Determinism in Industrial Converged Networks: Evaluating Approaches to Jitter Mitigation in 5G and TSN Integration

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***Abstract*— Integrating 5G (3GPP) and Time Sensitive Networking "TSN" (IEEE) is critical for setting up converged networks in future factories, offering the high dependability and flexibility needed for industrial applications in the times of cyber-physical systems. A key challenge of that integration is the jitter introduced by 5G due to physical and technological limitations. Current standards suggest a hold-and-forwarding buffer at the 5G-TSN interface to homogenize the frame residence time in the 5G System, ensuring determinism at the cost of increased latency. This study evaluates that approach in comparison with an alternative combining Per-Stream Filtering and Policing (PSFP) and the hierarchical queuing techniques used in Asynchronous Traffic Shaping (ATS) in the TSN switches. This alternative approach mitigates jitter similarly but avoids raising the end-to-end latency considerably. Simulations in OMNeT++ using the INET Framework support this finding, with future tests planned when the features are available in commercial TSN switches.**

Keywords—De-jittering, 5G-TSN Integration, Hold-and-Forward Buffering, Time-Aware Shaping, Asynchronous Traffic Shaping, Hierarchical Queuing.

I. Introduction

The integration of wired and wireless networking technologies is an essential requirement for implementing the deterministic converged networks that will enable the factories of the future. This will allow novel use cases, such as flexible modular manufacturing [1], software-defined automation [2], or next generation industrial IoT with human-in-the-loop [3].

To achieve that integration, the interworking of 5G (3GPP) and Time Sensitive Networking "TSN" (IEEE) is gaining significant traction in research because, in theory, those technologies individually guarantee the particularly high level of determinism, reliability, availability and maintainability (qualities often condensed in the term "dependability") that industrial applications require.

A. The challenge of Jitter

A Fundamental challenge of the integration between 5G and TSN is that the 5G network will unavoidably introduce some jitter to the traffic. That is due to numerous reasons, such as physical effects (e.g. obstacles, multipath fading, interference) or technology limitations (e.g. insufficient QoS enforcing, inconvenient retransmissions). To overcome this issue, the current 5G standards (Rel 17-18) [4] introduce the idea of using a hold-and-forwarding buffer where the 5G network interfaces the TSN network, delaying the packets up to a point when the residence time inside of the 5G network is equal for all the packets of a given flow. That way, the traffic coming from the 5G System (5GS) can be deterministic enough to fit, for example, in a Time-Aware Shaping (TAS) schedule. It is known that this mechanism will increase the traffic latency, but it is generally accepted as a compromise to keep that latency bounded.

B. Contribution

This study compares the abovementioned approach for jitter mitigation (using hold-and-forwarding buffers) to a second one that leverages a combination of Per-Stream Filtering and Policing (PSFP) and Asynchronous Traffic Shaping (ATS) in the TSN switches. This comparison is focused on the trade-off between the efficacy of the jitter mitigation and its effects on the end-to-end latency of frames. Ultimately, this study seeks to highlight the variety of configuration possibilities that exist for jitter mitigation in integrated 5G/TSN networks, their advantages, and challenges.

The evaluation is done in a simulated environment using OMNeT ++ and the INET Framework and will be replicated in a real testbed once commercial TSN switches that contain the necessary features are available.

II. Background

A. Traffic Shaping in TSN

Traffic Shaping refers to the techniques in TSN used to manage network traffic to ensure timely and predictable communication. These techniques are generally applied at the egress of TSN switches or TSN devices, allocating specific resources for different types of data traffic. They regulate the flow of data packets through a network, reducing congestion and ensuring that high-priority, time-sensitive data reaches its destination within a bounded latency threshold. These techniques allow for the coexistence of both time-critical and less critical data on the same network infrastructure, optimizing the utilization of network resources and enhancing the overall reliability and efficiency of data transmission.

Two techniques for traffic shaping are relevant for this study: Time-Aware Shaping (TAS) and Asynchronous Traffic Shaping (ATS).

a) Time-Aware Shaping: Defined by the IEEE 802.1Qbv standard, and superseded by 802.1Q-2022 [5],

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Time-Aware Shaping (TAS) involves the use of time-controlled transmission gates, which TSN switches and devices are configured to open and close for data flow according to a precise schedule. This schedule is planned and optimized to ensure that high-priority and time-sensitive data packets are transmitted within convenient time frames, minimizing the risk of congestion and interference that could lead to delays and packet loss.

An important aspect to consider about TAS, is its dependence on a reliable method for keeping the time of all the devices synchronized to a single source. To achieve it, normally the Generalized Precision Time Protocol (gPTP), defined by IEEE 802.1AS-2020 [6], is used.

b) Asynchronous Traffic Shaping: ATS is defined in IEEE 802.1Qcr, and superseded by 802.1Q-2022 [5]. In contrast to TAS, ATS does not require time synchronization of all the switches in the TSN network. Instead, it operates on local times and optimizes the use of resources in every switch individually. To do so, it depends on per-stream filtering and policing at the ingress of the switches, where an algorithm calculates an eligibility time for every frame based on its priority, time of ingress and the required rate for its stream. That eligibility time, that will be shorter for high-priority frames, and longer for less-priority ones, is then used to arrange the transmission of frames at egress. Combining these two features: calculation of eligibility times at ingress and time-based queuing at egress, ATS achieves the effect of giving a sense of urgency to the transmission of time-sensitive frames.

This approach varies fundamentally from the one in TAS, because ATS does not reserve resources that can exclusively be used for a certain class, that means that those resources are not wasted in case of under-utilization. ATS, in contrast, shares resources among classes but utilizes them differently depending on the priority and requirements of each stream.

B. Per-Stream Filtering and Policing in TSN

As described in IEEE 802.1Qci, and superseded by 802.1Q-2022 [5], Per-Stream Filtering and Policing (PSFP) is a set of mechanisms applied at the ingress of TSN switches designed to manage and regulate the incoming traffic. It operates by filtering and policing individual data streams based on predefined rules and parameters, such as data type, priority, and bandwidth requirements. This can be done for various purposes, such as the identification and prioritization of time-sensitive traffic, or the protection of the network against malfunctioning devices or brute-force attacks.

C. 5G and TSN integration

The integration of 5G and TSN networks is actively under development by the research community and the corresponding Standardization Developing Organizations (SDOs): 3GPP and IEEE. The Releases 16, 17 and 18 of the 5G Standardization, in particular [4] and [7], define a considerable number of mechanisms and features that enable the interworking of the two technologies and the carrying of traffic across them with a certain level of dependability.

A comprehensive systematic review of the integration of 5G and TSN, available in [9], showcases the work from the research community on the integration. Several perspectives are displayed, and challenges are highlighted, for instance, the critical task of time synchronization of all TSN devices, when TAS is used in the integrated network.

D. Other studies on jitter mitigation for 5G-TSN

In the 5G standardization, specifically in [4], the idea of a hold-and-forwarding buffer in the 5GS for de-jittering is introduced. The idea is further developed in [8], and consists of a set of buffers, that hold the frames up to a point in which it is guaranteed that every one of them resided the same amount of time inside of the 5GS. The intention behind that is to be able to consider the 5GS as a network element of deterministic latency that does not add jitter to the traffic. This consideration allows for the planning of tightly scheduled integrated networks at the expense of higher end-to-end latency.

In addition, the authors of [9], identified 20 other studies that considered jitter as a variable to optimize in the end-to-end schedule generation problem for the integrated network. Those studies take different approaches into the problem of handling jitter, and make different assumptions, however most of them revolve around finding TAS schedules and gating schemes for the TSN sections of the integrated network that tolerate an expected amount of jitter and mitigate it. Some of those studies even measure their results on real testbeds displaying promising results.

III. Methodology

In this study, the network and traffic scenarios depicted in Figure 1 are used to evaluate and compare two possible configurations for jitter mitigation: One leveraging hold-and-forward buffering in the 5GS in tandem with Time-Aware Shaping in the TSN network, and another one using Per-Stream-Filtering and Policing in combination with Asynchronous Traffic Shaping. Some relevant disclaimers about the methodology are:

- Both configurations focus on jitter mitigation mechanisms that can be applied in the TSN section of the integrated network, in the 5G core network, or in the 5G UE (User Equipment). For this study, possible QoS mechanisms that could be applied to the 5G RAN (Radio Access Network) are not considered.
- This study does not entail the time synchronization of the 5G System and the TSN network. When Time-Aware Shaping is used, time synchronization is always assumed between the two regular TSN switches only.

The following sections detail the different elements of the evaluation.

A. The Virtual 5G TSN Switch

Considering the mechanisms described by the 3GPP standards [4], it is observed that the main architectural principle of the integration with a TSN network is that the 5GS should be perceived and recognized by the other devices in the network as a TSN switch. Therefore, the 5G system in this study is modelled as a virtual TSN switch with several modifications. The INET network node type *TsnSwitch* was extended to create the *FiveGTsnSwitch* type, which includes:

- A fixed minimum residence time for every frame inside of the 5GS.

- A function that generates delay values added to the abovementioned minimum residence time, following normal probability distributions characterized by the parameters shown in Table 1. This function is in following referred to as *jittergenerator(packet_size).*
- A Hold-and-Forwarding Buffer. This simplified version of the one described in [8] can retain the frames during a configured holding time.

The fixed minimum residence time and jitter values are derived from the analysis of the dataset available at [10], which was captured from a real 5G campus network similar in configuration to one that would be used for the industrial applications considered here.

TABLE 1: PARAMETERS OF THE NORMAL PROBABILITY DISTRIBUTIONS OF JITTER ADDED BY THE 5GS FOR DIFFERENT IP PACKET SIZES [10]

IP Packet Size (bytes)	Jitter Values (ms)				
	Min	Q_1	***Mean***	Q_3	***Max***
128	1.9	3.9	4.2	5.7	7.3
256	1.3	3.5	4.3	5.8	7.7
512	2.3	3.5	4.7	5.9	9.1

B. *The network*

The simulated network in this study comprises one client that generates the traffic streams, the virtual 5G TSN switch, two regular TSN Switches, and two servers that consume the traffic. The links and ethernet interfaces in the switches are dimensioned for 100 $Mbps$.

The devices are connected as shown in Figure 1.

The rationale for using two different servers consuming similar traffic in different positions of the network is to analyze the effect of the topology in mitigating jitter. The traffic flowing to Server 1 traverses only two switches (the virtual 5G TSN switch and one regular TSN switch), while the traffic consumed at Server 2 is forwarded by three switches.

C. *The Traffic*

Figure 1 also depicts the traffic being carried by the network. The client generates application traffic of two classes: Higher Priority and Lower Priority, and sends it to both servers. The characteristics of those traffic streams are shown in Table 2.

Given the particular interest of this study in industrial applications and networking for control systems, the higher priority traffic was modelled after the real traffic generated by a PLC and captured for the dataset available at [11]. The lower priority traffic was modelled after another frequent industrial application: video streams with codecs using fixed packet sizes.

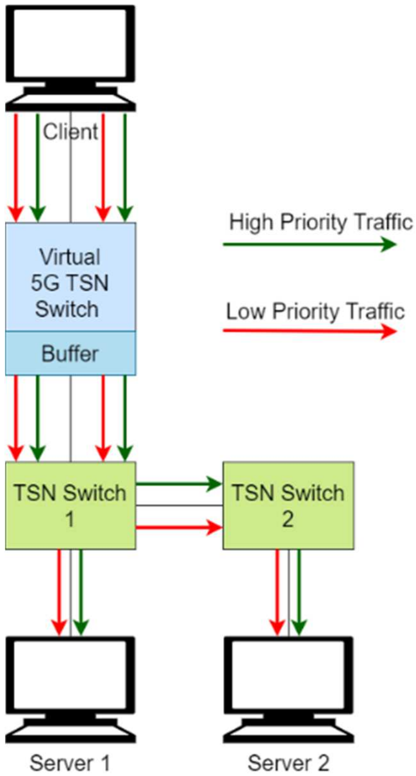

Figure 1: Simulated network and traffic

TABLE 2: CHARACTERISTIC OF THE DIFFERENT TRAFFIC CLASSES

Traffic Class	**Higher Priority**	**Lower Priority**
Application	PLC traffic (Modelled after [11])	Video traffic (Fixed packet size)
Transport Protocol	UDP	UDP
IP Packet sizes	Varying from 128 $bytes$ to 512 $bytes$	512 $bytes$
Periodicity	Periodic	Periodic
Bandwidth	5 $Mbps$	5 $Mbps$
PCP	4	2

From a network design perspective, this study presents a simple scenario: There are four streams, three endpoint devices, and two traffic classes. Additionally, the links and switches are over-dimensioned with regards to the actual bandwidth required for the classes. The reason of this simplicity is to allow for the observation of the effects the two configurations in the jitter mitigation without being greatly influenced by the different scheduling and resource reservation algorithms that can be used for TAS or ATS depending on the traffic conditions.

D. Configuration "5GBuf+TAS": Hold-and-Forwarding Buffering at 5G edge + Time-Aware Shaping in the TSN Switches

The first configuration evaluated to mitigate jitter and achieve a deterministic integrated network is the one suggested in 3GPP standards and most used in testbeds: the use of a Hold-and-Forwarding Buffer at the place where the 5G and TSN networks interface.

This feature is frequently paired with a scheduled and time-synchronized TSN network, using TAS, to guarantee that the traffic will continue its path through the network with zero-jitter conditions achieved thanks to the buffer. Thus, that shaping mechanism is also used in this configuration.

a) Buffer implementation: A buffer was implemented at the egress interface of the virtual 5G TSN switch as shown in Figure 1. The holding time in the buffer is calculated per frame as the difference between the maximum value of jitter possible for packet size in *Table 1 (*$9.1\ ms$*)* and the value of jitter assigned to that particular frame by the *jittergenerator()* function. This guarantees that every frame resides inside of the virtual 5G TSN switch for exactly $13.1\ ms$, corresponding to the maximum possible value of jitter *(*$9.1\ ms$) plus the minimum fixed residence time in the 5GS *(*$4\ ms$*)*. This certainty in the total residence time of every frame means the propagation of the periodic conditions with which the client generated the traffic, and makes the use of TAS in the TSN network downstream convenient, as discussed in *[8]*.

b) TAS implementation: As discussed in III.C, the relatively uncomplicated network scenario suggests that employing either a basic or a more sophisticated scheduler would not result in significant differences. Therefore, the *TSNschedGateScheduleConfigurator* module *[12]* available in the INET Framework was used to automatically set up the TAS schedules in the two TSN switches. The gate cycle duration is set to $0.9\ ms$, approximating the interarrival time of the frames of both traffic classes, calculated from the data in *Table 2*. Additionally, two egress queues are set in the switches (one per traffic class). And lastly, the maximum latency is bounded to $1\ ms$ for the higher priority streams and $5\ ms$ for the lower priority streams.

It should be noted that the TAS schedules and configurations were not applied to the virtual 5G TSN switch, as this study assumes a 5GS that does not include this feature.

E. Configuration "PSFP+ATS": Per-Stream Forwarding and Policing + hierarchichal queuing in the TSN Switches

The second configuration evaluated is entirely focused on mechanisms applied in the TSN section of the network. Thus, this configuration considers a level of tolerable jitter coming from the 5GS and attempts to mitigate it while the traffic traverses the TSN switches. Here, a combination of per-stream filtering applied at the ingress of the switches and hierarchical queuing applied at the egress (as defined for ATS in [5]) is used.

It is important to stress that in this case, the hold-and-forwarding buffer of the virtual 5G TSN Switch is disabled. With this, only the *jittergenerator()* function and the addition of fixed minimum residence time are applied to every frame, as discussed in Section III.A. For this approach, the 5GS is assumed to lack any mechanisms for jitter mitigation, which corresponds to the current reality in commercial 5G equipment.

a) Per-Stream filtering and calculation of eligibility times: The TSN switches are configured to decode the streams at ingress and classify them according to their PCP values (4 for the higher priority traffic and 2 for the lower priority one). Once classified, the *EligibilityTimeMeter* module [13] of the INET Framework is used to assign eligibility times to every frame. To do so, two parameters are configured per stream: the committed information rate and the committed burst size. The information rates are all set to the original bandwidth required for the streams ($5\ Mbps$), while the burst sizes are calculated considering the maximum sizes of the frames ($542\ Bytes$) and a "tolerable burstiness" per switch.

The abovementioned tolerable burstiness refers to the amount of frames that can be allowed to burst (suddenly arrive in a short time interval) in the shaper. This parameter is used in this study to control the shaper's jitter mitigation effect. It is set differently and progressively in the two switches. Given that TSN Switch 1 will receive highly jittered traffic, its maximum burstiness must be comparably high to avoid excessive frame dropping; in contrast, TSN Switch 2 receives better-shaped traffic and intends to decrease its jitter even further. Considering that, the committed burst sizes are set to 27 Kb for higher priority traffic and 54 Kb for lower priority traffic in TSN Switch 1; and 5.4 Kb for higher priority traffic and 27 Kb for lower priority traffic in TSN Switch 2. It is to be observed that considerably less burstiness is allowed to the higher priority traffic than to the lower priority one. In that same direction, the maximum residence time parameter of the module is disabled, to avoid packet drops due to timeouts, and the queue sizes are set large, to deal with the repercusions of that decision.

b) Hierarchical queuing for traffic shaping: Similarly as in the case with TAS, two queues are used (one per traffic class), but in contrast, in this case these are not simple FIFO queues, but a virtual implementation of the arrangement of shaped and shared queues used by the Urgency-Based Scheduler explained in [14]. This hierarchichal queuing organizes the frames in the different queues according to their eligibility time, allowing that delayed frames skip positions in the queues and are sent quicker. This behaviour is implemented in the *EligibilityTimeQueue* module of the INET Framework [15].

Regarding the gate control at the egress, the *EligibilityTimeGate* module [16] was used to prevent that frames leave the queues before their time is up.

IV. Results and Discussion

Two metrics are of particular interest in this study: jitter and end-to-end latency. All the values displayed in this section were recorded during the same time window of one minute.

A. Jitter

The first measurement provided is the jitter for the different traffic classes in the two servers. Jitter can be measured in various ways; in this study it is understood as the frame delay variation measured with respect to the mean end-to-end latency per traffic class and frame size in the respective measurement window. Figure 2 shows a timeline of measurements of the jitter per frame in Server 1, discriminated by traffic class. Table 3 shows the minimum, maximum, and mean values for clarity.

Figure 3 displays the jitter measurements in Server 2. And Table 4 depicts its minimum, maximum and mean values.

TABLE 3: JITTER MEASURED AT SERVER 1

Configuration	*Traffic Class*	*Jitter (ms)*		
		Min	*Mean*	*Max*
5GBuf+TAS	Higher Priority	0.0	0.3	0.5
	Lower Priority	0.1	1.1	2.0
PSFP+ATS	Higher Priority	0.0	0.8	1.7
	Lower Priority	0.1	1.2	3.5

TABLE 4: JITTER MEASURED AT SERVER 2

Configuration	*Traffic Class*	*Jitter (ms)*		
		Min	*Mean*	*Max*
5GBuf+TAS	Higher Priority	0.0	0.3	0.5
	Lower Priority	0.1	1.1	2.0
PSFP+ATS	Higher Priority	0.0	0.5	0.9
	Lower Priority	0.1	0.8	1.2

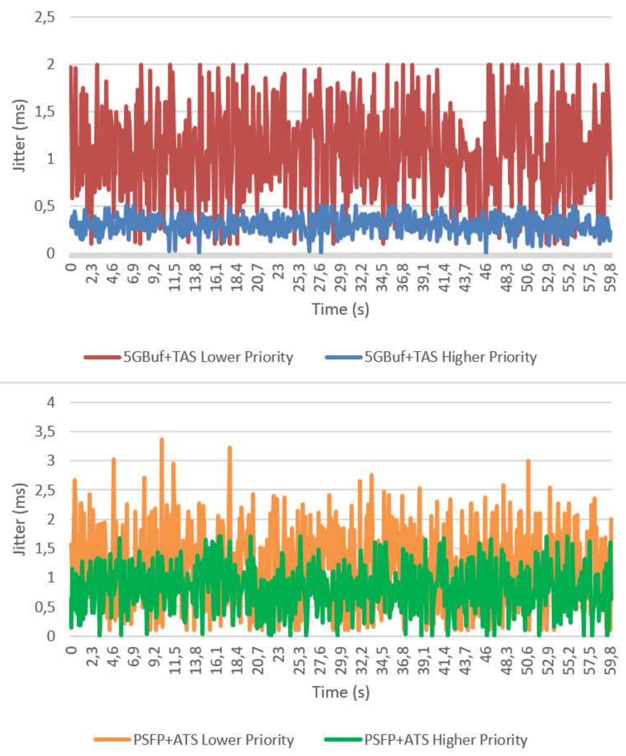

Figure 2: Jitter measurements for Server 1

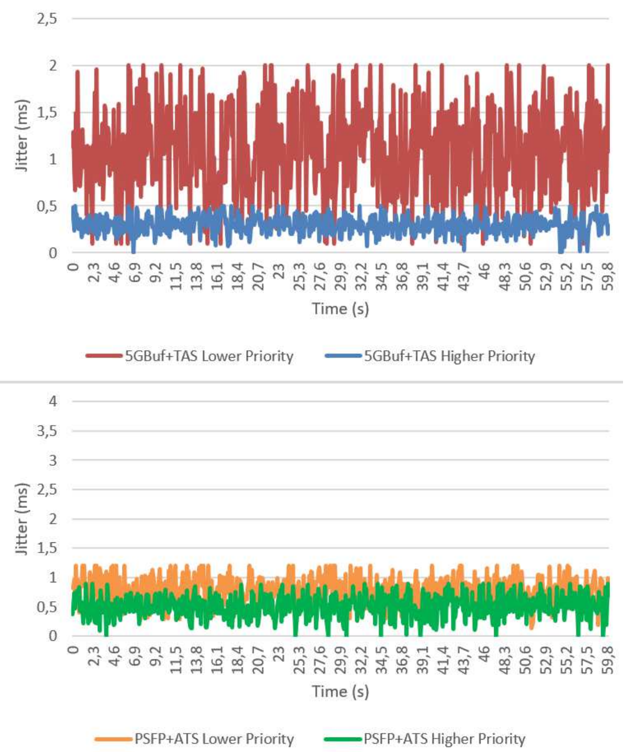

Figure 3: Jitter measurements for Server 2

B. End-to-end Latency

Figure 4 depicts a box diagram that summarizes the measurements of end-to-end latency at Server 2. In this occasion, the measurements of Server 1 are omitted because they show a similar trend and do not offer additional information.

C. Discussion

From the inspection of the results, several facts can be observed. The use of hold-and-forwarding buffers, in combination with a time scheduled TSN network, is indeed the configuration that achieves the best mitigation of jitter and guarantees the propagation of this condition up to the endpoints. However, that comes at a very high cost, as it can elongate the end-to-end latency drastically. In the other hand, relying on the TSN mechanisms of PSFP and ATS to handle the jitter introduced by the 5G network, is also arguably very effective, while barely influencing the end-to-end latency.

An interesting feature of configuration PSFP+ATS is that it can be implemented in a certain way that progressively mitigates jitter as traffic travels through the network. The idea is that the first switches that encounter the jittered traffic, have long queues and relaxed configurations of maximum allowed burstiness, so that the frame drop is kept minimum, but for the switches downstream, the parameters are set gradually stricter, to achieve the jitter mitigation. Naturally, this is only valid for medium or large networks that contain several switches. In this study, this effect was achieved with the configuration of the committed burst sizes in the shapers.

The simplicity of the network design used for this study, allowed for the observation of the fundamental differences of the two configurations, however, measurements in real testbeds (with more complicated topologies) will be performed as soon as the required features are released in commercial TSN switches.

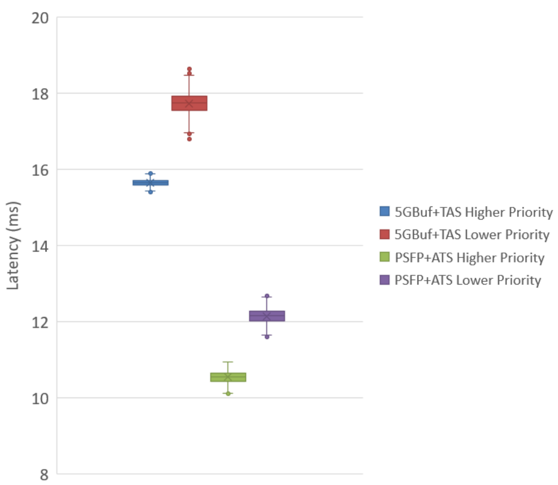

Figure 4: Diagram of end-to-end latency values in Server 2

V. Conclusions

This study evaluated and compared two different approaches for jitter mitigation in an integrated 5G-TSN network, namely the “5GBuf+TAS” and “PSFP+ATS” configurations.

The choice of which configuration to use will depend on the particular requirements of each use case, however, considering the following points, it can be preliminarily concluded that the configuration using PSFP and ATS is applicable to a larger number of industrial scenarios:

- This study showed that jitter mitigation is possible and convenient in the integrated network using ingress policies and asynchronous traffic shaping.
- This study showed that this jitter mitigation method can be less costly in terms of end-to-end latency than the popular option of using hold-and-forwarding buffers.
- The use of buffers and TAS would require the time synchronization of all switches in the network (and, for some use cases, even some components of the 5G system), which entails a considerable technical challenge.

Given the diversity of shaping, scheduling, policing and QoS handling mechanisms introduced by the TSN and 5G standards, there are many other configurations and approaches that can be implemented. Because of that variety, proper evaluation work is required to better guide the roadmaps of the designers and vendors of TSN and 5G equipment.

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