



Time Synchronization for TSN Applications in Private 5G Networks

July 2026

Executive Summary

Digital transformation is driving the use of communication technologies for industrial applications such as collaborative robotics, automated guided vehicles (AGVs), machine vision, motion control, process automation and smart grid monitoring. These applications require precise time synchronization to operate seamlessly, correlate events accurately, and ensure reliable system control.

Time-Sensitive Networking (TSN), a family of IEEE 802.1 standards, has emerged as the preferred framework for deterministic Ethernet communication in industrial and mission-critical wired networks. As these networks evolve to hybrid wired-wireless architectures to support greater deployment flexibility, device mobility, and massive connectivity, there is a need to extend the precise time synchronization provided by TSN over the 5G network as well.

This whitepaper presents two complementary architectures for delivering TSN-grade synchronization over a private 5G wireless network segment, each suited to different deployment priorities.

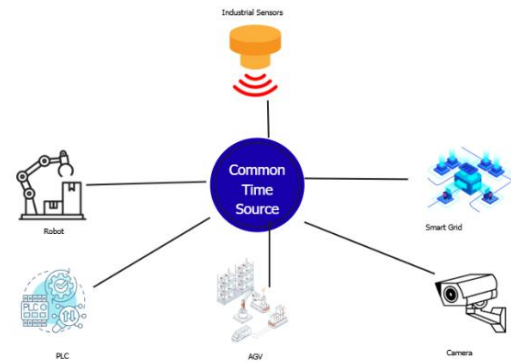
The first, **based on the complete 5G System (5GS)**, implements the 3GPP Rel-16 TSN bridge model, in which the 5G System acts as a virtual TSN bridge, tunneling IEEE 802.1AS (gPTP) synchronization messages over the 5G user plane between the Network-side TSN Translator (NW-TT) at the UPF and the Device-side TSN Translator (DS-TT) at the UE. This approach combines accurate time synchronization with predictable traffic scheduling and Quality of Service (QoS) mechanisms, enabling seamless integration with existing wired TSN infrastructure. However, it requires TSN-specific control- and user-plane functions implemented in both the 5G Core (5GC) and Radio Access Network (RAN).

The second, **RATS (RAN-Assisted Time Synchronization)**, is an alternative architecture that provides accurate time synchronization using only the capabilities of the 5G RAN. RATS leverages 5G radio capabilities to derive and maintain a synchronized clock in the UE using System Information Block Type 9 (SIB9) timing information and a Timing Advance (TA) correction to derive and maintain a synchronized clock within the UE, which is then made available to industrial devices through the UE-side TSN interface. This eliminates the need for TSN-specific synchronization support within the 5GC and QoS-managed user-plane transmission for time distribution. The solution targets 5G deployments where simplified synchronization, reduced complexity, and compatibility with existing core network implementations are desirable, including open-source cores such as Open5GS, Network-in-a-Box systems, and defence or remote industrial deployments.

Lekha supports both 3GPP-based industrial device synchronization architectures, enabling network architects to deploy either the complete 3GPP TSN architecture or the streamlined RAN-assisted architecture.

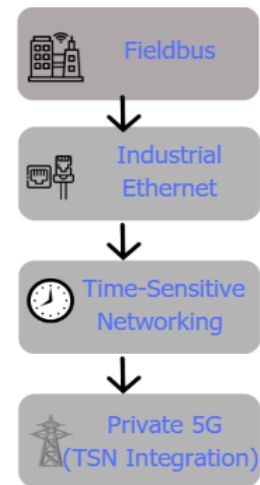
Evolution of Time Synchronization in Industrial Networks

Industry 4.0 is transforming manufacturing through automation, smart sensors, and real-time control. Industrial environments increasingly rely on connected robots, Programmable Logic Controllers (PLCs), AGVs, machine vision systems, and distributed sensors to improve productivity, safety, and operational efficiency. These industrial systems require devices to share a common notion of time. With this, distributed industrial devices operate as a coordinated system, executing time-critical operations simultaneously, correlating events accurately, and maintaining deterministic system behavior across different parts of a factory or different sites.



Evolution from Ethernet to TSN

Conventional Ethernet was originally designed for best-effort data communication and provides no guarantees on latency, packet delivery timing, or clock synchronization. While suitable for enterprise IT applications, it does not satisfy the deterministic communication requirements of industrial automation. To address these limitations, the IEEE developed the Time-Sensitive Networking (TSN) family of standards. TSN extends standard Ethernet by introducing mechanisms for precise network-wide synchronization, deterministic scheduling, traffic prioritization and bounded latency communication. Within TSN networks, synchronization is typically achieved using IEEE 802.1AS (gPTP), allowing all participating devices to operate using a common network time.



Emergence of 5G for Industrial Automation

5G networks are increasingly being deployed in industrial environments to support production system flexibility, device mobility, and massive connectivity. With its attributes of low latency, high QoS and throughput, deterministic scheduling, network slicing, and carrier-grade security, 5G technology is enabling new levels of automation on the factory floor. However, extending the precise device time synchronization provided by TSN-based Ethernet networks to a 5G access network introduces significant complexity. In a combined wired and wireless industrial network, two separate but related timing domains coexist, as summarized in the table below.

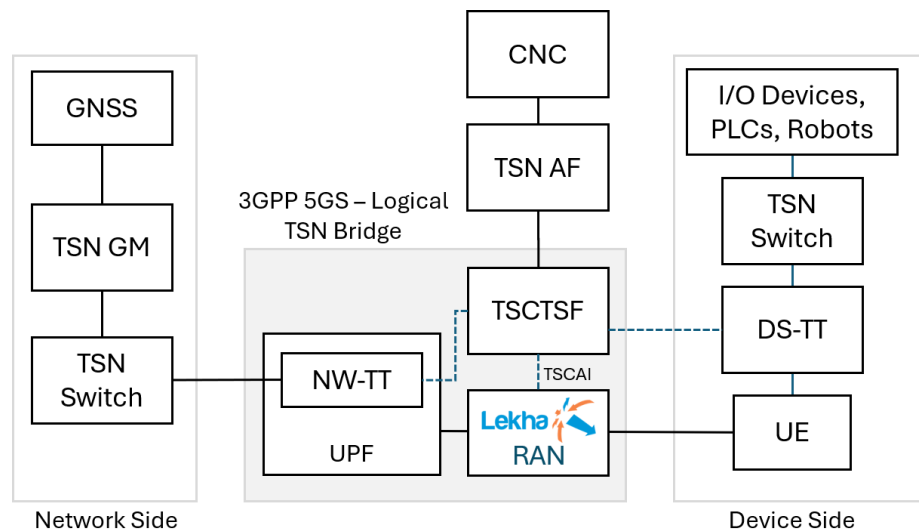
Timing Domain	Protocol	Standard	Purpose	Users
TSN Grandmaster	gPTP (IEEE 802.1AS)	IEEE 802.1AS-2020	Synchronizes industrial end devices on factory floor	PLCs, robots, AGVs, TSN switches
Telecom Grandmaster	PTP (IEEE 1588)	ITU-T G.8275.1	Synchronizes 5G infrastructure — gNB, transport, UPF	gNB, transport switches, UPF

3GPP Standard TSN Architecture — 5GS Based

To ensure industrial devices connected through 5G continue to operate within the same synchronized timing domain as those connected on conventional TSN networks, the 5G System functions as a logical TSN bridge, rather than a conventional wireless network. This approach introduces additional synchronization and translation functions within the 5G System that enable industrial timing information to be exchanged between wired TSN domains and wireless devices. From the perspective of the industrial network, the wireless segment becomes transparent, allowing synchronized operation across both wired and wireless devices.

In this model, the wired TSN Grandmaster (TSN GM) sends gPTP synchronization frames into the network. The NW-TT at the UPF receives these frames, adds an ingress timestamp (TSi) to each frame using the 5G System clock, and transports them over a GTP-U tunnel as regular user-plane data. The RAN (gNB) forwards the traffic over the air interface using the configured QoS treatment (with no awareness that the payload contains timing-critical gPTP frames). At the UE, the DS-TT extracts the gPTP frame, applies the egress timestamp (TSe), determines the delay introduced by the logical TSN bridge (the 5GS) using the ingress and egress timestamps, and updates the correction field in the gPTP Follow_up message before forwarding it to downstream TSN devices.

An external Centralized Network Configuration (CNC) computes the communication and synchronization requirements for TSN streams and communicates these to the TSN Application Function (TSN AF) using the IEEE 802.1Qcc interface. The TSN AF conveys these requirements to the Time Sensitive Communication and Time Synchronization Function (TSCTSF), a logical control-plane function within the 5GS, via the Network Exposure Function (NEF). Based on these requirements, the TSCTSF configures and manages the Network-side TSN Translator (NW-TT) and Device-side TSN Translator (DS-TT), maps the TSN stream requirements to the appropriate 5G QoS parameters, and provides TSC Assistance Information (TSCAI), including the burst arrival time and periodicity of TSN flows. The TSCAI is provided to the gNB scheduler, enabling advance reservation of radio resources and reducing air-interface jitter.



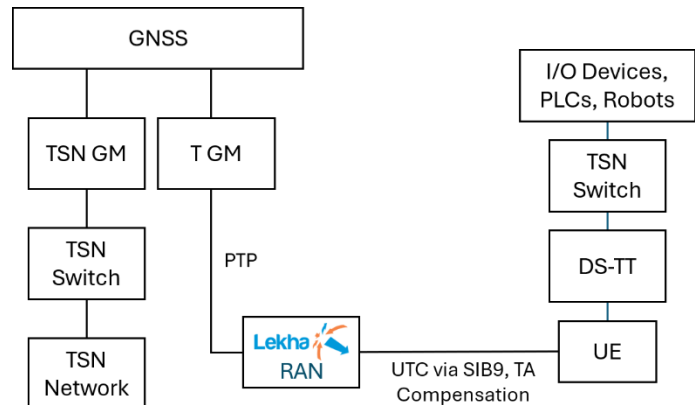
The TSN bridge operation is performed by the Time Sensitive Communication and Time Synchronization Function (TSCTSF), a logical control-plane function within the 5GS. The TSCTSF receives TSN stream requirements from an external Centralized Network Configuration (CNC) using IEEE 802.1Qcc, and through the TSN Application Function (TSN AF). The TSN AF interfaces with the CNC and communicates the TSN requirements to the 5G Core. Based on these requirements, the TSCTSF configures and manages the NW-TT and DS-TT functions, maps TSN stream requirements to the appropriate 5G QoS parameters, and generates TSC Assistance Information (TSCAI), including the burst arrival time and periodicity of TSN flows. The TSCAI is provided to the gNB scheduler, enabling advance reservation of radio resources and reducing air-interface jitter.

RAN-Assisted Time Synchronization (RATS)

RATS adopts a different approach from the 5G-TSN integration described above. While GNSS continues to serve as the primary network time reference for both the wired and wireless network segments, RATS passes the reference timing from a grandmaster clock to the RAN via PTP.

The RAN in turn broadcasts Coordinated Universal Time (UTC) over the air using System Information Block Type 9 (SIB9) control channel messages. The UE compensates for the one-way over-the-air propagation delay using Timing Advance (TA) to derive the synchronized local time.

The Device-Side TSN Translator (DS-TT) uses this synchronized time to originate standard IEEE 802.1AS (gPTP) Sync and Follow_Up messages as a grandmaster port, encapsulating timing information in Ethernet frames. To ensure these messages receive prioritized treatment in the downstream network, the interface marks frames with IEEE 802.1Q VLAN tags using appropriate Priority Code Point (PCP) values enabling downstream switches to classify and queue them ahead of best-effort traffic. Time-aware TSN switches implementing IEEE 802.1Qbv open dedicated scheduled transmission gates for these frames at pre-determined intervals, delivering the time signal through microsecond-accurate, jitter-free forwarding windows to edge PLCs, collaborative robots, and other time-sensitive end stations.



Key Characteristics of RATS

RATS is designed for private industrial 5G deployments and offers the following advantages:

- Requires no TSN-specific synchronization functions in the 5G Core
- Leverages existing 5G RAN timing capabilities
- Requires minimal changes to existing private 5G deployments
- Supports both stationary and mobile industrial devices

Conclusion

Industrial automation and mission-critical private 5G networks require reliable and deterministic synchronization across distributed systems and end-user devices. This whitepaper presents two complementary architectures that address this need across different deployment contexts.

The 3GPP standard TSN bridge model implements a complete 5G RAN and Core architecture, where the 5G System acts as a logical TSN bridge, tunneling gPTP synchronization over the user plane with NW-TT and DS-TT translators. It offers seamless integration with existing wired TSN infrastructure and full CNC-based stream management, making it usable where a TSN-capable 5G Core is available, typically for greenfield industrial deployments.

Lekha RATS is a more streamlined approach that also supports integration of both wired and wireless network segments but leverages standard 3GPP Rel-16 RAN timing mechanisms — SIB9 and Timing Advance — to distribute synchronized time without any 5G Core TSN dependency. Deployable with any standard 5G Core implementation and requiring minimal changes to existing infrastructure, it is ideal for deployments where operational simplicity and rapid availability are priorities.

Lekha supports both architectures through its maRUt RAN portfolio.

References

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Abbreviations

Abbreviation	Description
3GPP	3rd Generation Partnership Project
5GC	5G Core
AGV	Automated Guided Vehicle
BMCA	Best Master Clock Algorithm
CNC	Centralized Network Configuration
DS-TT	Device-Side TSN Translator
gNB	Next Generation NodeB
GM	Grandmaster
GNSS	Global Navigation Satellite System
gPTP	Generalized Precision Time Protocol (IEEE 802.1AS)
GTP-U	GPRS Tunnelling Protocol – User Plane
NIB	Network-in-a-Box
NW-TT	Network-Side TSN Translator
PCP	Priority Code Point
PLC	Programmable Logic Controller
PTP	Precision Time Protocol (IEEE 1588)
QoS	Quality of Service
RAN	Radio Access Network
RATS	RAN-Assisted Time Synchronization
SIB9	System Information Block Type 9
SMO	Service Management and Orchestration
TA	Timing Advance
TSCAI	TSC Assistance Information
TSC	Time Sensitive Communication
TSCTSF	Time Sensitive Communication and Time Synchronization Function
TSN	Time-Sensitive Networking
TSN AF	TSN Application Function
UE	User Equipment
UPF	User Plane Function
UTC	Coordinated Universal Time
VLAN	Virtual Local Area Network

About Lekha 5G

Lekha 5G helps manufacturing establishments drive factory floor transformation and realize their Industry 4.0 vision by enhancing productivity, reducing costs and improving ROI. Built on O-RAN Alliance and 3GPP standards, Lekha 5G is an open, interoperable 5G solution that eliminates vendor lock-in and scales easily using disaggregated functional components from Lekha and 3rd parties with open interfaces.

Lekha's maRUt Radio Unit (RU) portfolio includes a range of products in multiple form factors suitable for various deployment scenarios – rugged high-power and mid-power units for outdoor use, and lightweight low-power units indoors. All popular FDD and TDD bands are supported. The Distributed Unit (DU) and Central Unit (CU) are fully disaggregated, feature open interfaces, and deployed on commercial off-the-shelf (COTS) servers for scalability. Lekha's Service Management and Orchestration (SMO) software also runs on COTS servers and provides RAN network management capability. It can be integrated with third party network elements using REST APIs.

Lekha Wireless is a deep-tech company that designs and manufactures 5G, 4G and 6G RAN infrastructure for private, public and defence networks. Started in 2010, Lekha is focused on R&D of these wireless connectivity technologies and actively participates in 5G-Advanced and 6G standardization. Lekha is a member of the TSDSI SDO and is a founding member of the Bharat 6G Alliance.

For more information or a demonstration, please send a request to business@lekhawireless.com. For details on other products please visit www.lekhawireless.com.

