Time-Sensitive Networking over the Air: Combining 5G and TSN

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***Abstract*—The combination of guarantees from Time-Sensitive Networking and wireless transmission via 5G radio technology is an ongoing challenge in literature and standardization efforts. This paper summarizes the concepts behind this combination, their technical requirements, the existing solutions, and suggests a slightly different approach at the end.**

I. INTRODUCTION

The proliferation of the Internet of Things (IoT) and the demand for ultra-reliable, low-latency communications have driven the evolution of 5G networks from connecting people to connecting things. This shift transforms industry operations, enabling innovative use cases in manufacturing, energy, healthcare, transportation, and more that require real-time, mission-critical communication.

Time-Sensitive Networking (TSN) [1] addresses the requirements of time-critical applications. Operating over standard Ethernet networks, TSN offers precise time synchronization, low predictable latency, and seamless coexistence with Best-Effort traffic. Integrating TSN with 5G and future 6G deployments could provide a scalable infrastructure for reliable transmission in public, on-premise, or campus networks. The data plane is crucial for this integration, acting as the backbone for packet forwarding, scheduling, and QoS provisioning.

Integrating TSN into the 5G ecosystem presents challenges, particularly regarding the architectural and operational differences. 5G serves diverse devices and applications, while TSN is tailored for real-time communication in localized environments. On top of that, modern Ethernet can transmit in full duplex free of collisions, while 5G is subject to interference and other disruptions common to radio technologies. Bringing them together requires analyzing the technical implementations and differences of the two technologies.

This work explores the challenges of integrating TSN into the 5G ecosystem, focusing on enhancing the 5G data plane. By analyzing 5G and TSN technologies, protocols, architectures, and requirements, we identify necessary enhancements for a cohesive, future-proof infrastructure. Ensuring seamless coexistence of TSN and traditional 5G traffic is crucial as 5G evolves. Solutions must address all planes of operation, including resource allocation, scheduling, and shaping.

In this ongoing work, we aim to address the following research questions: (RQ1) What is the current state-of-the-art regarding the integration of TSN and 5G? (RQ2) Which challenges arise from the integration of these technologies? (RQ3) What modifications to either technology are required? (RQ4) What are the limitations of their seamless integration? Note that this work is not finished and shows our current state in that process.

In the following, Section II presents an overview of TSN technologies from the perspective of their implementation requirements. Then, Section III addresses the existing concepts towards the integration of TSN and 5G from available literature. Further, Section IV presents our perspective on this issue, showing a different approaches towards the same problem. Finally, Section V concludes the paper.

II. CONCEPTS BEHIND TSN AND DETNET

A major challenge with Time-Sensitive Networking (TSN) [1] and Deterministic Networking (DetNet) [2] is their wide array of tools and flexibility. Both aim to provide deterministic transmission with guaranteed latency and no congestion loss at layer 2 (TSN) and layer 3 (DetNet). However, their architecture, implementation, and services can vary greatly based on use case and tools used. This section provides an overview of deterministic networking tools, summarized in Table I. For more details, refer to the working groups [1], [2] and surveys [3].

In literature, TSN tools are typically structured by their intent, into the categories *time synchronization*, *bounded low latency*, *ultra reliability*, and *dedicated resources*. However, to better assess their integration into a 5G architecture, they are categorized by technical implementation in Table I. In the simplest case, the standards define new *protocols and data types for configuration and signaling*, implemented in software on the control plane and forwarded with Best-Effort service. In contrast, *time synchronization* requires hardware support for sub-microsecond accuracy from both end stations and switches. Many standards in the bounded low latency category suggest *new service disciplines*, such as shapers that add artificial delays to reduce network burstiness. They are usually implemented in ASICs to ensure full throughput and minimal latency variance. Some standards adjust the underlying *forwarding mechanism*, like frame preemption and cut-through forwarding. Preemption pauses and resumes low-priority frame transmissions to allow higher priority frames to pass, while cut-through forwarding transmits frames as soon as the destination MAC address is known, at a higher risk of transmitting frames with invalid checksum. To enhance the *reliability* of frame transmissions in case of device malfunctions and link failures, several mechanisms provide seamless

Table I
SUMMARY OF TSN AND DETNET TOOLS FROM AN IMPLEMENTATION PERSPECTIVE

Category (Layer 2 TSN)	**Examples**	**Technical implementation & hardware responsibilities**
Protocols, data types, signaling	Configuration, stream reservation	Typically handled by CPU / in software, no strong QoS requirements
Time synchronization	PTP packets	Time stamping, header rewrites
Service disciplines	Traffic shapers, timed gates	Priority based transmission, timed gates, shaping
Forwarding mechanisms	Frame preemption, cut-through	Pause and resume transmissions, forward incomplete frames before fully received
Reliability mechanisms	Filter, meter, duplicate elimination	TCAM, SRAM, frame matching, conditional frame dropping before queuing
Category (Layer 3 DetNet)	**Examples**	**Technical implementation & hardware responsibilities**
Config & end-to-end signaling	YANG config model, RSVP	Typically handled by CPU / in software, no strong QoS requirements
Lower layer technologies	MPLS, TSN	Typically, mapping is performed by controller in software, part of configuration

(The completion of this Table is subject of ongoing research.)

redundancy and reduce the impact of malfunctions on other components, such as filters and meters. These functions are typically performed by the ASIC before queuing.

DetNet, as a layer 3 technology, focuses on end-to-end addressing and signaling of individual flows rather than specific packet forwarding methods. Configuration tasks use frequently updated YANG models. DetNet implementation often relies on lower layer technologies like MPLS and TSN. The challenge is mapping desired behaviors to lower layer configurations. Routers must ensure outgoing traffic adheres to layer 2 reservations, typically achieved by per-flow re-shaping using methods like token bucket shapers.

In summary, the implementation complexity is scattered ranging from simple software solutions (signaling), over common hardware features (PTP, priority), to specific hardware features (timed gates, preemption, redundancy). Depending on the use case and the required features, the challenges towards integration of these features in the 5G architecture may vary.

III. TSN INTEGRATION IN 5G BY 3GPP

Section III-A provides an overview of existing literature in TSN and 5G integration, highlighting methodologies, architectures, and performance evaluations from relevant studies. Afterwards, Section III-B presents the most important models from a technical perspective.

A. Literature Overview

For industrial Ethernet, several architectures have been proposed based on 3GPP 22.804 Release 16 [4]. Baek, Kim, Tesanovic, *et al.*[5] analyze features relevant to robotics and autonomous systems (RAS) in industrial IoT, identifying radio scheduling, intra-UE prioritization, Ethernet header compression, packet duplication, and reference time provisioning as key enablers. Shi, Aijaz, and Jiang[6] evaluate over-the-air time synchronization, showing synchronization error between $250\,\mathrm{ns}$ and $2200\,\mathrm{ns}$ depending on configuration, achieving the desired $1000\,\mathrm{ns}$ error in some cases [4]. Other studies investigate scheduling impacts on throughput and latency [7], Ethernet header compression [8], and resource allocation [9]. Recently, Satka *et al.* [10] published a survey of TSN-5G research, highlighting the lack of real evaluations, experience papers, and tools in the area.

Several works outline a fully transparent integration of 5G as a logical TSN bridge based on 3GPP 22.804 Release 16 [7], [11]–[13]. TSN translators are introduced on both the device and network sides to interface with external TSN entities and the 5G core network. These translators map TSN streams to PDU sessions, with each session internally mapped to multiple QoS flows, including best-effort traffic.

According to 3GPP 23.501 [14], two approaches for TSN and 5G integration are present in standardization. The first approach involves transparently abstracting the 5G environment as a logical TSN bridge, introducing device-side TSN translators (DS-TT) and network-side TSN translators (NW-TT) that communicate with the Time Sensitive Communication and Time Synchronization Function (TSCTSF). These translators provide functionality for de-jittering and filtering. Optional features include link layer connectivity discovery and time synchronization [14]. The document also outlines support for IETF DetNet by abstracting the 5G system as a logical DetNet transit router, with TSCTSF interfacing with an external DetNet controller [14]. These approaches are detailed in the following Section.

B. 3GPP Virtual TSN Bridge

The 3GPP proposes two distinct adaptations for integrating TSN functionality into the 5G System (5GS), detailed in 3GPP technical specification 23.501 [14]. Four specialized additions to the 5GS are explored, two in the control plane and two in the user plane.

In the control plane, the Time Sensitive Networking Application Function (TSN AF) supports control plane translator functionality, ranging from bridge management to mapping TSN streams according to IEEE standards. The Time Sensitive Communication and Time Synchronization Function (TSCTSF) implements time synchronization capabilities within the 5GS, managing synchronization requests and status reporting based on data from the NG-RAN and UPF/NW-TT. It also supports BAT offset and adjusted periodicity for RAN.

In the user plane, the device-side TSN translator (DS-TT) and network-side TSN translator (NW-TT) support the same capabilities on different sides of the 5GS. These translators support various PTP instance types and can act as PTP grandmasters, supporting at least one PTP profile described

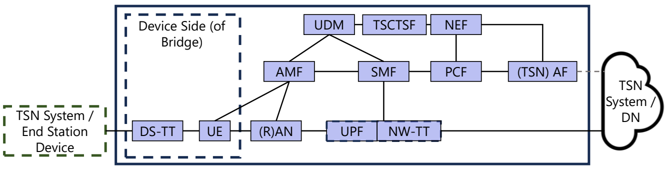

Figure 1. Logical TSN bridge from the 3GPP specification

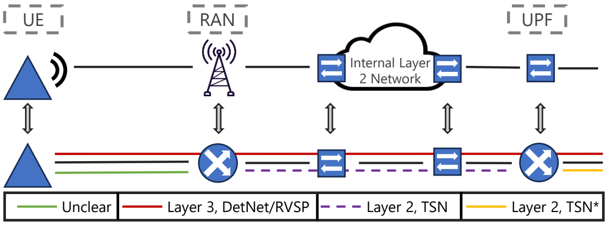

Figure 2. Coexistence of TSN and 5G networks, connected by routers

in IEEE Std 1588 [15]. PTP functionalities are set by the TSN AF and TSCTSF using port and node management information. The DS-TT and NW-TT optionally support de-jittering and per-stream filtering and policing, and can discover link layer connections for attached Ethernet devices. Together, these translators and network functions implement a fully transparent logical TSN bridge, illustrated in Figure 1.

A distinguished TSN transport network can be established between the UPF and (R)AN of the 5GS, using a fully centralized configuration as specified in IEEE Std 802.1Q [16]. This supports TSN-based communication between the access network and the data network.

Note that the 3GPP's approach towards the *logical DetNet router* is very similar and omitted here due to space constraints.

IV. ANOTHER PERSPECTIVE

The abstraction of the entire 5G transmission path into a logical TSN bridge comes with certain caveats. Most importantly, pure TSN networks are typically very homogeneous with respect to hardware and configuration. Providing ultra-low latency guarantees requires very tight cooperation between neighboring devices, which often means that all switches are configured with the same shapers, and with similar parameters. Further, as a layer 2 TSN bridge, it must forward all kinds of incoming signaling packets through the radio interface to the other end, including ARP, spanning tree protocols, device discovery protocols, and various other broadcasts. This provides additional strain on the radio interface, which, as a shared half-duplex medium, is inherently limited in capacity. Note that this strain only increases for the entire network with the number of individual UEs in that logical bridge, unlike real Ethernet bridges, where every port has its own isolated full-duplex communication channel.

As a result, our suggestion is to integrate the 5G communication channel as an entirely separate LAN, logically connected to the wired TSN network via routers. The general idea is depicted in Figure 2. Here, the 5G network does not pretend to be a logical TSN bridge, but the layer 2 TSN network terminates at the UE and at the UPF, respectively. From that perspective, the RAN and the UPF take the roles of routers, separating three entirely different LANs from each other: the outside TSN network (yellow), the LAN within the 5G user plane (purple, dashed), and the wireless network between UE and RAN (green). Each individual network can be configured differently, for example taking into account the allocation of time slots on the radio interface.

From the perspective of layer 2, each router acts as an end device in both neighboring networks. Therefore, it is under no obligation to forward local broadcast messages, as this is not expected from a layer 3 device. Further, it is free to aggregate multiple individual layer 2 data streams into a single stream inside the 5G network in order to consolidate resources. Finally, there is no need to consider changes in traffic parameters, such as increased frame lengths due to tunnel protocols between RAN and UPF.

Despite the logical separation into different layer 2 networks, end-to-end signaling between end devices can still be performed via higher layer protocols, for example utilizing DetNet or RSVP. This enables the establishment of deterministic communication channels without the need to hide parts of the network behind an abstraction.

While this alleviates some of the integration challenges, it requires that the end devices are actually able to communicate on layer 3 or above. This is not necessarily the case, especially in the context of industrial automation and automotive networks where fieldbus technologies are still prevalent. Further, if a tight coupling of the TSN and 5G scheduler is desired, the logical bridge abstraction might still be the preferred approach. However, it should be considered that the radio interface is not as reliable as a wired connection, and it might be dangerous to integrate it seamlessly given the expectations towards real TSN bridges.

V. CONCLUSION

The desire for ultra reliable low latency communications is embedded deep in the specification and marketing of 5G and its successors. Consequently, the idea to integrate mechanisms from the Time-Sensitive Networking tool set into the 5G architecture receives ample attention. However, the logical TSN bridge abstraction is not necessarily the ideal approach for every use case.

In this work, we presented an overview of TSN mechanisms from an implementation complexity perspective, as well as the state-of-the-art integration approach from literature. We argued that the concept of a logical bridge abstraction, while enticing in theory, comes with a number of challenges in practice. From our perspective, the first approach should be to keep the external and the 5G networks separate and to implement the transitions in the form of routers between networks. This would make early implementations more approachable, and should still suffice for many use cases.

While this work continues, the required modifications for both approaches, as well as their limitations, should be better understood and compared to each other. In addition, future work can deal with potential gains from aggregation of multiple TSN streams into a single stream on the radio link, as well as concrete approaches towards redundancy in the presence of wireless communication channels.

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