Enhancing Real-Time Networked Embedded Systems with End-to-end TSN-5G Networks

Zenepe Satka, Saad Mubeen, Mohammad Ashjaei, Didrik Nordin, Daniel Ragnarsson
Networked and Embedded Systems
Mälardalen University
Västerås, Sweden
firstname.lastname@mdu.se

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***Abstract*—This paper explores the integration of Time-Sensitive Networking (TSN) with 5G cellular networks to support high-bandwidth and low-latency end-to-end communication in networked embedded systems. Integrating TSN with 5G has the potential to support predictable and deterministic end-to-end communication, as well as to significantly enhance scalability, particularly in industrial automation, by providing flexibility, efficiency, and responsiveness. To ensure smooth integration while preserving TSN's Quality of Service (QoS) requirements, effective traffic translation and forwarding within the network are crucial. In this regard, this paper addresses key challenges related to traffic translation, QoS implementation, and latency in both TSN and private 5G networks on a realistic scenario. Through experiments, measurements, and evaluation, this paper thoroughly assesses latency and network capabilities in the integrated networks. Understanding these metrics is essential for devising effective integration strategies. Our findings indicate that it is possible to achieve latencies under 20 ms in an integrated TSN-5G network, given our specific configuration of a private 5G setup with a channel bandwidth of 40 MHz. We also identify an urgent need for the implementation of a proper QoS mechanism in the Open Air Interface software to enable the prioritization of high-critical data transmission.**

***Index Terms*—Networked embedded systems, Time-sensitive networking, TSN, 5G, Heterogeneous real-time networks.**

I. Introduction

As we transition into the era of Industry 4.0, the demands for networked embedded systems are growing. This evolution necessitates more reliable network communication with low and predictable latencies in many time-critical industrial applications such as cooperating vehicles in an autonomous construction site, collaborating robots, customized manufacturing systems, and real-time monitoring of industrial connected machines, to mention a few [1], [2]. These applications often have timing predictability and reliability requirements on both wired communication (communication within devices, machines, vehicles) and wireless communication (communication among devices, machines, vehicles, and their control center) [3], [4]. Moreover, these applications increasingly demand the combined support of both wired and wireless networks for enhanced flexibility [5].

In the above context, one of the promising solutions for wired communication is the set of Time-Sensitive Networking (TSN) standards developed by the IEEE TSN task group [6]. TSN is based on switched Ethernet. High-bandwidth, low-latency, traffic shaping, deterministic and reliable communication are some of the features supported by TSN [7], [8]. The fifth generation of cellular networks (5G) is known for its ability to meet demands for high bandwidth, low latency, and high reliability. 5G stands out as a fitting choice for wireless communication as well as for the integration with the wired communication in these applications [9]. 5G offers significant improvements in network speed, capacity, and responsiveness over its predecessor, 4G [10]. It includes key features like high bandwidth for rapid data transfer, low latency for real-time applications, network slicing for customized virtual networks, and enhanced reliability for critical tasks. These advancements not only improve mobile broadband but also support a diverse range of applications and new use cases, enhancing the capabilities and performance of embedded systems across various industries. Looking ahead, the development of the sixth generation of cellular networks (6G) aims to further revolutionize wireless communication with even faster speeds, lower latency, and more advanced features enabled by the full integration of machine learning (ML) and artificial intelligence (AI) as part of wireless networks [11].

Integrating TSN with 5G allows industries to leverage both wired and wireless technologies, leading to more efficient, flexible, and future-proof operations [12]. The reliable transfer of time-sensitive data across networks necessitates careful consideration of factors such as time synchronization, resource management, and ensuring determinism in communication and processing within both TSN and 5G frameworks [4].

Our focus is on ensuring end-to-end (E2E) communication within the integrated TSN-5G network, with specific attention to examining latencies and jitter to provide valuable insights for implementation within industrial areas. Our work is centered on establishing realistic E2E communication within the TSN-5G network with the help of a standalone private 5G network in our lab environment. To meet the requirements on latency and reliability from the E2E perspective in the integrated TSN-5G network, the Quality of Service (QoS) requirements within the TSN network must be forwarded and translated into the 5G QoS profiles [13]. Therefore, in our work we develop a gateway that acts as a bridge between these two heterogeneous networks, translating data traffic with proper QoS-es, to meet stringent timing constraints and reliability requirements of time-sensitive traffic in our realistic private 5G lab environment. We monitor the network and analyze network traffic to contribute to a better understanding of the E2E communication in the integrated TSN-5G networks. Moreover, our findings indicate the need for a robust QoS mechanism implementation to enable the prioritization of high-critical data transmission for specific users when multiple devices are connected to the network.

The rest of the paper is structured as follows: Section II covers the background information, Section III reviews related work, Section IV introduces the prototype of the end-to-end TSN over 5G, Section V delves into the experimental evaluation, and Section VI presents the conclusions and future research directions on end-to-end TSN-5G networks.

II. Background

This section provides an overview of the TSN-5G network context to help the reader understand the rest of the work.

A. Time-Sensitive Networking

Time-Sensitive Networking (TSN) is a set of standards designed to support the reliable and deterministic delivery of time-sensitive data over Ethernet [8]. TSN includes a set of features such as path control and reservation, scheduled traffic, and per-stream filtering and policing, among others. It is used in time critical industrial and automotive applications with a support of high bandwidth and low latency [7], [8].

TSN prioritizes the transmission of time-sensitive data over less critical traffic by using the concept of VLAN tagging, as shown in Figure 1. The VLAN tag consists of two main parts: Tag Protocol Identifier (TPID), and Tag Control Information (TCI). TPID is a 16-bit field set to a value of 0x8100 to indicate that the frame contains a VLAN tag. The TCI includes subfields such as Priority Code Point (PCP), Drop Eligible Indicator (DEI), and the VLAN Identifier (VID). The Priority Code Point (PCP) is used to classify incoming frames and apply QoS mechanisms such as, traffic shaping, priorities, and reservations to make sure data is delivered with a guaranteed level of reliability.

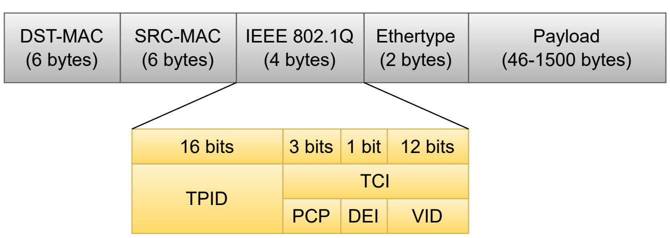

Fig. 1. TSN frame format.

The PCP value defines eight FIFO (first-in first-out) queues for a port in TSN switch with priorities of 0–7, from high to low [14]. Each PCP value defines a class of service, shown in Table I for network control ensuring prioritized network capacity to critical applications [15].

B. Private 5G Network

Private 5G refers to a dedicated 5G network with enhanced communication characteristics designed for the exclusive use of a factory, or organization. Reusing the 5G technology, private 5G networks are characterized by high availability, ultra-low latency, high reliability, and scalability for numerous devices [16]. Moreover, it is an isolated network, also known as a standalone non-public network (SA NPN 5G), that restricts wireless connectivity only to the authorized devices, therefore minimizing the wireless interference from unknown devices. More importantly, it allows the owner to totally control every aspect of the network, enabling customized configurations for specific use cases and performance requirements such as low latency, high throughput, and availability, among others [16], [17]. The key enabling advancements and technologies for private 5G networks include spectrum management, Ultra-Reliable Low Latency Communication (URLLC), integration with TSN, network slicing, interference management, localization and tracking, and private edge computing [16].

TABLE I
TSN Class of Service based on PCP value and Priority [15]

PCP value	Priority	Class of Service
1	0	Scavenger / Bulk Data
0	1	Best Effort
2	2	Network Management
3	3	Mission Critical
4	4	Interactive Video
5	5	Voice
6	6	Internet control (Routing)
7	7	Network control

The deployment of the private 5G network, including the 5G core network, is depicted in Figure 2. All network functions are contained inside the logical boundaries of the defined premises (e.g. factory) and the private network operates independently from the public network [18]. The subscriber database stores the information about the users that can access the network including user credentials and subscription information. The control plane handles tasks such as mobility management, session management, and network access control. In addition, the user plane is responsible for the actual data transmission within the network. It handles the transmission of the IP data traffic between UEs and the external networks. The 5G core network is responsible for managing both the control plane and user plane functions.

Although, TSNs can meet the high bandwidth and low-latency requirements of various applications, they require high maintenance costs and fail to provide the mobility required by future industries. Therefore, it is of paramount importance to integrate TSN with private 5G networks as a promising solution to achieve scalable, future-proof networks that can meet the growing demands of Industrial IoT and other emerging technologies.

1) Differentiated services in private 5G: In 5G the tremendous number of connected devices share the radio resources with heterogeneous QoS requirements. 5G uses the QoS mechanism for a proper prioritization among all the devices. The base station (gNB) carries all the information regarding the QoS requirements from the devices, and applies a proper scheduling mechanism of the radio resources to ensure the

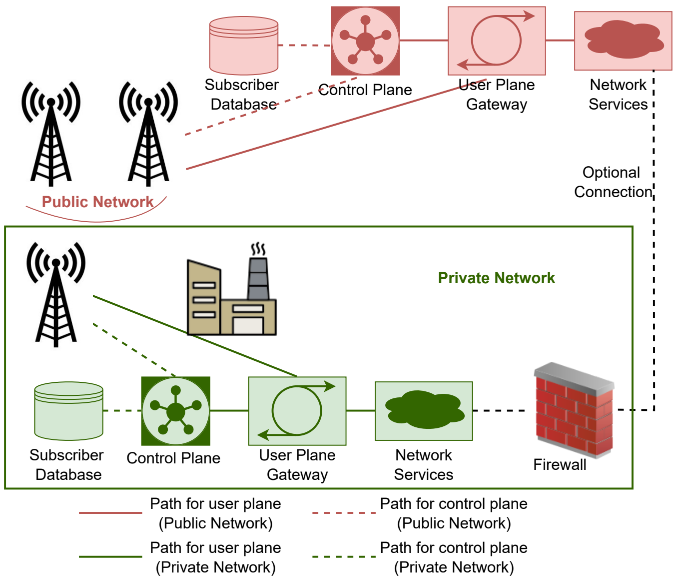

Fig. 2. The private 5G network deployment.

QoS requirements and prioritize the transmission of high critical data [19].

5G classifies transmission of data as Guaranteed Bit Rate (GBR), Non-Guaranteed Bit Rate (Non-GBR), and Delay Critical Guaranteed Bit Rate (DC-GBR) [13]. Non-GBR QoS flows are best effort flows that has no guarantees, this means that the traffic won´t be given any bandwidth or latency guarantees within the network. GBR QoS flows are used for real-time traffic where the traffic must meet a certain level of QoS requirements. To meet these requirements a GBR flow is guaranteed a certain level of network resources. The DC-GBR flow is similar to the GBR flow but has extra requirements on bandwidth. To separate the different QoS flows, each flow has a unique QoS flow Identifier (QFI). The QFI is used when forwarding and handling the traffic within the network to ensure each packet is guaranteed the specified level of QoS requirements [20].

In addition, GTP-U protocol is utilized to enable the transmission of user data across 5G network, enabling seamless connectivity and data transmission. Moreover, the Differentiated Service Code Point (DSCP) can be used to mark and prioritize packets carried within GTP-U tunnels. DSCP is a field in the IP header used to identify and classify packets based on the type of service required [21]. Integrating 5G with TSN networks involves a proper mapping of 5G QFI/DSCP to the PCP values of TSN, as shown in Section IV, to ensure end-to-end QoS continuity.

III. Related Work

In this section, we position our work in a broader context of the field and conduct a comprehensive comparison with previously published studies and their findings.

Within the realm of integrating Time-Sensitive Networking (TSN) and 5G networks, there have been several significant contributions [4], [9], [13], [19], [22]–[24].

Authors in [13], [19] introduce QoS mapping algorithms designed for systematic mapping of QoS characteristics and seamless integration of traffic flows in converged TSN-5G networks. Satka et al. [13] propose the static implementation of QoS algorithms to map each TSN traffic flow with specific requirements such as deadline, jitter, packet loss and bandwidth, to the standardized 5G QoS profiles from 3GPP Release 16 [25]. On the other hand, Cai et al. [19] propose a dynamic and load-aware QoS mapping method based on the improved K-means clustering algorithm and the rough set theory. We will be introducing a static mapping method as part of our work, and test the performance on real equipment, while also using them as a reference point when considering potential changes and exploring possible improvements.

In addition, Larrañaga et al. [24] explores the analysis of bridge delay within the 5G-TSN network. The primary objective is to understand how this integration can meet the demands of latency-critical applications in the industrial sector. The study centers on the formal analysis of the TSN and 5G bridge's minimum and maximum delays, considering different traffic classes. This assessment aims to evaluate the Radio Access Network (RAN) capabilities, particularly its potential to achieve low Packet Delay Budget (PDB) values for industrial applications. In line with this, our initial testing phase focus is on real-time evaluations of the SA 5G network, specifically using Quality of Service (QoS) priority traffic and measuring the PDB in 5GS. This step precedes the implementation of TSN and aims to establish a foundational understanding of the 5G network's performance characteristics under standard conditions.

Authors noted in [23] present a translator design between TSN-5G communication protocols and a proof-of-concept implementation in OMNET++ simulator. The translation is facilitated using two algorithms. One handles the translation flow representing traffic from the 5G network to the TSN network and the other from the TSN network going to the 5G network. This work will serve as a reference when building our gateway and implementing a translating technique in our real-world experiment.

Moreover, authors in [4], [9] provide a comprehensive perspective on the integration of TSN and 5G. Their research describes challenges and advantages of transitioning from a wired TSN network to wireless TSN with the support of cellular 5G, with emphasize on potential improvements in flexibility while maintaining and supporting real-time requirements such as deterministic and ultra reliable communication. Additionally, they highlight the benefits when used in different applications, including industry automation and automotive, and the potential challenges when integrating TSN with wireless 5G technologies. This research serves as a foundation and background for evaluating and measuring our results, assessing the performance, and determining if our results can meet industry requirements.

To summarize, our work is centered on establishing real-world end-to-end communication within the TSN-5G network with the help of standalone private 5G network. A crucial aspect involves configuring a gateway that acts as a bridge between these two networks, translating data traffic with proper QoS algorithms to meet stringent time constraints and reliability requirements of time-sensitive networks in the real time environment.

IV. Prototype Design of TSN-5G Network

In this section, we present the prototype of the end-to-end TSN over 5G utilized for the experimental analysis. The prototype integrates TSN capabilities with 5G network infrastructure to evaluate round-trip latency and reliability in scenarios requiring low-latency communication, i.e. collision avoidance systems in autonomous vehicles.

A. Prototype Design

The prototype design of the E2E communication in a converged TSN-5G network is depicted in Fig. 3. It includes 1) the TSN endpoints connected to the TSN switch, 2) the 5G endpoints connected to the 5G core network, and 3) the TSN-5G gateway to support the end-to-end communication.

*1) **TSN network**:* The TSN network includes various TSN endpoints, such as cameras or sensor nodes that send TSN traffic. These endpoints are connected to a TSN switch that manages the traffic forwarding and prioritization using the IEEE 802.1Q protocol [15].

*2) **5G Network**:* On the 5G side, the network consists of various 5G endpoints or user equipment (UE) connected to the private 5G network via the 5G modems. A Universal Software Radio Peripheral (USRP) is used to facilitate the development and implementation of the 5G radio system using software. In this prototype setup, the USRP is a B200 based on the AD9361 chipset with a frequency range of 70 MHz - 6 GHz. The complete setup of the private 5G network is part of the Firecell Solutions [26]. The technology is built on the Open Air Interface (OAI) Software Alliance, an open-source project under the public license V1.1 [27]. In addition, data transmission and routing over the 5G core network utilize the GTP_U protocol, which uses a tunnel mechanism to carry the user data traffic running over UDP transport [28].

*3) **TSN-5G Gateway**:* The TSN-5G gateway in Fig. 3 acts as an interface to support the protocols translation between TSN and 5G networks. The gateway includes mapping TSN PCP priority values to DSCP priority values for traffic that traverses from the TSN network to the 5G network. Moreover, the gateway maps the DSCP priority values to TSN PCP priority values for traffic coming from the 5G network into the TSN network. Two algorithms are employed for this translation, as detailed in Section IV-B. The time required by these algorithms to map the values is referred to as the gateway processing latency.

The *E2E TSN-5G communication latency* includes the time taken for the sensor data to be transmitted from the TSN endpoint over the TSN network, processed by the TSN-5G gateway to be further sent over the private 5G network to the 5G UE, processed by the controller, and then sent back to the actuator residing on the TSN network. To measure this latency, we utilized the built-in functionality for measuring round-trip time of Internet Control Message Protocol (ICMP) packets. The round-trip time for an ICMP packet is the time it takes for the packet to return to the sender after getting a response from the receiver. This approach allows us to accurately determine the end-to-end latency for individual packets without the need to synchronize clocks across different network units.

B. Prototype Implementation

To measure the response time of our integrated TSN-5G system, we use Wireshark along with sending ICMP packets of varying sizes. In this context, the integrated TSN-5G system refers to the entire data transmission pathway, encompassing the UE, the TSN-5G Gateway, and the 5G core network. Wireshark is a widely used tool for network traffic analysis that features packet timestamping upon capture. We installed Wireshark in the UE, TSN-5G Gateway, and 5G core network to track the time it takes for packets to traverse the overall system. This visual representation helps us analyze the latency, identify trends, and draw conclusions about the network's performance over the measurement period. To gain a deeper understanding and precise timing of each network component, we measured the latency separately for each component, including the TSN network, 5G radio access, gateway processing, and the 5G core network. These detailed measurements help us pinpoint potential sources of latency and jitter within these integrated networks.

In this work, we focus on transmitting VLAN-tagged traffic to evaluate how well TSN-specific properties like the PCP are retained in wireless networks. We noted that a 1000-byte packet, when sent with a VLAN tag over Wi-Fi or 5G, was reduced to 996 bytes upon reception. This four-byte reduction clearly indicated the removal of the VLAN tag. This observation is depicted in Fig. 4, which illustrates the changes in packet size before and after transmission. From these results, we deduced that wireless networks, strip VLAN tags from frames, highlighting a potential challenge in maintaining TSN-specific properties such as PCP in wireless environments.

Therefore, it is crucial to convert the PCP values of TSN into appropriate 5G QoS metrics, shown in Table II, at the gateway to ensure the preservation of TSN traffic priorities throughout the 5G network. The packet delay budget (PDB) is the time a packet can spend within 5G system without being dropped and added to the Packet Error Rate (PER). Both PDB and PER are part of the QoS parameters in 5G.

*1) **Gateway Implementation**:* Within the TSN framework, PCP values ranging from 0 to 7 were successfully mapped to a format recognized by the 5G network, shown in Algorithm 1. By converting the PCP value to a DSCP value in the IPv4 header and removing the VLAN tag before the packet is sent to the 5G network, we enabled the packet to be processed by the 5G core network.

Algorithm 1 below is used to process and forward network packets from a UE. It defines a function handle_packet that checks if a packet contains a Dot1Q VLAN tag and is from a specific sender. It retrieves the PCP value from the VLAN

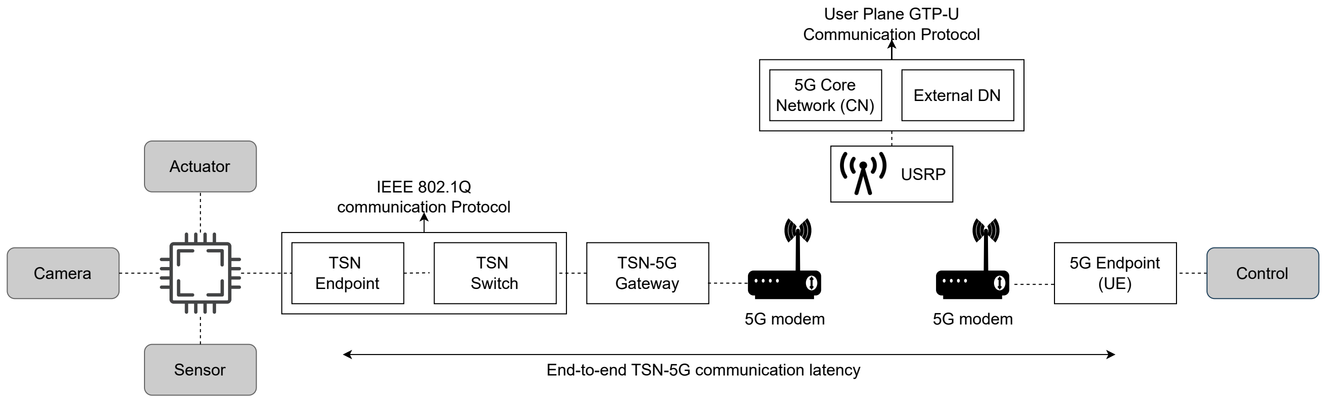

Fig. 3. The prototype design of the end-to-end communication in TSN-5G network.

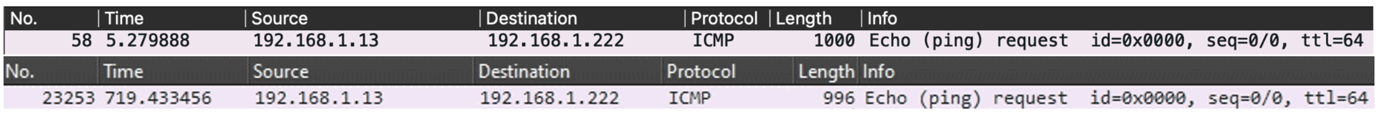

Fig. 4. A screenshot showing Wireshark dropping TSN VLAN tag in wireless domains.

TABLE II
SERVICE CLASS MAPPING [29].

5QI	Resource Type	Priority	PDB	PER	DSCP	Service (CoS)
1	GBR	20	100 ms	10^{-2}	EF(44)	Voice
66	GBR	20	100 ms	10^{-2}	EF(44)	Voice
2	GBR	40	150 ms	10^{-3}	AF41(34)	C Video
67	GBR	15	100 ms	10^{-3}	AF43(38)	C Video
3	GBR	30	50 ms	10^{-3}	CS4(32)	Gaming
75	GBR	20	50 ms	10^{-2}	CS4(32)	Gaming
79	Non-GBR	65	50 ms	10^{-2}	CS4(32)	Gaming
5	Non-GBR	10	100 ms	10^{-6}	CS5(40)	Signaling
4	GBR	50	300 ms	10^{-6}	AF32(28)	NC Video
6	Non-GBR	60	300 ms	10^{-6}	AF31(26)	NC Video
70	Non-GBR	55	200 ms	10^{-6}	AF33(30)	NC Video
80	Non-GBR	68	10 ms	10^{-6}	CS3(24)	BR Video
7	Non-GBR	70	100 ms	10^{-3}	AF23(22)	Low Latency
8-9	Non-GBR	90	300 ms	10^{-6}	CS0	Standard Best Effort
82	DC-GBR	19	10 ms	10^{-4}	AF31(27)	Mission Critical
83	DC-GBR	22	10 ms	10^{-4}	AF32(29)	Stream Video / V2X
84	DC-GBR	24	30 ms	10^{-5}	AF33(31)	Intelligent Transport Systems

tag, converts it to DSCP using a predefined mapping, creates a new packet without the VLAN tag, sets the destination MAC to the gateway MAC address, sets the IP type of service (ToS) field to the new DSCP value, and forwards the packet to the egress port of the gateway.

Similarly, Algorithm 2 is used to process and forward network packets from the 5G UEs to TSN endpoints. It defines a function handle_packet that checks if a packet is a returning packet. If so, it retrieves the DSCP value from the IP ToS field, converts DSCP to PCP using a predefined mapping, creates a new packet with a VLAN tag, sets the destination MAC to the TSN endpoint MAC address, and forwards the packet to the TSN switch.

Algorithm 1 Gateway Implementation: TSN to 5G

begin
- define handle_packet function with parameter packet
- **if** packet contains 802.1Q VLAN tag **then**
  - retrieve PCP value from VLAN tag
  - convert PCP to DSCP using a predefined mapping
  - create a new packet without VLAN tag
  - set destination MAC to 5G UE MAC address
  - set IP ToS field to new DSCP value
  - forward the new packet towards the gateway
- **end if**

end

Algorithm 2 Gateway Implementation: 5G to TSN

begin
- define handle_packet function with parameter packet
- **if** packet is a returning package **then**
  - retrieve DSCP value from IP ToS field
  - convert DSCP to PCP using a predefined mapping
  - create a new packet with VLAN tag
  - set destination MAC to TSN endpoint MAC address
  - forward the new packet towards the gateway
- **end if**

end

V. Experimental Evaluation

In this section, we delve into the evaluation of TSN-5G networks through hands-on experiments conducted on a realistic standalone private 5G network for indoor scenarios. Our objective is to assess the performance, reliability, and overall effectiveness of the TSN-5G networks in real-world scenarios. To achieve this, we have designed a series of practical tests for the TSN and 5G equipment to measure latency and packet error rates.

A. Comparative Evaluation of 5G SA and Wi-Fi

We start the overall evaluation by evaluating the performance of the standalone private 5G technology. We perform a comparison study of our private 5G network with other well-known wireless technologies such as Wi-Fi, and its predecessor 4G LTE. Moreover, we conduct a comparative evaluation of the private standalone (SA) and public non-standalone (NSA) 5G networks. To compare 5G SA with Wi-Fi we conducted a Wi-Fi latency test. In this experiment, we measured the latency between two Linux computers using Wi-Fi in a controlled environment. This revealed large and inconsistent variations, with a median latency of over 25 ms, with extreme values reaching up to 250 ms and a minimum value of approximately 8 ms. The test was conducted in the same room as the 5G SA equipment, to keep similar environmental conditions, and the results are depicted in Fig. 5, where both tests utilized Algorithm 3 with 64-bit ICMP packets.

Algorithm 3 is used to measure the end-to-end latency between two or more units by sending 100 ICMP packets with predefined sizes and a one-second latency to the end unit's IP address. The variable input parameters are packet size (number of bytes) and receiver IP address.

Algorithm 3 ICMP Ping Execution

begin
1: input IP address as ip
2: input packet size as size
3: initialize latency_results as an empty list
4: **for** each count from 1 to 100 **do**
5: construct command with "ping", "-c", "1", "-s", size, ip
6: execute command and capture output
7: append output to latency_results
8: **end for**
end

Unlike Wi-Fi, 5G SA offers more reliable and consistent connectivity with significantly lower latency, shown in Fig. 5. This makes 5G SA a preferable choice for industrial applications and other scenarios that demand stringent timing and reliability, as demonstrated by the evaluation results.

B. Comparative Evaluation of 5G SA, 5G NSA and LTE

Similarly, we measure the performance of the LTE, and public 5G NSA, which relies on LTE network infrastructure, and compare them with our private 5G SA network sending ICMP packages towards the public server by Google (8.8.8.8) to identify any differences. Again, the 5G SA deployment reveals lower-latencies with a median of 12 ms and better consistency than both LTE and 5G NSA, as shown in Fig. 6.

Fig. 5. Comparison of Wi-Fi and 5G SA RTT latencies.

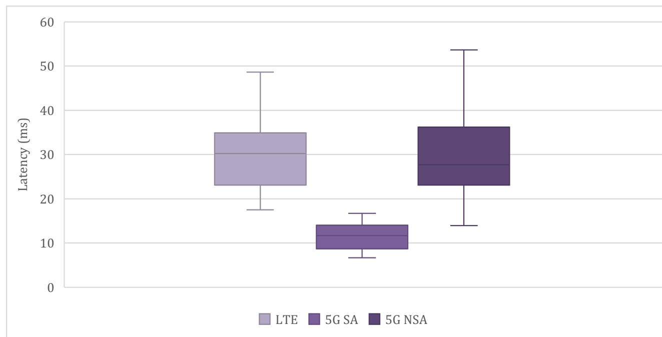

Fig. 6. Comparison of LTE, 5G NSA and 5G SA RTT latencies.

Please note that we utilized the same outdoor environment for each experiment to ensure a consistent comparison of performance across different wireless technologies.

C. End-to-End TSN-5G Environment

In this experiment, we enhanced the capabilities of our existing private 5G setup by integrating a TSN environment with two TSN endpoints (running on Linux) and a TSN Switch. One of the TSN endpoints connects to the private 5G network via the 5G modem and incorporates the TSN-5G gateway implementation to facilitate the proper traffic forwarding in both environments. By implementing this integrated setup, we aim to evaluate the effectiveness of TSN and 5G integration, focusing on the QoS parameter translation in the gateway and the overall network performance. Our comprehensive measurement of end-to-end latency includes the following time measurements:

- TSN transmission time - the time it takes for the data to be transmitted from the TSN endpoint to the TSN-5G gateway via the TSN switch.
- TSN-5G gateway processing time - the execution time of Algorithm 1 and Algorithm 2 to map the specific QoS parameters.
- 5G radio transmission time - the time required to transmit data over the air from a UE to the 5G core network.

- Processing time of the 5G core network - the time it takes for the 5G core network to process various functions and tasks necessary to establish, maintain, and terminate communication sessions within the 5G network.

TSN is deterministic therefore the transmission time for data over a TSN network is both predictable and consistent. It depends on the packet sizes, transmission speed, and the propagation latency of the Ethernet cable in use. In addition, the processing time of the TSN-5G gateway depends on the computing power of the gateway. In our experiments, the average RTT for the TSN-5G gateway is 0.0342 ms.

Moreover, the radio transmission time over private 5G network remains steady without significant fluctuations for packets below 128 bytes. However, when packet sizes exceed 256 bytes, the latency begins to show variability, depicted in Fig. 7. This suggests that our private 5G network handles smaller packets more efficiently, maintaining a consistent transmission latency. As packet sizes increase, the network may encounter bottlenecks or resource allocation challenges that affect its ability to maintain a steady latency, highlighting the importance of optimizing network configurations, resource management, and scheduling to prioritize data packets and ensure consistent reliability.

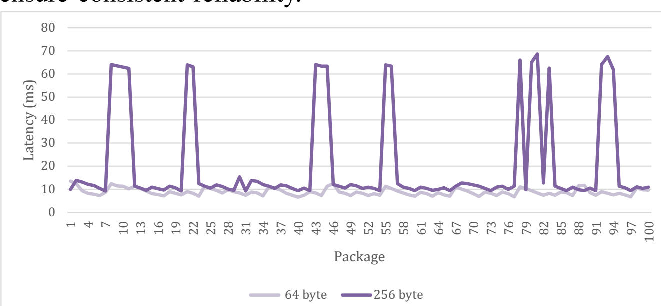

Fig. 7. 5G Radio Transmission RTT for different packet sizes.

Additionally, we measure the processing time of the 5G core network from the moment it receives a signal from the radio to when it processes the packet and sends a response. The results, depicted in Table III show a steady average response time of the 5G core network at 0.1 ms. The average measurements of the aforementioned components that contribute to the overall E2E TSN-5G latency are shown in Table III. Please note that the presented values are the round trip times (RTT) taken for each component of the E2E latency.

Finally, the E2E TSN-5G network when transmitting a packet size of 64 bytes resulted in an average latency of 9.97316 ms, as illustrated in Fig. 8. When packet sizes increase to 256 bytes the average E2E latency increase to 21.67111 ms

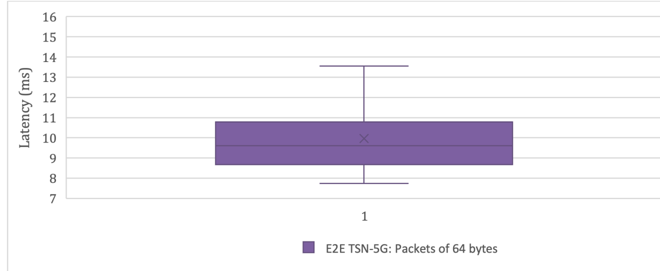

Fig. 8. E2E TSN-5G Latency when transmitting 64 bytes of data.

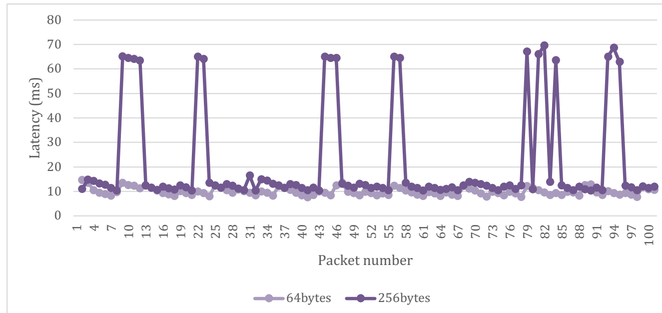

Fig. 9. E2E TSN-5G Latency for various bytes of data.

with reoccurring spikes in latency of around 64 ms resulting in a very high level of jitter, shown in Fig. 9. The main contributor to the reoccurring spikes is the bandwidth restriction and the way how the scheduler is allocating the radio resources in the 5G gNB implementation.

D. Observations

Our investigation into the QoS capabilities within the OAI platform reveals significant findings. The default UE QoS flow session for GTP-U in OAI is designated as the non-GBR type, intended for non-privileged users engaged in best-effort data traffic. This outcome necessitates the initiation of a Packet Data Unit (PDU) Session Modification request to the Access Management Function (AMF) by the UE to effectively apply the new QoS parameters for the high-priority data traffic. Notably, our analysis indicates that in the current version of OAI software (2.0.1), the functionality for automatic QoS mapping has not yet been implemented. Consequently, it is required to manually configure the QFI for specific UE priority data traffic within the MySQL database that maintains the priority levels of the PDU sessions. Our results underscore the limitations of the OAI platform, particularly in enhancing its QoS functionalities to effectively manage and prioritize network traffic in a real-world 5G environment.

TABLE III
END-TO-END LATENCY COMPONENTS IN A TSN-5G ENVIRONMENT.

Packet Size	TSN Transmission Time (ms)	Gateway Processing Time (ms)	5G Radio Transmission Time (ms)	5G Core Network Processing Time (ms)	E2E TSN-5G Latency (Avg) (ms)	Min E2E Latency (ms)	Max E2E Latency (ms)
64 bytes	1.07006	0.0342	8.8689	0.1	9.97316	6.57	13.6
128 bytes	1.09143	0.0342	8.7787	0.1	9.90433	6.46	12.8
256 bytes	1.07841	0.0342	20.4585	0.1	21.67111	9.24	68.6

VI. Conclusions

In this paper, we investigated the potential benefits and challenges associated with integrating TSN and 5G networks in industrial communication settings. Our findings indicate that while integrating Firecell 5G solutions with TSN networks holds significant promise, the current capabilities of Firecell 5G setup do not fully meet TSN's stringent latency and bandwidth requirements with minimal jitter. Key challenges arise within the 5G radio transmission, particularly with latency variations as packet sizes increase. To fully harness the potential of private 5G networks in industrial and real-time applications, implementing robust QoS mechanisms within the 5G network is essential. When comparing our results between Wi-Fi, LTE, and 5G, 5G demonstrates stability and promise in terms of lower jitter and latency. However, the current limitation lies in the inability to implement QoS mapping with OAI technology. Addressing this limitation is crucial for achieving reliable TSN-5G integration. While this study provides valuable insights, several challenges and limitations remain. Detailed exploration of these issues is necessary to fully realize the potential of TSN-5G integration. In our future work, we plan to enhance the interoperability and performance of TSN and 5G technologies to meet the stringent requirements of networked embedded system applications applications, by implementing the QoS mechanism and a proper scheduling approach of 5G radio resources.

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