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Simulations of the 5G-TSN bridge delay: towards a joint QoS model

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Abstract: To integrate 5G mobile radio into Time-Sensitive Networking (TSN), the 3rd Generation Partnership Project (3GPP) specified the model of a virtual 5G-TSN bridge. This contains TSN translators which map principles such as time synchronization and Quality of Service (QoS) mechanisms from TSN to 5G. However, practical implementations with fine-granular QoS differentiation are not available yet. Therefore, in this paper, we examine the transmission delays of frames of the eight TSN traffic classes by simulating different scenarios while varying the QoS parameters priority, periodicity, and frame length. Our research contribution includes indications for the 5G bridge delay and Packet Delay Budget (PDB) depending on the traffic characteristics in a converged wired and wireless 5G-TSN network. This serves as a basis for the development of TSN translators and finally of a joint QoS model.

Keywords: 5G, Time-Sensitive Networking, Quality of Service, simulations, delay

1 Introduction

Flexible production processes and applications for Industry 4.0 require mobility and effortless reconfigurability and therefore a combination of deterministic wired and wireless communication technologies. This is specifically essential for time-critical machine communication. Possible use cases include wireless human-machine interfaces with emergency stop or automated guided vehicles to ensure personal safety in mobile applications. TSN and 5G are considered key technologies to meet the communication requirements of these use cases in converged wired and wireless networks.

TSN is the umbrella term for multiple IEEE 802.1 sub-standards that enable real-time capabilities and determinism for Ethernet. TSN includes mechanisms for time synchronization, bounded latency, high reliability, and dedicated resource management [IE23a]. The IEC/IEEE 60802 TSN Industrial Automation Profile intends to explicitly standardize the use of TSN in industrial automation, but is currently still in the draft stage [IE23b]. According to IEEE 802.1Q – Strict Priority, the traffic types in industrial communication are assigned to a total of eight traffic classes [In19], as listed in Tab. 1. A traffic class is identified using the Priority Code Point (PCP) as part of the Virtual Local Area Network (VLAN) tag. Priorities range from 0 to 7, where 7 represents the highest and 0 the lowest priority.

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Traffic Type	Periodicity [ms] (periodic/sporadic)	Data Delivery Guarantee	Data Size [bytes] (fixed/variable)	Criticality
Isochronous	0.1-2 (p)	Deadline	30-100 (f)	High
Cyclic synchronous or asynchronous	0.5-20 (p)	Latency	50-1000 (f)	High
Network control	50-1000 (p)	Bandwidth/data rate	50-500 (v)	High
Events	10-50 (s)	Latency	100-200 (v)	High
Alarms	2000 (s)	Latency	100-1500 (v)	Medium
Configuration & Diagnostics	N/A (s)	Bandwidth/data rate	500-1500 (v)	Medium
Audio/Video	A: 40 / V: 10 (p)	Bandwidth/data rate, latency	1000-1500 (v)	Low
Best effort	N/A (s)	None	30-1500 (v)	Low

Tab. 1: Traffic types and properties according to Industrial Internet Consortium [In19]

Tab. 2 shows the assignment of traffic types to traffic classes and priorities according to IEC/IEEE 60802, which differs slightly from that of the Industrial Internet Consortium. The combination of both serves as the traffic model for the simulations and will be discussed later.

Traffic Class	Priority (PCP)	Traffic Type
7	6	Isochronous
6	5	Cyclic synchronous
5	4	Cyclic asynchronous
4	7	Network control
3	3	Alarms & Events
2	2	Configuration & Diagnostics
1	1	Best effort high
0	0	Best effort low

Tab. 2: Traffic classes and priorities according to IEC/IEEE 60802 [IE23b]

5G as the fifth mobile radio generation is expected to meet industrial performance requirements, e.g., with the Ultra-Reliable Low Latency Communication (URLLC) feature to support time-critical machine communication. QoS in 5G is specified in 3GPP TS 23.501. Each QoS flow between the User Plane Function (UPF) and the User Equipment (UE) contains a certain QoS profile with multiple QoS parameters [5G21]:

- *Resource Type* defines how strictly other parameters should be handled. Guaranteed Bit Rate (GBR), Delay-Critical GBR, or Non-GBR can be distinguished.

- *Priority Level* indicates a flow's priority in relation to other flows for scheduling resources. Unlike TSN, the lowest value corresponds to the highest priority.
- *Packet Delay Budget (PDB)* sets an upper time limit for the delay between the UPF and the UE, before the packet is counted as lost.
- *Packet Error Rate (PER)* defines the reliability level by providing an upper bound on the number of incorrectly received or lost packets divided by the total number of received packets. The larger the packet and the lower the PDB, the higher the PER.
- *Maximum Data Burst Volume (MDBV)* indicates the data amount that can be sent without exceeding the PDB.

To integrate 5G into TSN, 3GPP specified the model of a virtual 5G-TSN bridge, as shown in Fig. 1 [3G22]. This model contains TSN translators which map information and parameters, e.g., for time synchronization and QoS, between TSN and 5G [RCK20]. 5G and TSN parameters can be translated as follows:

- TSN PCP ≙ 5G Priority Level
- TSN periodicity ≙ 5G transfer interval
- TSN frame length ≙ 5G MDBV.

One important aspect of QoS is the time delay that frames experience when traversing the 5G-TSN bridge, expressed by the PDB or bridge delay (BD). TSN AF determines and reports the minimum and maximum BD per port pair and traffic class to the CNC to check whether the delay requirements of the TSN stream to be added can be met.

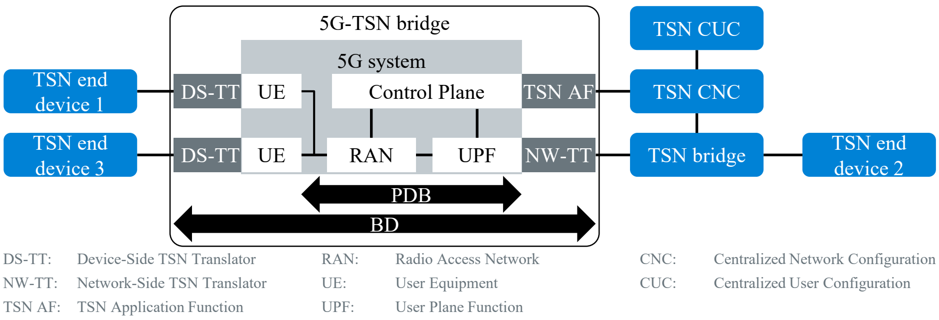

Fig. 1: 5G system as a virtual TSN bridge according to 3GPP TS 23.501 [3G22]

TSN traffic types and classes have different characteristics and requirements in terms of priority, periodicity, and frame length. They affect the delays within the 5G system and need to be considered to determine realistic BD and PDB values for frames of different TSN traffic types and classes. Using simulations of TSN traffic over 5G in OMNeT++, this paper examines the delays to provide indications for the parameters BD and PDB as a basis for a pre-configured 5G-TSN QoS mapping table, complementing previous theoretical considerations and analytical calculations. Thus, our paper contributes to the concretization of a joint 5G-TSN QoS model.

The remainder of this paper is organized as follows: Section 2 presents relevant related work. Section 3 explains the simulation framework. Section 4 presents the simulation results, which are discussed in Section 5. Section 6 concludes the paper with a summary and an outlook. Note that the paper contains an appendix with boxplot diagrams.

2 Related work

This section provides an overview of simulations of 5G delays in OMNeT++, which can be identified as relevant related work. Prototype implementations that reflect the scope of the simulations are not known.

Martenvormfelde et al. investigate only one TSN traffic class with 1 ms periodicity and a frame length of 256 bytes in downlink (DL) or 64 bytes in uplink (UL) according to the 5G-ACIA traffic model [5G19], for which they vary the UL/DL slot size [Ma20]. Magnusson and Pantzar and Satka et al. use their independently developed TSN translators and 5G link model and validate it in a use case with two different examples of TSN traffic classes, i.e., with two different PCP values, but without addressing all parameters of the TSN traffic classes [MP21], [Sa22]. Rost and Kolding use the commercial version OMNEST and also the 5G-ACIA traffic model. They achieve a bridge delay of 1 ms and less by replicating the 5G radio access network (RAN) through randomly selected signal-to-interference-to-noise-ratio (SINR) values [RK22].

Our simulations differ from the previous ones as follows: Based on the value ranges discussed in [AU22] and [AU23] as part of previous work, we use fixed worst-case and variable values for the parameters priority, periodicity, and frame length for each of the eight TSN traffic classes as input for the simulations.

3 Simulation framework

This section explains the simulation model in OMNeT++ with INET and Simu5G. INET Framework is a model library for the OMNeT++ simulation environment. It provides protocols, agents, and other models for communication networks, such as models for the Internet stack or wired and wireless link layer protocols. Several other simulation frameworks take INET as a base and extend it into specific directions, e.g., Simu5G [Bo23]. Simu5G simulates the data plane of the 5G RAN (according to 3GPP Release 16) and core network. It allows the simulation of 5G communications with multiple features and provides 3GPP-compliant protocol layers [VN20]. In this paper, INET 4.4.1 and Simu5G 1.2.1 are used.

To evaluate suitable values for the BD and PDB per traffic class, we simulate the 5G transmission times with Simu5G in the following four scenarios with different numbers of UEs and according to the traffic parameters shown in Tab. 3:

1. DL (UPF to UE)
2. UL (UE to UPF)
3. UE to UE (UL+DL)
4. Mixed (UL+DL between UPF and UE)

TSN traffic class	TSN traffic type	TSN priority/ 5G priority level	TSN periodicity/ 5G transfer interval [ms]	TSN frame length/ 5G MDBV [bytes]
7	Isochronous	6 / 2	1	68
6	Cyclic synchronous	5 / 3	10	500
5	Cyclic asynchronous	4 / 4	30	500
4	Network control	7 / 1	500	250
3	Alarms & Events	3 / 5	2000	800
2	Configuration & Diagnostics	2 / 6	1000	1000
1	Best effort high	1 / 7	25	1250
0	Best effort low	0 / 8	1000	1500

Tab. 3: Configuration of TSN traffic parameters for 5G transmission time simulations

In factories, the most likely scenario is an overarching 5G network for the entire plant site and several separate TSN networks per production cell, group of production cells, or, at its largest, an entire production hall. To evaluate scalability, we increase the number of UEs, starting from one UE. For better comparability, all of them are located in the same position at a distance of 10 m from the gNB. In total, the simulation contains 22 iterations (four scenarios, each with different numbers of UEs and without and with prioritization).

A timer is configured within the network to timestamp the packets at the sender and receiver (depending on the scenario). Fig. 2 shows a schematic drawing of the components and modules. To implement prioritization, modules need to be adapted by proprietary developments (depicted in green boxes): The server and gNB are modified by a *Ppp* compound module, including sub-modules called *DropTailQueue*, *Classifier* and *PriorityScheduler* to support eight priority queues. The modules *CbrSender* and *CbrReceiver*, which are genuinely used to transmit constant bit-rate (CBR) packets over the network, are modified to enable labeling packets in order to later being prioritized in the Ppp modules.

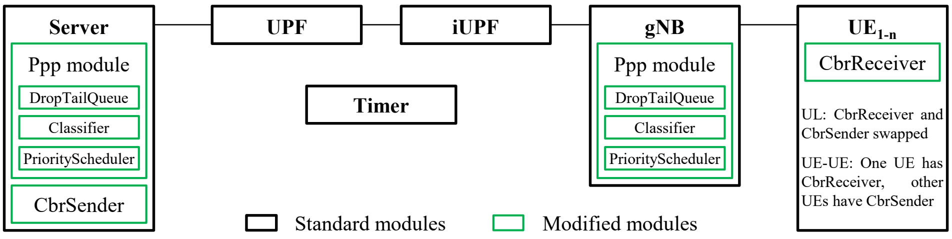

Fig. 2: Schematic drawing of the components and modules in OMNeT++

4 Simulation results

This section presents the simulation results of 32 iterations, including four scenarios with four different numbers of UEs each, both with and without prioritization.

Tab. 4 shows the maximum transmission times per iteration and traffic class. In all scenarios, a similar pattern can be observed. Large packets and packets sent with a low periodicity take longer. Prioritization affects the transmission times. They are higher in UL than in DL since the 5G time-division duplex (TDD) pattern typically provides fewer time slots and capacity for UL. The UL/DL slot ratio cannot be configured or changed in OMNeT++. Mixed traffic increases the network load and consequently the transmission times compared to pure UL or DL traffic. UE-UE communication always includes UL+DL and represents the most complex scenario with the highest transmission times.

Traffic classes 4, 6, and 7 with the highest priorities and traffic class 1 benefit from prioritization and rather in UL. In general, delays of small packets up to 500 bytes and low periodicities up to 25 ms improve. Two exceptions are traffic classes 1 (with 1250 bytes) and 4 (with 500 ms), where the prioritization also has a positive effect. Other traffic classes experience additional delays due to the packet queues introduced with the prioritization.

The more UEs are used, the higher are the mean values, maxima and outliers of the transmission time. In DL, UEs perform differently, although they are located in the same distance to the gNB. There is only one absolute maximum, but the mean values are similar. Due to separate time measurements per UE, multiple values can be obtained for DL. The UL provides only one value since the time is measured only at the server. The minimum values of the transmission time are 4-7 ms in DL, 4-15 ms in UL, and 9-20 ms for UE-UE (where three UEs perform better than two). For mixed traffic, minimum values are 5-7 ms in DL and 4-15 ms in UL. They seem to be independent of the packet size and periodicity.

Iteration	Scenario	Prioritization	Traffic class 7 1 ms, 68 bytes	Traffic class 6 10 ms, 500 bytes	Traffic class 5 30 ms, 500 bytes	Traffic class 4 500 ms, 250 bytes	Traffic class 3 2000 ms, 800 bytes	Traffic class 2 1000 ms, 1000 bytes	Traffic class 1 25 ms, 1250 bytes	Traffic class 0 1000 ms, 1500 bytes
1	DL 1 UE	N	13	13	12	14	12	11	11	8
2		Y	12	12	12	12	12	12	12	12
3	DL 2 UEs	N	21	21	19	22	19	18	20	15
4		Y	21	21	21	21	21	21	21	21
5	DL 3 UEs	N	46	43	40	46	29	36	42	28
6		Y	43	43	43	43	43	43	43	43
7	UL 1 UE	N	28	28	27	24	20	23	25	22
8		Y	28	28	27	28	26	26	26	23
9	UL 2 UEs	N	35	35	30	32	29	28	31	27
10		Y	31	31	30	31	30	30	30	27
11	UL 3 UEs	N	53	53	47	46	43	42	53	37
12		Y	51	51	49	51	49	49	49	39
13	UE-UE 2 UEs	N	35	35	33	32	27	31	34	30
14		Y	34	34	34	34	34	34	34	30
15	UE-UE 3 UEs	N	43	43	39	40	38	37	43	35
16		Y	44	44	40	44	40	40	40	35
17	Mixed 1 UE	N	DL: 13 UL: 28	DL: 13 UL: 28	DL: 12 UL: 27	DL: 14 UL: 24	DL: 12 UL: 20	DL: 11 UL: 23	DL: 11 UL: 25	DL: 8 UL: 22
18		Y	DL: 12 UL: 28	DL: 12 UL: 28	DL: 12 UL: 27	DL: 12 UL: 28	DL: 12 UL: 26	DL: 12 UL: 26	DL: 12 UL: 26	DL: 12 UL: 23
19	Mixed 2 UEs	N	DL: 23 UL: 35	DL: 23 UL: 35	DL: 22 UL: 30	DL: 23 UL: 31	DL: 21 UL: 29	DL: 20 UL: 28	DL: 21 UL: 31	DL: 16 UL: 27
20		Y	DL: 21 UL: 33	DL: 21 UL: 33	DL: 21 UL: 30	DL: 21 UL: 33	DL: 21 UL: 30	DL: 21 UL: 30	DL: 21 UL: 30	DL: 21 UL: 26
21	Mixed 3 UEs	N	DL: 42 UL: 54	DL: 40 UL: 54	DL: 33 UL: 46	DL: 37 UL: 49	DL: 30 UL: 45	DL: 35 UL: 42	DL: 39 UL: 51	DL: 29 UL: 35
22		Y	DL: 43 UL: 57	DL: 43 UL: 57	DL: 43 UL: 56	DL: 43 UL: 57	DL: 43 UL: 56	DL: 43 UL: 56	DL: 43 UL: 56	DL: 43 UL: 43

Tab. 4: Maximum transmission times per iteration and traffic class

Fig. 3-10 depict boxplot diagrams of those iterations where differences and effects are visible and comparable. The mean values and box sizes (lower and upper quartile) tend to be highest at traffic class 0 and 2, which is due to the combination of large packets and long time intervals. The whiskers of the boxplot diagrams end at the 5th and 95th percentile. The arithmetic mean, minimum and maximum values are given as numbers in the diagrams. The median is depicted as an orange line within each boxplot.

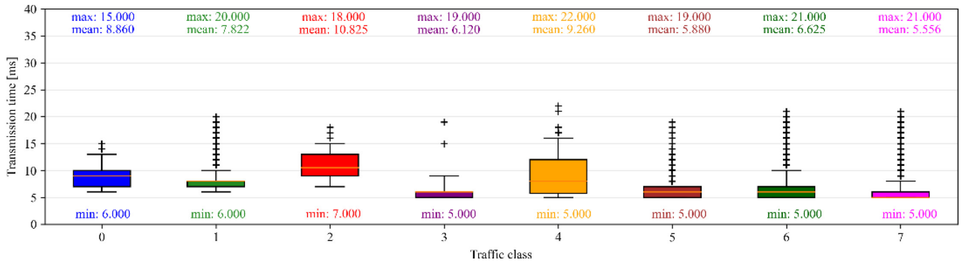

Fig. 3: Two UEs in DL without prioritization (iteration 3)

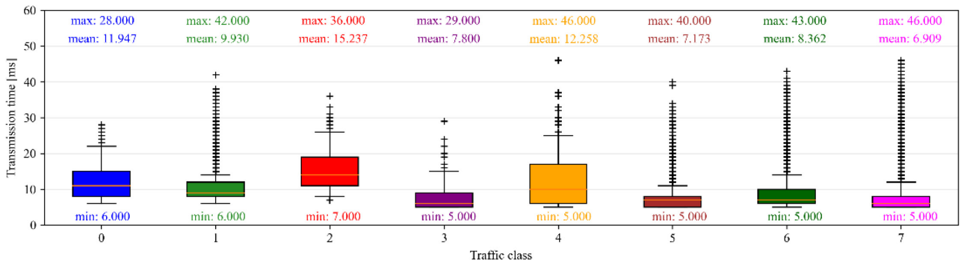

Fig. 4: Three UEs in DL without prioritization (iteration 5)

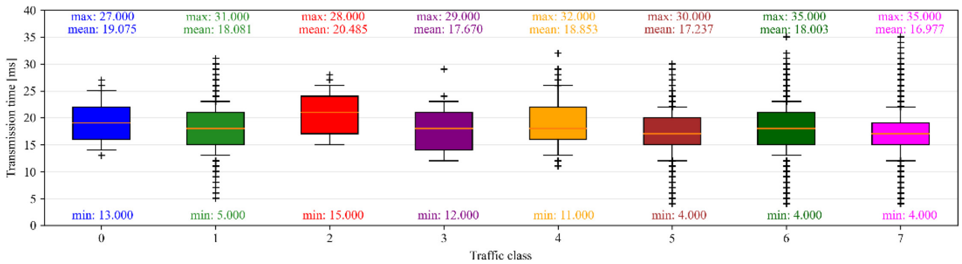

Fig. 5: Two UEs in UL without prioritization (iteration 9)

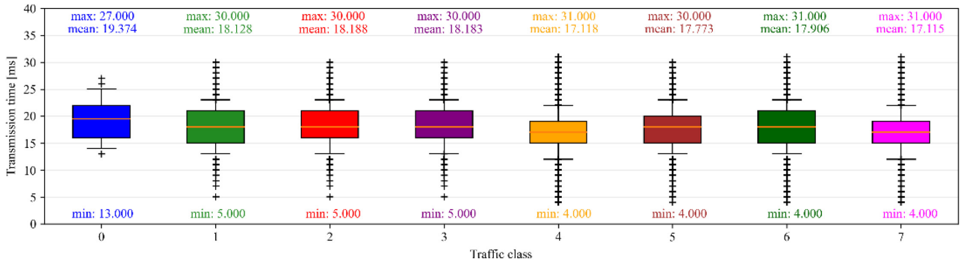

Fig. 6: Two UEs in UL with prioritization (iteration 10)

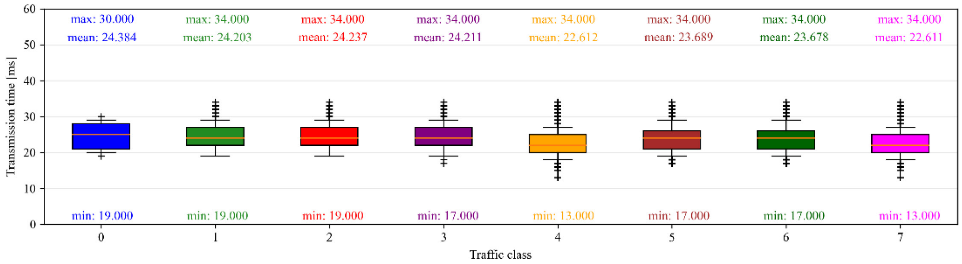

Fig. 7: UE to UE with prioritization (iteration 14)

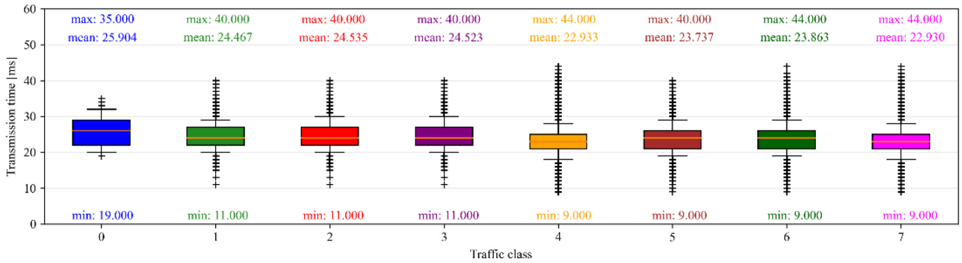

Fig. 8: Three UEs (two senders and one receiver) with prioritization (iteration 16)

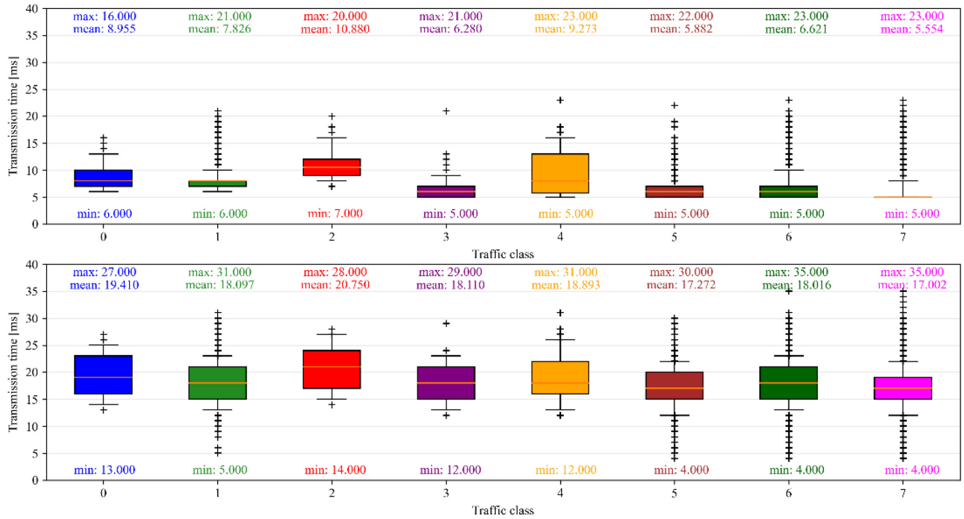

Fig. 9: Mixed traffic with two UEs and without prioritization; a) DL and b) UL (iteration 19)

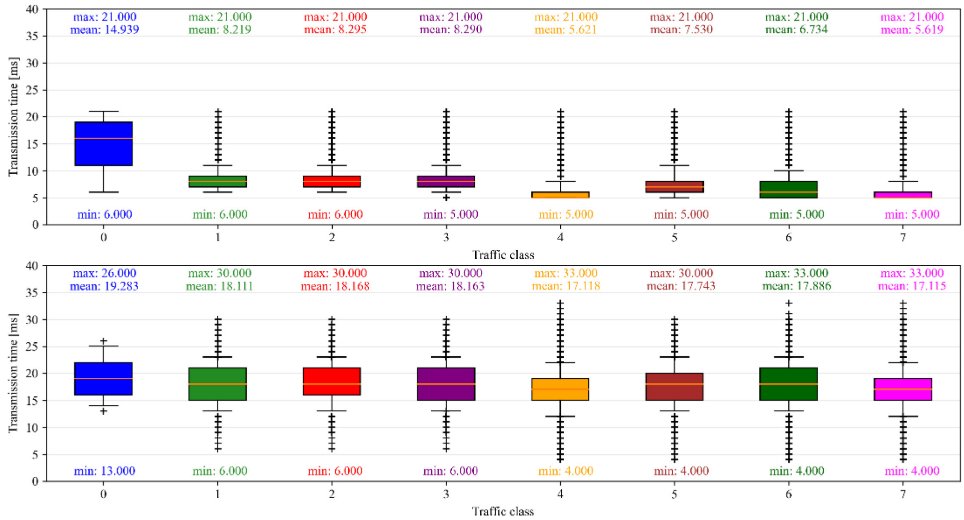

Fig. 10: Mixed traffic with two UEs and prioritization; a) DL and b) UL (iteration 20)

5 Discussion

In this section, the simulation results are discussed and conclusions for the 5G BD and PDB in the context of TSN are drawn.

The results are not reliable for more than three UEs since the transmission times are in the range of seconds. With four and more UEs, anomalies with packet loss and extremely high delays occur in each scenario and traffic class, e.g., in DL up to 16.9 s with five UEs or up to 46.7 s with ten UEs. Note that some packet loss may have occurred because the simulation had already finished when the packets were received. Therefore, the scalability of the simulation model is limited and the original plan with 50 and 100 UEs needs to be discarded. However, it can be estimated that the difference between the delays for prioritized and non-prioritized packets increases proportionally when the number of UEs increases. This issue can be further solved in more advanced simulations. Mobility of the UEs was not considered, but can be implemented in a future refinement of the simulation model. Although all UEs at the same location do not represent reality, this simplification was chosen for better comparability of the results.

Moreover, it is relevant to interpret the meaning of the simulation results for the BD and PDB. Transmission time can be equated with the BD. The transmission times are measured at the application level, since they are always about 1 ms between UPF and UE, regardless of the packet characteristics. Consequently, the applications at the sender and receiver cause the delays, which is assumed to be comparable to the delays introduced by NW-TT and DS-TT in the 3GPP bridge model, i.e., due to the conversion between wired and wireless transmissions. However, the simulated BDs significantly exceed expected values for time-critical TSN transmissions over 5G.

QoS in general and specifically the PDB cannot be simply set in Simu5G. The maximum transmission time values could be defined as PDBs of TSN traffic classes, but they still exceed the expectations for URLLC, which is obviously not supported by Simu5G. Prioritization could be implemented with a positive effect on high priority traffic classes. The more traffic occurs in the network due to larger packets, shorter periodicities and/or more UEs, the longer transmission times (≙ BD) result and the more a possible PDB is exhausted. It is questionable whether PDBs can simply be scaled down to values in the µs range and whether future 5GS will be able to comply with them under all circumstances.

6 Conclusion

In this paper, we analyzed relevant QoS parameters of the eight TSN traffic classes and simulated the transmission delays of typical TSN traffic flows in a 5G system. The results show that the delays depend on the parameters priority, periodicity, and frame length as well as on the examined scenarios and the number of UEs. The 5G bridge delays are too high for time-critical TSN traffic and the PDB cannot simply be limited to a certain value.

The QoS mechanisms need to be further investigated on the way to a joint 5G-TSN QoS model for future factory networks. Therefore, future work includes enhancements of the simulation model, e.g., a mobility model and improved scalability for more UEs, and experiments with QoS in real 5G-TSN implementations.

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