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Distributed Performance Evaluation of 5G and Wi-Fi for Private Industrial Networks

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***Abstract*—Wireless communication plays an increasingly large role in modern industrial environments, enabling highly flexible manufacturing processes. While Wi-Fi is still a dominant technology, private 5G networks promise to provide a sophisticated, more reliable solution in licensed frequency bands. However, it remains uncertain in practice which level of end-to-end performance can actually be achieved. To this end, this contribution focuses on a technology-independent performance evaluation with distributed test devices based on the STING concept (Spatially Distributed Traffic and Interference Generation). We present a comparative analysis of 5G and Wi-Fi technologies for private industrial networks under realistic network load scenarios, focusing on latency to determine their suitability within industrial contexts. It can be seen that the current Wi-Fi 6 technology can keep critical applications reliable in low to medium load scenarios, but struggles when multiple stations have critical Quality of Service (QoS) requirements. In contrast, it is shown that 5G technology maintains lower latency times and has fewer outlier effects that are considered unacceptable in functional safety applications, especially in scenarios with medium to high network utilization. In order to maintain the advantage of simple Wi-Fi technology while increasing latency stability, we have optimized channel access (EDCA) in a further step on the basis of an open source Wi-Fi stack. It is shown that Wi-Fi technology with suitable modifications beyond the standard can also be able to reliably serve several stations with high QoS requirements.**

***Index Terms*—Wireless Industrial Networks, OpenWiFi, QoS**

I. INTRODUCTION

In the era of Industry 4.0, the convergence of digital technologies with traditional industrial processes has ushered in a new wave of innovation and efficiency. Central to this transformation is the establishment of robust, high-speed communication networks within industrial settings, facilitating mission critical automation use cases like industrial robotics and intralogistics. These application areas utilize highly autonomous systems which contain a multitude of different communication profiles, from high data rate video transmission of security cameras to safety critical telemetry data of mobile robots with small data volumes, but high requirements on reliability and low latency. Due to more and more flexibility being introduced in modern manufacturing workflows, wired connections are not feasible in these scenarios. In this context, the debate between adopting the 5th Generation of mobile networks (5G) cellular technology or Wi-Fi for private industrial networks has become increasingly pertinent, as private 5G networks promise high data rates and reliable low latency communications. However, these claims have yet to stand a real world evaluation, as most analysis are performed under ideal conditions. Contrastingly, Wi-Fi technology has long been the cornerstone of local area networking, offering cost-effective solutions with widespread compatibility and ease of deployment. With advancements such as Wi-Fi 6 (IEEE 802.11ax), which boast enhanced throughput, reduced latency, and improved spectral efficiency, Wi-Fi remains a suitable contender for supporting industrial connectivity requirements.

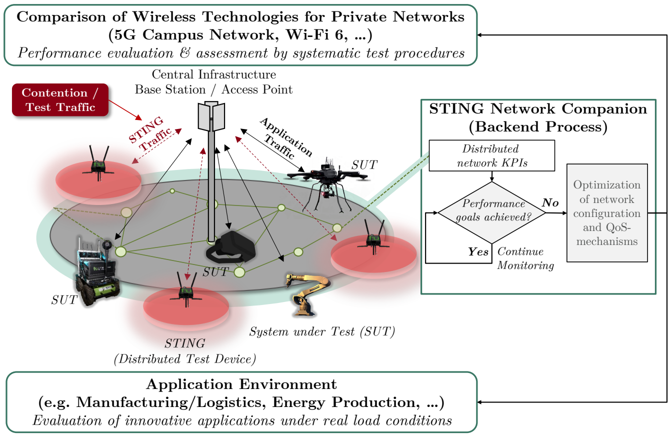

Fig. 1. Technology-independent monitoring & control for private networks using Spatially Distributed Traffic and Interference Generation (STING)

In addition to industrial environments, flexible, high-performance communication networks are also relevant in other sectors such as sustainable power plants. In Concentrated Solar Power (CSP) plants, for example, the mirrors for sunlight concentration do not require high data rates and can be addressed via narrowband 5G IoT solutions [1]. However, other applications in CSP plants like drone-based field calibration require broadband communication solutions that can be provided by private 5G networks or flexible Wi-Fi solutions, depending on the locally available frequency spectrum.

This paper aims to provide a comparative analysis of 5G and Wi-Fi technologies concerning their suitability for private industrial networks. By focusing on latency and latency distribution, this work shows the strengths and limitations of each technology within industrial contexts.

We therefore extended the Spatially Distributed Traffic and Interference Generation (STING) framework proposed in [2] and [3] to enable technology-independent, multi-network stress testing under real world conditions with multiple distributed test devices, as shown in Fig. 1. Both technologies incorporate Quality of Service (QoS) measures to enable prioritization of critical applications and end devices. The distributed nature of the STING system enables challenging the QoS mechanisms of both technologies to analyze their impact in high load scenarios. In addition to Common off the Shelf (COTS) hardware, the Field Programmable Gate Array (FPGA) based open source Wi-Fi system OpenWiFi [4] is integrated into the STING system, enabling an exploration of more flexible QoS configuration to determine Wi-Fi capabilities beyond the standard's boundaries.

The structure of this work is as follows: Sec. II provides a brief summary of relevant and prior publications. Sec. III discusses the proposed system architecture, while Sec. IV presents the proof of concept test case configuration at TU Dortmund University and discusses the results of this analysis. Sec. V shows an improvement approach of Wi-Fi for small networks with high QoS requirements and Sec. VI brings this work to a conclusion.

II. RELATED WORK

In [5] the concept of private 5G networks is addressed. The author provides a brief description of use cases and their corresponding needs concerning the communication infrastructure. The harsh requirements of Mission-critical Machine-Type Communication (MTC) are outlined in [6], which pose a main driver for Ultra-Reliable Low Latency Communication (URLLC) development relevant for industrial wireless networks. The authors in [7] present a comprehensive study on the design and deployment of a private 5G standalone network tailored for vertical industries, particularly focusing on smart factories. They highlight the potential of 5G technology to meet the stringent communication requirements of industrial applications regarding data rates and latency, however they did not analyze latency performance in high network load conditions. The implementation of private 5G networks in smart manufacturing environments is also explored in [8]. The paper compares the performance of 5G with Wi-Fi and Ethernet for a robot application by analyzing the establishment time of a Transmission Control Protocol (TCP) session. They conclude with a more stable latency for 5G compared to Wi-Fi, but did only consider two active devices in the networks. In [9], the authors investigate the feasibility of using private 5G networks for mobile industrial robots. The study focuses on evaluating the performance of a 5G Standalone (SA) in a production environment, particularly in terms of delay and reliability as specified by 3GPP standards. The results indicate that 5G can meet the stringent requirements for remote control and fleet management of mobile robots under ideal conditions. However, the study also highlights significant challenges when cross-traffic is introduced, particularly in the uplink, which affects the reliability and latency of the network.

The authors of [10] conducted an extensive simulation study on Wi-Fi 6 and 5G downlink performance for Industrial Internet of Things (IIoT) use cases, where they conclude that Wi-Fi 6 is capable of high reliability with low latency in low network loads, while 5G is able to provide good performance also in higher load scenarios. In [11], the authors draw an experimental comparison of Wi-Fi 4, Wi-Fi 6 and 5G for a firmware download use case. They also conclude in a reduced reliability of Wi-Fi in high load scenarios. Both of these studies however do not take prioritization mechanisms into account. While they focused on large scale scenarios with multiple Access Points (APs) or base stations, our contribution focuses on a measurement framework for real world performance utilizing isolated networks.

This work extends the concept of [2], where we introduced the STING framework and presented a robotic test case to assess the resilience to interference as an exemplary use case, and [3], where we used the framework for a systematic private 5G performance evaluation. For enhancing Wi-Fi latency performance, this work relies on the open source OpenWiFi approach introduced in [4], with the source code available in [12]. This framework is able to achieve very low latency due to being based on FPGA and Software Defined Radio (SDR) hardware, enabling wireless time synchronization for Time Sensitive Networking (TSN) applications as shown in [13]. The OpenWiFi stack was used in [14] to evaluate an approach to bring Wi-Fi into the licensed frequency bands of private 5G, enabling very low latency while still retaining reliability of a controlled spectrum. Enhancement of QoS was recently investigated in [15] for downlink operations in industrial automation by introducing a new access category in the MAC layer to reduce delay and jitter. Simulation results show that this new access category significantly improves the performance of time-sensitive networking (TSN) traffic, making Wi-Fi a viable option for certain industrial automation use cases, though further improvements are needed to fully meet TSN requirements. That work, as well as earlier analysis e.g. in [16] which introduces custom Enhanced Distributed Channel Access (EDCA) parameter sets for first responder applications, and [17], which proposes EDCA adaptions to ensure efficient Orthogonal Frequency Division Multiple Access (OFDMA) usage in Wi-Fi 6, rely on either analytical analysis or simulations, whereas this work shows a proof of concept real world implementation of adapted QoS parameters for Wi-Fi. Further concepts as in [18] implement machine learning methods for dynamically allocating channel access parameters to Stations (STAs) based on their context, could be enabled by this framework in future works.

III. TECHNOLOGY-INDEPENDENT NETWORK PERFORMANCE EVALUATION CONCEPT

This section provides a summary of the fundamental architecture of the STING system designed for technology-agnostic stress testing. Illustrated in Fig. 2, the STING system comprises two main elements: a central management and control system, and distributed end devices.

The distributed devices are responsible for generating traffic as well as collecting passive network Key Performance Indicators (KPIs) like Received Signal Strength Indicator

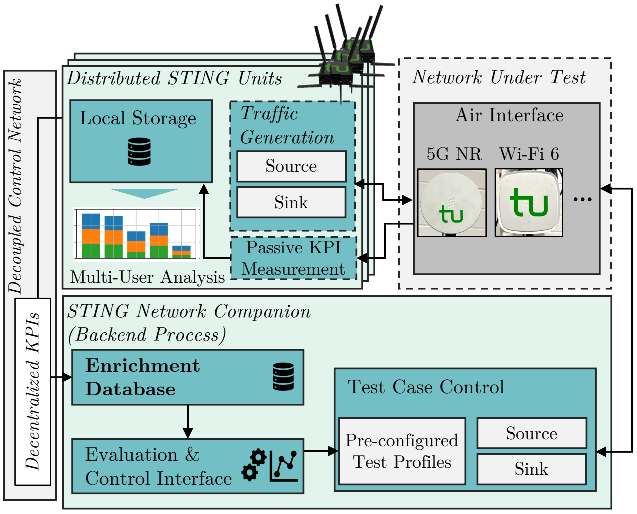

Fig. 2. Overview of STING system architecture

TABLE I
CONFIGURATION OF NETWORKS UNDER TEST

	Parameter	5G	Wi-Fi 6
Cell Configuration	System	Ericsson Private 5G (EP5G)	Cisco Catalyst 9130
	Frequency Band	5G NR n78 (TDD)	5 GHz
	Center Frequency	3.775 GHz	5.3 GHz
	TDD Pattern	DDDSUUDSUU	-
	TDD Special Slot Pattern	6:4:4 and 10:4:0	-
	Bandwidth	50 MHz	40 MHz
	Subcarrier Spacing	30 kHz	-
	Transmit Power	100 mW (EIRP)	100 mW (EIRP)
UEs	Number of Active Devices	16 UEs	16 STAs
	Device Model	Quectel RM520N-GL	Intel AX200
	MIMO Capabilities	DL 4×4, UL 2×2	2×2

(RSSI), Reference Signal Received Power (RSRP), Signal to Interference and Noise Ratio (SINR) etc., and enable a holistic overview of network performance, while taking into account spatial distribution of the User Equipments (UEs) as well as multi-user aspects of the corresponding channel access mechanisms, which are not captured in classic test systems. Passive KPIs as well as active measurement results like Round Trip Times (RTTs) and datarate are locally stored on the devices and, if available, directly sent to the central server instance via a decoupled control network. The central server instance serves as a database for enrichment data, allowing future private networks to make informed decisions on network configuration and optimizations. This is enabled via an evaluation and control interface, allowing to configure test cases with different traffic profiles as well as user prioritization as supported by the underlying network under test. Traffic generators can be modularly integrated. In this work, udpping [19] is used. As networks under test, a 5G and a Wi-Fi 6 network are analyzed, with one being actively tested while the other one can serve as the control network.

IV. COTS SYSTEMS PERFORMANCE ANALYSIS IN LAB ENVIRONMENT

The system described in Sec. III is implemented in the lab environment at TU Dortmund University in Germany, as depicted in Fig. 3. As network under test in this work, a telco-grade private 5G system is used in conjunction with an enterprise grade Wi-Fi 6 system. The following subsections describe the parameterizations of these subnetworks, as well as the measurement concepts.

A. 5G Configuration

The used private 5G network is a telco grade system operating in the 3.7 GHz band which can be rented for the use of campus networks to obtain a temporary license. 50 MHz of bandwidth are used with a balanced Time Division Duplex (TDD) pattern of DDDSUUDSUU, with the two special slots configured as 6:4:4 and 10:4:0, respectively. The configuration of the system is listed in Tab. I.

To allow a QoS differentiation between UEs, the 5G system uses different 5G QoS Indicators (5QIs), which can be assigned to separate Access Point Names (APNs) within the 5G network. It uses a 5QI of 132 for best effort traffic in Radio Link Control (RLC) acknowledged mode, and up to 129 for real time automation applications in RLC unacknowledged mode, which are able to completely starve lower priority classes. These two extreme classes are used within this work to analyse prioritization impacts.

B. Wi-Fi Configuration

The Wi-Fi System under test is a commercial state-of-the-art access point supporting the current Wi-Fi 6 standard. The AP uses 40 MHz bandwidth in the 5 GHz band with no other network present in the same band. Further configuration is listed in Tab. I.

Prioritization takes place in the form of classic EDCA. Prioritized STAs use Access Category (AC) Voice, while non-

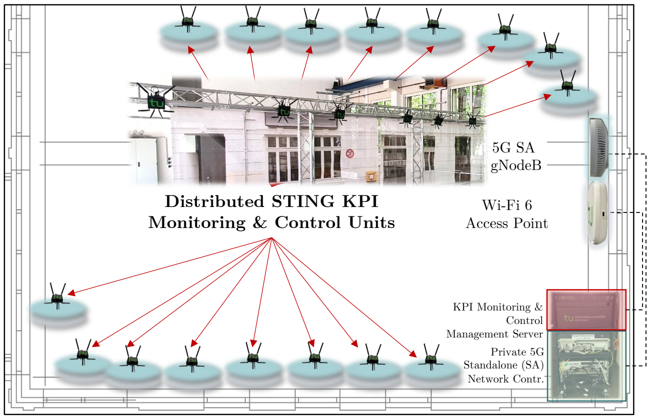

Fig. 3. Crossband monitoring & control testbed at TU Dortmund University

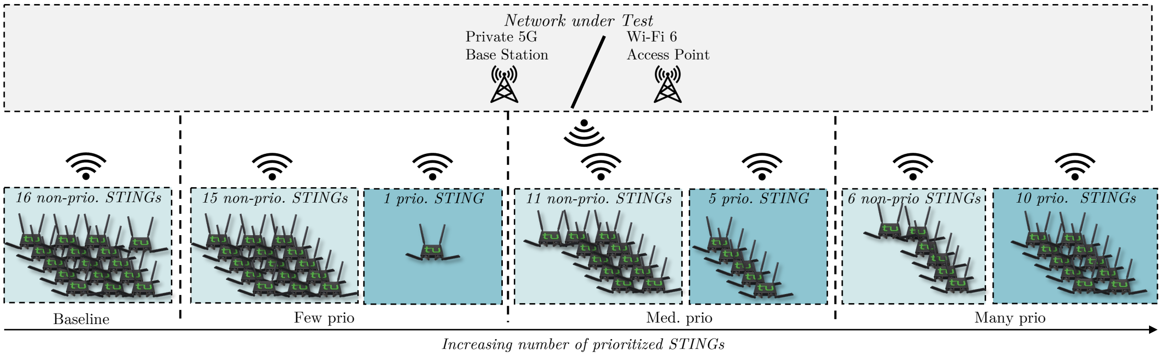

Fig. 4. Evaluation setup of 16 STING units for evaluation of technology specific QoS measures

prioritized STAs use AC Background. This is enforced by manipulating the Differentiated Services Code Point (DSCP) classes of the STAs traffic to Telephony (EF) and Low Priority Data (CS1), which is mapped to the aforementioned ACs in the AP as described in [20].

C. Evaluation Setup

For this work, an open source User Datagram Protocol (UDP) ping tool provided by Ericsson Research [19] is used to gain an insight on the latency performance by conducting RTT tests. This poses an advantage over Internet Control Message Protocol (ICMP) ping, as this allows a more unbiased performance indication on the application layer. The tool is used for measuring the perceived RTT of the STING Units, as well as generate traffic to stress the network under test. Therefore, always 16 STING units are active in the network, generating round trip UDP traffic while evaluating their RTT. They generate 1400 Byte packets with a corresponding Inter Arrival Time (IAT) to result in the network load depicted in Tab. II. The reference throughput for the network loads was defined by the maximum throughput of a single unit in Uplink (UL) direction, as this is the bottleneck especially in the 5G system. The measured maximum throughputs for the aforementioned network configurations are the following:

- 5G Downlink: 380 Mbit/s
- 5G Uplink: 160 Mbit/s
- Wi-Fi 6 Downlink: 440 Mbit/s
- Wi-Fi 6 Uplink: 380 Mbit/s

These result in the network loads listed in Tab. II for load scenarios of 20 %, 50 % and 90 % network load.

TABLE II
NETWORK LOADS DEFINED WITH 16 STINGS

	Network Load	Total Throughput	Throughput per STING
5G	20 %	32 Mbit/s	2 Mbit/s
	50 %	80 Mbit/s	5 Mbit/s
	90 %	144 Mbit/s	9 Mbit/s
Wi-Fi 6	20 %	76 Mbit/s	4.8 Mbit/s
	50 %	190 Mbit	11.9 Mbit/s
	90 %	342 Mbit/s	21.4 Mbit/s

As high network loads severely affect the reliability of wireless applications, both 5G and Wi-Fi use different means of QoS mechanisms in order to allow specific applications to be prioritized. The underlying mechanisms were described in the previous sections. In this work, these different approaches are taken to the test by evaluating the impact of an increasing number of prioritized units within both networks. Therefore, four distinct configurations are defined, each with all 16 STING units active: no priorization, one prioritized STINGs, five prioritized STINGs and ten prioritized STINGs. These configurations are illustrated in Fig. 4.

D. Performance Results

Fig. 5 shows the RTTs for the aforementioned configurations. Every scenario is run for 60 s. For every configuration, the prioritized and non-prioritized STING units are grouped into one statistic. On the x-axis, the number of active STINGs is shown per group for the configurations separated by the dotted lines. At the top, the results for 5G are shown, while the Wi-Fi results are at the bottom, with increasing network load from left to right. Additionally, 100 ms are marked as an exemplary threshold for the RTT, which is a requirement of a teleoperated mobile robot application as stated in [21]. It can be seen that the private 5G system is always capable of fulfilling this requirement even in high network load conditions. Wi-Fi 6, due to the random access nature of the channel contention, can not reliably keep the RTT below that threshold without prioritization when 16 STAs are active in the network. However, prioritizing critical STAs using the standard EDCA measures can keep them below 100 ms in a low load scenario. With medium network load, the Wi-Fi 6 network starts to struggle when more than half of the stations get a prioritization, as this tightens the channel access timings of most of the stations, resulting in increased collision probabilities. Under high network load, Wi-Fi 6 can only keep up to 5 STAs reliably under 100 ms, as RTT increases with every prioritized STA due to higher channel contention.

V. ACHIEVING LOWEST LATENCIES WITH ADAPTED WI-FI CHANNEL ACCESS

The previously discussed results show a promising stability of a 5G system under QoS requirements compared to Wi-Fi 6.

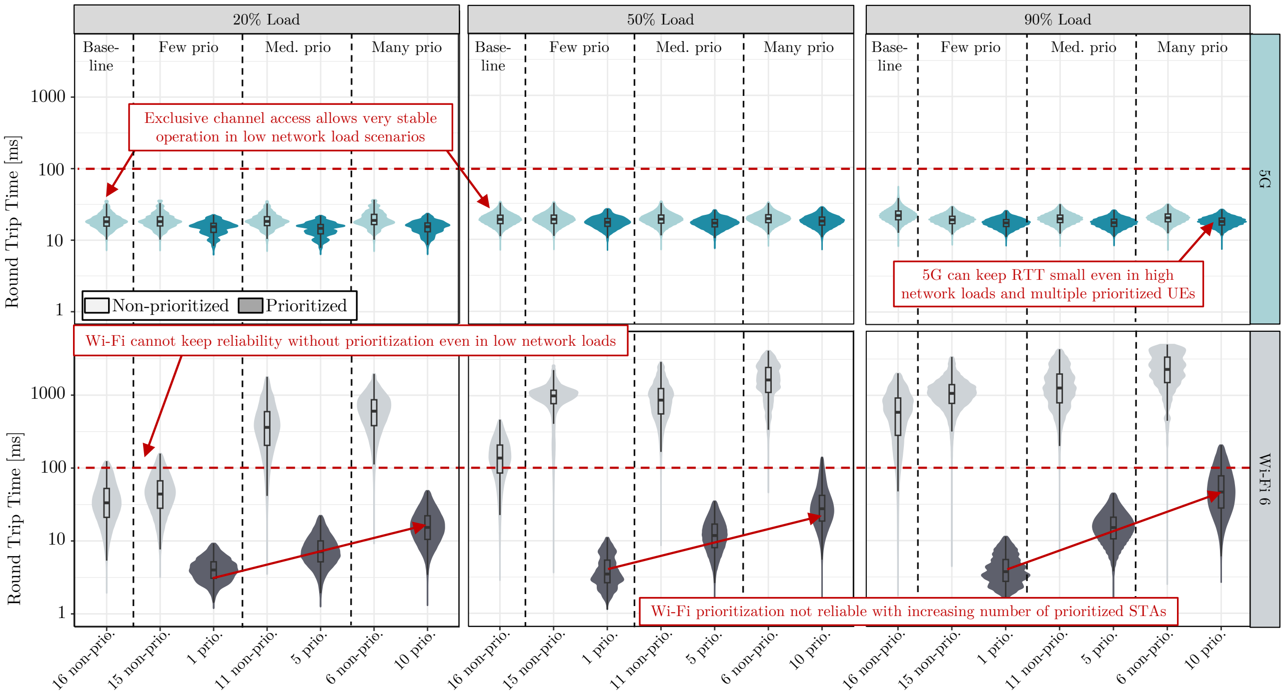

Fig. 5. Comparison of round trip time of 16 STING units with prioritization for 5G and Wi-Fi under varying load conditions

In this section, the open source Wi-Fi implementation OpenWiFi [4] is utilized to explore if optimization of the EDCA channel access mechanism is feasible to increase latency performance for critical applications in Wi-Fi, by sacrificing some performance of low-priority STAs. Therefore, a subset of 6 STING units is equipped with OpenWiFi hardware, as depicted in Fig. 6. The following subsections show the configuration of the OpenWiFi setup, as well as measurement results in comparison to the COTS system performance in a downscaled network.

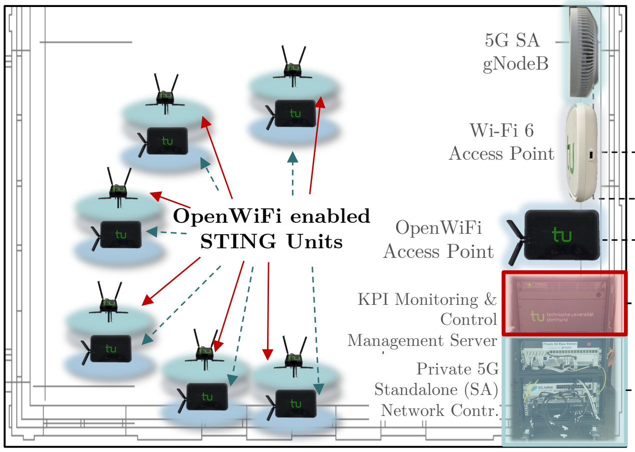

Fig. 6. OpenWiFi enabled STING lab setup

A. *OpenWiFi Configuration*

The OpenWiFi System under test is an open source realization of the Wi-Fi standards a, g, n. The functionality of a Wi-Fi chip which is realized with hardware by default is implemented as a software solution and FPGA implementation based on a Linux 802.11 Medium Access Control (MAC) subsystem. The board supports 27 MHz continous bandwidth and frequency range from 70 MHz - 6 GHz. [12], [4], bringing the flexibility to operate beyond the standard frequency bands and therefore allowing operation in licensed frequency bands as shown in [14]. In this work, the AP uses 20 MHz bandwidth in the 3.7 GHz band with no other network present in the same band. Further configuration is listed in Tab. III. While this setup with a peak reliable datarate of 20 Mbit/s does not

TABLE III
CONFIGURATION OF OPENWIFI SYSTEM.

	Parameter	Description/Value
AP	System	Xilinx zed_fmcs2
	Frequency Band	3.7 GHz
	Center Frequency	3.725 GHz
	Bandwidth	20 MHz
	Transmit Power	20 mW (EIRP)
STAs	Number of Active Devices	6 STAs
	Modem Model	Xilinx zed_fmcs2
	Prioritized STA CW	min: 7, max: 31
	Non-prioritized STA CW	min: 127, max: 1023
	Prioritized STA AIFSN	2
	Non-prioritized STA AIFSN	127

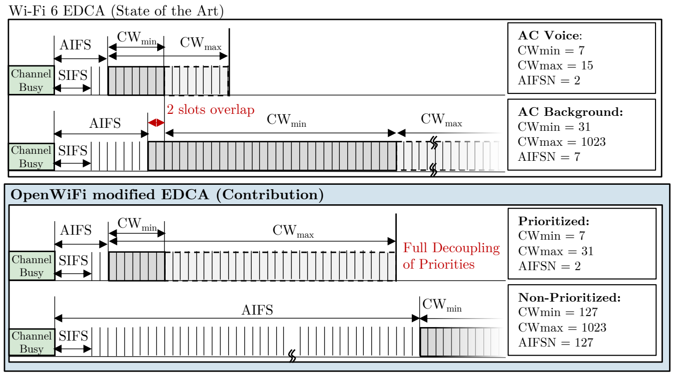

Fig. 7. Comparison of channel access parameters for COTS Wi-Fi and OpenWiFi enabled adapted channel access

reach throughput performance of COTS hardware mainly due to limited bandwidth and a lack of Multiple Input Multiple Output (MIMO) capabilities, it does reach very low latencies below 1 ms in ideal network conditions due to the FPGA basis. This setup however enables flexible configuration of system parameters in a real world measurement, allowing to analyze the general characteristics of the system's behavior in high load scenarios relative to its individual capacity.

Prioritization takes place in the form of modified EDCA parameters, as shown in Fig. 7. The goal is to fully decouple prioritized and non-prioritized STAs as depicted in Fig. 7, by manipulating the Contention Window (CW) and the Arbitration Interframe Space (AIFS), which is used before the channel access itself is initiated, of the non-prioritized STAs to an AIFS Number (AIFSN) of 127, leading to the non-prioritized STAs only accessing the channel after the prioritized STAs CW. Additionally, a high $\mathrm{CW}_{\mathrm{min}}$ and $\mathrm{CW}_{\mathrm{max}}$ value is choosen for the non-prioritized STA, further decreasing the collision probability by reducing the chance of multiple stations choosing the same number of contention slots. The full adapted EDCA parameterset is listed in Tab. III.

B. Evaluation Results

For this evaluation, 6 STING modules equipped with OpenWiFi hardware are used. The reduced number of modules results in the adapted scenario configuration depicted in Tab. IV. Fig. 8 shows the results of this evaluation, with a focus on low and high network load. Due to the reduced number of available end devices, a more detailed analysis of configurations is shown from 1 to 5 prioritized STA. As expected, 5G can again keep the RTT low and stable due to its centrally managed channel access. Wi-Fi 6 is also more stable than in the configuration in Fig. 5 due to the reduced number of STAs and therefore reduced contention on the channel resources. OpenWiFi can also maintain a stable operation, while reaching RTTs below 10 ms. In high network loads, 5G is able to maintain stable operation with only minor increase in RTT for non-prioritized UEs, while the spread of RTTs in the COTS Wi-Fi 6 system increases, even if it stays much lower than in the 16 device scenarios. OpenWiFi however, with the more strict separation between prioritized and non-prioritized channel access configurations, is able to retain very low RTTs for the prioritized STAs. This indicates that a thorough configuration of Wi-Fi systems, also beyond the standard configuration, can yield to very reliable operation, especially when paired with exclusive spectral resources, while still offering the benefit of more simple Wi-Fi deployment compared to a more sophisticated private 5G system.

TABLE IV
NETWORK LOADS DEFINED WITH 6 STINGS

	Network Load	Total Throughput	Throughput per STING
5G	20 %	32 Mbit/s	5.33 Mbit/s
	90 %	144 Mbit/s	24 Mbit/s
Wi-Fi 6	20 %	76 Mbit/s	12.67 Mbit/s
	90 %	342 Mbit/s	57 Mbit/s
Open-WiFi	20 %	4 Mbit/s	0.66 Mbit/s
	90 %	18 Mbit/s	3 Mbit/s

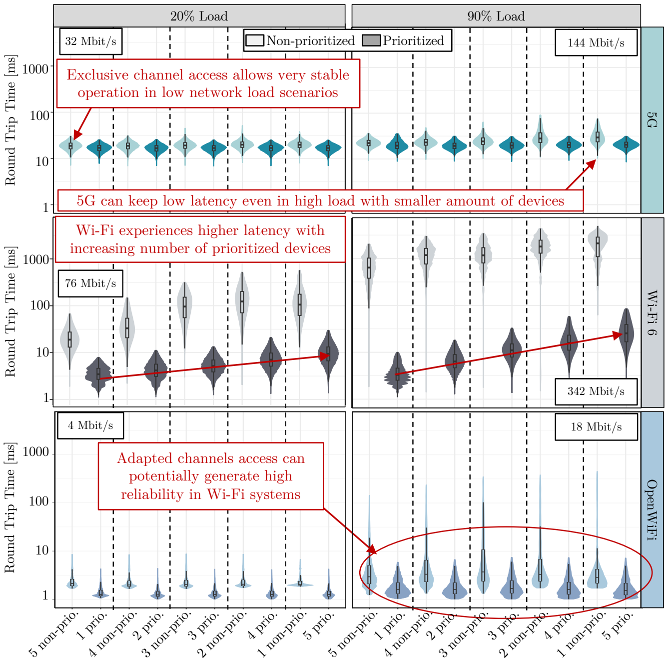

Fig. 8. RTT performance of OpenWiFi compared to COTS 5G and Wi-Fi 6 with 6 STING units

VI. CONCLUSION & OUTLOOK

In this work, an experimental comparative performance evaluation of 5G and Wi-Fi 6 has been conducted with a focus on RTT performance. Both technologies have been analyzed using their respective QoS mechanisms to evaluate their suitability for critical applications in a network with increasing saturation. It is shown, that both technologies can handle a high number of prioritized end devices in low load scenarios. With increasing network load, 5G is able to keep a stable low latency even in high network load scenarios. Wi-Fi 6 can only retain low latency for a small number of STAs under high load, due to the random nature of it's channel access. Stretching the boundaries of the standard channel access configuration however, it can be seen that a reliability near to 5G can be achieved in a reduced network size with high QoS requirements.

In future work, the OpenWiFi prioritization approach will be explored further to close the gap between 5G and Wi-Fi technologies and allow a flexible integration into future Crossband 6G systems. Based on this work, monitoring of live network performance in the sense of a network companion will be integrated into flexible network and QoS reconfiguration, to enable Artificial Intelligence (AI) based autonomous mitigation and optimization strategies.

ACKNOWLEDGMENT

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