P5G-TSN: A Private 5G TSN Simulation Framework

Laura Becker, Wolfgang Kellerer
Chair of Communication Networks, Technical University of Munich, Germany
Email: {laura.alexandra.becker, wolfgang.kellerer}@tum.de

***Abstract*—To address Smart Factories' rising requirements regarding deterministic low latency communication, flexibility, and mobility, the 5G system must be integrated into Time Sensitive Networking (TSN). Quality of Service (QoS) mapping between the 5G and TSN systems and end-to-end scheduling are essential, to guarantee a deterministic end-to-end communication in the converged network. In this paper, we propose a network simulator that simulates 5G networks integrated with TSN to analyze end-to-end schedulers and QoS mapping algorithms considering different channel models and mobility scenarios. The network simulator extends the OMNeT++ framework 5GTQ. The main improvement is the applicability of the simulator for private 5G networks, including the implementation of arbitrary Time Division Duplex (TDD) patterns. Resources can be pre- or dynamically allocated to satisfy latency requirements. The simulation results consider typical use cases of industrial communication and demonstrate the impact of the TDD pattern and the resource allocation procedure on the delay.**

***Index Terms*—TSN, 5G, TDD, Simu5G, INET, 5GTQ**

I. Introduction

Deterministic, low-latency communication of time-sensitive data is one of the main challenges in industrial and automotive communication. To target these demands, Time Sensitive Networking (TSN) Ethernet standards were defined [1]. TSN provides deterministic end-to-end communication in fixed networks using traffic prioritization and shaping. However, the need for wireless connectivity arises in mobility scenarios with applications such as Automated Guided Vehicles (AGVs) and Low powered Internet of Things (IoT) devices. To address this gap, 3GPP outlines an approach to integrate a 5G network into a TSN system in its Release 16 [2]. In such integrated 5G TSN networks, Quality of Service (QoS) mapping between the two domains and end-to-end scheduling are crucial aspects. To ensure low-latency communication, joint scheduling has to be developed considering the shapers of TSN and the Radio Access Network (RAN) characteristics of 5G. Besides the dynamic allocation of radio resources, varying channel conditions and mobility are additional challenges to guaranteeing time-sensitive communication.

To analyze and compare end-to-end schedulers and QoS mapping algorithms, we propose a simulator for private 5G networks integrated into TSN. In contrast to relatively complex and expensive hardware testbeds, a simulator can be easily extended and provides a reproducible setup. Furthermore, it can simulate randomness, like varying channel conditions, and special failure scenarios, such as breaking paths.

Our proposed framework runs in the discrete event simulator OMNeT++. The frameworks INET [3] and Simu5G [4] already provide the simulation of TSN and the 5G data plane, respectively. Debnath et al. publish the framework 5GTQ [5] integrating Simu5G into INET. Hence, 5GTQ enables an end-to-end simulation of 5G systems integrated with TSN.

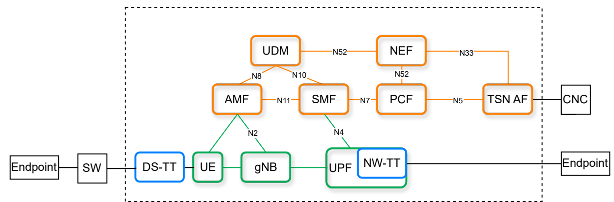

Fig. 1: Transparent 5G bridge in a TSN system [2].

In this paper, we introduce a network simulation framework extending 5GTQ by implementing modules that are essential for the simulation of private 5G networks. Therefore, this improves the applicability of the simulation for industrial communication networks, typically using private 5G networks. The advantage of a private 5G network is the utilization of a dedicated reserved frequency. The usage of Time Division Duplex (TDD) instead of Frequency Division Duplex (FDD) makes the configuration of TDD patterns a crucial feature to simulate 5G TSN networks. Therefore, our framework implements arbitrary TDD patterns and aligns the resource allocation procedure to the configured pattern. Moreover, our framework provides, in addition to dynamic allocation, pre-allocation of radio resources in the Uplink (UL), in order to fulfill the latency requirements of industrial communication.

II. Background

3GPP specifies in [2] the integration of 5G as a transparent bridge in a centralized managed TSN system, visualized in Figure 1. The bridge ports are represented by the Network-Side (NW) and the Device-side TSN translators (DS-TTs). The 5G bridge communicates its characteristics, such as the delay per port and traffic class, via the TSN Application Function (TSN AF) to the Central Network Controller (CNC). Based on all bridge capabilities and the streams' requirements, the CNC configures the bridges, such as the scheduling.

In Release 16 [2], 3GPP standardizes 35 QoS profiles, characterized by parameters including resource type, priority, and Packet Delay Budget (PDB). The profiles enable a granular description of the most common industrial use cases and provide different QoS levels.

The bridge configuration of the CNC has to define the mapping

traffic types	P/S	period	data [Byte]	jitter	latency
Isochronous	P	$[100\mu s, 2ms]$	$30 \sim 100$	0	deadline
Cyclic-Sync.	P	$[500\mu s, 1ms]$	$50 \sim 1000$	$\leq t$	t
Cyclic-Async.	P	$[2ms, 20ms]$	$50 \sim 1000$	$\leq t$	t
Events: control	S	$[10ms, 50ms]$	$100 \sim 200$	n.a.	t
Events: alarm	S	$2s$	$100 \sim 1500$	n.a.	t
Network control	P	$[50ms, 1s]$	$50 \sim 500$	n.a.	n.a.
Configuration	S	n.a.	$500 \sim 1500$	n.a.	n.a.
Video	P	frame rate	$1000 \sim 1500$	n.a.	n.a.
Audio	P	sample rate	$1000 \sim 1500$	n.a.	n.a.
Best effort	S	n.a.	$30 \sim 1500$	n.a.	n.a.

TABLE I: An overview of **p**eriodic and **s**poradic traffic types discussed in IEC/IEEE 60802 [7].

between TSN streams and 5G profiles. This QoS mapping alone is insufficient to enable time-sensitive communication because the scheduler has to verify that the characteristics of the 5G profiles, such as the PDB, are fulfilled. 3GPP does not provide implementation guidelines for such a scheduler or a QoS mapping. Hence, mapping algorithms and QoS-aware schedulers are highly discussed in current literature [5], [6].

According to 3GPP, the CNC considers the 5G bridge in the same way as all other bridges, which are normally TSN switches. Consequently, the CNC cannot provide scheduling information considering the 5G resource allocation. Therefore, the TSN AF extracts information about the streams from the configuration provided by the CNC. Regarding 3GPP, this shall be done in case the wired network part is scheduled using the TSN shaper Per-Stream Filtering and Policing (PSFP). Based on the gate control list of PSFP, the TSN AF determines streams' characteristics, such as the arrival window at the 5G bridge, and creates a TSC Assistance Information (TSCAI). Using the TSCAI, the 5G scheduler can pre-allocate radio resources while considering the streams' arrival window.

The TSN working group [1] currently specifies TSN profiles for industrial automation use cases in an ongoing joint project with IEC. The IEC/IEEE 60802 project should describe profiles by focusing on the traffic characteristics such as periodicity and latency requirements and the required TSN features. The 5G-ACIA Alliance summarizes the traffic types discussed in IEC/IEEE 60802 as shown in Table I [7].

In particular, for low latency communication in the UL, the TDD pattern limits the minimum delay. The TDD pattern defines the time it takes to switch between UL and Downlink (DL) sending by defining an amount of UL and DL slots. To avoid interference, a shared slot including UL and DL symbols separated by some guard symbols is used to switch the transmission direction. In the case of dynamic resource allocation, a User Equipment (UE) has to send a Scheduling Request (SR) in an UL slot, but the gNB has to wait for the next DL slot to send the grant. Afterward, the UE transmits the packet in the next UL slots. Hence, depending on the numerology and the TDD pattern, certain delay bounds cannot be fulfilled even if no packets have to be re-transmitted.

III. Related Work

In current literature, most simulations of TSN are performed in the discrete event simulator OMNeT++ using the INET framework [3] providing the main features of TSN. The frameworks SimuLTE [8] and Simu5G [4] simulate the user plane of LTE and 5G in OMNeT++, including models of network nodes and protocol stack. Simu5G supports FDD and TDD mode but is limited to one slot TDD patterns.

Martenvormfelde et al. design a network simulator based on INET and a custom 5G user plane [9]. They consider different slot sizes including mini slots and an evaluation scenario with a single periodic stream. However, [9] does not consider multiple streams, and the framework does not support QoS mapping and dynamic resource allocation. Hence, the allocation procedure cannot be adapted to the traffic type, implying pre-allocation even in the case of best-effort traffic.

Ginthör et al. [10] analyze end-to-end scheduling by combining INET and SimuLTE. To minimize the delay of periodic streams, the authors configure a Time-Aware Shaper (TAS) in the wired part to control the arrival of the streams at the 5G bridge. Suiting the arrival time, Resource Blocks (RBs) are pre-allocated. In addition to periodic traffic, they simulate best-effort traffic transmitted using the non-reserved RBs. Due to the joint framework based on INET and SimuLTE, they can analyze the performance of end-to-end schedulers considering the timing of a TSN shaper and the 5G RAN characteristics. Nevertheless, the authors only consider DL traffic and use a TDD pattern consisting only of a single DL slot. The simulator does not cover the mapping between TSN streams and 5G profiles and consequently does not implement a scheduler considering the 5G profiles.

QoS-aware scheduling combined with static QoS mapping is evaluated using the 5GTQ simulator by Debnath et al. [5]. They integrate Simu5G into INET by implementing the TSN translators, which map the streams on 5G profiles. The implemented QoS-aware scheduler ranks the flows based on different parameters depending on the configuration. Per default, the flows are sorted by their priority. Alternatively, the flows can be ranked based on their PDB or a metric combining the PDB and the priority value. The simulation scenarios only consider the FDD mode and DL use cases. Hence, the scheduler should be further evaluated in the TDD mode and in the UL to analyze its feasibility for industrial communication.

A similar framework consisting of Simu5G and INET is used by Ambrosy et al. [11]. Different from [5], the authors consider UL and DL traffic and the TDD mode. However, the simulator only maps the TSN stream to a priority level but not to a profile. Hence, the gNB only considers the priority in its own transmission order. Additionally, they did not extend Simu5G such that the TDD pattern consists of a single slot.

Although extensive work is done in simulating 5G integrated with TSN, the simulators published so far do not cover arbitrary TDD patterns reducing the relevance for private 5G.

IV. Network Simulator and Evaluation

The simulation framework proposed in this paper extends 5GTQ [5], improving the applicability for private 5G networks by implementing arbitrary TDD patterns. 5GTQ provides an

Parameters	Sporadic Traffic	Periodic Traffic
#RBs	50	
Frequency	3.7 GHz	
#Repetitions	50 (simulation time per run 50 s)	
Send Interval	exponential (10 ms)	constant (2 ms)
Payload Size	100 B	100 B
Numerology μ	1 (slot length 0.5 ms)	2 (slot length 0.25 ms)
TDD pattern	DDDDDDDSUUU	DDDSU
Resource Allocation UL	dynamic (#RBs after SR = {1,5})	pre-allocation (5 RBs)

TABLE II: Simulation scenarios including traffic and RAN parameters.

appropriate base for simulating 5G TSN networks because it already implements QoS mapping and TSN translators. Besides implementing the TDD patterns, the dynamic resource allocation is adapted. We implement the exchange of the messages for dynamic allocation, such as SR and grant allocation messages, in the respective slots. To reduce the delay in the UL, pre-allocation of RBs is implemented as an alternative to dynamic allocation. Moreover, this enables the evaluation of end-to-end schedulers based on aligning the PSFP schedule and pre-allocation in 5G as proposed by 3GPP.

We evaluate our framework in two simulation scenarios, shown in Table II, considering typical traffic types of industrial communication. Using periodic and sporadic traffic with different sending intervals, we analyze the impact on the delay of resource allocation parameters, the TDD pattern, and the numerology μ. The sporadic traffic is sent following an exponential distribution with a rate of 10 ms fitting the traffic type called event control (Table I). In the sporadic case, resources are allocated dynamically. The numerology and amount of slots per TDD pattern are aligned with the defaults of the open-source RAN implementation of OpenAirInterface (OAI) [12]. By default, a gNB in Simu5G provides a single RB after receiving a SR. This is compared to the default configuration of OAI, providing five RBs.

In the periodic use case, the packets are sent using a constant sending interval of 2 ms. Therefore, the use case fits the isochronous and cyclic-asynchronous traffic types. Due to the constant sending interval, the worst-case delay in the UL can be bounded by pre-allocating the radio resources. A single frame should be transmitted during one TDD pattern to reduce the jitter. Hence, the length of the TDD pattern is decreased to be smaller than the sending interval of the stream. Consequently, a higher numerology and a smaller number of slots are required, resulting in a TDD pattern consisting of five slots, each taking 0.25 ms. In the UL slot of the TDD pattern, five RBs are pre-allocated for the UE. In all simulations, an optimized channel is used to avoid retransmissions. Hence, it is assumed that a whole packet can be transmitted by the UE in each reserved slot, resulting in a reduced worst-case delay compared to dynamic resource allocation.

A. Initial Evaluation Results

In this Section, we evaluate the initial simulation results shown in Figure 2, considering the different traffic characteristics and RAN configurations. The simulation results are based on 50 simulation runs, each taking 50 s simulation time. Considering the UL results, the first configuration shows the sporadic traffic case using a TDD pattern with a periodicity of 5 ms. Per default, a single RB is granted after a SR, which is insufficient to send the whole packet. Hence, the UE has to wait for a second grant sent in the next DL slot. Combined with the transmission of the SR, the complete packet transmission takes at most 30 slots resulting in a delay of 15 ms until the packet transmission is finished. Because in 5GTQ, the receiver always waits to forward the packet to the upper layer until the acknowledgment is sent, the maximum delay is further increased by one slot.

In the case of granting five RBs after a SR, a single grant should be sufficient to transmit the packet, reducing the worst-case delay to 10.5 ms. However, due to the randomized sending interval, multiple packets can be buffered simultaneously. Hence, only the average delay is decreased by approximately 25% compared to the first configuration, but the maximum delay remains. This is verified by repeating the simulation with a static interval of 10 ms in configuration c), resulting in the expected reduced worst-case delay. Consequently, in the case of sporadic traffic, an interpacket gap smaller than the sending interval should be ensured, which can be achieved by a TSN traffic shaper such as the TAS.

The last UL configuration investigates the pre-allocation of resources and an adapted TDD pattern consisting only of five slots to transmit a periodic stream with an interval of 2 ms. The results show that the expected worst-case delay of less than 2 ms is fulfilled. Due to the pre-allocation and the static sending interval, the UE can always transmit its packet in a time interval of five slots.

In the DL, the gNB can allocate RBs dynamically in the next available DL or shared slot. Consequently, in this scenario, the delay is bounded by the length of the TDD pattern plus a single slot to transmit the acknowledgment.

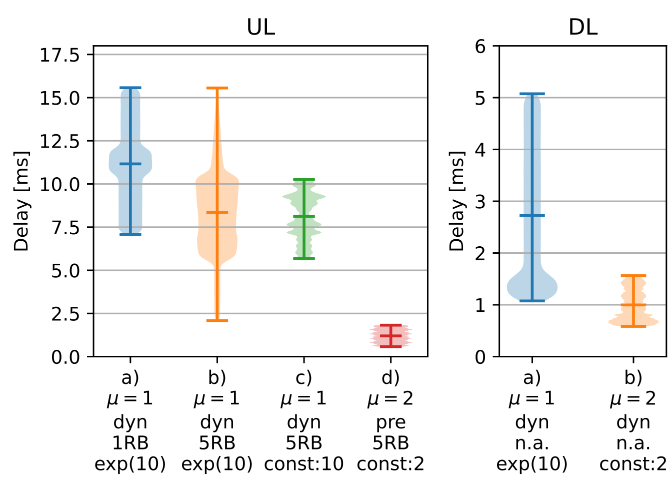

Fig. 2: Simulation results differentiated by their configuration parameters (numerology μ), dynamic or pre-allocation, #RBs granted after a SR, sending interval (exponential distributed or constant) given in ms.

V. Conclusion and Future Work

The proposed network simulator provides a suitable platform to simulate different industrial communication use cases, considering the characteristics of private 5G networks. Due to the support of TSN shapers and QoS mapping, different mapping algorithms and end-to-end schedulers can be compared under the consideration of arbitrary TDD patterns. The simulation results show the impact of the TDD pattern and the resource allocation on the delay and, therefore, demonstrate the significance of the integrated features in the simulator.

In future work, the simulation results should be verified and compared to the measurement results of hardware testbeds. Furthermore, end-to-end scheduling should be considered, such as aligning the PSFP gate control lists and the pre-allocation in the 5G RAN. To target the requirements of different 5G profiles, the existing QoS-aware schedulers should be further evaluated in the context of TDD. In scenarios including critical and best-effort sporadic traffic in addition to periodic traffic, pre-allocation for periodic flows should be combined with a QoS-aware scheduler controlling the dynamic allocation of the non-reserved resources. We plan additional implementations to enable the pre-allocation of resources for multiple streams.

References

[1] Time-Sensitive Networking (TSN) Task Group. IEEE 802.1. (accessed: 24.06.2024). [Online]. Available: https://1.ieee802.org/tsn/

[2] 3rd Generation Partnership Projec (3GPP), "Technical Specification Group Services and System Aspects; System architecture for the 5G System (5GS)," no. TS 23.501, 12 2023, version v18.4.0.

[3] Z. Bojthe, L. Meszaros, G. Szászkő, R. Hornig, A. Varga, and A. Török. INET Framework. (accessed: 30.06.2024). [Online]. Available: https://inet.omnetpp.org/

[4] 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.

[5] R. Debnath, M. S. Akinci, D. Ajith, and S. Steinhorst, "5GTQ: QoS-Aware 5G-TSN Simulation Framework," in *2023 IEEE 98th Vehicular Technology Conference (VTC2023-Fall)*, 2023, pp. 1–7.

[6] 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.

[7] 5G Alliance for Connected Industries and Automation (5G ACIA), "Integration of 5G with Time-Sensitive Networking for Industrial Communications," *5G-ACIA White Paper*, 2021.

[8] A. Virdis, G. Stea, and G. Nardini, "SimuLTE - A modular system-level simulator for LTE/LTE-A networks based on OMNeT++," in *2014 4th International Conference On Simulation And Modeling Methodologies, Technologies And Applications (SIMULTECH)*, 2014, pp. 59–70.

[9] 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.

[10] 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.

[11] N. Ambrosy, A. Abazari, and L. Underberg, "Simulations of the 5G-TSN bridge delay: towards a joint QoS model," 2023.

[12] Eurecom. OpenAirInterface Source Code for Next Generation Cellular Standard. (accessed: 27.06.2024). [Online]. Available: https://gitlab.eurecom.fr/oai