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Time-Sensitive Networking (TSN) for 5G/6G and Cloud-RAN

Architecture, Challenges,

and Implementation Status in OpenAirInterface (OAI)

Version: 1.0

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Authors /

Arash Sahbafard
Hosein Kangavar Nazari
Kay Dai
Stefan Senk
Stefan Spettel
Tariro Mukute

Organizations /

PHINE·TECH

Dresden University of Technology

TMYTEK

Contact /

arashsahbafard@ieee.org
hosein.kangavar_nazari@tu-dresden.de
kay_dai@tmytek.com
stefan.senk@tu-dresden.de
stefan.spettel@phine.tech
tariro.mukute@phine.tech

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Chapter 1. Executive Summary

Smart factories depend on communication systems that are no longer fixed, isolated, or purely wired. As production environments become more flexible, mobile, and software-defined, industrial networks must support deterministic communication across both wired Time-Sensitive Networking (TSN) domains and wireless 5G segments.

This white paper examines how TSN can be integrated with 5G mobile networks, future 6G-oriented architectures, and Cloud-RAN (C-RAN) deployments, with a particular focus on practical experimentation and validation in OpenAirInterface (OAI). OAI is an open-source, 3GPP-compliant platform for 4G/5G Radio Access Network (RAN) and Core Network (CN) research, prototyping, and integration on commercial off-the-shelf (COTS) hardware. In this context, OAI serves as an open experimental and validation platform for proving 5G-TSN capabilities, identifying implementation gaps, and developing transferable architectural blueprints that can be adapted to other 5G platforms.

The 3GPP 5G System (5GS) supports integration with IEEE TSN networks by modeling the 5GS as a logical IEEE 802.1Q bridge [1,2]. This architecture introduces key functions such as the TSN Application Function (TSN AF), Device-Side TSN Translator (DS-TT), Network-Side TSN Translator (NW-TT), time synchronization support, and deterministic scheduling assistance for the radio network. Together, these mechanisms define a path toward integrating wireless 5G segments into existing industrial TSN domains.

Using OAI as an experimental reference platform, this paper provides an implementation-oriented view of that path. It reviews the relevant TSN mechanisms, maps them to the 5GS architecture, evaluates the current state of support in OAI, and highlights practical implementation strategies based on Linux networking tools, Ethernet PDU sessions, Quality of Service (QoS) mechanisms, and deterministic RAN scheduling.

The key conclusion is that OAI already provides important foundational building blocks for validating industrial Layer 2 communication over 5G, including Ethernet PDU sessions and emerging QoS support. However, full end-to-end deterministic 5G-TSN operation still requires additional development in TSN control-plane integration, PMIC/UMIC transport, NW-TT and DS-TT functionality, gPTP-based time synchronization, and deterministic radio resource scheduling. By closing these gaps in an open experimental environment, the resulting methods, software components, and integration lessons can be transferred to other 5G platforms and accelerate the practical deployment of wireless TSN systems.

Chapter 2. Introduction

The transition from traditional best-effort connectivity to deterministic networking represents a fundamental paradigm shift in wireless communication. As 5G and future 6G networks evolve toward deployment in smart manufacturing environments, wireless systems are expected to support applications that were previously confined to deterministic wired networks. In this context, the integration of TSN becomes a foundational requirement for extending industrial-grade determinism into the vision of the "**Wireless Factory of the Future.**"

While theoretical studies and standardization efforts provide essential foundations, the research and development community requires a practical reference platform that enables complete end-to-end TSN support. In this regard, OAI is uniquely positioned, as it provides an open, fully functional mobile network stack that can be extended and experimentally validated.

The availability of such an open-source platform helps bridge the gap between theoretical specifications and real-world deployment. By enabling a functional end-to-end testbed, OAI can significantly accelerate applied research in deterministic communications and support the practical realization of robust 5G–TSN systems in industrial environments.

Motivation

Industrial applications such as high-speed motion control, collaborative robotics, and closed-loop process automation rely predominantly on deterministic Ethernet technologies, including PROFINET and EtherCAT. These systems provide tightly bounded latency and jitter, which are essential for cyclic control traffic and coordinated actuation [3].

However, the increasing adoption of flexible production lines, autonomous mobile robots, automated guided vehicles, and reconfigurable industrial environments is driving the demand for wireless connectivity that can complement or replace fixed wired infrastructure [3].

5G, particularly its URLLC service category, is a key enabler of this transition. While URLLC provides high reliability and low latency, these characteristics alone are insufficient for time-critical industrial communication. To integrate seamlessly into existing industrial networks, the 5GS must operate as part of a TSN domain, effectively acting as a logical bridge that forwards time-sensitive Ethernet traffic in a predictable and deterministic manner.

Industrial controllers, typically programmable logic controllers (PLCs), execute tightly synchronized control cycles. Any unbounded jitter introduced by the wireless segment can disrupt these cycles and degrade system performance. Therefore, the 5GS must not only minimize latency but also actively control and bound jitter through coordinated scheduling, precise time synchronization, and buffering mechanisms.

Scope

This paper focuses on the end-to-end integration of TSN features within the OAI software stack. The scope of this work includes the following aspects:

- **Architectural Mapping:** Analysis of how TSN mechanisms are integrated into the OAI RAN and CN, with particular emphasis on modeling the 5GS as a logical IEEE 802.1Q bridge.
- **Implementation Status:** Assessment of the current software capabilities within the OAI ecosystem, including support for Ethernet PDU sessions, QoS enforcement, and native Linux networking tools.
- **Performance Evaluation:** Evaluation of baseline end-to-end latency and jitter based on empirical measurements obtained from current 5G-TSN testbeds.
- **Out of Scope:** To maintain a focused technical analysis, this work explicitly excludes the evaluation of proprietary telecom software, closed-source 5G deployments, and Wi-Fi-based TSN extensions.

Contributions

While 3GPP specifications provide the theoretical framework for 5G-TSN [1,2], transitioning from standardization to a functional open-source platform requires active engineering execution. Through the combined expertise of **phine.tech** (CN and software development), **TMYTEK** (RAN), and **TU Dresden** (TSN and empirical evaluation), this paper moves beyond theoretical architecture to deliver actionable insights. The primary contributions of this work include:

- **Practical Integration Blueprint:** We provide a concrete, hardware-agnostic methodology for vertically integrating complex translation entities (NW-TT and DS-TT) alongside OAI network functions using standard Linux tools.
- **Empirical Validation:** We establish precise, real-world performance baselines by deploying a dedicated 5G-TSN testbed. By eliminating synchronization artifacts, we captured accurate one-way latency metrics and identified the current limits of air-interface scheduling.
- **Critical Gap Analysis:** We deliver a transparent, implementation-focused roadmap detailing the exact readiness of TSN features within the OAI ecosystem. This categorizes fully available prerequisites versus critical control-plane development targets to guide future open-source integration.

Ultimately, by defining these architectural blueprints and directly identifying the remaining development gaps, our collaborative consortium provides the deep technical expertise and implementation capabilities necessary to help industrial partners deploy their own custom 5G-TSN solutions.

Chapter 3. TSN Fundamentals

TSN is a set of IEEE 802.1 standards designed to provide deterministic, low-latency data transmission over Ethernet networks. While achieving perfectly constant latency in packet-based networks is inherently challenging, TSN aims to provide consistently tightly bounded delays through coordinated control of packet transmission. Rather than relying on a single technique, TSN integrates a flexible toolkit of mechanisms categorized into time synchronization [4], traffic shaping [5,6], reliability [7], and resource management [8,9]. By combining selected features from these categories, TSN enables predictable Ethernet-based communication and forms the foundation for emerging real-time and mission-critical networking applications [10].

For the purpose of integrating a 5GS as a logical bridge, the following core mechanisms form the critical foundation:

Time Synchronization (IEEE 802.1AS / PTP)

Time synchronization establishes a common notion of time across all network elements, which is strictly required for time-aware scheduling. IEEE 802.1AS [4] defines a profile of the Precision Time Protocol (PTP, IEEE 1588 [11]) tailored for Ethernet-based, time-sensitive communication. It relies on a best-clock selection mechanism to elect a single grandmaster clock. Time is then distributed across the network using either boundary clocks (which regenerate timing information) or transparent clocks (which forward messages while compensating for residence delay). By continuously exchanging timestamped messages and adjusting local oscillators, typically via a PI control loop, PTP maintains the stable, network-wide time base required by downstream shaping mechanisms.

Time-Aware Shaper (IEEE 802.1Qbv / TAS)

The Time-Aware Shaper (TAS) [6] provides bounded latency and extremely low jitter by operating in a time-division multiple access (TDMA) manner. It organizes outgoing traffic into up to eight priority queues, each controlled by a transmission gate. The opening and closing of these gates are governed by a Gate Control List (GCL), which specifies the exact global time windows and durations during which each queue is allowed to transmit. By enforcing these global schedules, TAS enables the deterministic separation of time-sensitive control traffic from best-effort flows, making it essential for applications with strict latency requirements.

Stream Reservation (IEEE 802.1Qat / Qcc)

Stream Reservation, initially specified in IEEE 802.1Q at [13] and later extended by IEEE 802.1Qcc [8], is a TSN control-plane mechanism that enables deterministic, end-to-end resource reservation for traffic streams with guaranteed latency and bandwidth requirements. IEEE 802.1Qcc defines a TSN domain as a set of end-stations and bridges managed by a Centralized Network Controller (CNC). This centralized architecture supports reservation coordination both within a single domain and across interconnected TSN domains.

The standard specifies protocols, procedures, and managed objects that allow the CNC and network bridges to identify specific traffic streams and allocate the required resources with sufficient granularity to meet strict timing constraints. A dedicated signaling protocol handles the registration, deregistration, and maintenance of these stream reservations across all relevant network elements, enabling dynamic admission control and lifecycle management. By providing CNC-assisted, end-to-end resource allocation, stream reservation establishes the control-plane foundation strictly required for deterministic TSN operation.

Additional TSN Mechanisms

Depending on specific industrial requirements, TSN domains may employ supplementary mechanisms to enforce reliability and manage congestion:

- **Credit-Based Shaper (CBS, IEEE 802.1Qav):** Credit-Based Shaper [5] prevents sudden bursts of traffic (such as video streams) from overwhelming the network by using a strictly regulated allowance system. A priority queue accumulates "transmission credits" at a defined rate (the IdleSlope) while it is waiting, and consumes these credits (the SendSlope) when actively transmitting packets. If a queue runs out of credits, it must pause transmission and wait to accumulate more. This smoothly spaces out traffic spikes without requiring global time synchronization.
- **Per-Stream Filtering and Policing (PSFP, IEEE 802.1Qci):** PSFP [9] acts as a strict gatekeeper for individual data streams rather than entire queues. It utilizes Stream Gate Control Lists (SGCLs) to inspect specific packet headers and ensure a stream behaves correctly. For example, it can instantly drop packets that exceed a maximum allowed size, arrive outside their permitted time window, or violate a bandwidth limit (the Committed Information Rate, or CIR). This prevents a malfunctioning end-device from flooding the network and disrupting other critical streams.
- **Frame Replication and Elimination for Reliability (FRER, IEEE 802.1CB):** FRER [7] provides seamless fault tolerance without the latency penalty of retransmissions. It achieves this by duplicating critical packets and sending them simultaneously across entirely disjoint physical network paths. Each copy is appended with an identical sequence number, known as a redundancy tag (R-tag). At the destination, the receiver uses the Match Recovery Algorithm (MRA) to accept the first arriving copy and immediately discard any subsequent duplicates. If a network link fails, the data still arrives on time via the backup path with zero interruption.
- **Frame Preemption (FP, IEEE 802.1Qbu):** FP [12] is a MAC-layer mechanism that ensures large, best-effort packets do not block urgent traffic. If a time-critical frame arrives while a large packet is halfway through transmission, FP temporarily suspends (preempts) the standard packet, transmits the urgent one immediately, and then resumes the rest of the preempted packet. When combined with the TAS, FP can utilize a Hold-Release mechanism to enforce a guard band, actively preventing a low-priority packet from starting its transmission if a scheduled time-critical slot is about to open.

Chapter 4. Architecture: Mapping TSN to the 5GS

The integration of TSN into the 5GS is architecturally realized by modeling the 5GS as a single logical IEEE 802.1Q bridge. This abstraction allows the reuse of most standard 5GS procedures in the CN, gNB, and User Equipment (UE), while providing the necessary intersection points for deterministic control and management. The guiding philosophy of this architecture is transparency. Rather than forcing the internal 5G CN to understand complex TSN standards, the 5GS relies on specialized translation entities at its edges to do the heavy lifting.

While the 5GS relies on various network functions (NFs) for connectivity, this white paper focuses on those critical to the logical bridge: the TSN Application Function (AF), Policy Control Function (PCF), Session Management Function (SMF), Time Synchronization Service Function (TSCTSF), to some extent Access and Mobility Management Function (AMF) and especially User Plane Function (UPF). Other NFs, such as Network Repository Function (NRF) or Unified Data Management (UDM), perform standard roles defined in 3GPP TS 23.501 [2] and do not require TSN-specific enhancements for bridge operation.

Control Plane Integration and Functional Split

The architecture relies on tight coordination between the TSN-native environment and the 5G control plane. As shown in Figure 1, the configuration flow follows a centralized model:

- **TSN AF:** Acts as the primary interface to the industrial domain, translating commands from the CNC into 5G CN-native requirements.
- **PCF:** Receives requirements from the AF and triggers policy procedures to notify the SMF of TSN-specific parameters. These include the Port Management Information Container (PMIC) and User Plane Management Information Container (UMIC), which the 5G CN forwards completely transparently.
- **SMF:** Distributes these configurations to the logical bridge ports, which are implemented as TSN translators. Specifically, it updates the Network-side TSN Translator (NW-TT) residing at the UPF via the N4 interface using the Packet Forwarding Control Protocol (PFCP), and the Device-side TSN Translator (DS-TT) located at the UE via Non-Access Stratum (NAS) signaling.

Additionally, the NG Application Protocol (NGAP) on the N2 interface between AMF and gNB is utilized to deliver Time-Sensitive Communication Assistance Information (TSCAI) to the gNB, ensuring the radio scheduler can align resources with deterministic arrival patterns. Since TSN and QoS mechanisms are inherently linked, the 5GS leverages its internal priority handling to enforce the determinism required by the logical bridge model.

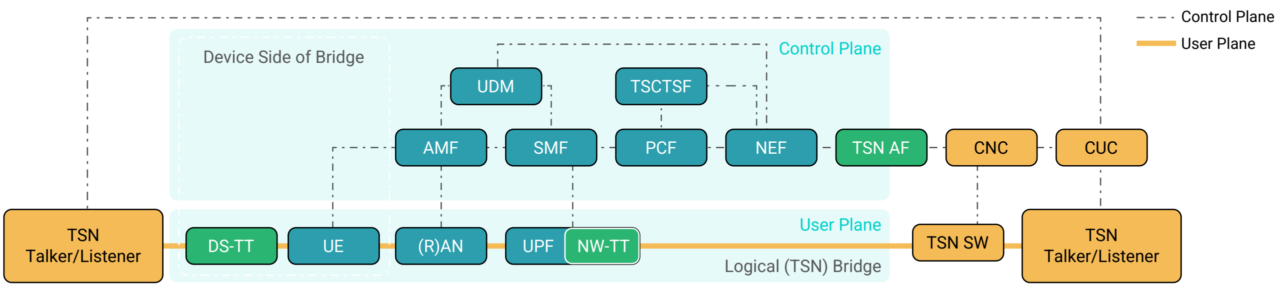

Figure 1: Illustration of the 3GPP architecture for integrating 5G as a logical TSN bridge. The TSN system is highlighted in yellow, while the 5GS, acting as a logical TSN bridge, is shown in the central dotted region in blue. TSN translators are indicated in green. User-plane connections are represented by solid lines, whereas control-plane signaling is depicted using dash-dotted lines.

User Plane Integration: DS-TT and NW-TT

To fulfill the requirements of a logical IEEE 802.1Q bridge, the 5GS introduces two specialized translation entities at its edges: the DS-TT and the NW-TT. These entities act as the physical or logical ports of the bridge, ensuring that the internal 5G procedures remain transparent to the external TSN domain.

Functional Roles and Integration

The NW-TT is co-located with the UPF and serves as the network-side interface. It is responsible for interfacing with the external TSN network, typically connecting to other TSN switches. Conversely, the DS-TT is co-located with the UE, providing the necessary translation for industrial end-stations.

In the OAI implementation, these translators are integrated as functional extensions within the user plane stacks. The UPF, which co-locates the NW-TT, handles both the encapsulation and de-encapsulation of Ethernet frames and the user-plane QoS enforcement required to map TSN stream identifiers to 5G QoS flows. These mapping configurations are driven by the control plane, specifically by the PCF based on inputs from the TSN AF.

Configuration via PMIC

The management of these ports is performed through the PMIC and UMIC. These containers allow the TSN AF to deliver port-specific configurations (such as traffic classes, capabilities, and status) across the 5G control plane without requiring the intermediate 5G NFs to parse the TSN-native content.

The PMIC exposes standardized TSN bridge/port management parameters, as specified in detail in Table 5.28.3.1-1 of 3GPP TS 23 501 V17.7.0:

- **Configuration of TSN bridge ports:** Defines the fundamental operational state of the NW-TT and DS-TT, including MAC address learning and basic port capabilities.
- **Per-stream filtering & gating:** Directly maps to the PSFP and TAS mechanisms. It delivers the GCLs that tell the translators exactly when to open and close their transmission queues.
- **Time synchronization (IEEE 1588 / 802.1AS):** Configures the port's role in the time domain, including how the translators should handle PTP timestamping and calculate the internal 5G residence time to maintain the grandmaster clock's accuracy.
- **LLDP-based neighbor discovery:** Enables the Link Layer Discovery Protocol (LLDP) so the CNC can actively map the network topology and recognize the 5GS as an integrated, logical bridge.
- **Read/Write access control:** Specifies whether the CNC has permission to actively modify these port parameters (RW) or simply monitor their status (R).

Time Synchronization

To support deterministic communication, 3GPP TS 23.501 specifies that the 5GS operates as an IEEE 802.1AS time-aware system. This allows the entire 5G network to integrate logically as a clock node within the broader TSN domain. By maintaining this strict time synchronization across the network, the 5GS ensures that connected industrial end-stations can reliably execute precise, time-aware control loops. The Time Synchronization Service Function (TSCTSF) provides services to configure and monitor time synchronization parameters and supports the distribution of precise time information across the 5GS. It enables authorized network functions to subscribe to notifications about time synchronization capabilities and status changes, and to create, update, activate, or deactivate synchronization configurations, including the distribution of precise time (e.g., gPTP-based timing) through the 5G access network, as specified in 3GPP TS 29 565 V18.5.0 [14].

Jitter Management and Buffering

A critical challenge for 5G-TSN is the inherent jitter of the Radio Access Network (RAN). To maintain deterministic delivery, the NW-TT implements a hold-and-forward buffering mechanism. By utilizing the timing information provided by the control plane, the NW-TT can buffer outgoing packets and release them at precise intervals. Consequently, latency is intentionally added to smooth RAN scheduling fluctuations, effectively de-jittering the end-to-end user plane communication. The hold-and-forward buffering mechanism is the 3GPP 5G pendant of the TAS in the TSN domain (see IEEE 802.1Qbv), as described in Chapter 3.

Deterministic RAN Scheduling

While the UPF and translators handle logical bridging at the network edges, the wireless segment presents its own distinct challenges. Traditional cellular networks rely on dynamic resource allocation, where a device must send a Scheduling Request (SR) and wait to receive an uplink grant before it is allowed to transmit. The latency overhead and jitter inherent to this dynamic request-grant cycle are fundamentally incompatible with the stringent timing requirements of URLLC.

To overcome this, the 5G RAN must bypass dynamic allocation entirely. This is achieved through configured scheduling, a mechanism where the base station (gNB) pre-allocates a recurring, periodic pattern of radio resources. This allows devices to transmit or receive immediately upon packet arrival without prior control-plane negotiation. This approach aligns perfectly with the periodic, frame-synchronous nature of TSN traffic, such as cyclic industrial control loops.

- **Uplink - Configured Grants (CG):** CG allows uplink resources to be pre-allocated to time-critical flows, eliminating dynamic scheduling delays and significantly reducing control-plane overhead. 3GPP defines two formats relevant to this context:
  - Configured Grant Type 1 (CCG): Relies on a single, statically configured transmission pattern with fixed periodicity. Its high predictability and low complexity make it the primary mechanism for supporting strict, TSN-like deterministic operation.
  - Multiple Configured Grant (m-CG): Introduces multiple concurrent grant patterns that can be flexibly selected by the device. This provides a mechanism to adapt to slight traffic variations or jitter from the industrial network while still avoiding the latency penalty of per-packet scheduling requests.
- **Downlink - Semi-Persistent Scheduling (SPS):** SPS serves as the downlink equivalent to CG. The gNB establishes recurring downlink resource allocations, enabling deterministic data delivery from the network core to the UE without requiring control signaling for every packet. This is strictly required to close the loop in symmetric industrial control applications.

Chapter 5. Status of TSN in OAI

While the previous section outlined the theoretical architecture required to model the 5GS as a logical TSN bridge, translating the standardization into a functional open-source platform presents distinct engineering challenges. To bridge the gap between 3GPP specifications and real-world deployment, the OAI community has actively begun implementing these required mechanisms.

Foundation and Prerequisites in OAI

Before complex TSN features, such as hold-and-forward buffering or precise time synchronization, can be realized, the underlying network must first be capable of handling non-IP industrial traffic natively. Therefore, the fundamental prerequisite for any 5G-TSN integration is the ability of the 5GS to establish Ethernet PDU sessions, allowing it to act as a transparent Layer 2 bridge. This Layer 2 transport must then be coupled with robust QoS enforcement for baseline traffic prioritization, and paired with deterministic RAN scheduling to fulfill the strict latency requirements of URLLC.

Ethernet PDU Sessions

While Ethernet PDU sessions were introduced in 3GPP Release 15 and further refined in Release 16 [15] for TSN integration, widespread open-source adoption has historically been limited. In 2025, a collaborative effort involving phine.tech, TU Dresden, Firecell, and other partners achieved a significant milestone by implementing and open-sourcing Ethernet PDU session support within the OAI CN.

This implementation allows the PDU session to function as a Layer 2 LAN, fulfilling the critical requirement for supporting non-IP industrial protocols. To achieve this, the UPF operates as a transparent learning bridge, dynamically mapping MAC addresses to PDU sessions by analyzing traffic, such as intercepting gratuitous ARP requests from the UE. Currently, the OAI implementation supports unicast, multicast and broadcast traffic. However, because the UPF acts transparently during multicast, multicast group management must be handled by an external switch located in the N6-LAN. To facilitate end-to-end testing without reliance on commercial hardware, the OAI UE has also been updated to support Ethernet PDU sessions.

QoS Enforcement

Beyond basic Layer 2 transport, robust QoS enforcement is strictly required to prioritize time-critical industrial flows over best-effort traffic. The OAI CN has established the necessary groundwork to support these requirements. Delay-critical QoS flows can now be configured via the PCF, propagated to the SMF, and actively enforced at the UPF using eBPF and Linux Traffic Control (TC) mechanisms [16].

Currently, the specific QoS packet filters required for Ethernet PDU sessions are under active development. Furthermore, QoS enforcement within the OAI RAN itself is still in the development phase. Consequently, while various QoS mechanisms are being heavily developed across different community branches, they are not yet fully integrated end-to-end across the entire 5GS.

Deterministic RAN Scheduling (URLLC)

While the CN handles bridging and prioritization, the RAN must bypass dynamic scheduling delays to meet URLLC latency requirements. Within the OAI ecosystem, deterministic scheduling features are currently in a transitional state.

A basic implementation of Configured Grant Type 1 (CCG) for the uplink is under development, allowing devices to transmit on a statically configured schedule. Furthermore, while a single CG Type 1 handles baseline periodic traffic, expanding the network to support complex industrial environments with multiple overlapping traffic streams will require the ongoing development of advanced features like multiple Configured Grants (m-CG). Because these advanced scheduling mechanisms and their tight integration with the rest of the network are still being actively developed, full deterministic RAN scheduling is currently classified as an emerging potential capability within the broader OAI roadmap, rather than a fully integrated feature.

Roadmap for TSN supported in OAI CN

While the foundational Ethernet and QoS mechanisms are supported by OAI, specific TSN control flows require further integration. Specifically, the transport of PMIC and UMIC through the CN remains unimplemented. Although the necessary control plane interfaces, N5 (AF to PCF), N7 (PCF to SMF), N4 (SMF to UPF), and N1 (UE to CN) are established, they require updates to carry TSN-specific payloads. Additionally, the N5 interface and subsequently the N7 and N4 interfaces need to be updated to support dynamic provisioning of QoS rules.

The most significant implementation challenges lie within the DS-TT and the NW-TT. While DS-TT functionality is currently offloaded to commercial COTS vendors, the NW-TT must be integrated directly into the UPF domain. Two primary architectural approaches are currently under evaluation for this integration.

The first approach involves coupling the UPF with a commercial TSN switch, linking the switch's exposed APIs to the UPF logic. This allows TSN bridge information received from the CN to be applied directly to the switch hardware. While this method offers high stability and performance, it necessitates porting the UPF to the switch's specific operating system and hardware architecture (typically ARM-based). This introduces significant integration effort and hardware dependency, potentially limiting reproducibility across different switch vendors.

The second approach proposes a re-implementation of TSN functionality directly within the UPF using Linux TC and queuing disciplines (qdiscs). This software-defined approach offers the advantage of being fully open-source, hardware-agnostic, and executable on general-purpose computing resources. Because it is constrained by the Linux kernel's evolving native support for TSN standards, bridging potential gaps will require custom development. However, the exact scope of these missing requirements will be mapped out iteratively as development progresses, dictated by the specific TSN performance demands of individual applications.

Practical Realization via Linux Tooling

To realize the software-defined approach outlined above, the strategy for implementing TSN alongside OAI does not require deeply embedding complex TSN protocols directly into the 5G network functions. Instead, translation entities like the NW-TT and DS-TT are implemented as vertical overlays that build directly upon the native capabilities of the underlying Linux kernel. This integration architecture relies heavily on two core Linux subsystems to achieve synchronization and deterministic scheduling at the boundaries of the 5GS.

Time Synchronization (linuxptp)

To bridge the 5G network into the external IEEE 1588 timing domain, the software-based TSN translators interface directly with the standard linuxptp stack [17]. This stack bridges network time to host applications via two cooperating user-space processes:

- **ptp4l:** Interfaces directly with the network interface card (NIC) to receive PTP event messages, executes the Best Master Clock Algorithm (BMCA), and continuously disciplines the PTP Hardware Clock (PHC) embedded in the NIC.
- **phc2sys:** Propagates this precisely synchronized hardware time into the host operating system by adjusting the kernel system clock (e.g., CLOCK_REALTIME).

Once synchronized, this global system clock becomes accessible to all kernel subsystems, establishing the unified time base strictly required for the vertically integrated TSN components to perform time-aware scheduling.

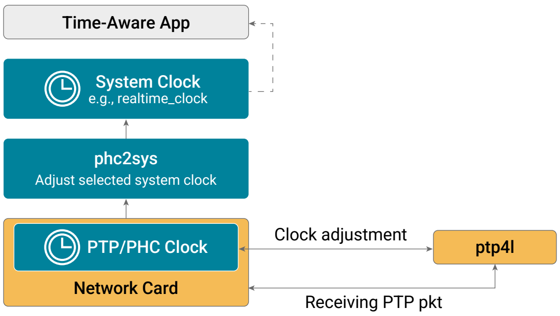

Figure 2: Synchronization of Time-Sensitive Applications on a Time-Aware End-Station Using the PTP Clock and Linux Synchronization Tools (ptp4l and phc2sys)

Deterministic Scheduling (Linux Traffic Control)

As introduced in the UPF roadmap, packet buffering, shaping, and precise transmission must be enforced exactly where the 5GS interfaces with the external industrial network. By operating on top of the UPF's data interfaces, the NW-TT manages these flows using the Linux TC subsystem and its specialized queuing disciplines (qdiscs). To meet the strict latency and jitter demands of the logical 5G bridge, the TSN implementation may leverage the following qdiscs:

Qdisc	Primary Mechanism	TSN Function & Determinism Level
mqprio	Priority mapping	Maps traffic classes to specific hardware queues to physically separate prioritized traffic.
taprio	Gate Control List (GCL)	Enables highly deterministic, time-aware, and cycle-based transmission.
etf	SO_TXTIME scheduling	Dictates precise send times (strict mode drops late packets; deadline mode meets transmission cutoffs).
cbs	Credit mechanism	Shapes bandwidth to bound latency under contention, without requiring strict time-triggered guarantees.

Overview of Supported and Planned Features

To consolidate the implementation details and challenges discussed in the preceding sections, the following table provides a comprehensive snapshot of the 5G-TSN feature landscape within the OAI ecosystem. It categorizes the essential building blocks across the user plane, control plane, RAN scheduling, and specific TSN translation domains.

To accurately reflect the dynamic nature of open-source development and the specific focus of this research, the status of each feature is classified into one of three distinct categories:

- **Available:** The feature is successfully implemented, functionally verified, and integrated into the current OAI baseline (e.g., Ethernet PDU sessions and foundational QoS flows).
- **Potential:** These features may exist in partial forms across various experimental community branches, or they represent theoretical 3GPP capabilities that have not yet been consolidated into the main repository.
- **Roadmap:** Critical components and integrations that phine.tech, TMYTEK, TU Dresden and partners in the ecosystem explicitly intend to develop, test, and contribute back to the OAI ecosystem in upcoming releases (e.g., NW-TT and TSN AF integration).

Feature Domain	Feature Name	Status	Description & Relevance to TSN
User Plane (L2)	Ethernet PDU Session	Available	Support for Ethernet PDU sessions acting as a Layer 2 bridge. Allows transport of non-IP TSN traffic.
	Ethernet Header Compression (EHC)	Potential	Compressing Ethernet headers in the gNB (3GPP TS 38.413) to increase spectral efficiency.
QoS & TSN Control	5G QoS Identifier (5QI) & QoS Flows	Available	Support for standard and delay-critical GBR (Guaranteed Bit Rate) flows mapped to specific TSN traffic classes.
	N5 / N7 / N4 Interfaces	Available	Control plane interfaces (AF - PCF - SMF - UPF) are implemented to provision QoS policies dynamically.
	TSN AF	Roadmap	A dedicated function to translate CNC requests into 5G QoS policies and PMIC requests.
Uplink Scheduling	Configured Grant Type 1	Potential	Pre-allocated uplink resources for periodic traffic. Eliminates Scheduling Request (SR) latency; ideal for deterministic TSN flows.
	Configured Grant Type 2 (m-CG)	Potential	Flexible, activation-based configured grants. Allows the network to adapt to traffic variations without full dynamic scheduling delays.
Downlink Scheduling	Semi-Persistent Scheduling (SPS)	Available	The downlink equivalent of Configured Grant. Critical for symmetric industrial control loops
Reliability	PDCP Duplication	Potential	Redundant transmission of packets via different logical channels/-carriers.
Time Sync	Reference Time Information	Potential	Propagation of absolute time (Grandmaster clock) from the network to the UE to synchronize the 5GS with the industrial domain.
	gPTP Support (802.1AS)	Roadmap	Transporting Generalized Precision Time Protocol (gPTP) events transparently to support end-to-end synchronization.
TSN Translation	NW-TT (Network-Side)	Roadmap	Functionality inside the UPF to handle hold-and-forward buffering, traffic shaping, and PMIC translation.
	DS-TT (Device-Side)	Potential	Functionality at the UE side to interface with industrial devices. OAI UE supports Ethernet PDU sessions. TSN DS-TT support is being evaluated.

Chapter 6. Currently Achievable End-to-End Latency and Jitter

Empirical evaluation of 5G-TSN end-to-end latency and jitter requires highly precise measurement methodologies. Because TSN applications operate on exceptionally strict time scales - typically in the millisecond to microsecond range for data delivery, and down to the nanosecond range for time synchronization - every single element in the communication path (UPF, gNB, UE, and transport links) introduces potential latency and jitter. The primary objective of a TSN integration is to map and strictly minimize these cumulative effects.

Capturing these metrics accurately is inherently difficult. Measuring one-way, microsecond-level latencies across a distributed network introduces significant measurement uncertainty if the sender and receiver rely on separate, synchronized clocks. To completely eliminate this synchronization error, the baseline measurements in this evaluation were conducted using a dedicated network tap simultaneously attached to both the sending and receiving network ports. This approach utilizes a single, unified hardware clock, successfully bypassing the complex time-synchronization challenges that typically distort microsecond-level measurements.

Component-Level Performance and Testbed Setup

Within the CN, the baseline residence time of a typical low-bitrate TSN stream passing through the OAI UPF ranges from tens of microseconds to a few hundred microseconds. However, the dominant factor in end-to-end delay and jitter is the RAN, where performance is highly asymmetric depending on the transmission direction.

To establish a baseline for current air-interface performance in OAI, measurements were conducted in an isolated RF chamber using two state-of-the-art gNBs operating in FR1 (Sub-6 GHz). Both setups utilized identical CN and UE configurations over Ethernet PDU sessions, relying on dynamic scheduling, with one gNB slightly optimized for lower latency via fixed Modulation and Coding Scheme (MCS) values.

Empirical Results

- **Downlink Latency:** Median latencies were recorded between 3.5 ms and 4.0 ms. The distribution was relatively tight (2 ms to 5 ms), though outliers still reached two to three times the median value.
- **Uplink Latency:** Median latencies varied significantly between the two gNBs, ranging from 7–8 ms to 12 ms. More critically, the uplink exhibited a pronounced latency spread and a long tail of high outliers, peaking at 10 to 20 times the median delay.

The Impact of Traffic Shaping

The introduction of traffic shaping via external TSN switches effectively reduced general variation, grouping latencies into two distinct clusters corresponding to the active Time Division Duplex (TDD) slot pattern. However, this external shaping did not eliminate the significant high-latency outliers (those exceeding 10 times the median delay).

These findings demonstrate that while external traffic shaping can organize baseline transmission intervals, it is insufficient as a standalone solution for industrial URLLC. Achieving true determinism requires deep control-plane and user-plane enhancements, specifically deterministic configured scheduling (as discussed in Section 4), to control jitter and proactively eliminate latency spikes.

Chapter 7. Challenges and Risks

As demonstrated by the empirical measurements in Chapter 6, realizing strict deterministic wireless communication via 5G-TSN integration presents significant engineering hurdles. Because achievable end-to-end performance is strictly bound by the weakest link in the communication path, guaranteeing determinism requires addressing several systemic complexities across the network.

Architectural Complexity and Multi-Service Overhead

First, the 5GS inherently possesses greater architectural complexity than traditional localized networks (such as standard industrial Ethernet or Wi-Fi). The 5G standard is engineered to support a broad, highly diverse spectrum of use cases simultaneously, ranging from high-throughput enhanced Mobile Broadband (eMBB) to strict industrial Ultra-Reliable Low-Latency Communication (URLLC). Accommodating these disparate multi-service requirements introduces significant control-plane overhead and processing layers across the CN, RAN, and UE. Meticulous orchestration is required to physically and logically isolate time-critical industrial flows from these broader network functions.

Standardization Ambiguities and Interoperability

Secondly, while 3GPP and IEEE standards provide comprehensive frameworks, they are highly extensive and frequently include optional features or open-ended implementation clauses. While this flexibility allows vendors to innovate and differentiate their products, it inherently leaves room for interpretation. In the context of TSN - where absolute predictability is the primary objective - such ambiguities inevitably lead to multi-vendor interoperability issues and inconsistent deterministic performance across different hardware deployments.

Hardware and Software Disaggregation

Furthermore, the telecom industry's evolution toward disaggregated, software-defined architectures fundamentally changes how deterministic networks are built. The transition from monolithic, vendor-locked proprietary appliances to network functions running on COTS general-purpose servers provides tremendous flexibility. This hardware-agnostic approach is a major advantage for researchers, vertical industries, and open ecosystems like OAI. It significantly lowers the barrier to entry, accelerates innovation, and allows for rapid, application-specific development without being tied to specialized silicon.

However, executing complex, time-critical network functions natively on general-purpose CPUs naturally introduces variable processing delays. Because strict microsecond-level determinism historically relied on tightly coupled hardware and software, the new engineering challenge lies in overcoming this CPU-induced jitter purely through software optimization. Bridging this gap requires leveraging advanced capabilities, such as real-time kernels, CPU pinning, and highly optimized Linux queuing disciplines, to enforce strict determinism without sacrificing the benefits of an open, flexible architecture.

The Open-Source Imperative (OAI)

To overcome these systemic challenges, open-source platforms like OAI offer a strategic pathway forward. While community-driven software may currently lack the proprietary, carrier-grade optimization found in closed enterprise solutions, it provides unparalleled extensibility.

For vertical industries with specialized wireless needs, such as factory automation or robotics, relying on the slower, mass-market deployment schedules of commercial telecom vendors is often impractical. Open architectures empower organizations to bypass these rigid roadmaps. By partnering with specialized software developers and experienced integrators, enterprises can rapidly prototype, implement, and deploy the exact TSN capabilities they require, significantly accelerating time-to-market.

Furthermore, this open-source paradigm fosters a robust, collaborative ecosystem. Global researchers, industrial partners, and publicly funded projects can continuously validate specific hardware and software combinations, systematically improving code maturity. This collective, transparent verification not only drives the rapid evolution of features like configured scheduling and TSN translation, but ultimately increases industry confidence in deploying software-defined 5G networks in critical production environments.

Chapter 8. Conclusion

The integration of TSN into the 5G/6G and Cloud-RAN landscape represents a critical milestone for the realization of the "Wireless Factory of the Future." By modeling the entire 5G network as a transparent, logical IEEE 802.1Q bridge, the industry can leverage the flexibility of wireless mobility without sacrificing the deterministic rigor required by industrial automation.

As demonstrated in this paper, the OAI ecosystem has made significant strides toward this goal. The successful implementation of Ethernet PDU sessions and the upcoming support for QoS provide a robust foundation for Layer 2 deterministic traffic. However, empirical performance evaluations highlight that standard 5G mechanisms running on general-purpose hardware are not yet enough on their own. The inherent jitter of wireless scheduling and the processing complexity of the 5G stack still result in latency outliers that challenge strict industrial control loops.

Key Takeaways and Next Steps

- **Completing the Logical Bridge:** While OAI has successfully established the foundational prerequisites for industrial communication, control-plane integration and edge translation remain the primary development priorities. The active propagation of PMIC/UMIC parameters and the full, vertical integration of the NW-TT and DS-TT functions are strictly required to enforce end-to-end determinism.
- **Reducing Wireless Jitter:** Practical measurements confirm that baseline traffic shaping is essential, but insufficient on its own. Further optimization in gNB deterministic scheduling (such as m-CG and SPS) and the implementation of de-jittering, hold-and-forward buffers at the network edges are critical next steps to eliminate high-latency tails.
- **The Open-Source Imperative:** The transition toward software-defined, hardware-agnostic implementations using native Linux tooling offers a highly promising path. It empowers researchers, vertical industries, and agile integrators to accelerate innovation cycles, avoid vendor lock-in, and tailor deployments to highly specific industrial requirements.

In conclusion, achieving a fully deterministic, end-to-end 5G-TSN system is no longer a theoretical exercise, but an active engineering challenge of integration and optimization. Future work within the OAI community will focus on validating precise gPTP time synchronization across the air interface and maturing the TSN AF and CN to provide a seamless management interface for industrial controllers. By bridging these remaining gaps, OAI will solidify its position as the premier open-source reference platform for transforming 5G into a reliable industrial utility.

Chapter 9. Acknowledgments

This work was funded by the German Federal Ministry of Research, Technology, and Space (BMFTR), project VICTOR6G, grant 16KIS2550, and project CampusTwin4In, grant 16KIS2447.

Funded by the ESF-Plus Fond and the Free State of Saxony as part of the "InnoTeam" funding program – joint project "EMAIRIS - Embodied AI for adaptive Robotic Industrial Systems" between Dresden University of Technology and Wandelbots GmbH.

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Chapter 10. Abbreviations

Abbreviation	Meaning	Abbreviation	Meaning
3GPP	3rd Generation Partnership Project	NEF	Network Exposure Function
5GS	5G System	NFs	Network Functions
5QI	5G QoS Identifier	NGAP	Next Generation Application Protocol
6G	Sixth Generation	NIC	Network Interface Card
AF	Application Function	NRF	Network Repository Function
AMF	Access and Mobility Management Function	NW-TT	Network-Side TSN Translator
ARM	Advanced RISC Machine	OAI	OpenAirInterface
ARP	Address Resolution Protocol	O-RAN	Open Radio Access Network
BMCA	Best Master Clock Algorithm	PCF	Policy Control Function
CBS	Credit-Based Shaper (IEEE 802.1Qav)	PDCP	Packet Data Convergence Protocol - noted as PDCP Duplication
CCG	Configured Grant Type 1		
CG	Configured Grant	PDU	Protocol Data Unit
CIR	Committed Information Rate	PFCP	Packet Forwarding Control Protocol
CN	Core Network	PHC	PTP Hardware Clock
CNC	Centralized Network Controller	PI	Proportional-Integral
COTS	Commercial Off-The-Shelf	PMIC	Port Management Information Container
C-RAN	Cloud Radio Access Network	PSFP	Per-Stream Filtering and Policing (IEEE 802.1Qci)
CUC	(Visible in Figure 1)		
DS-TT	Device-Side TSN Translator	PTP	Precision Time Protocol (IEEE 1588)
eBPF	Extended Berkeley Packet Filter	qdisc	Queuing Discipline
EHC	Ethernet Header Compression	QoS	Quality of Service
eMBB	enhanced Mobile Broadband	RAN	Radio Access Network
ETSI	European Telecommunications Standards Institute	RF	Radio Frequency
		R-tag	Redundancy tag
FP	Frame Preemption (IEEE 802.1Qbu)	SGCL	Stream Gate Control List
FR1	Frequency Range 1	SMF	Session Management Function
FRER	Frame Replication and Elimination for Reliability (IEEE 802.1CB)	SPS	Semi-Persistent Scheduling
		SR	Scheduling Request
GBR	Guaranteed Bit Rate	SRP	Stream Reservation Protocol (IEEE 802.1Qa-t/cc)
GCL	Gate Control List		
gNB	Next-generation NodeB (5G Base Station)	TAS	Time-Aware Shaper (IEEE 802.1Qbv)
gPTP	Generalized Precision Time Protocol (IEEE 802.1AS)	TC	Traffic Control
		TDD	Time Division Duplex
HARQ	Hybrid Automatic Repeat Request	TDMA	Time-Division Multiple Access
IEEE	Institute of Electrical and Electronics Engineers	TSCAI	Time-Sensitive Communication Assistance Information
IP	Internet Protocol	TSCTSF	Time Synchronization Service Function
L2	Layer 2 (Data Link Layer)	TSN	Time-Sensitive Networking
LAN	Local Area Network	UDM	Unified Data Management
LLDP	Link Layer Discovery Protocol	UE	User Equipment
MAC	Media Access Control	UMIC	User Plane Management Information Container
m-CG	multiple Configured Grant		
MCS	Modulation and Coding Scheme	UPF	User Plane Function
MRA	Match Recovery Algorithm	URLLC	Ultra-Reliable Low-Latency Communication
NAS	Non-Access Stratum		

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https://cn.ifn.et.tu-dresden.de/
stefan.senk@tu-dresden.de
hosein.kangavar_nazari@tu-dresden.de
tobias.scheinert@tu-dresden.de

TMYTEK

TMYTEK.com
sales@tmytek.com