in [14]. In reality, even with minimum slot delays K_2 and K_0, processing delays and data not arriving exactly before an uplink slot increase the actual RTT. These effects are shown in [15], where with a similar 5G configuration mean one-way delays of around 4 ms have been measured, which would result in a RTT of around 8-10 ms with processing delay. For URLLC applications, performance could be improved by assigning periodic uplink resources using Semi-persistent Scheduling (SPS) as shown in [16], and the integration of the Time Sensitive Networking (TSN) protocol family as presented in [17].

A comparison of the theoretical RTTs for both technologies is shown in Fig. 6. For Wi-Fi, different numbers of retransmissions due to collisions within the CSMA/CA scheme are shown, which due to the centralized scheduling do not affect 5G. It is evident that the Wi-Fi RTT increases significantly with increasing number of retransmissions, while also getting less stable due to the increasing contention windows with consecutive unsuccessful transmissions. In 5G however, RTT mainly depends on the time of uplink data arrival within the TDD slot scheme which defines if the transmission can be scheduled right away or after the next SR, leading to a more predictable expected channel access delay. These theoretical values are calculated for ideal channel conditions, without external interference or mobility-related effects, and without consideration of processing delays on device or base station side. In a production environment with multiple active STAs or UEs and multiple co-located networks as well as mobility and highly metallic environments, higher RTTs are expected, as will be shown in Sec. VI.

VI. PERFORMANCE EVALUATION

A two-fold performance evaluation of the private 5G as well as the deployed Wi-Fi 6 network was conducted. Tab. II shows the configuration of the networks.

At first, the coverage of the private 5G system within the AGV operation area was determined using the mobile STING unit (cf. Sec. III), which is depicted in Sec. VI-A. Then, RTT measurements were conducted with increasing network load

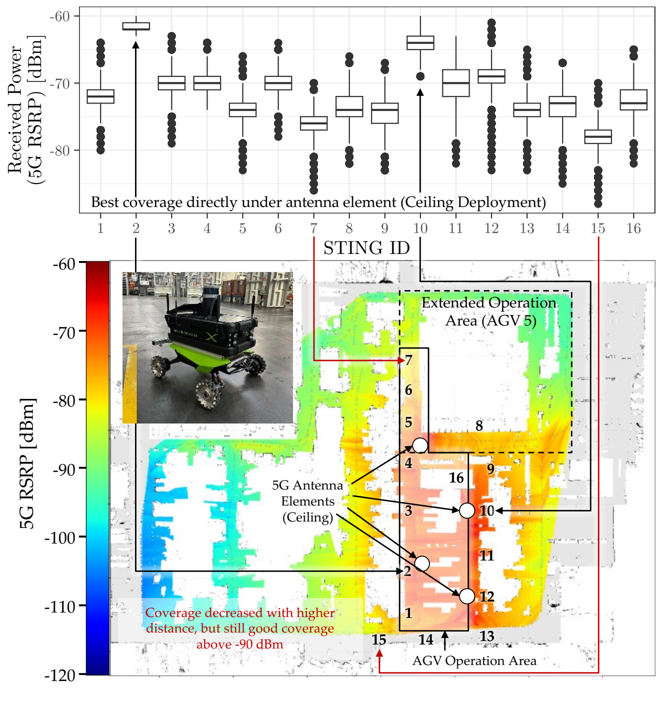

Fig. 7. Radio environmental map shows excellent 5G coverage of AGV operation area

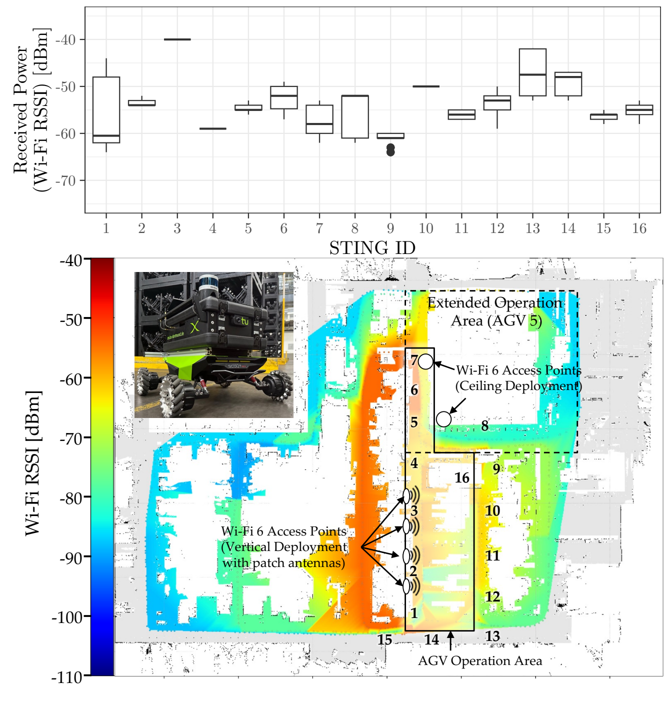

Fig. 8. Radio environmental map of Wi-Fi coverage of AGV operation area

in the 5G system, as well as the present Wi-Fi 6 system for comparison, as shown in Sec. VI-B.

A. Coverage of AGV operation area

Fig. 7 shows the RSRP REM of the mobile STING unit, in addition to the RSRP statistics of the 16 deployed static STING units. It can be seen, that a very good coverage can be achieved within the main AGV operation area. The static STING units, while being installed higher, follow the characteristic measured by the mobile STING. The units 2 and 10 have the best coverage as they are located directly under an antenna element, while 7 and 15 have the highest distance and therefore worst received power, while still being in a good coverage overall.

In addition to the coverage of the temporarily applied private 5G system, the coverage of the facility's Wi-Fi 6 system was analyzed in the same way. In order to make show the coverage over all deployed APs, the mobile STING device periodically scanned for access points, and the Received Signal Strength Indicator (RSSI) of the best AP per coordinate was chosen. The REM together with the RSSI statistics of the static STING units is shown in Fig. 8. Again, the network provides a very good coverage with all STING units within the AGV operation area achieving RSSI values above -65. This is achieved using 6 APs, which opposed to the 5G antenna elements are operated on different frequency channels. That results in the need for roaming procedures for mobile STAs like the logistics AGVs traversing the area, which could lead to performance drops in the transition areas between two access points.

In addition to the static STING units, five AGVs were equipped with STINGs to serve as a bridge into the 5G network and allow constant mobile network monitoring on top of that. AGV 1 to 4 operate in the highlighted AGV operation area, while AGV 5 has an adjacent operation area which was not part of the main proof of concept deployment. Fig. 9 shows the 5G RSRP and the Wi-Fi RSSI the AGVs experienced over one day of operation. It can be seen that AGV 1 to 4 have a very good 5G coverage all of the time. AGV 5 experiences worse coverage as expected, while still always staying in an operational state above -100 dBm.

For Wi-Fi, AGVs 1 to 4 have a similiarly good coverage with a mean RSSI of around -57 dBm, as the Wi-Fi 6 system

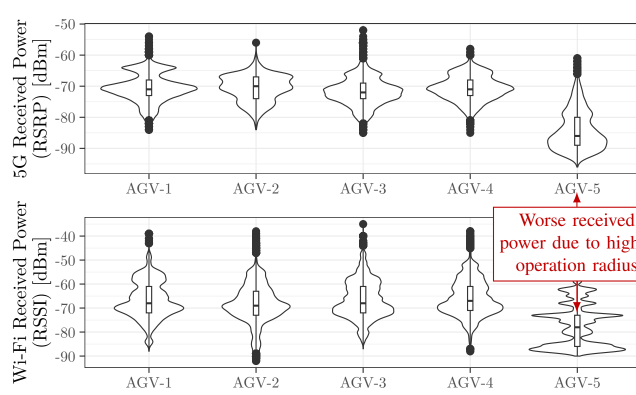

Fig. 9. Comparison of AGV connectivity with deployed 5G and Wi-Fi 6 networks during one exemplary work day

TABLE III
NETWORK LOADS DEFINED WITH 16 STINGS

	Network Load	Total Throughput	Throughput per STING
5G	20 %	20 Mbit/s	1.25 Mbit/s
	50 %	50 Mbit/s	3.125 Mbit/s
	90 %	90 Mbit/s	5.625 Mbit/s
Wi-Fi 6	20 %	30 Mbit/s	1.875 Mbit/s
	50 %	75 Mbit/s	4.686 Mbit/s
	90 %	135 Mbit/s	8.438 Mbit/s

was dimensioned for the AGV operation area as well. Again, AGV 5 has worse coverage within this network, up to where connectivity is not always guaranteed.

B. Latency robustness under network load

To evaluate robustness of the aforementioned use case against network congestion, the STING system was used to generate iteratively increasing network load. The network load is generated as percentage of the maximum throughput in uplink direction, as this is typically the bottleneck. The calculated network load is then distributed over all 16 static STING devices. Traffic is generated using iperf3 [18] User Datagram Protocol (UDP) traffic in uplink direction, with a payload of 1,470 B, to the central STING server running one iperf3 server instance per STING UE. Tab. III shows the generated data rates per UE for both technologies and every configuration.

The RTT of the AGV under test is measured using ping messages with a payload of 50 B and an Inter Arrival Time (IAT) of 20 ms to the central STING server, in addition to the application itself. Fig. 10 shows the resulting RTT for both technologies.

In addition to the RTT, the application loss ratio over the 5 min experiments is given on top. With 5G, no ping packets have been lost completely. During the Wi-Fi experiments, a low amount of up to 0.3 % were completely lost with increasing network load. Most of the packets lost on the PHY and MAC layers are recovered with the corresponding retransmission mechanisms, and are therefore contributing to the increasing experienced RTT as opposed to resulting in

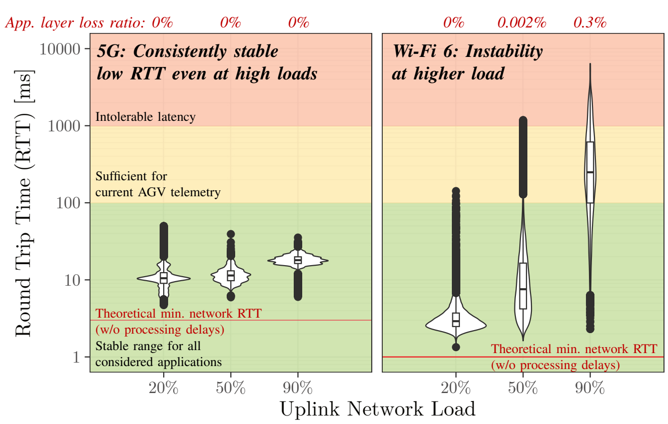

Fig. 10. Comparison of 5G and Wi-Fi RTT with increasing network load

completely lost application layer packets. It is evident that with lower network load of 20 %, both technologies can keep a low RTT, with Wi-Fi enabling mean RTT of below 5 ms and 5G of around 10 ms, coming close to their theoretical minimum in some cases (cf. Sec. V). A difference between both technologies is already apparent in the outliers. While Wi-Fi has outliers above 100 ms already in low load scenarios, which can be too high for mobile robot applications in general [19], 5G can keep the RTT below 50 ms in all cases. With increasing network load, this difference becomes more obvious. While 5G can keep the RTT below 50 ms even under 90 % network load, Wi-Fi gets more unstable with even the mean RTT increasing above 100 ms in high load scenarios. Despite being higher in absolute values due to additional processing and channel effects, the main characteristics of both technologies are in line with the expected RTT characteristics discussed in Sec. V and shown in Fig. 6. This analysis proves private 5G networks to be a capable solution for industrial use cases which rely on low latency, and especially latency stability due to the exclusive channel resources and strictly scheduled channel access. Wi-Fi networks are still a viable solution for many use cases, as they offer good performance with high throughputs at low cost, but due to the underlying free for all CSMA/CA channel access, it can not provide a guaranteed low latency for mission critical applications at all times. These measurements show a snapshot of the underlying environment. In this specific facility, no drastic environmental changes are expected, therefore the shown results prove to be meaningful. In general, continuous monitoring of the network performance is favourable to ensure the network can meet the requirements of the applications even in changing environments, and to resolve issues before they impact the production process.

VII. CONCLUSIONS & OUTLOOK

In this study, a private 5G network was deployed temporarily in a real-world manufacturing facility and evaluated in live production. The system coverage was analyzed for an intralogistics area, and in the second step, the RTT performance was evaluated and compared to an existing Wi-Fi 6 deployment. It has been shown that private 5G networks can outperform Wi-Fi in terms of latency stability, especially in highly congested networks, making it a good fit, especially for mission-critical applications such as wireless control of AGVs. Wi-Fi, on the other hand, provides very good performance at a low cost, especially in low-load scenarios, which is sufficient for many non-critical applications.

Therefore, there is no one-size-fits-all technology available for future industrial connectivity. Diverse application requirements can best be met with a Multi-Radio Access Technology (RAT) approach incorporating different technologies such as Wi-Fi, private and public 5G, and 6G networks, with lower frequencies in Frequency Range 1 (FR1), as well as high-capacity millimeter-wave technologies in FR2 and the upcoming FR3 in between. A first measurement campaign using our STING approach with a crossband private 5G system with sub-6 GHz as well as mmWave radios in an industrial environment was conducted in [20]. In that work, the more challenging directional propagation characteristics, together with the very high and promising throughput performance, were analyzed for suitability in industrial environments. An overview of the scenario, deployed at Fraunhofer Institute for Production Technology (IPT), is shown in Fig. 11.

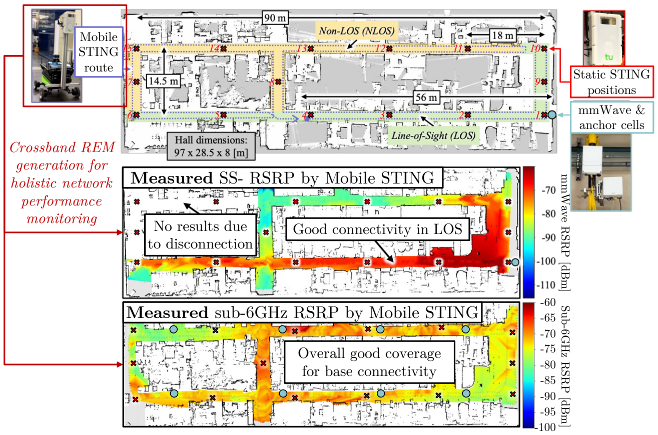

Fig. 11. Crossband KPI Monitoring & Control deployment for mmWave system at Fraunhofer IPT [20]

Future enhancements will focus on incorporating predictive analytics to forecast KPI trends and further refine automated control mechanisms. Additionally, expanding the system's integration with emerging technologies, such as 5G RedCap, will be explored to address more diverse application areas. To provide an even more detailed performance insight, we are working on time synchronization measures to allow distributed One-Way Delay (OWD) measurements. Finally, the measurement traffic will be used to provide value-added services for sensing applications, such as object detection and safety warnings, to provide value beyond the network monitoring and control aspect of the STING system.

Acknowledgment

This work has been partly funded by the Ministry of Economic Affairs, Industry, Climate Protection and Energy of the State of North Rhine-Westphalia (MWIKE NRW) along with the *5Guarantee* project under grant number 005-2008-0077 and supported by the *Competence Center 5G.NRW* under grant number 005-01903-0047, as well as the German Federal Ministry of Education and Research (BMBF) in the course of the *6G-ANNA* project under grant number 16KISK101 and the *6GEM* research hub under grant number 16KISK038.

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