Journal of Systems Architecture 168 (2025) 103531

Contents lists available at ScienceDirect

Journal of Systems Architecture

journal homepage: www.elsevier.com/locate/sysarc

Bridging TSN and 5G networks: Prototype design and evaluation for real-time embedded systems

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ARTICLE INFO

Keywords:
Networked embedded systems
Time-sensitive networking
TSN
5G
Heterogeneous real-time networks
Time synchronization

ABSTRACT

Integrating Time-Sensitive Networking (TSN) with 5G cellular networks facilitates high-bandwidth, low-latency end-to-end communication in networked embedded systems. An integrated TSN-5G network 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. This paper aims to facilitate the end-to-end (E2E) communication over the integrated TSN-5G networks, by addressing two of the main challenges: (1) design and implementation of an effective TSN-5G gateway that not only ensures an effective forwarding mechanism to translate the traffic among both networks, but also maps the TSN traffic to the corresponding 5G quality-of-service profiles to ensure the timing requirements of highly critical traffic, and (2) establishment of clock synchronization across all network components to support the E2E communication in TSN-5G networks. The paper outlines the design and implementation of a robust TSN-5G gateway that bridges TSN and 5G network architectures, ensuring seamless interoperability between them. We utilize a standalone private 5G network within a controlled lab environment to establish the E2E communication for the TSN-5G network, with a particular emphasizes on analyzing latencies and jitter to provide valuable insights for industrial implementation. Moreover, the gateway facilitates a time synchronization approach, to enable time coordination between network components that supports E2E communication on TSN-5G networks considering the hardware limitation. Our findings indicate that achieving latencies below 20 ms is feasible in an integrated TSN-5G network using the proposed configuration of a private 5G setup with a channel bandwidth of 40 MHz.

1. Introduction

The rapid evolution of Industry 4.0 is driving an increasing demand for networked embedded systems. This evolution necessitates more reliable network communication with low and predictable latency in many time-critical industrial applications such as autonomous construction vehicles, collaborating robots, customized manufacturing systems, and real-time monitoring of industrial connected machines, to mention a few [1,2]. These applications require stringent timing predictability and reliability across both wired communication (facilitating interactions within devices, machines, and vehicles) and wireless communication (which enables connectivity among devices, machines, vehicles, and their control center) [3,4]. As these applications grow in complexity, the integration of wired and wireless networks becomes essential for enhanced flexibility [5].

A leading solution for wired communication is Time-Sensitive Networking (TSN), a set of IEEE standards designed to enhance Ethernet with features such as high-bandwidth, low-latency, traffic shaping, deterministic and reliable communication [6,7]. Meanwhile, the fifth generation of cellular networks (5G) has emerged as a promising solution for wireless connectivity, delivering high-bandwidth, ultra-low latency, and enhanced reliability. Such features make 5G ideal for industrial applications as well as for the integration with the wired TSN communication [8]. Compared to its predecessor, 5G offers improvements in network speed, capacity, and responsiveness, with 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 [9]. 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 forward, the sixth generation of cellular networks (6G) aim to further revolutionize wireless communication with even faster speeds, lower latency, and advanced capabilities enabled by artificial intelligence (AI) and machine learning (ML) [10].

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https://doi.org/10.1016/j.sysarc.2025.103531
Received 14 February 2025; Received in revised form 22 June 2025; Accepted 25 July 2025
Available online 5 August 2025

The integration of TSN and 5G networks allows industries to harness the strengths of both wired and wireless technologies, enhancing efficiency, flexibility, and future-proof operations [11]. However, achieving seamless and reliable time-sensitive data transfer necessitates careful consideration of factors such as time synchronization, resource management, and ensuring deterministic communication within both TSN and 5G framework [4].

This paper extends the work presented in [12] to facilitate the end-to-end (E2E) communication over the integrated TSN-5G network, by addressing two additional challenges as follows.

1. Design and implementation of an effective TSN-5G gateway that not only ensures an effective forwarding mechanism to translate the traffic among both networks, but also maps the TSN traffic to the corresponding 5G Quality of Services (QoS) profiles to ensure the requirements of highly critical traffic.
2. Establishment of clock synchronization across all network components to support the E2E communication in TSN-5G networks.

We utilize a standalone private 5G network within a controlled lab environment to establish the E2E communication for the TSN-5G network, with a particular emphasizes on analyzing latencies and jitter to provide valuable insights for industrial implementation.

The TSN-5G gateway serves as a bridge between TSN and 5G networks, incorporating two main functionalities. First, it translates packets from the TSN communication protocol format into IP packets to ensure seamless interoperability among the networks. Secondly, it handles the mapping of TSN traffic into the corresponding 5G QoS profiles to ensure the timing requirements of highly critical traffic when coexisting with less-critical traffic. By effectively managing the mapping of QoS parameters between the two networks, the gateway enables seamless integration for time-sensitive applications across the TSN-5G architecture. In addition, the gateway facilitates a time synchronization approach, to enable time coordination between network components that supports E2E communication on TSN-5G networks considering the hardware limitations. We monitor the network and analyze network traffic on a realistic setup to contribute to a better understanding of the E2E communication in the integrated TSN-5G networks. The key contributions of the work presented in this paper can be summarized as follows:

- We design and implement a TSN-5G gateway that not only supports traffic forwarding between TSN and 5G, but also maps TSN traffic with appropriate 5G QoS profiles to ensure the stringent latency requirements of highly critical traffic when coexisting with less-critical traffic.
- We facilitate a time synchronization approach, to enable time coordination between network components to support E2E communication on TSN-5G networks considering the hardware limitations.
- We demonstrate the practical feasibility of our solutions on a realistic industrial use case to provide valuable insights into the system's performance under realistic operating conditions.

The rest of the paper is structured as follows: Section 2 covers the background information, Section 3 reviews related work, Section 4 introduces the prototype of the end-to-end TSN-5G communication, Section 5 delves into the experimental evaluation, and Section 6 presents the conclusions and future research directions.

2. Background

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

Table 1
TSN traffic classes based on PCP value.

PCP value	Traffic class
000	Background (BK)
001	Best Effort (BE)
010	Excellent Effort (EE)
011	Critical Application (CA)
100	AVB, B
101	AVB, A
110	Internet control (Routing)
111	Network Control/ Scheduled Traffic (ST)

2.1. *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 [7]. 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 [6,7].

TSN prioritizes the transmission of time-sensitive data over less-critical traffic by using the concept of VLAN tagging, as shown in Fig. 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. The PCP value defines eight FIFO (first-in first-out) queues for a port in the TSN switch with priorities of 0–7, from low to high [13]. Each PCP value defines a class of service, shown in Table 1 for network control ensuring prioritized network capacity to critical applications [14].

Different types of traffic can be assigned to TSN queues based on the system requirements. Scheduled Traffic (ST) is the highest priority TSN class and usually reserved for highly critical traffic with low-latency demands. The IEEE TSN standards provide the real-time guarantees of ST traffic by utilizing the Time Aware Shaper (TAS) mechanism, which ensures strict temporal isolation controlled by the Gate Control List (GCL) [15]. Audio-Video Bridging (AVB) class is usually utilized for real-time applications with a high-bandwidth utilization but with no strict deadlines, such as the video streaming demonstrated later in this work. TSN standards introduce Credit Based Shaper (CBS) mechanism to support the transmission of AVB traffic. CBS manages traffic based on credit accumulation and depletion rules, such that the queue consumes credit when it sends a message, and replenishes the credit when it has a pending message. The Best Effort (BE) traffic class consists of non-critical data with no real-time guarantees. An example of traffic forwarding in a TSN egress port is shown in Fig. 2.

2.2. *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 authorized devices, therefore minimizing 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

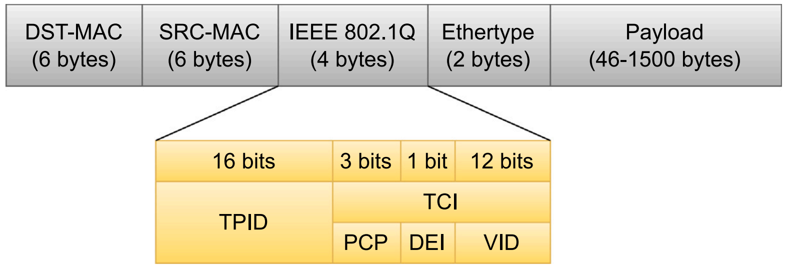


Fig. 1. TSN frame format.

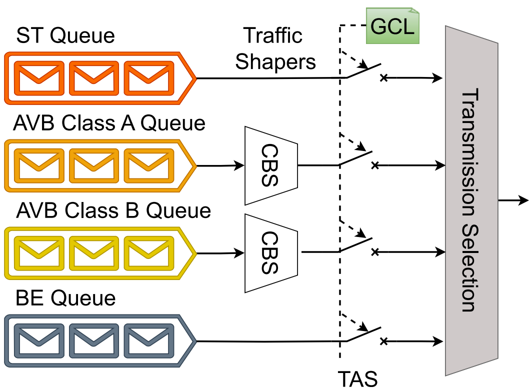


Fig. 2. An example of traffic forwarding in a TSN egress port.

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].

The deployment of the private 5G network, including the 5G core network, is depicted in Fig. 3. 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 User Equipments (UEs) and the external networks. The 5G core network is responsible for managing both the control plane and user plane functions.

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

2.2.1. Differentiated services in private 5G

All connected devices to a 5G private network share the radio resources with heterogeneous QoS requirements. 5G utilizes the QoS mechanism to ensure efficient prioritization across all connected devices. The base station (gNB) carries all the information regarding the QoS requirements from the devices, and allocates the necessary radio resources prioritizing the transmission of high-critical data [19].

5G establishes a Packet Data Unit (PDU) session to provide the end-to-end connectivity from the devices towards a Data Network such as Internet, or any private corporate network. The transmission of data in 5G can be classified as the Non-Guaranteed Bit Rate (Non-GBR), Guaranteed Bit Rate (GBR) and Delay Critical Guaranteed Bit Rate (DC-GBR) [20]. The Non-GBR QoS flows are best-effort flows that have no guarantees, this means that the traffic will not be given any bandwidth or latency guarantees within the network. The 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 [21,22].

In addition, GTP-U protocol is utilized to enable the transmission of user data across the 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 [23]. To ensure end-to-end QoS continuity, integrating 5G with TSN networks requires a mapping of the DSCP of a 5G packet to the TSN PCP values, and vice versa, as will be discussed in Section 4.

2.3. 5G as a logical TSN bridge

The integrated TSN-5G architecture supported by 3GPP Release 18 [20] is presented in Fig. 4. In this architecture, the 5G system is represented as a logical TSN bridge and seen as a blackbox from the TSN system. To secure the interoperation between both systems, there is a need for the TSN translators in both user plane and control plane. There are three translators in TSN-5G architecture: (1) Device-side TSN Translator (DS-TT), (2) Network-side TSN Translator (NW-TT), and (3) TSN Application Function (TSN AF). The DS-TT and NW-TT handle the physical and protocol translation on the device and network sides. They perform functions such as protocol translation, time synchronization, per-stream filtering and policing, traffic mapping based on the control information provided in TSN AF and Policy Control Function (PCF). Whether DS-TT and UE are combined or separate is up to the implementation [20]. The TSN AF is part of the 5G core network and provides the control plane translator functionality for managing and coordinating the integration between the 5G QoS framework and the TSN domain. It communicates with the PCF to ensure that the TSN traffic requirements are reflected in the network policies, 5G QoS profiles, and resource allocations.

The following concepts are also part of the core architecture for a TSN-5G design presented also in Fig. 4; a brief overview is given to better understand the function of the individual components.

- Control Plane (CP) – Definition of a plane that handles connection management, QoS policies, authentication, and other management functions, separated from the User Plane (UP).
- Access and Mobility Management Function (AMF) – Receives information related to 5G sessions within the network and manages handovers between gNB components.

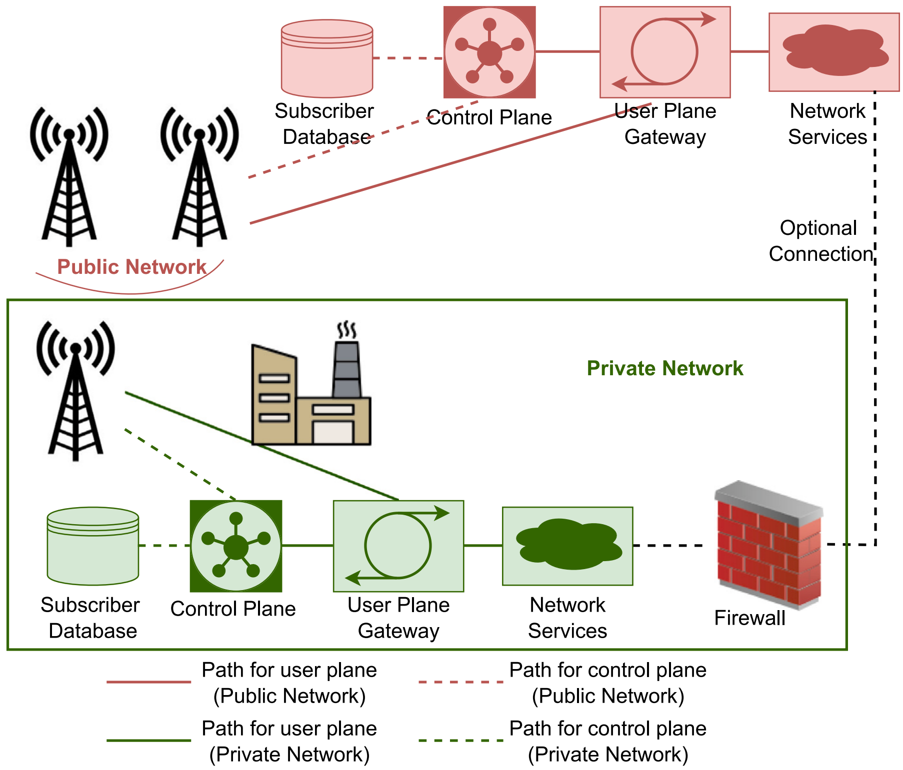


Fig. 3. The private 5G network deployment.

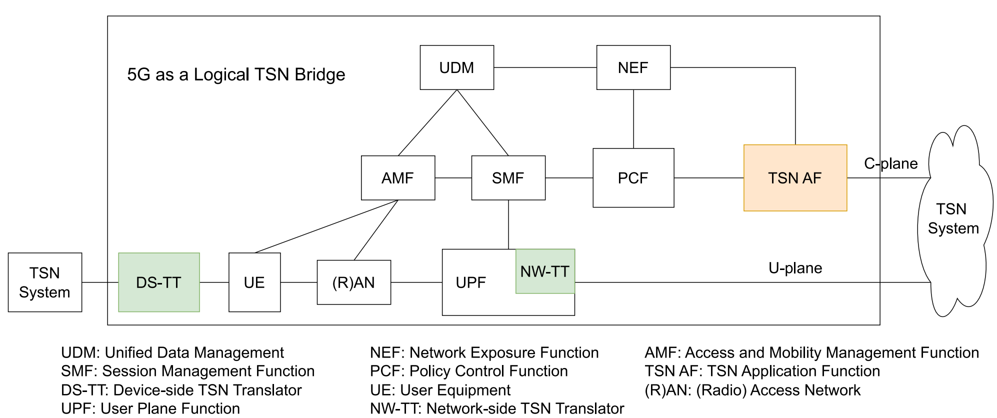


Fig. 4. The integrated TSN-5G architecture, where 5G appears as a logical TSN bridge.

- Unified Data Management (UDM) – Follows the design of the Home Subscriber Service (HSS) in 4G networks. It stores user data information regarding what components are connected to the network, customer data, and customer information.
- Session Management Function (SMF) – Creates a communication channel between the CP and the UP. It handles the UPF concerning session context by dealing with creating, updating, and deleting PDUs. It communicates with the TSN AF via the PCF, giving the MAC addresses of the TSN Translators per PDU session.
- Network Exposure Function (NEF) – Provides a secure connection between 5G and third-party applications. Communication with 5G services is done via the NEF.
- Policy Control Function (PCF) – Receives the QoS information from the TSN AF, and maps the TSN QoS parameters to a 5G QoS profile.
- User Plane (UP) – Definition of the plane which deals with data-traffic forwarding, separated from the CP.
- User Plane Function (UPF) – The communication scheme established between the gNB and the NW-TT.
- User Equipment (UE) – Components capable of communicating with the RAN.
- Radio Access Network (RAN) – A 5G capable device which acts as the access point for the wireless side of the logical TSN bridge, sometimes also known as next generation Node B (gNB). It communicates with one or many UEs.

3. Related works

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. There are several works that have targeted integration of TSN and 5G networks.

The works in [19,21] introduce QoS mapping algorithms designed for systematic mapping of QoS characteristics and seamless integration of traffic flows in integrated TSN-5G networks. Satka et al. [21] propose

Table 2
Comparison of the proposed work with related state-of-the-art approaches.

Paper	Protocol translation	QoS mapping	Time synchronization	Real-world implementation
Cai et al. [19]	✗	✓	✗	✗
Satka et al. [21]	✗	✓	✗	✗
Larrañaga et al. [25]	✗	✓	✗	✗
Satka et al. [26]	✓	✗	✗	✗
Agusti et al. [27]	✓	✗	✗	✓(partially)
Gundall et al. [28]	✗	✗	✓	✓(but 4G)
Striffler et al. [29]	✗	✗	✓	✗
SIES paper [12]	✓	✗	✗	✓
This paper	✓	✓	✓	✓

a 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 [24]. On the other hand, Cai et al. [19] propose a dynamic QoS mapping method based on the improved K-means clustering algorithm and the rough set theory. In this paper, we introduce a static mapping method and evaluate its performance on real equipment. We also use these evaluations as reference points when considering potential changes and exploring possible improvements.

Larrañaga et al. [25] explore the analysis of bridge delay within the 5G-TSN network. Their 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 evaluation phase focuses on the evaluation of an actual standalone 5G network, specifically using 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 performance characteristics of 5G network under standard conditions.

Satka et al. [26] present a translator design between TSN-5G communication protocols and a proof-of-concept implementation in the 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. Similarly, the authors in [27] showcase the need for an effective translation mechanism, since TSN is a layer 2 technology, and the 802.1 Q tag is lost when packets enter the 5G network. Moreover, the authors demonstrate a 5G-TSN testbed where the 5G network is built with emulators, therefore missing a real implementation of the radio-frequency equipment, as the utilized emulators do not emulate the physical layer.

In addition, the authors in [28,29] explore the time synchronization mechanisms of 5G with the TSN standards defined by IEEE 802.1AS, to ensure that the stringent timing requirements of applications, such as those involving cooperative work of mobile robots, can be met effectively. Gundall et al. [28] presents a concept for the integration of TSN time synchronization (IEEE 802.1AS) conform with 5G to fulfill the requirements of these use cases, however, due to missing hardware, the authors evaluate their mechanism on an alternative solution compatible with 4G. Striffler et al. [29] investigate how synchronization and synchronization errors affect the achievable end-to-end time synchronization accuracy in integrated 5G and TSN networks, where 5G appears as a logical TSN bridge. The 5G network does not need to synchronize itself to the TSN time. Instead, timestamping is utilized to adjust the Precision Time Protocol (PTP) messages by the time a TSN packet spent within the 5G network. The findings show that even small frequency offsets between ingress and egress of the 5GS can result in significant synchronization errors.

Table 2 presents a detailed comparison of our work with relevant state-of-the-art approaches described above.

To summarize, our work is centered on establishing real-world end-to-end communication within the TSN-5G network with the help of a standalone private 5G network. A crucial aspect involves configuring a gateway that acts as a bridge between these two networks, translating data traffic and configuring QoS profiles to meet stringent time and reliability requirements of time-sensitive networks. Moreover, we facilitate a time synchronization approach to enable time coordination among all the network components, and demonstrate the practical feasibility of our solutions on a realistic industrial use case.

4. Prototype design of TSN-5G network

This section presents the prototype of the end-to-end TSN-5G system. The prototype integrates TSN capabilities with 5G network infrastructure. The prototype will be used to evaluate E2E latency and reliability in scenarios requiring low-latency communication, e.g, collision avoidance systems in autonomous vehicles.

4.1. Prototype design

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

4.1.1. TSN network

The TSN network includes various TSN endpoints, such as cameras or sensor nodes that send TSN traffic. These endpoints are connected to one or more TSN switches that manage traffic forwarding and prioritization using the IEEE 802.1Q protocol [15].

4.1.2. 5G network

A private 5G network is a dedicated network tailored specifically for the unique requirements of an organization. It consists of several 5G endpoints or UEs that are connected to the private 5G network via the 5G modems. The Radio Access Network (RAN) handles the wireless communication between the UEs and the core network. A Universal Software Radio Peripheral (USRP) is used to facilitate the development and implementation of the 5G RAN using software. Furthermore, data transmission and routing over the 5G core network utilize the GTP_U protocol, which employs a tunneling mechanism to encapsulate the user data traffic over User Datagram Protocol (UDP) [30].

4.1.3. TSN-5G Gateway

Priority fields, such as PCP in the TSN frame and DSCP in the IP frame, are defined at different layers of the OSI model, natively making them incompatible without translation. Since the TSN network operates on Layer 2 of the OSI model, while 5G operates on Layer 3, there is a gap that prevents direct communication. To ensure compatibility within the TSN-5G network, a gateway is needed for translating communication protocols and aligning priority markers. This guarantees seamless interoperability between the networks while maintaining QoS, ensuring low-latency communication and reliable data transmission.

Our aim is to develop a robust TSN-5G Gateway capable of translating traffic prioritization markers between both networks. The TSN-5G

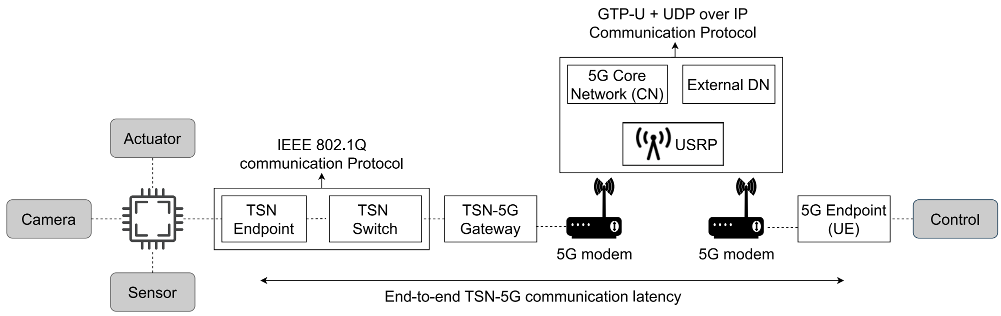


Fig. 5. The prototype design of the end-to-end communication in TSN-5G network.

gateway, depicted in Fig. 5, acts as an interface to support the protocol translation between TSN and 5G networks. The gateway includes mapping of TSN traffic with different 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 traffic with different 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 4.2.1. The time required by these algorithms, ensuring that the TSN traffic requirements are accurately mapped to the 5G QoS profiles, is referred to as the gateway processing latency.

4.1.4. End-to-end TSN-5G communication

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 (RTT) of Internet Control Message Protocol (ICMP) packets. The RTT for an ICMP packet is the time it takes for the packet to return to the sender after getting a response from the receiver.

To measure the response time of our integrated TSN-5G system, we use Wireshark along with sending ICMP packets of varying sizes. The packet sizes were selected to reflect typical traffic patterns observed in real-world network environments. For instance, smaller packets (64 bytes) represent control and signaling messages, while larger packets correspond to standard Maximum Transmission Unit (MTU) commonly used in data payloads such as file transfers and streaming.

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. 6, 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. However, the removal of VLAN tags is not a well-documented behavior, as the handling of TSN packet transmission by different wireless technologies remains largely unknown.

Therefore, it is crucial to convert the PCP values of TSN into appropriate 5G QoS parameters, as shown in Table 3.[1] This conversion at the gateway is imperative to ensure the preservation of TSN traffic priorities throughout the 5G network. As an example, a QoS profile with the 5G QoS Identifier (5QI) value of 1 is treated with GBR resources under the priority value of 20 and a DSCP value of EF(44) is classified under the Voice service class. In addition, a 5QI profile of value 82 is treated with DC-GBR resources with a higher priority value of 19, a DSCP value of AF31(27), and is classified under the Mission Critical service class. 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.

4.2. Prototype implementation

In this section, we delve into the implementation of the TSN-5G gateway to facilitate the end-to-end communication in TSN-5G networks.

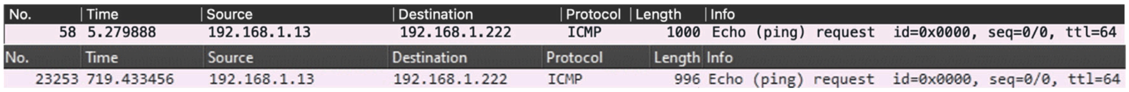
For the E2E TSN-5G setup, we utilize switches developed by SoC-e[2] to support the TSN communication from the TSN endpoints to the TSN-5G gateway. In addition, the TSN-5G gateway is a Linux-based machine which connects to the private 5G network via the 5G modem. The complete setup of the private 5G network is part of the Firecell Solutions.[3] The technology is built on the Open Air Interface (OAI) Software Alliance, an open-source project under the public license V1.1.[4]

4.2.1. 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 is used to process and forward network packets from a UE. It defines a function handle_packet that checks if a packet contains an IEEE 802.1Q standard VLAN tag and is from a specific sender. It retrieves the PCP value from the VLAN tag, converts it to DSCP using a predefined mapping, creates a new packet without the VLAN tag, sets

[1] H. Jerome, Diffserv to QCI Mapping - https://datatracker.ietf.org/doc/draft-henry-tsvwg-diffserv-to-qci/00/.
[2] MTSN Kit - https://soc-e.com/mtsn-kit-a-comprehensive-multiport-tsn-setup/.
[3] Firecell Solutions - https://firecell.io/.
[4] Open Air Interface Software Alliance - https://openairinterface.org/.



No.	Time	Source	Destination	Protocol	Length	Info
58	5.279888	192.168.1.13	192.168.1.222	ICMP	1000	Echo (ping) request id=0x0000, seq=0/0, ttl=64

No.	Time	Source	Destination	Protocol	Length	Info
23253	719.433456	192.168.1.13	192.168.1.222	ICMP	996	Echo (ping) request id=0x0000, seq=0/0, ttl=64

Fig. 6. A screenshot showing Wireshark dropping TSN VLAN tag in wireless domains.

Table 3
Service class mapping.

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

```
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 1: Gateway Implementation: TSN to 5G.

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, as presented in Fig. 7.

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, as also shown in Fig. 8.

```
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
```

Algorithm 2: Gateway Implementation: 5G to TSN.

We verified the success of the PCP to DSCP mapping by inspecting the packets in the TSN endpoint and 5G UE using Wireshark. The VLAN tagged packets contain a field, labeled Primary Rate Interface (PRI) in Wireshark, where we can read the PCP value when the packet was sent from the TSN endpoint to the Gateway, as shown in Fig. 9. By capturing the same packet in the 5G UE, we can read the DSCP value from the DS field in the IP header, as shown in Fig. 10. When the 5G UE/controller receives the packet, it is evident that the Gateway has successfully translated PCP value of 5 into DSCP value of 40 corresponding to the signaling service class in Table 3.

We further enhance the gateway to support the transmission of camera packets with additional supportive functionality. The complete implementation script of the TSN-5G gateway is freely accessible[5].

Mapping TSN packets to specific 5G QoS profiles. In addition to the translation of the protocol in the TSN-5G Gateway, achieving end-to-end communication on a TSN-5G network requires a predefined QoS mapping table used by the PCF in Fig. 4. This table assists the TSN AF in managing and coordinating the integration between the 5G QoS framework and the TSN domain. The predefined mapping table consists of a mapping that translates all TSN traffic requirements into appropriate 5G QoS profiles with QoS characteristics such as Packet Delay Budget (PDB), Packet Error Rate (PER), among others. To ensure an effective mapping approach to TSN packets with different priority values and QoS requirements, we utilize a similar mapping algorithm as the one presented in our previous work [21] with the limitation of only four different QoS profiles supported by our private 5G setup. However, this is not a general limitation as the QoS profiles are taken only as input for the mapping approach. The QoS profiles, with different QoS IDs (QID) or QFIs, supported in our private 5G network include:

1. Security Messages (QID 1) - packets must always be delivered, provided the total available bitrate is sufficient.
2. Regular Operation (QID 2) - packets must be delivered if the total available bitrate is sufficient and security messages can be sent without delays.
3. Real-time Video (QID 3) - packets take priority over lower-priority streams, but may be degraded if the available bitrate is insufficient.
4. Technical data transfer (QID 4) - packets can be delivered at lower bitrates and tolerate delays if bandwidth is limited. They will use any of the remaining capacity left after the higher-priority packets have been processed.

[5] https://github.com/nordpolen/DVA333-source-code

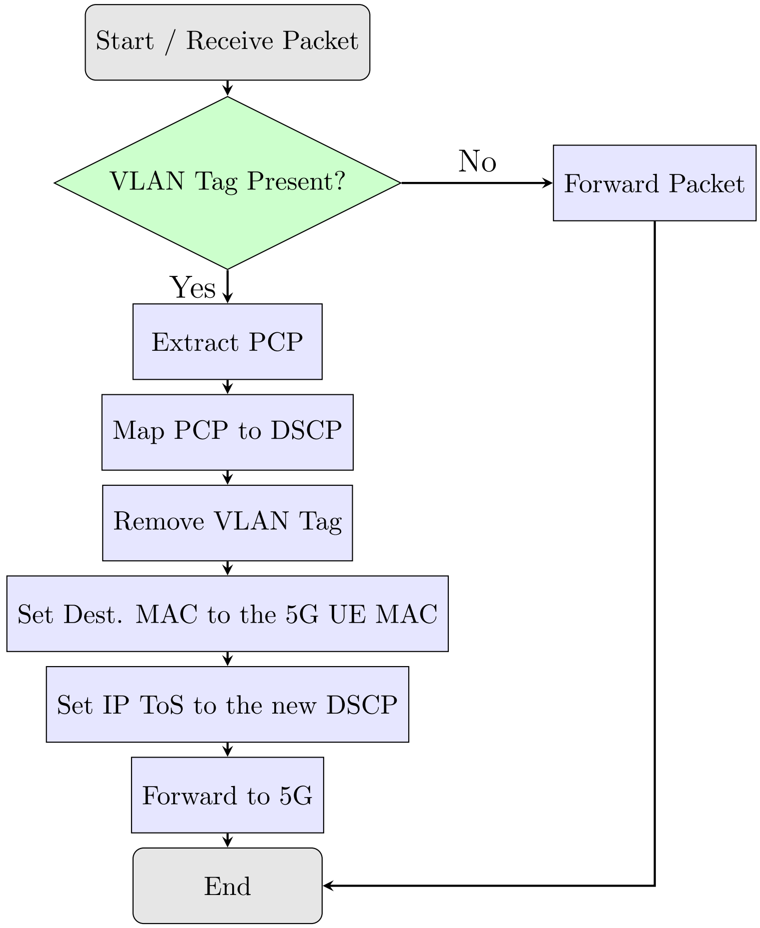


Fig. 7. Flowchart representation for the TSN to 5G Gateway packet handling.

We manually configure the QoS profile of each device connected to the private 5G network in our prototype, as our 5G hardware does not support the automatic configuration of QoS profiles. For every device connected to the private 5G network, we analyze the requirements in deadline, bandwidth, packet error rate, and jitter to configure the QoS profile from the list above.

Ensuring time synchronization between TSN and 5G domains. Time synchronization is a critical component in the integration of TSN and 5G networks. A time synchronization approach is needed to enable precise coordination of time across devices for real-time and deterministic communication. This synchronization ensures that time-critical applications, such as industrial automation, and autonomous vehicles, function reliably and efficiently. Although 3GPP classifies the Precision Time Protocol (PTP), defined by the IEEE 1588 standard [31], as the most promising solution in TSN-5G networks, an effective PTP implementation across both networks requires advanced synchronization techniques and specific hardware to ensure precise time alignment for time-sensitive applications. Therefore, due to hardware limitations and the aforementioned challenges, in our approach we utilize the Network Time Protocol (NTP), a widely used protocol for synchronizing clocks across devices in a network, to support the end-to-end communication over integrated TSN-5G networks. The implementation of PTP within a TSN-5G network remains an open area for future research.

5. Evaluation

In this section, we provide an evaluation of the proposed prototype of the end-to-end communication in TSN-5G networks through hands-on experiments conducted on an actual standalone private 5G network for indoor scenarios. Our objective is to evaluate the performance, reliability, and overall effectiveness of the TSN-5G networks in real-world scenarios. To achieve this, we have designed a series of experiments to measure end-to-end latency and packet error rates.

5.1. 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 indoor 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 experiment was performed in the same room as the 5G SA equipment, to maintain similar environmental conditions. The results are depicted in Fig. 11, illustrating both experiments conducted with 64-bit ICMP packets.

Unlike Wi-Fi, 5G SA offers more reliable and consistent connectivity with significantly lower latency, shown in Fig. 11. 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.

5.2. 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

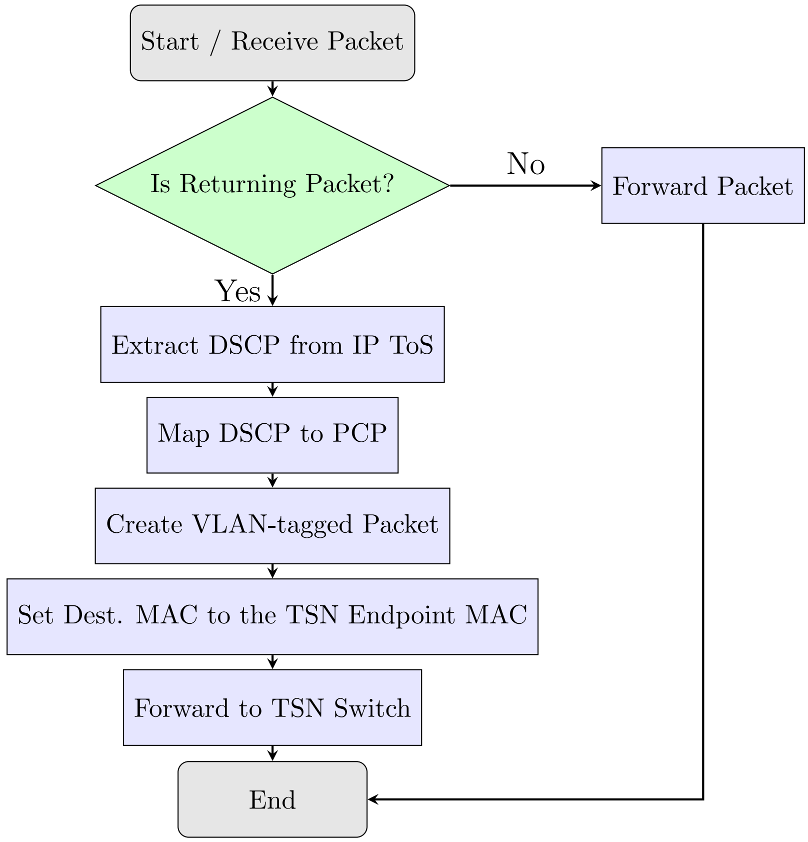


Fig. 8. Flowchart representation for the 5G to TSN Gateway packet handling.

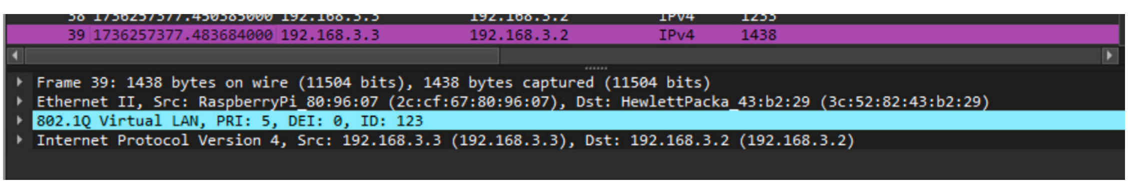


Fig. 9. Outgoing TSN packets from the TSN endpoint with PCP=5 in the VLAN tag.

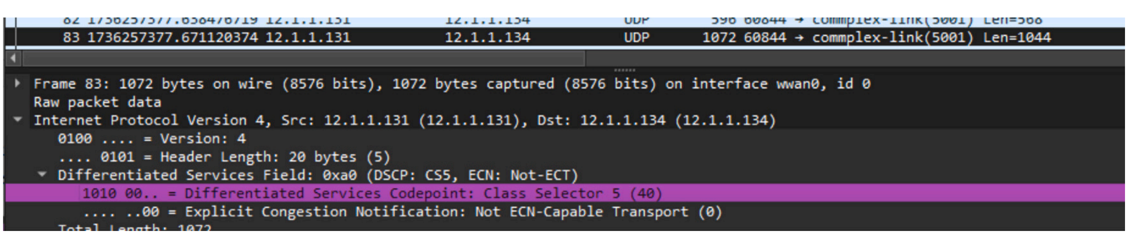


Fig. 10. Incoming IP packets on the 5G UE with DSCP=40 in the ToS field of the IP header.

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. 12.

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

5.3. 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 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.

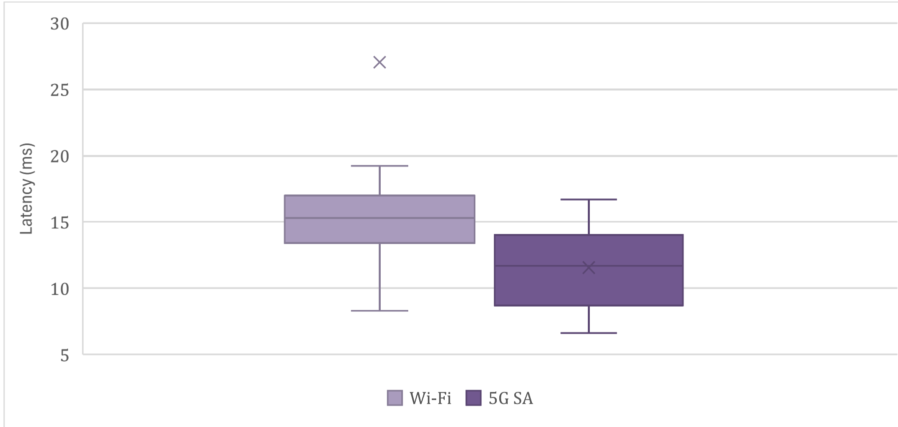


Fig. 11. Comparison of Wi-Fi and 5G SA RTT latencies.

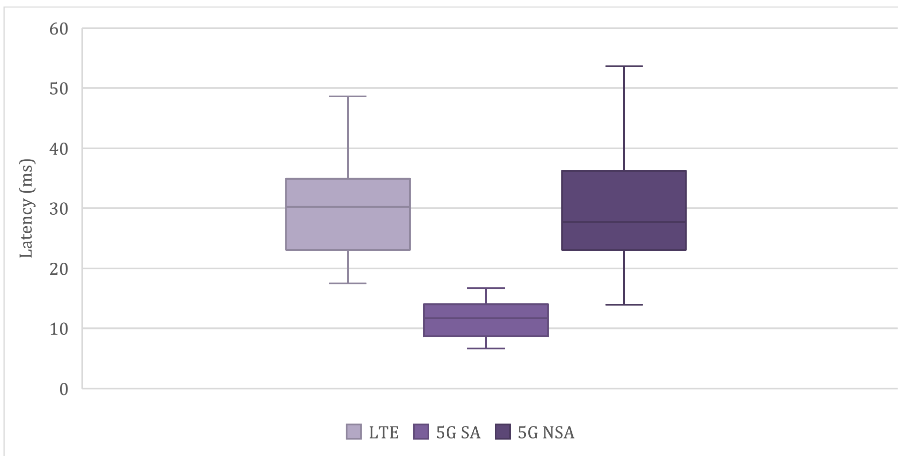


Fig. 12. Comparison of LTE, 5G NSA and 5G SA RTT latencies.

- 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 our experiments, we used a 1 Gbps Ethernet connection and cables of 3 meters with a propagation speed of roughly 2/3 of the speed of light.

In addition, the processing time of the TSN-5G gateway depends on the computing power of the gateway. In our experiments, the average processing time for the TSN-5G gateway is 0.0342 ms. 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. 13. 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.

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 4 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 4. Please note that the presented values are the 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 9.90433 ms, as illustrated in Fig. 14.

When packet sizes increase to 256 bytes the average E2E latency increase to 21.67111 ms with reoccurring spikes in latency of around 64 ms resulting in a very high level of jitter, shown in Fig. 15. 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.

5.4. 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/QID

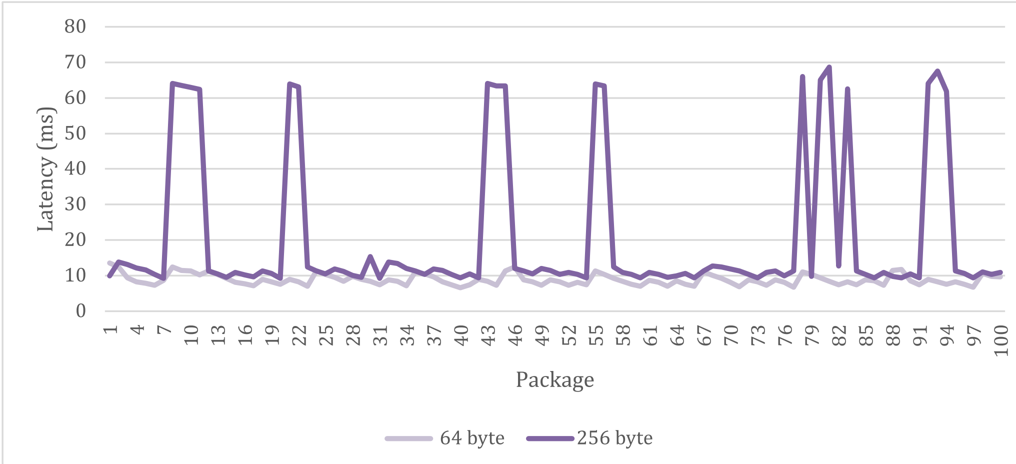


Fig. 13. 5G Radio Transmission RTT for different packet sizes.

Table 4
End-to-End latency components (in ms) in a TSN-5G environment.

Packet size (bytes)	TSN transmission time	Gateway processing time	5G radio transmission time	5G core network processing time	E2E latency (Avg)	Min E2E	Max E2E
64	0.00107006	0.0342	8.7787	0.1	9.90433	6.46	12.8
128	0.00218286	0.0342	8.8689	0.1	9.97316	6.57	13.6
256	0.00431364	0.0342	20.4585	0.1	21.67111	9.24	68.6

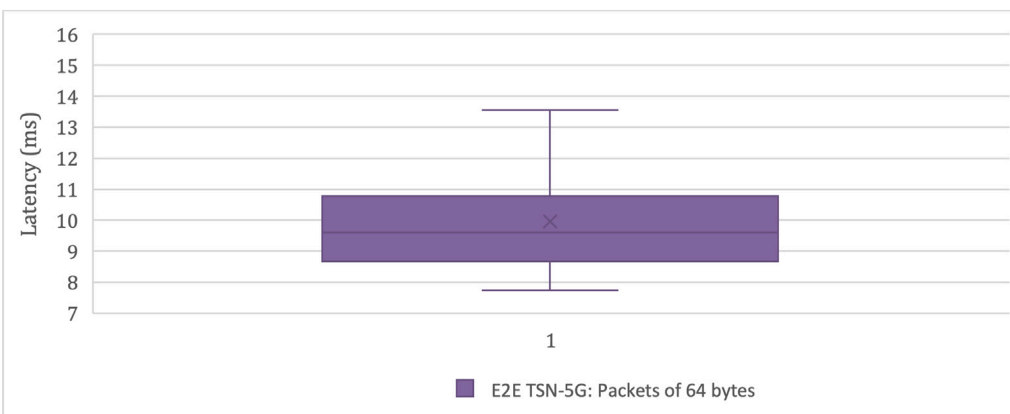


Fig. 14. E2E TSN-5G Latency when transmitting 64 bytes of data.

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.

5.5. Demonstration on an industrial use case

We also evaluate the end-to-end communication of the TSN-5G system on a use case from the vehicle industry as presented in Fig. 16. The use case comes from the deployment of a private 5G network in a construction site in the areas where cable connection is not feasible. To avoid any catastrophic event, the driver is remotely controlling one of the excavators at the construction site. The sensors connected to a TSN switch inside the vehicle transmit critical data to the remote controller via the private 5G network. On the other side, the driver standing on the controller performs the necessary operations, such as forward, backward, steering of the excavator's arm, via the remote controller connected to 5G. In addition, there are other devices connected to the 5G network, e.g., environmental sensors that monitor dust levels and air quality, smartphones or tablets to enable site managers, engineers, and workers to communicate, share data, and coordinate tasks.

However, we have a limited capacity for the transmission of data of different types of traffic sent from various devices over the network with timing and reliability constraints. Therefore, a structured prioritization of highly critical packets is essential, such as the packets sent to the remote controller from the camera and other sensors on the excavator, with bounded and low latency and higher reliability. Our gateway ensures an effective mapping of the QoS requirements of highly critical data transmitted from the TSN devices over the 5G network. In addition, the data transmitted from different smartphones and tablets is considered as non-critical data. Therefore, this data can be transmitted as the BE traffic or technical data transfer according to the QoS profiles available in our private 5G network.

We mimic the industrial environment to remotely control a robot car via the controller using the private 5G network following the end-to-end prototype presented in Fig. 17. A camera is attached to the robot car providing the necessary information to control the direction of the

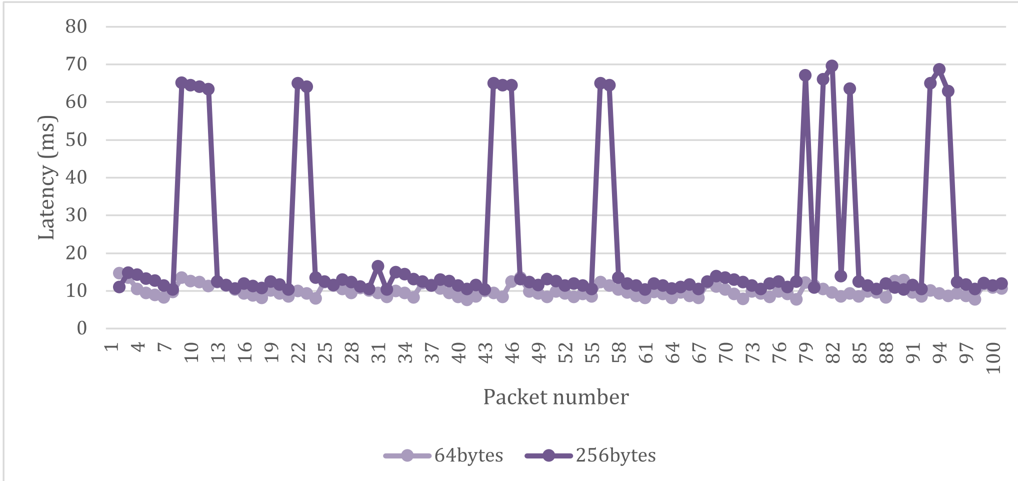


Fig. 15. E2E TSN-5G Latency for various bytes of data.

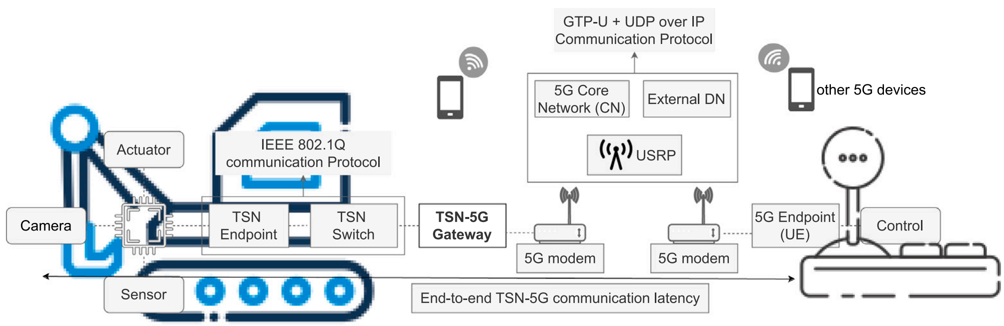


Fig. 16. Use case applicability of our gateway in an industrial environment.

car and avoiding any obstacles. On the other hand, a controller provides the necessary steering control information via the private 5G network.

The network architecture, as seen in Fig. 17, comprises four interconnected nodes:

- Node 1 (Server): A Raspberry Pi 5 controlling a remotely operated robot car, connected via Ethernet to the TSN switch.
- Node 2: A TSN switch providing deterministic Ethernet. We use the Multiport Time Sensitive Networking Switch IP (MTSN) provided by System-on-Chip Engineering (SoC-e) .
- Node 3 (TSN-5G Gateway): A Linux-based Laptop equipped with a Quectel modem, facilitating communication between the TSN domain and the Firecell private 5G network.
- Node 4 (Client): A second Linux-based Laptop, also equipped with a Quectel modem, serving as the endpoint for wireless 5G communication with a PS4 controller.

In Node 3, we run the proposed TSN-5G gateway presented earlier, to support the translation between the TSN and 5G network communication protocol. The Gateway works like a middleman, which receives the data from the Client or Server, and forwards the data to its endpoint. When the Client sends the data of coordinates, it sends the packets via the 5G network to the Gateway, which is in the TSN network. The Gateway receives the data using a raw socket, which listens for transmissions on the 5G interface. The DSCP value from the Client will be translated into a PCP value when the data arrives at the Gateway and later forwarded to the Server. The process is the same when data is sent from the Server to the Gateway, instead it translates the PCP value to DSCP so it can forward the data to the Client. Moreover, we configure the necessary QoS profiles in the 5G system core, assigning the highest priority QoS profile, QID 1, to the controller (Node 4), and a lower priority, QID 3, to Node 3. Socket programming helps us to communicate and guarantee delivery of the packets through our setup. Regarding the synchronization, we configure NTP to achieve smooth operation. The gateway was configured to reference a public server despite the potential variability introduced by benchmarking to external servers. Meanwhile, the remaining clients were referred to the gateway to retrieve time information.

5.5.1. Experimental setup

We conducted experiments indoors in a lab room, ensuring controlled conditions that minimize external interference. The wired link distance between components was kept under 3 m, which allows us to demonstrate the feasibility of TSN-5G integration in a small-scale environment. This serves as a proof-of-concept before extending the approach to larger setups. Regarding the wireless link, distances varied between 1 to 1.5 m, appropriate for our indoor lab conditions. The hardware and software specifications of each component from the implemented use case (refer to Fig. 17) are described in Table 5.

Private 5G Setup. The complete setup of the private 5G network is part of the Firecell Solutions.[6] The kit is less complex than commercial systems, rendering it well-suitable for testing and experimental applications in lab environments. The hardware consists of a Software Defined Radio (SDR) with two antennas (the USRP B210 module developed by the Ettus Research[7]), also referred to as a base station or Next Generation Node B (gNB), a PC server running the 5G Core, and the 5G User

[6] Firecell Solutions - https://firecell.io/.
[7] Ettus USRP B210 SDR Kit - https://www.ettus.com/all-products/ub210-kit/.

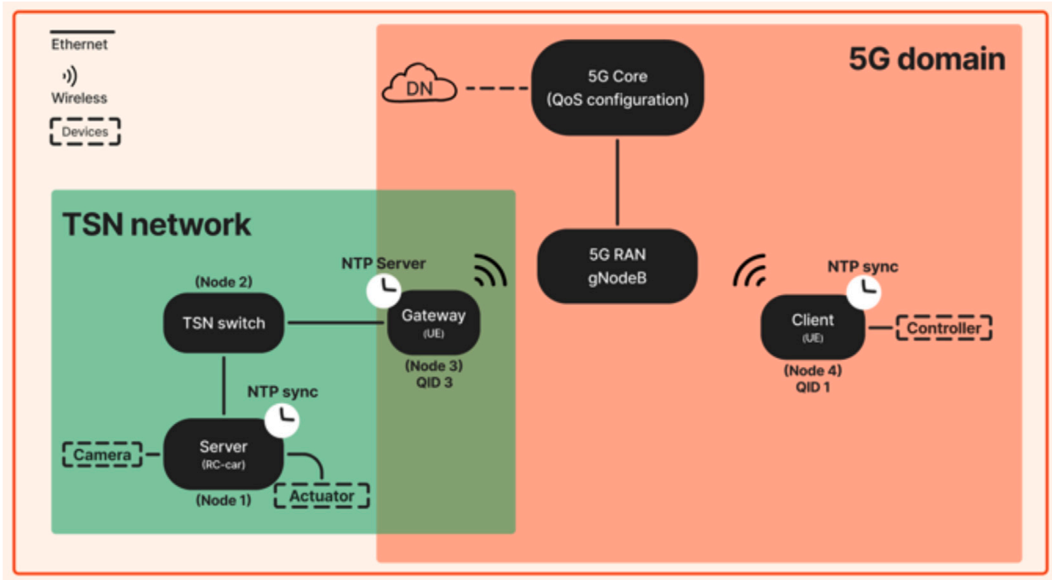


Fig. 17. Remotely controlling a vehicle using a TSN-5G network.

Table 5
Hardware and software specifications of each Node from Fig. 17.

Node 1 (Server) - Robot Car	
Model	Playknowlogy Arduino Robot Car Start Kit
Single-board computer	Raspberry Pi 5 Model B
Camera	Raspberry Pi Camera Module V2 plus adapter
Node 2 (TSN switch)	
Model	Multiport Time-Sensitive Networking (MTSN) from SoCe
TSN-Specific Features	Timing and Synchronization, TAS, CBS
Configuration	Web based GUI, 1 Gbps transmission speed
Node 3 (Gateway)	
Operating System	Ubuntu 20.04 LTS
CPU	Intel Core i3
RAM	8GB
5G modem	Quectel RM500Q-GL
Node 4 (Client) - Controller	
Operating System	Ubuntu 20.04 LTS
CPU	Intel Core i3
RAM	8GB
5G modem	Quectel RM500Q-GL

Equipment (UE) such as a smartphone with a pre-configured SIM card. The USRP is a tunable transceiver for prototyping and deploying communication systems. The Firecell equipment supports 5G Standalone (SA), and the USRP supports frequencies in the range of 70 MHz to 6 GHz with a maximum transmit power of 10dBM. The system achieves a maximum downlink (DL) throughput of 131Mbps and a maximum uplink (UL) throughput of 21Mbps, achieved in optimal environments and network configurations. The RAN software supports bandwidth up to 40 MHz. The software controlling the Firecell 5G hardware is based on open-source code and supports both the 5G Core Network and RAN, compliant with 3GPP Release 16 [24].

Fig. 18 presents a snapshot of our lab environment where we run the experiments to test the integration of TSN-5G networks.

5.5.2. Results

To evaluate the performance of our end-to-end TSN-5G network, we perform various experiments and analysis. First, we analyze the communication latency when transmitting the first 100 camera packets from the Server node (Node 1) to the Client node (Node 4) traversing both TSN and 5G networks, and also the latency when transmitting steering packets from the Client node (Node 4) to the Server node (Node 1).

Fig. 19 depicts the latency of both camera and steering packets when QoS is enabled. When analyzing the results, it is important to note that these packets were measured at run-time while performing the remote control of the robot car. From Fig. 19, it is evident that the STEER packets maintain a lower trend compared to the CAM packets, which shows a slight upward trend over time. This also reflects the average jitter shown in Table 6. Jitter values would still spike to a value of 30.40 ms even when the QoS were enabled, but this could be mitigated by employing an optimized scheduling algorithm for allocating 5G radio resources to TSN packets, which is beyond the scope of this study.

Moreover, we perform the same experiment when the QoS mechanism is disabled in the 5G system, and show the results in Fig. 20. As can be noticed, without the QoS mechanism the steering packets although smaller in size could experience similar delays on the transmission as the camera packets. In addition, Fig. 20 also indicates the initial buffering delays and processing overheads for the very first packets.

Furthermore, we analyze how the communication latency is affected when multiple devices are connected to the 5G network, to show the affect of the QoS mechanism in TSN-5G networks. In this experiment,

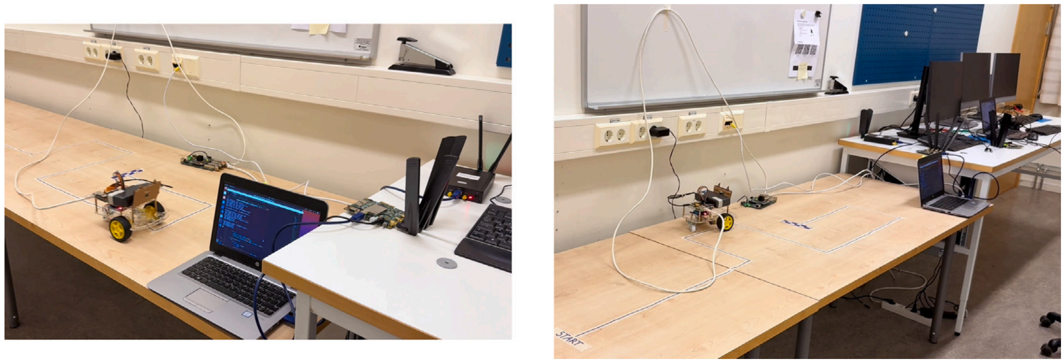


Fig. 18. A snapshot from the lab environment.

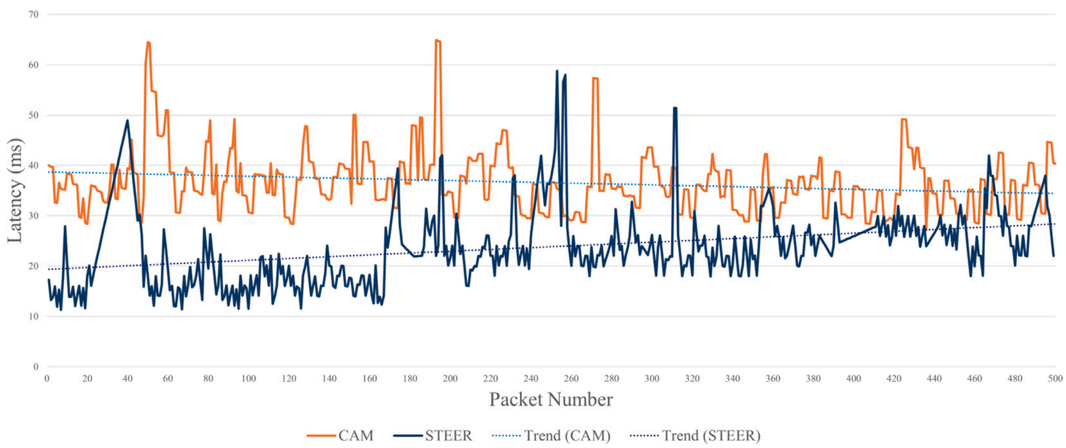


Fig. 19. The communication latency of camera and steering packets when QoS were enabled on the 5G system.

Table 6
Communication latency and jitter values (in ms) of camera and steering packets when QoS were enabled on the 5G system.

	Min. packet size (bytes)	Max. packet size (bytes)	E2E latency (avg)	E2E latency (min)	E2E latency (max)	E2E jitter (avg)	E2E jitter (min)	E2E jitter (max)
CAM	72	1438	36.553	27.1999	64.8901	2.3061	0.02	30.3797
STEER	48	63	23.843	11.3203	58.7601	3.3363	0.00977	30.4000

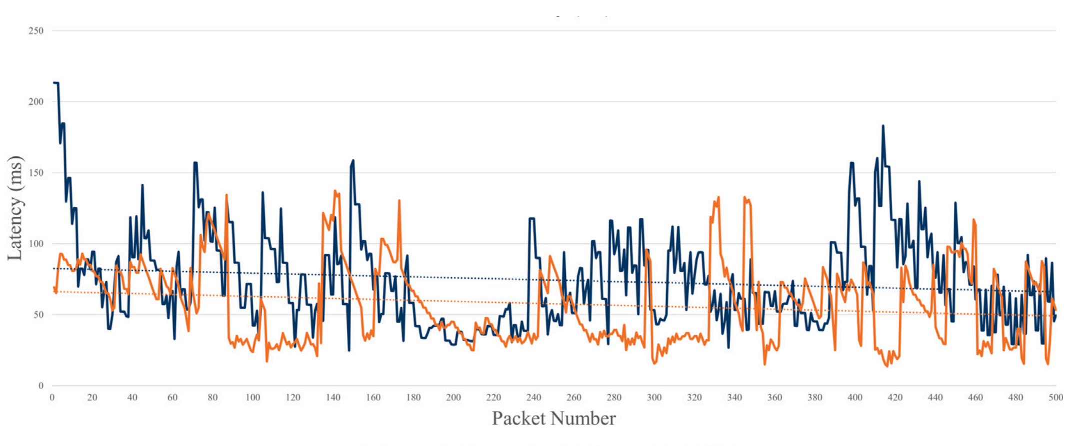


Fig. 20. The communication latency of camera and steering packets when QoS were disabled on the 5G system.

we measure the communication latency of the first 500 camera packets transmitted from the robot car (Node 1) to the TSN-5G gateway (Node 3) via the TSN network, and then to the controller (Node 4) via the private 5G. In Fig. 21, we analyze the communication latency of camera packets across three different scenarios. The blue line represents the baseline scenario where only the camera device is connected to the network, with QoS profile (QID 3). The orange line represents a scenario where an additional device, such as a smartphone streaming high-definition video, is connected without any QoS profiles enabled in the system, with NTP activated. In contrast, the gray line represents

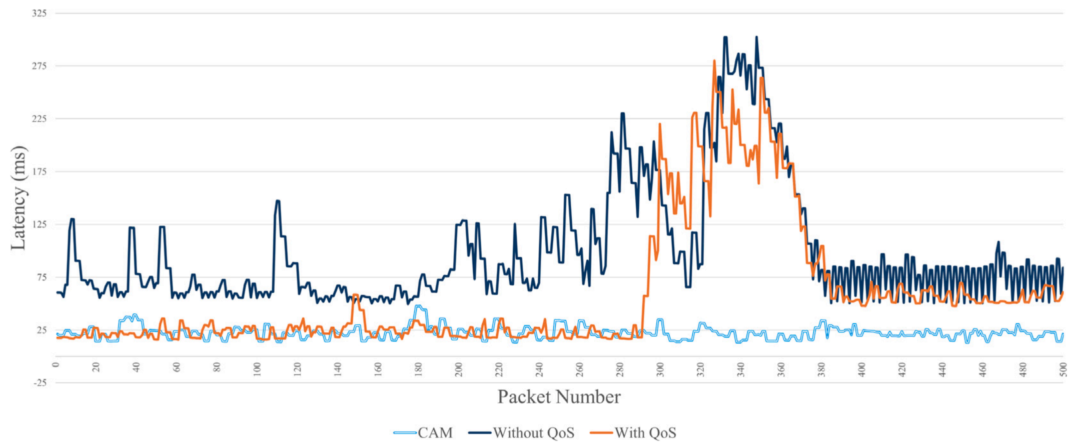


Fig. 21. The E2E latency of camera frames when multiple devices are connected to the 5G network.

Table 7
Communication latency and jitter values (in ms) of camera packets when multiple devices are connected to the 5G network.

QoS	Min. packet size (bytes)	Max. packet size (bytes)	E2E latency (avg)	E2E latency (min)	E2E latency (max)	E2E jitter (avg)	E2E jitter (min)	E2E jitter (max)
Disabled	94	1438	99.06	49.55	302.4098	13.2928	0.000238	127.7799
Enabled	134	1438	57.81	15.7599	279.9301	5.6480	0.01001	120.1999

the same multi-device scenario as the orange line, but with both NTP and QoS profiles enabled. The smartphone was configured with a lower priority than the camera device, with QID 4 (Technical data transfer). From the results, we can see an increase in the communication latency of the camera packets when QoS was not enabled, and multiple devices were connected to the 5G network. When QoS is not enabled, there is no prioritization among UEs, allowing the smartphone streaming high-definition video to potentially create a bottleneck and consume a significant portion of the 5G channel bandwidth. In contrast, when we enable QoS profiles, the camera packets take higher priority and we notice lower communication latencies.

The data highlights the significant impact of QoS on communication latencies. The orange line demonstrates high variability and frequent latency spikes, indicating issues by traffic prioritization. Meanwhile, the latency values in the gray line are more stable, with fewer spikes, similar to the blue line. Table 7 presents latency and jitter averages from the orange and the gray line. The smartphone's high-definition video streaming session is consuming a significant portion of the available radio and core network capacity. This creates congestion, particularly at the air interface, resulting in buffering and queuing delays at the gNB, which leads to high jitter values. In addition, wireless channels are inherently subject to fading, interference, and varying signal-to-noise ratios. These conditions can cause retransmissions and dynamic resource reallocation leading to jitter spikes, especially under high load.

6. Conclusion

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 5G OAI 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. However, our findings show that we can effectively operate remote control of a vehicle through the integrated TSN-5G network, even in scenarios where multiple devices are connected to the 5G network. 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. Comparing our results across Wi-Fi, LTE, and 5G, we find that 5G shows greater stability and promise with lower jitter and latency. However, the current limitation lies in the limited bandwidth and the scheduling of 5G radio resources in our private 5G setup. 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 performance of integrated TSN-5G networks to meet the stringent requirements of networked embedded system applications, by implementing a real-time scheduling mechanism for 5G radio resources to support the QoS requirements of TSN packets.

List of acronyms

Table 8 provides a list of acronyms used in the paper.

CRediT authorship contribution statement

Zenepe Satka: Writing – original draft, Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Mohammad Ashjaei:** Writing – review & editing, Supervision. **Josefina Nord:** Validation, Software. **William Rosales Mayta:** Validation, Software. **Didrik Nordin:** Investigation, Validation. **Daniel Ragnarsson:** Investigation, Validation. **Saad Mubeen:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

Acknowledgments

The work in this paper is supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA) via the PROVIDENT, INTERCONNECT, FLEXATION, and AORTA projects, and the Swedish Knowledge Foundation via the SEINE, and MARC projects. We would like to thank all our industrial partners, especially Arcticus Systems, HIAB, ABB, Westermo, and Volvo Construction Equipment.

Table 8
List of acronyms.

Acronym	Definition
3GPP	3rd Generation Partnership Project
5G	Fifth Generation of Mobile Networks
5GS	5G System
AF	Application Function
DC-GBR	Delay Critical Guaranteed Bit Rate
DS-TT	Device-side TSN Translator
DSCP	Differentiated Service Code Point
E2E	End-to-end
GBR	Guaranteed Bit Rate
gNB	next generation NodeB
MAC	Media Access Control
Non-GBR	Non-Guaranteed Bit Rate
NW-TT	Network-side TSN Translator
OAI	Open Air Interface
PCF	Policy Control Function
PCP	Priority Code Point
PDB	Packet Delay Budget
PER	Packet Error Rate
QoS	Quality of Service
QID	QoS profile ID
RTT	Round-Trip Time
ToS	Type of Service
TSN	Time-Sensitive Networking
UE	User Equipment
USRP	User Software Radio Peripheral

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