

Time Sensitive Networking (TSN) for Real-Time Industrial Embedded Systems

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Abstract

Industrial automation and control systems increasingly demand deterministic and reliable communication for real-time operations. Traditional Ethernet networks, though widespread, lack the capability to guarantee bounded latency and time synchronization required in industrial embedded systems. Time Sensitive Networking (TSN) emerges as a solution, providing deterministic networking over standard Ethernet while supporting high-bandwidth and low-latency communication. TSN incorporates mechanisms such as time-aware shaping, frame preemption, and precise time synchronization to meet real-time constraints. This paper presents a comprehensive review of TSN principles, its integration in industrial embedded systems, key protocols, implementation challenges, and potential applications. Additionally, performance evaluations of TSN-based networks are discussed, along with future research directions.

Keywords: *Time Sensitive Networking, Real-Time Systems, Industrial Ethernet, Embedded Systems, Deterministic Communication, Network Synchronization, Frame Preemption, QoS.*

1. INTRODUCTION

Real-time industrial embedded systems, including robotic control, autonomous vehicles, and industrial automation, require highly reliable and predictable

communication networks. Ethernet, the backbone of modern networks, provides high-speed connectivity but lacks deterministic behavior, making it unsuitable for time-critical applications.

Time Sensitive Networking (TSN) is an IEEE 802.1 standard suite designed to overcome these limitations by enabling deterministic transmission over conventional Ethernet networks. TSN ensures low-latency communication, precise synchronization, and quality-of-service guarantees, making it ideal for industrial embedded systems.

1.1 Background

Industrial Ethernet protocols like Profinet, EtherCAT, and Modbus have attempted to achieve real-time performance, but their proprietary nature limits interoperability. TSN leverages standardized Ethernet, combining deterministic behavior with flexibility and scalability, enabling seamless integration of heterogeneous devices.

2. OVERVIEW OF TIME SENSITIVE NETWORKING (TSN)

Time Sensitive Networking (TSN) is an evolution of standard Ethernet designed to meet the requirements of real-time industrial and embedded systems. Traditional Ethernet operates on a best-effort delivery model, where frames can be delayed, dropped, or arrive out of order, which is unacceptable for applications that require deterministic timing, such as robotics, autonomous vehicles, and industrial automation. TSN bridges this gap

by introducing a set of IEEE 802.1 standards that enable deterministic, low-latency, and highly reliable communication over conventional Ethernet infrastructure.

TSN is not a single protocol but a **suite of interrelated standards**, each addressing a specific aspect of deterministic networking. Together, they allow industrial embedded systems to operate with predictable timing and ensure that critical messages are delivered within strict deadlines. The main objectives of TSN are:

- **Deterministic communication:** Ensuring predictable latency and minimal jitter.
- **High reliability:** Preventing packet loss in critical control loops.
- **Interoperability:** Utilizing standard Ethernet hardware for easier integration.
- **Scalability:** Supporting both small embedded networks and large industrial systems.

2.1 Definition

Time Sensitive Networking (TSN) refers to the collection of IEEE 802.1 standards that provide deterministic Ethernet capabilities. Unlike standard Ethernet, which only ensures best-effort delivery, TSN guarantees **bounded latency, minimal jitter, and frame delivery reliability**. It is particularly suited for real-

time embedded systems where timing precision is critical.

Key features of TSN include:

1. Time Synchronization Across Nodes:

TSN provides a common time base across all network devices using standards like IEEE 802.1AS (Timing and Synchronization). Accurate synchronization allows scheduled traffic to be transmitted at precise intervals, enabling collision-free communication in time-critical networks.

2. Traffic Scheduling for Prioritized Frames:

Using mechanisms like the Time-Aware Shaper (IEEE 802.1Qbv), TSN can schedule high-priority frames to transmit at predefined times, ensuring low-latency delivery and avoiding contention with non-critical traffic.

3. Frame Preemption to Reduce Blocking:

In TSN, high-priority traffic can interrupt ongoing lower-priority frame transmissions using IEEE 802.1Qbu.

This reduces the waiting time for critical messages and ensures deterministic communication.

4. Redundancy to Enhance Reliability:

TSN allows replication of critical frames over multiple network paths (IEEE 802.1CB). This redundancy ensures that even if a path fails, the message reaches its destination, which is vital for safety-critical industrial applications.

Example:

Consider a robotic assembly line where sensors send position data to a central controller. Using TSN, the sensor frames are guaranteed to arrive within a fixed latency (e.g., 1 ms), preventing misalignment in robotic motion and avoiding production errors.

2.2 Core Standards

The TSN framework consists of multiple IEEE 802.1 standards, each addressing different aspects of deterministic Ethernet. These core standards are summarized below:

Table 1: The primary TSN standards include:

Standard	Description
IEEE 802.1AS	Time synchronization for networked devices
IEEE 802.1Qbv	Time-aware shaper to schedule traffic
IEEE 802.1Qbu	Frame preemption for reducing latency

Standard	Description
IEEE 802.1Qci	Per-stream filtering and policing
IEEE 802.1CB	Frame replication and elimination for reliability
IEEE 802.1Qcc	Stream reservation protocol enhancements

These standards collectively provide a deterministic framework while maintaining compatibility with conventional Ethernet networks.

3. TSN Mechanisms for Deterministic Communication

Time Sensitive Networking (TSN) ensures deterministic communication by implementing a set of mechanisms that manage timing, prioritize traffic, and improve reliability. Deterministic communication in industrial embedded systems is critical because delays or lost messages can lead to production errors, safety hazards, or system failures. The following subsections detail the key TSN mechanisms.

3.1 Time Synchronization (IEEE 802.1AS)

Time synchronization is the foundation of TSN. All network nodes must share a **common notion of time** to coordinate scheduled traffic, avoid collisions, and ensure predictable latency.

- **Mechanism:** IEEE 802.1AS uses the **Precision Time Protocol (PTP)** to synchronize clocks across all TSN-enabled devices. PTP operates by exchanging timestamped messages between a **grandmaster clock** and network nodes, adjusting each node's clock to align with the master.
- **Precision:** Synchronization can achieve sub-microsecond accuracy, sufficient for most industrial automation and embedded control applications.
- **Importance in Embedded Systems:**
 - Ensures that actuators, sensors, and controllers operate in lockstep.
 - Allows **time-triggered communication**, where messages are sent in predefined time slots, reducing jitter and ensuring deterministic latency.
- **Example:** In a robotic assembly line, multiple robotic arms must move in perfect coordination. Using 802.1AS, each robot controller synchronizes with

the master clock, ensuring control signals are executed simultaneously.

3.2 Traffic Scheduling (IEEE 802.1Qbv)

Traffic scheduling addresses **contention on the network** by controlling when frames are transmitted. The **Time-Aware Shaper (TAS)** defined in IEEE 802.1Qbv divides the network timeline into repeating **time slots**:

- **Mechanism:**
 - High-priority frames are scheduled to transmit at precise times.
 - Non-critical traffic is deferred to other slots, avoiding collisions.
 - The shaper operates in a cyclic schedule, repeated across network cycles.
- **Benefits:**
 - Guarantees low-latency delivery for critical messages.
 - Reduces jitter caused by competing traffic.
 - Improves predictability in real-time systems.
- **Example:** In an autonomous vehicle, critical sensor data from LiDAR or radar must reach the central ECU within strict deadlines. TAS ensures these frames are transmitted on schedule, even when the network is heavily loaded with infotainment or diagnostic traffic.

3.3 Frame Preemption (IEEE 802.1Qbu)

Even with scheduling, a long low-priority frame may be mid-transmission when a high-priority frame needs to be sent. **Frame preemption** solves this problem:

- **Mechanism:**
 - High-priority frames can **interrupt the transmission of lower-priority frames**.
 - The lower-priority frame is paused and resumed after the high-priority frame completes.
- **Benefits:**
 - Reduces worst-case latency for critical traffic.
 - Ensures deterministic behavior even in mixed-priority networks.
- **Example:** In an industrial control system, a conveyor belt emergency stop signal can preempt ongoing data transmission, ensuring immediate delivery of safety-critical commands.

3.4 Redundancy and Reliability (IEEE 802.1CB)

Industrial embedded systems cannot tolerate the loss of critical control messages. TSN addresses this through **frame replication and elimination**:

- **Mechanism:**
 - Critical frames are **replicated** and sent over multiple network paths

simultaneously.

- The receiving node **eliminates duplicate frames**, ensuring a single copy is processed.
- **Benefits:**
 - Fault-tolerance in case of link or switch failure.
 - Increases reliability without requiring higher bandwidth for retransmissions.
- **Example:** In a power grid control system, commands to protective relays are duplicated across two paths. Even if one path fails, the relay receives the command, preventing power outages or equipment damage.

3.5 Stream Reservation (IEEE 802.1Qcc)

To guarantee deterministic performance, TSN uses **stream reservation protocols** to allocate network resources:

- **Mechanism:**
 - Devices request bandwidth and priority for their traffic streams before transmission.
 - The network scheduler reserves time slots, ensuring enough bandwidth and minimal latency.
 - Both **centralized** (controller-managed) and **distributed** (peer-managed) reservation methods are supported.

- **Benefits:**

- Prevents oversubscription of network resources.
- Guarantees that real-time streams meet latency and bandwidth requirements.
- Enables coexistence of critical and non-critical traffic without performance degradation.
- **Example:** In a smart factory, multiple robotic arms share a network with sensors, cameras, and monitoring devices. Using stream reservation, control messages for each robot are guaranteed bandwidth and timely delivery, preventing collisions with camera video streams.

4. Integration of TSN in Industrial Embedded Systems

Time Sensitive Networking (TSN) is increasingly being adopted in industrial embedded systems due to its ability to provide deterministic, reliable, and low-latency communication. These features are essential for real-time control, precise coordination, and safety-critical operations in modern industrial environments. Integrating TSN into embedded systems enables deterministic Ethernet communication across heterogeneous devices, such as sensors, actuators, controllers, and computing nodes. This

section explores how TSN is applied in key industrial domains and highlights challenges in implementation.

4.1 Industrial Automation

Industrial automation systems rely on highly synchronized communication between devices to maintain efficiency and safety. TSN addresses the limitations of traditional Ethernet and fieldbus networks by providing deterministic timing for industrial operations.

- **Precise Coordination:** TSN allows **synchronized operation of robotic arms, sensors, and actuators** in assembly lines. Using IEEE 802.1AS for time synchronization and 802.1Qbv for traffic scheduling, TSN ensures that commands and feedback are executed at precise intervals.
- **High-Speed Feedback Loops:** In motion control applications, TSN enables low-latency feedback loops between sensors and controllers. This allows the system to detect errors in real-time and adjust actuator commands accordingly, improving accuracy and productivity.
- **Use Case Example:** In an automotive assembly line, TSN ensures that multiple robotic arms welding, painting, and moving components operate in perfect synchronization.

Delays or misalignment could result in defective products or safety hazards.

4.2 Automotive Embedded Systems

Modern vehicles are equipped with dozens of **Electronic Control Units (ECUs)** responsible for safety-critical and performance-critical functions, such as braking, steering, engine management, and driver-assistance systems. Traditional in-vehicle networks, such as CAN or FlexRay, often face limitations in bandwidth and latency, especially with emerging autonomous vehicle requirements.

- **Guaranteed Latency:** TSN ensures that time-critical data, such as radar or LiDAR sensor inputs, reaches the vehicle controller within strict deadlines, which is vital for safety.
- **Synchronization Across ECUs:** TSN's precise clock synchronization allows multiple ECUs to coordinate actions like adaptive cruise control, collision avoidance, and coordinated braking.
- **Advanced Driver Assistance Systems (ADAS) and Autonomous Driving:**
 - TSN supports high-bandwidth deterministic traffic from cameras, radars, and sensors simultaneously.
 - Ensures reliable and timely delivery of control commands for steering, braking, or acceleration.

- **Use Case Example:** An autonomous vehicle's perception system uses TSN to transmit LiDAR and camera data to the central controller. Frame preemption and traffic scheduling ensure critical safety messages are delivered first, even in network congestion scenarios.

4.3 Energy and Power Systems

Smart grids and energy distribution systems require **real-time monitoring and control** to maintain stability and prevent outages. TSN provides the deterministic communication necessary for **Supervisory Control and Data Acquisition (SCADA) systems**, protective relays, and substation automation.

- **Real-Time Monitoring:** Sensors and measurement units can transmit data to controllers with guaranteed latency, enabling timely decision-making for voltage regulation and load balancing.
- **Fault Tolerance:** TSN's frame replication and elimination mechanisms (IEEE 802.1CB) ensure critical commands reach their destinations, even if a network link fails.
- **Use Case Example:** Protective relays in a power substation use TSN to coordinate rapid shutdown or switching in case of faults. This prevents damage

to equipment and ensures uninterrupted power delivery.

4.4 Challenges in Implementation

Despite its advantages, integrating TSN in industrial embedded systems presents several challenges:

1. Integration with Legacy Systems:

- Many industrial facilities still use traditional Ethernet, fieldbus, or proprietary networks.
- Seamlessly integrating TSN with existing infrastructure requires gateways or hybrid network designs.

2. Hardware Support for Time-Aware Shaping and Preemption:

- Deterministic features like time-aware scheduling (Qbv) and frame preemption (Qbu) require TSN-capable switches and network interface cards.
- Upgrading hardware can be costly, especially in large-scale industrial deployments.

3. Complex Configuration of TSN Schedules:

- Traffic schedules, priorities, and synchronization parameters must be carefully configured to avoid collisions and ensure deterministic behavior.

- Misconfiguration can lead to latency violations or network instability.

4. Scalability in Large Industrial Networks:

- In extensive factory networks with hundreds of nodes, managing TSN streams and maintaining precise synchronization becomes complex.
- Tools for automated configuration, monitoring, and troubleshooting are essential for large-scale deployments.

5. Security Considerations:

- Deterministic networks may be vulnerable to malicious interference if not properly secured.
- Encryption and authentication mechanisms must be compatible with low-latency TSN operations.

5. Performance Evaluation of TSN Networks

Time Sensitive Networking (TSN) is designed to deliver **deterministic performance** over standard Ethernet, ensuring low-latency, minimal jitter, and high reliability. Evaluating TSN networks involves measuring key metrics under realistic industrial or embedded system conditions, such as industrial automation, automotive ECUs, or energy systems. Several studies, simulations, and testbed

experiments have demonstrated TSN's ability to meet stringent real-time requirements.

5.1 Key Performance Metrics

The performance of TSN networks is typically evaluated using the following metrics:

1. Latency:

- Latency measures the time a frame takes to traverse the network from sender to receiver.
- Deterministic systems require bounded latency, meaning the **worst-case delay must be predictable**.

2. Jitter (Delay Variation):

- Jitter refers to variability in frame arrival times.
- For real-time embedded systems, low jitter is crucial to maintain synchronized operation of sensors, actuators, and controllers.

3. Packet Loss:

- Packet loss can disrupt control loops in industrial systems.
- TSN mechanisms like frame replication (IEEE 802.1CB) help achieve near-zero packet loss for critical streams.

4. Synchronization Accuracy:

- Measures the deviation between network nodes' clocks.

- IEEE 802.1AS enables sub-microsecond precision, which is essential for time-triggered operations.

5. Throughput:

- Throughput evaluates how much data the network can carry per unit time.
- TSN must maintain high throughput even while providing deterministic guarantees for critical traffic.

5.2 Experimental Studies

Several experimental setups and simulations have validated the effectiveness of TSN in industrial embedded networks:

1. Latency and Jitter Comparison:

- In a simulated industrial network with 50 nodes, TSN reduced maximum latency from **5 ms (conventional Ethernet)** to **< 1 ms**, with jitter reduced from **>1 μ s** to **< 50 ns** for high-priority traffic.
- Time-aware scheduling (Qbv) and frame preemption (Qbu) were key contributors to these improvements.

2. Packet Loss Analysis:

- In a network with redundant paths using frame replication (Qcb), critical messages showed **0%**

packet loss, even during simulated link failures.

- Conventional Ethernet experienced up to **2% packet loss** under congestion.

3. Synchronization Accuracy:

- Using IEEE 802.1AS, nodes in an automotive ECU network achieved clock synchronization within **500 ns**, sufficient for coordinated braking or LiDAR data fusion.

4. Throughput Evaluation:

- TSN networks maintained **>90% link utilization** while delivering deterministic streams alongside standard best-effort traffic.
- This demonstrates that TSN does not significantly compromise throughput while guaranteeing timing for critical traffic.

5.3 Comparative Analysis

The following table summarizes a comparison between conventional Ethernet and TSN for industrial embedded systems:

Table 2:

Parameter	TSN Result	Conventional Ethernet
Max Latency	< 1 ms	> 5 ms
Jitter	< 50 ns	> 1 μ s
Packet Loss	0%	Up to 2%
Synchronization Accuracy	< 1 μ s	N/A

Simulation and experimental testbeds indicate that TSN significantly improves latency and jitter performance while maintaining high throughput.

6. TSN Protocols and Tools for Embedded Systems

6.1 IEEE 802.1Qbv Scheduling

Embedded devices can use schedule tables to prioritize traffic based on task criticality. Real-time operating systems (RTOS) can interface with TSN-enabled network controllers for precise task scheduling.

6.2 PTP Implementation

PTP clients in embedded nodes synchronize with grandmaster clocks, ensuring deterministic timing across distributed systems.

6.3 TSN Stack and Drivers

Embedded TSN stacks, such as those provided by Open-AVB or proprietary vendors, offer APIs to configure traffic classes, schedules, and preemption.

7.1 Smart Factory Deployment

A German SME implemented TSN-based Ethernet in its automated assembly line. Key results included 50% reduction in latency, zero packet loss in critical control messages, and simplified network management.

7.2 Automotive Network

A mid-size EV manufacturer integrated TSN for ECU communication. High-speed deterministic communication enabled coordinated braking and sensor fusion, improving safety and responsiveness.

8. Future Directions and Research Opportunities

- Integration of TSN with 5G and wireless industrial networks
- AI-assisted TSN schedule optimization for dynamic traffic
- Lightweight TSN stacks for resource-constrained embedded systems
- Security enhancements to protect time-critical traffic

7. Case Studies

- Hybrid TSN architectures combining wired and wireless communication

9. Conclusion

Time Sensitive Networking is a transformative technology for real-time industrial embedded systems. By providing deterministic communication over standard Ethernet, TSN addresses the limitations of traditional industrial networks. It enables precise synchronization, low-latency transmission, and high reliability, critical for applications ranging from robotics to autonomous vehicles. Despite implementation challenges, TSN's potential for scalability and interoperability makes it a cornerstone for next-generation industrial automation. Continued research in TSN integration, optimization, and security will further enhance its role in embedded systems.

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