5GTQ: QoS-Aware 5G-TSN Simulation Framework

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***Abstract*—The integration of Time-Sensitive Networking (TSN) and 5G communication is crucial for achieving ultra-reliable and low-latency communication (URLLC) in various domains. This includes applications like industrial automation involving mobile and collaborative robots, as well as Industrial IoT (IIoT). However, an exhaustive performance analysis of mixed 5G-TSN networks that support the unique features of TSN and 5G is lacking. Furthermore, a deeper understanding of TSN traffic scheduling in the 5G system (5GS) is necessary. To address this gap, we propose a novel 5G-TSN Quality-of-Service (QoS) aware simulation framework that incorporates priority-based scheduling in the 5GS. Our framework integrates the latest 5G and TSN simulation libraries using OMNeT++ and provides the first-ever results of the performance analysis of a 5G-TSN converged network. We implement the 5G-TSN bridge translation mechanism and introduce a QoS mapping algorithm for our framework. Through a detailed performance evaluation, we assess the impact of 5G QoS-aware scheduling methods on the overall network performance. Our open-source framework utilizes the latest Simu5G and INET4.4 libraries and simulates two different 5G-TSN scenarios to provide comprehensive insights. The results of our study demonstrate that the performance of the 5G-TSN network is significantly influenced by the scheduling in the 5G network, as a substantial portion of the overall delay originates from the 5GS. Notably, our findings reveal that the 5G-TSN network can achieve latency values within 3ms for TSN traffic, emphasizing the need for a joint scheduling mechanism to meet URLLC requirements.**

***Index Terms*—Time-Sensitive Networking, 5G, simulation, Quality-of-Service, 5QI, wired-wireless communication**

I. Introduction

Time Sensitive Networking (TSN) and 5G communication are two technologies that have gained widespread popularity in both industry and academia. TSN enables deterministic communication over the Ethernet layer, while 5G provides wireless communication with ultra-low latency communication (URLLC) support. There are multiple sub-standards in TSN that provide different Quality of Service (QoS). With Cyber-Physical Systems (CPSs) or industrial automation moving towards mobile wireless robot arms for manufacturing purposes, integrating wired and wireless communication has become a critical need. The integration of a wired TSN network and wireless 5G communication (refer to Fig. 1) will utilize the best features of both technologies. Despite ongoing research using simulation and hardware tools, a comprehensive 5G-TSN-related work that provides a proof of concept demonstrating the feasibility and effectiveness of integrating 5G and TSN technologies, focusing on 5G scheduling methods, is yet to be available. Performing TSN traffic to 5G QoS mapping, 5G scheduling, and conducting end-to-end simulations using state-of-the-art 5G and TSN simulators is critical for successfully verifying and validating different 5G-TSN joint architectures.

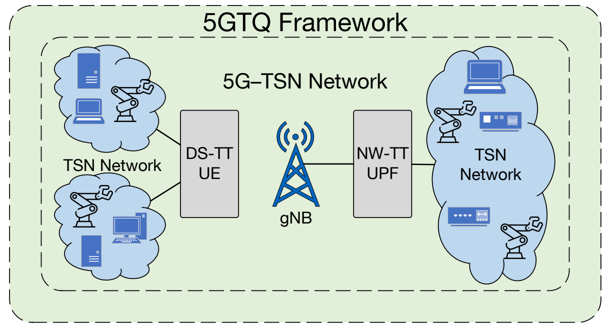

Fig. 1. Converged 5G-TSN network architecture, where 5G provides high-speed wireless, and TSN offers deterministic and low-latency wired communication. gNodeB (gNB) is the equivalent of a base station that supports the 5G New Radio. The QoS-Aware 5G-TSN Simulation Framework (5GTQ) is employed to analyze the network with the implementation of the device-side TSN translator (DS-TT) and the network-side TSN translator (NW-TT) for 5G-TSN translation.

Similar to TSN, 5G also supports various scheduling mechanisms that play a crucial role in determining the system's latency, reliability, and overall performance. Coordinating and integrating these scheduling mechanisms in both wireless and wired domains is essential for optimizing network performance, and it requires further research and development. Simulation serves as an effective initial step toward comprehensively evaluating network performance. Simulation is cost-effective compared to physical hardware as an initial setup for testing and research, and it provides valuable insights into the performance of different 5G-TSN network architectures and configurations. This enables researchers to identify and address potential performance bottlenecks before implementing the design in hardware, reducing the risk of costly hardware failure.

In the 5G System (5GS), both QoS Flow Identifiers (QFIs) and 5G QoS Identifiers (5QIs) are essential in ensuring the QoS for different types of traffic. QFIs serve the purpose of identifying individual QoS Flows within the 5GS. Each QoS Flow is associated with a QFI value, which can take on any value less than 64. On the other hand, the 5G QoS Identifier (5QI) is utilized as a reference to define specific QoS forwarding behaviors, such as packet loss rate and packet

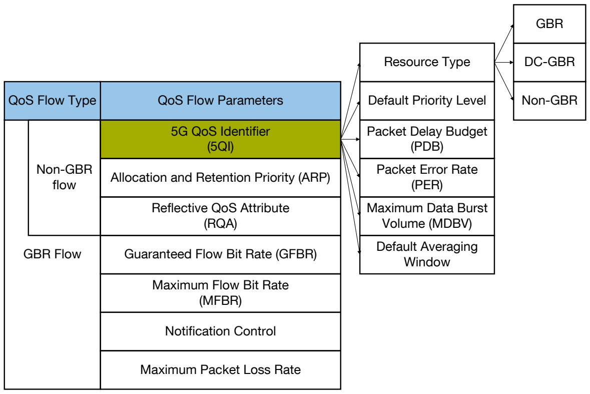

Fig. 2. 5G QoS flow types and their associated parameters, along with the 5G QoS characteristics.

delay budget (PDB), for a particular 5G QoS Flow. In essence, QFI is like numbering the flow IDs, while 5QI indicates the specific treatment or behavior that should be applied to each flow. There are two types of QoS Flows: Guaranteed Bit Rate (GBR) and Non-Guaranteed Bit Rate (Non-GBR) flows (refer to Fig. 2). The 5QI is grouped into three resource types: GBR, Non-GBR, and Delay-Critical Guaranteed Bit Rate (DC-GBR) (refer to Fig. 2). Each 5G QoS flow has a QoS profile, which includes QoS parameters and characteristics, and is identified by a 5QI value in the 5G System. The QoS characteristics consist of resource type, priority level, Packet Delay Budget (PDB), Packet Error Rate (PER), Default Averaging Window (GBR and DC-GBR), and Maximum Data Burst Volume (MDBV) (DC-GBR only) (refer to Fig. 2). Additionally, the 5G QoS characteristics assign priority values to each QoS Flow, allowing the 5GS to prioritize traffic accordingly. It is important to note that the TSN priority differs from the 5GS priority. There are some known challenges in the integration of 5G-TSN networks, such as - supporting different QoS modelling of 5G and TSN, ensuring deterministic and bounded delay guarantees in the 5G-TSN network, and efficient traffic scheduling within the 5G-TSN network.

II. Motivation and Significance

The evaluation of 5G-TSN networks presents a challenge due to the lack of simulation tools capable of accurately modeling the architecture. While there are few works on the simulation of 5G-TSN networks, they do not use state-of-the-art simulation libraries and lacks either the TSN capabilities or the 5G capabilities. Additionally, the performance analysis of a 5G-TSN network requires proper implementation of 5G QoS mapping and 5G scheduling mechanisms, as they significantly impact the performance of TSN flows. Hence, to answer these open research gaps, we developed 5GTQ, an open-source framework that includes a device-side TSN translator (DS-TT) and a network-side TSN translator (NW-TT) for 5G-TSN translation. Additionally, recognizing the significance of QoS mapping in the comprehensive performance study, we also implemented a QoS mapping algorithm that considers the specific QoS requirements of TSN traffic types. Furthermore,

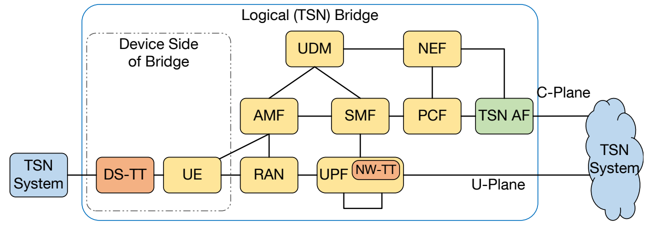

Fig. 3. System architecture view of the 5G-TSN network with 5GS appearing as a TSN bridge highlighting the NW-TT and DS-TT [2].

the scheduling mechanism in 5G plays a crucial role in determining the overall performance of the network. To address this, we have implemented a QoS-based priority scheduling mechanism for the 5GS. The main contributions of this paper are as follows:

1) **5GTQ framework:** Development of a 5G-TSN QoS-aware framework (Section IV), called 5GTQ, using state-of-the-art Simu5G [1] library and the latest INET4.4.1[1]. To ensure accessibility and promote validation, we have made our framework open source[2].
2) **QoS Mapping and 5G Scheduling:** We have implemented a QoS mapping algorithm for mapping TSN traffic to 5G, ensuring the QoS performance of industrial automation traffic types (Section IV-D). Additionally, we have developed a QoS-aware priority scheduling mechanism in the 5GS, supporting different 5QI values.
3) **Results and Analysis:** Our paper comprehensively analyzes multiple simulation scenarios, considering the mapping of TSN industrial traffic types to 5G QFIs. Unlike prior studies, our analysis evaluates the combined impact of 5G and TSN networks on overall performance, resulting in a more accurate and realistic network simulation (Section V). We further showed the results with different 5G scheduling methods. Our findings offer valuable insights into the influence of wireless 5G scheduling and TSN scheduling (Section VI).

III. Related Work

The integration of 5G-TSN is a crucial topic for the automation industry, and it is equally crucial for vehicular networks. Research is ongoing in this direction, with contributions from both industry and academia. Simulation studies of 5G-TSN are covered in related works. [3] implemented the 5G-TSN translation mechanism using NeSTiNg [4]. However, the major bottleneck of the framework is the lack of support for simulating 5G modules, such as User Equipment (UE), User Plane Function (UPF), Generation NodeB (gNB), 5G medium, 5G scheduling, or any other 5G functionalities. Consequently, the translator implementation of [3] cannot simulate the different scenarios of the 5G-TSN architecture, and the impact of the 5G medium on the overall performance is not considered. In our work, 5GTQ, we use the latest Simu5G, which has a 5G medium, UPF, UE, while taking into account all the

[1]https://inet.omnetpp.org/2022-07-27-INET-4.4.1-released.html
[2]https://github.com/tum-esi/5GTQ

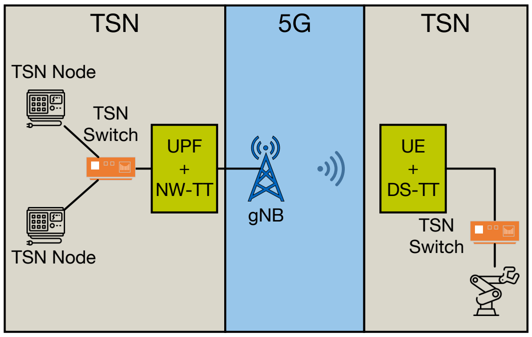

Fig. 4. **TSN-5G-TSN:** Simulated topology of the 5G-TSN architecture, where the 5GS serves as a bridge. The TSN flows are transmitted from the TSN Node to the Robot Arm. The robot arm is a wired TSN receiving node. This topology includes NW-TT and DS-TT, supporting communication in both directions.

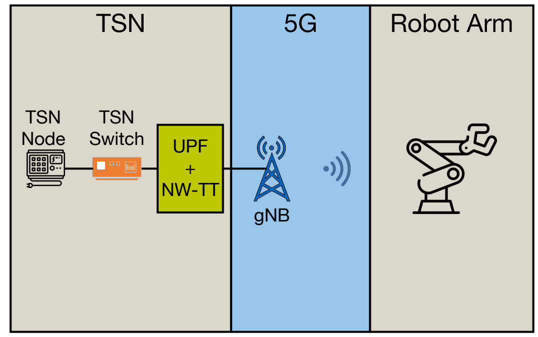

Fig. 5. **TSN-5G-Robot:** Simulated 5G-TSN architecture with a 5G-enabled Robot Arm as the receiving node, demonstrating practical implications for scenarios such as wireless collaborative robots. This topology excludes the need for a DS-TT, as the 5G packet is transmitted directly to the Robot Arm.

real-world scenarios, such as mobility, path loss, disturbances, and different 5G scheduling. [5] presented an early simulation model of NeSTiNg and a lightweight 5G user plane and modeled the 5G system as a transparent TSN bridge. However, their approach lacked support for Device-to-Device (D2D) communication, and the packet sizes were limited to 256 Bytes for downlink (DL) traffic and 64 Bytes for uplink (UL) traffic. Additionally, the 5G communication was best-effort (BE), with a First-In-First-Out (FIFO) queue without any 5G QoS-based scheduling mechanism. By contrast, our work supports UL, DL, and priority-based 5G scheduling mechanisms, including DC-GBR, GBR, and Non-GBR resource types.

We performed a detailed evaluation, considering industrial traffic type requirements. Moreover, the payload size in our evaluation ranges within the Ethernet standard limit (46-1500 Bytes). [6] proposed a system-level simulator for 5G integration using NeSTiNg and developed their own 5G simulation framework for the user plane function based on an existing 4G LTE simulator. [6] considered two types of traffic, isochronous and cyclic. However, it did not consider the QoS mapping, which is a crucial aspect in achieving the necessary QoS requirements. The mapping of TSN traffic to 5QI and vice versa is a crucial step towards the integration of 5G-TSN. [7] proposed an algorithm for mapping TSN traffic to 5QI identifiers. The proposed algorithm is evaluated using synthetic traffic with constraints on deadline, jitter, bandwidth (BW), and packet loss rate. The algorithm in [7] assigns DC-GBR to the TSN flows with delay, jitter, and BW constraints. It is important to note that isochronous traffic, mapped to Time-Triggered (TT) traffic in TSN, is a delay-critical traffic in industrial automation and does not have a BW constraint. [8] developed a virtual network function (VNF) mapping to address the QoS mapping problem. However, their work is mainly focused on the QoS mapping problem, and they used VNFs to create multiple virtual networks for different applications. Unlike our 5GTQ model, [8] does not take into account different TSN shapers and 5G scheduling mechanisms. Evaluating the 5G-TSN network is challenging due to the lack of cost-effective hardware. To address this issue, [9] proposed an open-source testbed for integrating 5G-TSN. However, [9] is in an early stage and future work is focused on developing an open-source 5GS with TSN testbed. Since hardware is generally expensive and scalability is a problem, it is highly crucial to validate and conduct preliminary studies using a simulation approach to save costs and resources. In order to address the research gap, we, therefore, propose 5GTQ.

IV. Implementation and Integration

In this section, we describe our 5GTQ implementation for 5G-TSN based on 3GPP Release 17 standards [2].

A. 5G-TSN architecture

A 5GS can be integrated as a Layer 2 Ethernet bridge into an IEEE TSN network, incorporating TSN translator (TT) functionality [2]. The 5GS bridge model includes two types of TSN translators: The Network-side TSN translator (NW-TT) located at the User Plane Function (UPF) and the Device-side TSN translator (DS-TT) located at the User Equipment (UE). As shown in Fig. 3, the TSN Application Function (TSN AF) is a component of the 5G Core (5GC) that provides the control plane translator functionality for the integration of the 5GS with a TSN network [2]. The implementation of DS-TT and NW-TT is the first step towards successful 5G-TSN integration, which is covered in 5GTQ. DS-TT is located on the UE side, while the NW-TT is situated on the UPF. In 5GTQ, we simulated two different integration scenarios for 5G-TSN: TSN-5G-TSN and TSN-5G-Robot, as shown in Fig.4 and Fig.5, respectively. While the architecture in Fig. 4 is mentioned in the standard, Fig. 5 architecture is not explicitly covered in the 3GPP release. We included TSN-5G-Robot in our implementation to showcase a network architecture where a 5G-enabled Robot Arm is directly controlled by the TSN network, providing enhanced flexibility and automation capabilities.

B. Device Side TSN Translator (DS-TT)

In the 5GTQ implementation, the DS-TT module is integrated into the UE and consists of four main modules:

TABLE I
TRAFFIC TYPES CONSIDERED IN THE 5G-TSN SYSTEM [10]–[12]

Traffic Type	Periodic (P)/ Sporadic (S)	Data Size [in Bytes]	Criticality	PCP	Data delivery requirements	TT Traffic	Tolerance to Jitter	Tolerance to Loss
Isochronous	P	1500	High	7	Deadline	Yes	0	None
Network Control	P (50ms-1s)	50-500	High	4	BW (1-2 Mbits)	No	Yes	Yes
Video	P	1000-1500	Low	1	BW	No	NA	Yes
Best Effort	S (500ms-2s)	30-1500	Low	0	NA	No	NA	Yes

Algorithm 1 QoS mapping Algorithm used in 5GTQ

```
TSN_QoS_Requirements ← read from XML file
DC_GBR_JSON ← DCGBR QFIs' based parameters
GBR_JSON ← GBR QFIs' based parameters
Non_GBR_JSON ← Non-GBR QFIs' based parameters
n ← total number of TSN flows taken from the XML file
for i ← 1 to n do
    if app[i].DeadlineConstraint then
        // TSN Flow is assigned to DC-GBR
        for j in DC_GBR_JSON do
            if app[i].PacketSize ≤ j[mdbv] then
                if j[PDB] > app[i].Deadline then
                    selectedQFI ← j[qfi]
                else
                    Select DCGBRQFI with largest PDB
                end if
            end if
        end for
    else if app[i].Latency or app[i].Bandwidth then
        // TSN flow is assigned to GBR
        smallest_pdb = float('inf')
        for j in GBR_JSON do
            if j[PDB] < smallest_pdb then
                selectedQFI ← j[qfi]
            else
                QFINotFound
            end if
        end for
    else
        // TSN Flow is assigned to Non-GBR
        largest_pdb = −1
        for j in Non_GBR_JSON do
            if j[PDB] > largest_pdb then
                selectedQFI ← j[qfi]
            else
                QFINotFound
            end if
        end for
    end if
end for
```

cellularNic, *translator*, *ethernetMAC*, and *ethernetGate*. The *cellularNic* module handles the reception and transmission of 5GS packets. In the DL, the *translator* module maps the 5GS QFI to TSN Priority Code Point (PCP). In this paper, the TSN PCP values can range from 0 to 7, with 0 being the smallest and 7 being the highest priority. The *ethernetMAC* encapsulates and decapsulates the 5G packet with Ethernet headers, and finally, the TSN frame is transmitted to the TSN network from the *ethernetGate* module. During the DL transmission, the *cellularNic* receives the 5GS packet and sends it to the *translator* module. Here, the *translator* assigns the destination MAC address and IEEE 802.1Q tag to make it TSN frame compliant. The QFI to PCP conversion is then

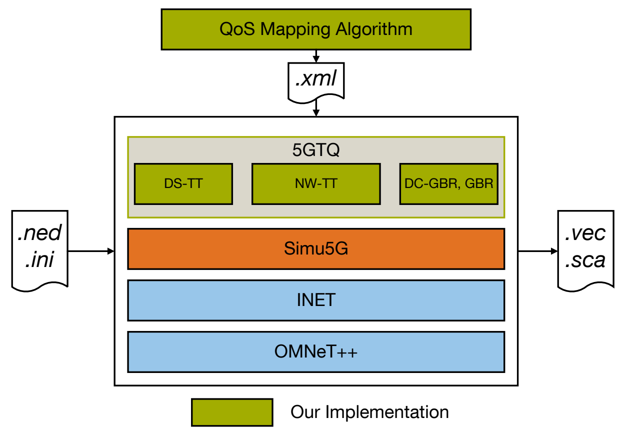

Fig. 6. The 5GTQ framework for 5G-TSN simulation includes NW-TT, DS-TT, QoS mapping, and support for DC-GBR and GBR. The **green** blocks highlight the proposed and implemented parts in this paper.

performed based on the QoS mapping, and the PCP value is set in the header information of the frame. During the UL transmission, the *cellularNic* receives the TSN frame from the *translator*, and the appropriate QFI is assigned.

C. Network Side Translator (NW-TT)

In 5GTQ, we have implemented the NW-TT as a component outside the UPF. In the DL communication, TSN flows enter the NW-TT through the Ethernet gate, and the IP layer routes the packet and forwards it to the UPF gateway. No processing, encapsulation, or decapsulation occurs in the NW-TT in the DL communication. In the UL communication, the 5GS packet enters the NW-TT through the *ppp* gate connected to the *trafficFilter* in the UPF. The *TSNRelayUnit* module performs Ethernet-compliant frame conversion of the 5GS packet and forwards it to the TSN switch. *TSNRelayUnit* performs the mapping from the QFI to the TSN PCP in the UL direction.

D. QoS mapping

The 5G QoS model consists of QoS Flows, each with a unique identifier called QFI, which is used to identify the QoS flow. Additionally, there is a unique identifier known as 5QI, which represents the QoS forwarding behavior of the QoS Flow. The 3GPP standard does not assign fixed QFI values to different QoS flows; instead, the QFI value can be any value below 64. However, the 3GPP standard specifies fixed standardized 5QI values that correspond to specific 5G

QoS characteristics. Traffics with the same 5QI values receive the same forwarding treatment, such as the same scheduling mechanism or resources in our 5GTQ implementation. Therefore, in our 5GTQ implementation, we map a 5QI value to TSN traffic to determine its treatment when entering the 5GS. In this paper, we have implemented an advanced QoS mapping algorithm to address the specific requirements of TSN industrial traffic, as presented in Table I. At the time of implementing 5GTQ, the Simu5G protocol stack did not support the 5GS QoS model, and hence the support of 5QI was missing. To overcome this limitation, we implemented a QoS model within 5GTQ to enable the necessary QoS mapping. Additionally, we extended the protocol stack of Simu5G to include support for DC-GBR and GBR flows. Furthermore, we implemented a QoS-aware priority-based 5G scheduling mechanism, where the traffic priority in the 5GS is determined by the corresponding 5QI value specified in the 3GPP standard [2]. In the standard [2], every 5QI value is mapped to one priority value. Our algorithm assigns priority values to the traffic flows based on the allocated 5QI value, following the same assignment as defined in the 3GPP standard [2].

The QoS mapping algorithm used in 5GTQ is given in Algorithm 1. In Lines 2-4 of the algorithm, the mapping of the 5QI to QoS parameters to their respective variables is defined, using the information obtained from Table 5.7.4-1 in [2], where the one-to-one mapping of standardized 5QI values to 5G QoS characteristics is given. In line 5, the variable n is initialized with the total number of TSN flows present in the network obtained from the XML file. Line 6 loops through all TSN flows present in the network. In line 7, if the current TSN flow has a deadline constraint, it is assigned to DC-GBR. In lines 9-17, the algorithm enters a loop to go through the parameters related to DC-GBR QFIs. If the packet size of the current TSN flow is less than or equal to the $mdbv$ value of the current DC-GBR QFI, the algorithm proceeds. In line 11, if the PDB value of the current DC-GBR QFI is greater than the deadline of the current TSN flow, it indicates that the TSN flow can be assigned to this QFI.

In line 14, if the PDB value of the current DC-GBR QFI is not greater than the deadline of the TSN flow, the algorithm searches for the DC-GBR QFI with the largest PDB value and selects it. In line 18, if the TSN flow doesn't have a deadline constraint but has a latency or bandwidth requirement, it is assigned to GBR. Lastly, if the TSN flow does not have any specific QoS requirements, it falls under the Non-GBR category. In line 31, the algorithm iterates through the parameters related to Non-GBR QFIs. The algorithm checks if the PDB value of the current Non-GBR QFI is larger than the current $largest_pdb$. If the algorithm fails to locate an appropriate QFI for the TSN flow, the flow remains unassigned.

E. Simulation Framework

Our 5GTQ framework, as shown in Fig. 6, is built on top of Simu5G and INET 4.4.1. Simu5G simulates the data plane of the 5G RAN and core network [1]. All simulations in 5GTQ were conducted with a link speed of 100 Mbps and a duration of 50 seconds. The simulation considered various traffic types, as outlined in Table I. We have summarized the simulation parameters of the 5G medium in Table II. For the TSN-5G-TSN scenario, the TSN flows follow the route: TSN Node $\longrightarrow$ TSN Switch $\longrightarrow$ NW-TT $\longrightarrow$ 5G $\longrightarrow$ DS-TT $\longrightarrow$ TSN Switch $\longrightarrow$ Robot Arm. In the TSN-5G-Robot scenario, the TSN flows follow the route: TSN Node $\longrightarrow$ TSN Switch $\longrightarrow$ NW-TT $\longrightarrow$ 5G $\longrightarrow$ Robot Arm.

V. Evaluation and Results

In the following section, we present experimental results obtained using 5GTQ to explore the integration of 5G-TSN in two distinct scenarios: TSN-5G-TSN and TSN-5G-Robot. Our experiments incorporate the use of our QoS mapping algorithm to generate the results. All experiments described in this paper were conducted on a workstation equipped with a 64-bit 4-core 2.70GHz Intel(R) Core(TM) i7-7500U processor and 16GiB of memory. All the results were generated by running the simulation for 50 seconds on the OMNeT++ simulation clock.

A. TSN-5G-TSN

In the TSN-5G-TSN scenario, we considered two TSN traffic types: Network Control and Video, and one non-TSN traffic type: BE. Within the TSN network, Network Control was assigned the highest priority, followed by Video. Video traffic was shaped using the Credit Based Shaper (CBS) with an *idleSlope* value of 75%. Although our QoS algorithm initially assigned Network Control to GBR, since there is no Time-Triggered (TT) traffic in the TSN network, we assigned Network Control to DC-GBR to demonstrate the difference between DC-GBR and GBR. Video traffic was assigned to GBR, and BE traffic was assigned to Non-GBR in the 5GS by our QoS algorithm. In the 5GS, the treatment of QoS flows is determined based on their priority. The 5G priority differs from the TSN priority. Each traffic type is assigned a 5G priority based on the 5QI mapping. The 5GS schedules the flows based on the priority. We conducted 10 test cases (TCs) with varying network loads following the traffic specifications of (Table I). The results, shown in Fig. 7, demonstrate the end-to-end delay of Network Control, Video, and BE traffic. The results indicate that the delay of TSN traffic remains within 3ms, even under high network load. This is attributed to the use of CBS as a traffic shaper in the TSN network and priority-based scheduling in the 5GS. On the other hand, BE traffic, which was assigned the lowest priority and no specific QoS, was not shaped using any TSN shaper and has the lowest priority in the 5GS. Therefore, even with very low network load, BE traffic experiences the highest delay.

B. TSN-5G-Robot

In the TSN-5G-Robot architecture (Fig.5), we demonstrated the communication of controlling a wireless-enabled Robot Arm from a TSN network. Similar to the TSN-5G-TSN network, Network Control is mapped to DC-GBR, Video to GBR, and BE to Non-GBR. In the 5GS, the scheduling is

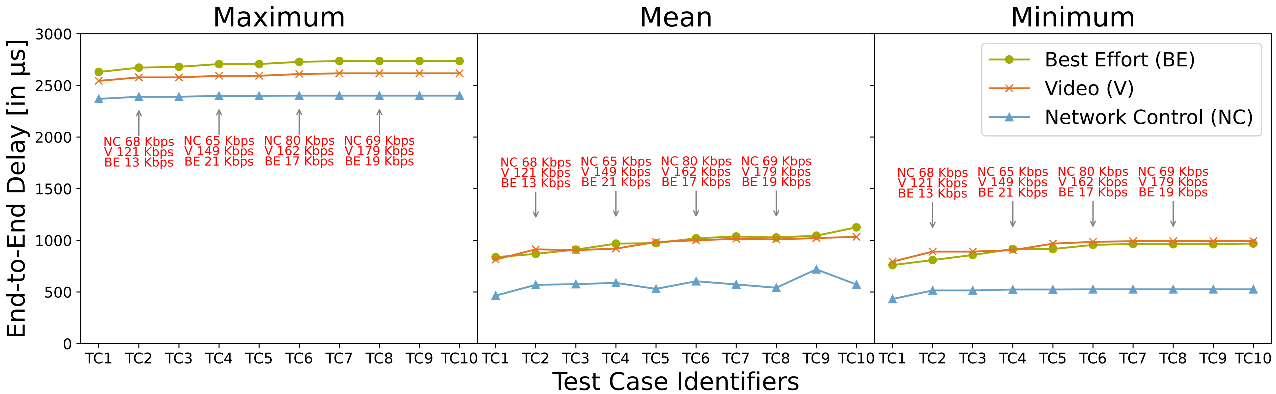

Fig. 7. Maximum, Mean, and Minimum simulated end-to-end delay of TSN and BE flows in the TSN-5G-TSN architecture (Fig. 4) under various test cases (TC) with different loads. Network Control and Video traffic are categorized as TSN flows, with Network Control assigned the highest priority, followed by Video traffic. Video traffic is shaped using the Credit-Based Shaper (CBS) with an *idleSlope* of 75%. It is noteworthy that, despite the considerably higher network load of Network Control and Video traffic compared to BE traffic, the maximum delay for the TSN flows remains below 3 ms.

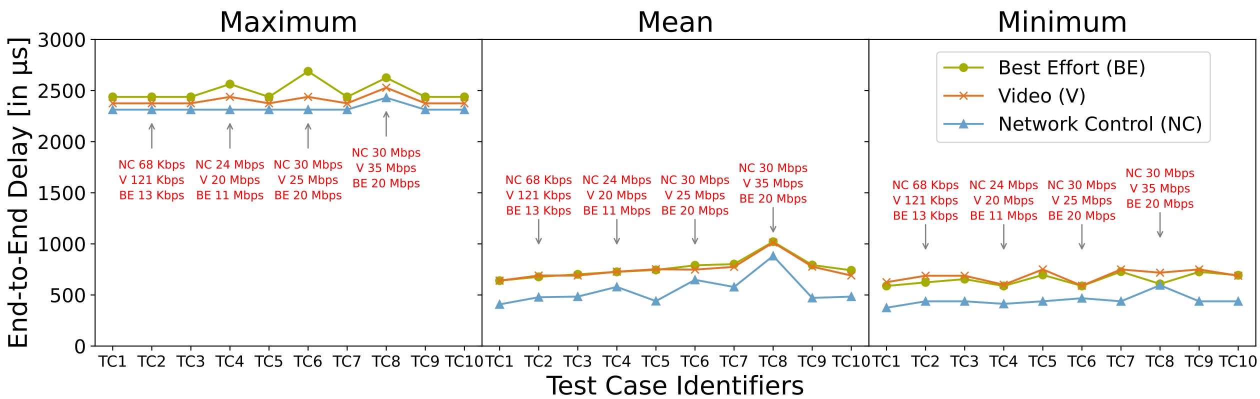

Fig. 8. Maximum, Mean, and Minimum end-to-end delay of TSN and BE flows in the TSN-5G-Robot architecture (Fig. 5) under different test cases (TC) with varying loads. Network Control and Video traffic are classified as TSN flows, with Network Control given the highest priority. Video traffic is shaped using the Credit-Based Shaper (CBS) with an *idleSlope* of 75%. The maximum delay for the TSN flows is within 3 ms, similar to the TSN-5G-TSN scenario. However, in TSN-5G-Robot, without an additional DS-TT, the delay is slightly lower compared to TSN-5G-TSN. This highlights that most of the delay in the network is attributed to the 5GS, NW-TT, and DS-TT.

again determined based on the priority assigned to the traffic flows according to their 5QI values. We conducted 10 test cases with different network loads following the specifications in Table I. Fig. 8 displays the End-to-End Delay of the TSN and BE flows. Even under high network load, the delay of Network Control and Video remains within 3ms, demonstrating bounded delay performance. Video traffic is shaped using CBS, and Network Control is given the highest priority in the TSN network, similar to the TSN-5G-TSN evaluation. On the other hand, BE has the lowest priority and does not have any specific QoS. Consequently, BE experiences the highest delay due to its low-priority treatment in both the TSN and the 5G network.

In the related work [3], the End-to-End Delay from the sending node to the receiving node, with one switch, was reported to be 5.57ms. However, through our implementation of proper TSN and 5G scheduling, we demonstrated that the End-to-End delay, even under high network load, can be reduced to within 3ms. It should be noted that a direct comparison with related work models was not feasible, as the previous models

TABLE II
5G PARAMETERS AND THEIR VALUES USED IN THE SIMULATION

Parameter	Value
Frequency	5.9GHz
Channel Model	Urban Macrocell
gNB Tx Power	46 dBm
Fading channel	Jakes (Since No Mobility)
Simulation Time	50s
Fading + Shadowing	Enabled
Carrier Aggregation	1
Numerology Index	4
No. of Resource Blocks	100
No. of gNBs	1
No. of UE	1
gNB antenna gain	18
gNB noise figure	5
UE antenna gain	0
UE noise figure	7

did not explore the 5GS and 5G scheduling with the same level of detail as our proposed 5GTQ. Therefore, conducting a direct comparison becomes challenging. Nonetheless, we conducted simulations on a similar network with two switches to showcase that the delay can be kept within 3ms, and potentially even lower with the use of optimized Time Aware Shaper (TAS) and 5G Joint Scheduling.

VI. Conclusion

We have implemented the 5GTQ framework, which includes NW-TT, DS-TT, and an advanced QoS mapping algorithm. Additionally, we have incorporated QoS-aware 5G scheduling with support for DC-GBR and GBR. Our experiments on industrial automation traffic types have demonstrated the importance of proper modeling, advanced QoS mapping, and 5G scheduling for ensuring the necessary QoS in the 5G-TSN network. We have also showcased the feasibility of directly controlling a 5G node using the TSN network in the TSN-5G-Robot architecture, which has potential benefits for industrial automation and factory setups. However, our results have revealed that the End-to-End Delay in the 5G-TSN network is still relatively high, with the majority of the delay originating from the 5GS. To effectively utilize TAS and Time-Triggered traffic in the 5G-TSN network, joint scheduling and new Gate Control List (GCL) generation are crucial. Unbounded delay in the 5GS can lead to the misalignment of gate opening and closing times in the DS-TT side TSN switch. Numerous studies are currently underway to integrate wired-wireless communication, including WiFi-TSN and 5G-TSN. Future versions of TSN are expected to support both WiFi and 5G technologies. However, the configuration and management of 5G-TSN networks remain challenging, particularly with regard to the scheduling of Time-Triggered traffic. Additionally, scheduling within the 5G network and resource management present their own set of challenges. In future work, we will further explore the 5G-TSN network by investigating other joint scheduling problems, with a focus on TAS. Overall, our work sheds light on the integration of 5G and TSN networks, highlighting the need for further advancements in scheduling and management techniques to fully harness the potential of 5G-TSN communication.

References

[1] G. Nardini, D. Sabella, G. Stea, P. Thakkar, and A. Virdis, "Simu5g–an omnet++ library for end-to-end performance evaluation of 5g networks," *IEEE Access*, vol. 8, pp. 181 176–181 191, 2020.

[2] 3rd Generation Partnership Project, "Technical Specification Group Services and System Aspects; system architecture for the 5g system (5gs); stage 2 (release 18)," Tech. Rep.

[3] Z. Satka, D. Pantzar, A. Magnusson, M. Ashjaei, H. Fotouhi, M. Sjödin, M. Daneshtalab, and S. Mubeen, "Developing a translation technique for converged tsn-5g communication," in *2022 IEEE 18th International Conference on Factory Communication Systems (WFCS)*, 2022, pp. 1–8.

[4] J. Falk, D. Hellmanns, B. Carabelli, N. Nayak, F. Dürr, S. Kehrer, and K. Rothermel, "NeSTiNg: Simulating IEEE time-sensitive networking (TSN) in OMNeT++," in *Proceedings of the 2019 International Conference on Networked Systems (NetSys)*, Garching b. München, Germany, Mar. 2019.

[5] L. Martenvormfelde, A. Neumann, L. Wisniewski, and J. Jasperneite, "A simulation model for integrating 5g into time sensitive networking as a transparent bridge," in *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, vol. 1, 2020, pp. 1103–1106.

[6] D. Ginthör, J. von Hoyningen-Huene, R. Guillaume, and H. Schotten, "Analysis of multi-user scheduling in a tsn-enabled 5g system for industrial applications," in *2019 IEEE International Conference on Industrial Internet (ICII)*, 2019, pp. 190–199.

[7] Z. Satka, M. Ashjaei, H. Fotouhi, M. Daneshtalab, M. Sjödin, and S. Mubeen, "Qos-man: A novel qos mapping algorithm for tsn-5g flows," in *2022 IEEE 28th International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA)*, 2022, pp. 220–227.

[8] Y. Zhang, Q. Xu, M. Li, C. Chen, and X. Guan, "Qos-aware mapping and scheduling for virtual network functions in industrial 5g-tsn network," in *2021 IEEE Global Communications Conference (GLOBECOM)*, 2021, pp. 1–6.

[9] S. Senk, H. K. Nazari, H.-H. Liu, G. T. Nguyen, and F. H. P. Fitzek, "Open-source testbeds for integrating time-sensitive networking with 5g and beyond," in *2023 IEEE 20th Consumer Communications Networking Conference (CCNC)*, 2023, pp. 1–7.

[10] "Iec cd / ieee 802.1 tsn time-sensitive networking profile for industrial automation," *P60802 Standard for Local and Metropolitan Area Networks – Time-Sensitive Networking Profile for Industrial Automation*, 2023, draft Version 2.0, accessed on May 1, 2023.

[11] 5G-ACIA, "Integration of 5g with time-sensitive networking for industrial communications," https://5g-acia.org/wp-content/uploads/2021/05/5G-ACIA_Integration_of_5G_with_Time-Sensitive_Networking_for_Industrial_Communicatins_single-pages.pdf, 2021, [Online; accessed 1-May-2023].

[12] I. I. Consortium, "Iic tsn testbed traffic whitepaper," https://www.iiconsortium.org/pdf/IIC_TSN_Testbed_Traffic_Whitepaper_20180418.pdf, 2018, [Online; accessed 1-May-2023].