Time Sensitive Networking for Industrial Automation

Texas Instruments

Introduction

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Time-sensitive networking (TSN) is an Ethernet extension defined by the Institute of Electrical and Electronic Engineers (IEEE) designed to make Ethernet-based networks more deterministic. Industries like automotive, industrial and performance audio use real-time communication with multiple network devices and will benefit from the TSN standard.

The consumer and enterprise world of Ethernet and wireless Ethernet communication are bandwidth oriented. For example, while browsing the Internet you accept a varying amount of delay before video playback starts. Although there is a preference for quick interaction, for the average user it is acceptable if one out of 100 clicks perform an order of magnitude worse. However, if a video is bad quality or even halted the typical consumer will be frustrated.

Even infrequent delays are unacceptable in control systems such as those inside automobiles, production lines or concert halls. The most important aspects for these systems are latency and jitter or variation in the latency of control data through the network. The maximum time a packet takes to reach the destination in the system defines the communication cycle or control frequency in the network.

Network parameters for various application examples provides an overview of network parameters for certain application examples. The network size and topology can be either fixed (to a certain application) or variable. The Internet is the worst-case example when it comes to the number of nodes and the route that a packet takes through the network. Latency is in the seconds range and jitter is very high when you repeat a packet transfer over the Internet.

By contrast, real-time deterministic Ethernet communication typically limits the number of devices connected to the network. Using a machine tool as an example of an embedded product, the number of motors connected with Ethernet to a single piece of control hardware is less than 100. New motor control parameters are exchanged every 250 µs. This fixed and pre-engineered setup requires deterministic real-time Ethernet with short cycle times and high-precision clock distribution.

Production systems in a modern factory are fully connected using real-time Ethernet. **Industry 4.0 TSN Backbone Production Cell**shows various control systems in a production cell.

Network Feature	Machine Tool	Automotive Radar	Professional Audio	Consumer Video
Scale	64 axes	4 sensors	20 speakers	1 screen
Bandwidth	100 Mb	1 Gb	100 Mb	100 Mb
Jitter	100 ns	20 ns	10 ns	100 ms
Latency	100 µs	1 ms	10 µs	1 s
Cycle time	<1 ms	10 ms	Stream	Burst
Time synchronize d	Yes	Yes	Yes	No
Topology	Line, ring	Star	Star, line	Point to point

Table 1. *Network parameters for various application examples.*

A time-sensitive network is a key technology with which to connect various control systems in real time.

Although the requirements for control systems are different in terms of scale, cycle time and accuracy, they can use the same communication interface to transfer data deterministically. Many sensors and actuators are deployed inside the control system. They either connect directly to real-time Ethernet or connect to a concentrator in the real-time Ethernet network using serial point-to-point connections. TSN with its deterministic networking performance is a good fit here, in the “field” level of a manufacturing floor.

The high number of connected sensors and actuators of the industrial control system is one of the key challenges for TSN network configuration.

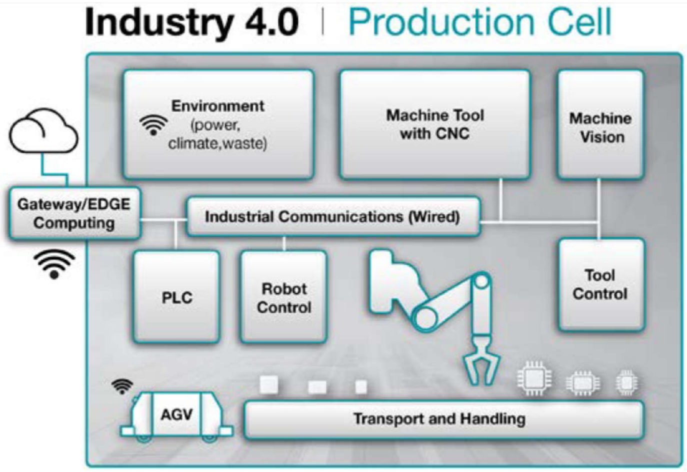

Figure 1. *Industry 4.0 production cell with TSN backbone.*

TSN provides the capability to classify streams and tag them with deterministic delivery through a network. In an ideal case, a converged network hosts different stream classes ranging from motion control to traffic to the cloud, in one TSN domain. But first, you should understand the basic functions of TSN before answering the question of network engineering.

Principles of TSN

IEEE 802 Ethernet combined with Internet Protocol has been a success story like few others in the tech industry. The only challengers to its dominance have been more sophisticated technologies in the areas of determinism and quality of service such as Asynchronous transfer mode (ATM), token ring and RapidIO®. TSN is a set of roughly 12 IEEE 802 standards aimed at addressing determinism and quality of service without compromising the strengths of Ethernet such as interoperability. Most of the above mentioned TSN standards are now included in the main Ethernet specification IEEE 802.1Q-2018.

TSN is a local area network (LAN)-level solution that can work with non-TSN Ethernet, but timeliness is only guaranteed inside the TSN LAN. You can group TSN standards based on what use case it solves: a common view of time, assured maximum latency, or co-existence with background or other traffic.

Like any popular standard, the TSN toolbox of standards is evolving; some of the individual standards like 802.1AS-Revision (Rev) was recently approved as 802.1AS-2020 but further enhancements are being defined in P802.1ASdm, and new alternative shapers are being introduced. Because of this on-going evolution, when choosing a solution it is important to consider the upgradability of the solution to support new or changed standards.

As shown in **IEEE TSN and the communications stack** on the following page, IEEE 802 Ethernet including the TSN features is a layer 2 or data link layer technology. Applications require an upper-layer protocol such as UDP/IP, OPC UA or PROFINET above TSN (**Industrial Ethernet Protocols and Ethernet**).

802.1AS – Timing and synchronization for timesensitive applications (gPTP)

All devices in a network expecting deterministic packet transmission will require a common understanding of time. The clock master or masters distribute time over Ethernet packets to all devices in the network running the Best Master Clock Algorithm (BCMA).

802.1AS-2020 is a tightly defined subset or a profile of IEEE1588-2008 (sometimes called 1588v2) precision timing over packet. The additions of 802.1AS-2020 to 802.1AS-2011 add support for more than one time domain, support for two timescales (precision time protocol and arbitrary), and optional support for one-step in addition to two-step. The underlying hardware must support the time stamping of transmitted and received packets as close to the wire as possible. For one-step delay reporting, the hardware must also be able to insert a time stamp into the packet as it is being transmitted. For two-step delay reporting, the transmit time stamp is included in a follow-up packet, in some cases increasing the packet load created by time synchronization over packet.

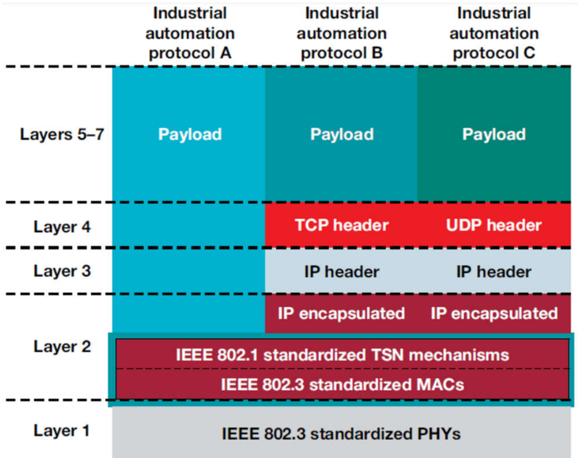

Figure 2. *IEEE TSN and the communications stack.*

802.1AS-2020 includes peer-to-peer line-delay measurement and bridge-delay calculation. Beyond time stamping, the rest of 802.1AS-2020 is typically implemented in software that runs on a dedicated core. Either on Linux capable cores like Cortex A53 or on the MCU cores like Cortex R5. TSN implementation for Texas Instruments (TI) Sitara™ processors supports 802.1AS-2011 and 802.1AS-2020. There are some further additions to improve the jitter in a line topology that are being worked on in P802.1ASdm, we expect those to be minor additions that can be supported with software updates.

802.1Qbv – Enhancements for scheduled traffic (EST)

Time-aware shaper (TAS) makes switches and endpoints aware of the cycle time for real-time traffic. The IEEE802.1Q-2018 name for this feature is Enhacements for Scheduled Traffic (EST). An egress per port scheduler for packets creates a periodic window during which there is no interfering traffic.

TI's TSN implementation for Sitara processors supports TAS. TAS is mostly a hardware feature, with a software stack configuring the hardware shaper in each bridge port and endpoint talker.

802.1Qbu – Frame preemption and 802.3br – Interspersing Express Traffic (IET)

Ethernet is a store-and-forward network. Once a packet starts to go on the wire it will block the wire from other packets until the end of the packet is reached. For example, a 100-Mbps network and a typical maximum transmission unit (MTU) packet size of 1.5 kB create a head-of-line blocking of about 120 μs (1.5 kB/100 Mbps). Higher-speed links reduce this linearly, but even 1-Gbps networks can have resulting jitter in the tens of microseconds.

To reduce head-of-line blocking issues, IEEE defined frame preemption (802.1Qbu) and the related physical layer standard interspersing express traffic (802.3br). Only express traffic can preempt, providing guaranteed latency for express traffic. The IEEE802.1Q-2018 name for this feature is Interspersed Express Traffic (IET).

Cut-through switching, together with TAS and frame pre-emption, are the basic technologies to reduce worst-case latency—even in a long daisy-chain topology network. TI's TSN implementation for Sitara processors supports cut-through switching, frame pre-emption and interspersing traffic.

Cut-through Switching

Enter a short description of your concept here (optional).

802.1Q Ethernet is a store-and-forward achitecture. This means once a frame starts arriving the ingress port will wait to see the end of the frame before forwarding it. The destination address is in the begining of the frame, and there is a CRC at the end of the frame. Cut-through switching takes advantage of the address being in the beginning to start forwarding the frame before the end of the frame has been received. The best bridge delay latency is achieved by taking advantage of only looking at the very beginning of the frame before making the forwarding decision. For example just the beginning of the destination address. The drawback with cut-through is that frames that are malformed with incorrect CRC also get forwarded. Texas Instruments supports cut-through switching and is working with the industry to have the feature standardized.

802.1Qch – Cyclic queuing and forwarding

Cyclic queuing and forwarding defines completely deterministic delays for all streams. TI's TSN implementation for Sitara processors does not initially support 802.1Qch; instead, we propose using 802.1Qbv (EST) and a fully managed network to avoid interfering traffic achieves the same netowrk level performance.

802.1CB – Frame replication and elimination for reliability (FRER)

Typical Ethernet networks rely on higher-level protocols such as Transmission Control Protocol (TCP) retransmission to recover from dropped Ethernet frames, and the Spanning Tree Protocol (STP) to construct new routes through the network. Both approaches sacrifice a nondeterministic amount of time to deliver the frame.

TSN uses redundancy to guarantee latency even in the presence of single-point failures such as cut cables or broken switches. To proactively guarantee the delivery of frames inside a LAN topology with multiple routes, 802.1CB provides redundancy by selectively duplicating frames at the sender and then discarding the duplicate at the destination. Selecting which frames to duplicate is based on the concept of streams. 802.1CB-2019 includes the definition of TSN streams based on layer-2 level headers called "null stream" and higher level called "IP stream", which is used in other TSN features.

802.1CB is compatible with existing industrial networks where earlier redundancy protocols such as High-Availability Seamless Redundancy (HSR) and Parallel Redundancy Protocol (PRP) provided no latency impact from single-point failures.

802.1Qcc – Stream reservation protocol enhancements and performance

TSN uses three identifying labels: stream ID, stream destination address and traffic class.

- Stream ID is the media access control (MAC) source address concatenated with a 16-bit handle.
- The stream destination address is the MAC destination address concatenated with the virtual LAN (VLAN) ID (802.1Q – VLAN support). Addresses are usually locally managed or multicast addresses.
- VLAN priority bits, typically using only one or two classes, determine the traffic class.

Stream ID is the unique identifier used by the resource management. Stream destination address and traffic class identify the data path taken.

802.1Qcc supports a centralized configuration model with a centralized user configuration (CUC), as shown in **TSN Configuration**. A centralized network configuration (CNC) calculates resource allocations and availability and configures the bridges.

Alternative architectures are possible: talkers and listeners talking directly to CNC, or even a fully distributed architecture. A centralized architecture and YANG-based network management protocol (YANG is a data modeling language for network configuration developed by IETF and defined in RFC 7950) like RESTCONF or NETCONF used over a standard secure networking stack like Transport Layer Security (TLS) are likely. The Linux software development kits (SDK) for Texas Instruments processors includes NETCONF starting with version 8.6 [4] and the MCU-PLUS SDKs include NETCONF starting with 9.0.

TSN's impact on industrial Ethernet

TSN adds real-time capabilities to standard IEEE Ethernet—capabilities that were once only available on specialized industrial field buses (also called industrial Ethernet). TSN does not remove the need for or replace the protocol used above Ethernet.

The interface to software is a good example. For Transmission Control Protocol/Internet Protocol (TCP/IP), a Berkeley software distribution (BSD) socket has become the standard interface with TCP/IP and networking in general, and has proven portable and scalable for a wide set of applications.

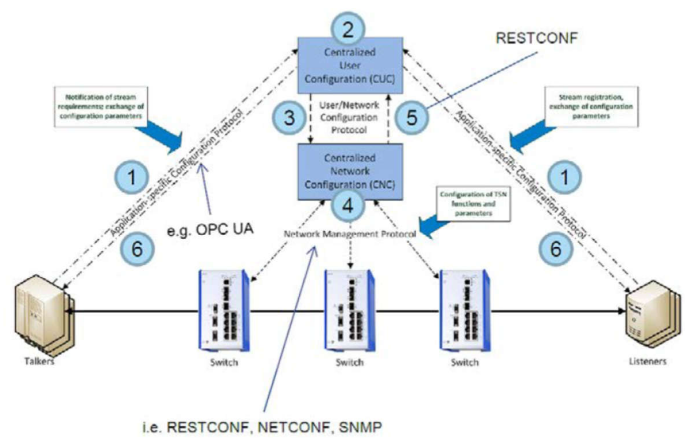

Figure 3. *TSN configuration.*

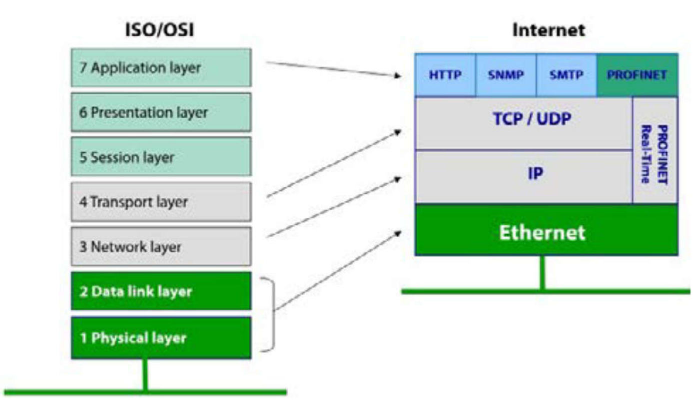

Figure 4. *Industrial Ethernet protocols and Ethernet.*

A Hypertext Transfer Protocol (HTTP) application works unmodified while reading from a local file or over the Internet. But these sockets are not necessarily relevant interfaces for a protocol that prioritizes solving worst-case latency and exposing the concept of time all the way to the application. For example, the industrial Ethernet protocol PROFINET expects TSN-enabled Ethernet to be just one data-link layer over which to run the protocol.

IEEE TSN defines layer-2 functionality and LAN-level switching, including the concept of time. What it does not define is the software interface with which to configure these hardware features. This means that management software for a switch from vendor A will need to use one application programming interface (API) to another API for vendor B.

A second (and perhaps more unique) area outside the scope of IEEE specifications centers around the concept of latency and the variation or the jitter of latency in the data-path software. As we mentioned, earlier sockets are great but do not even try to address real time or latency.

It is very likely that the API and software architecture around the data path for TSN networks will evolve over time. The PRU-ICSS-based programmable TSN solution addresses both the software stack portion of latency and configuration and management incrementally. The TSN solution can adapt to a software architecture that requires a very specific buffering mechanism for real time, while supporting mainline Linux® networking in parallel. And once Linux leverages more real-time features, a programmable solution can adapt to the new software architecture. TI is working with the community to enable more determinism and an open source configuration API for TSN hardware. For example EST hardware offload on AM6x is supported in Linux kernel versions since 5.4 [5]. For the microcontollers MCU+ SDK EST support is in [6].

Industrial Ethernet protocols like PROFINET® and EtherNet/IP™ already assume the IEEE Ethernet learning bridge as the underlying switching technology. These protocols can now adapt the extension of time aware shaping (EST) and frame pre-emption (IET) to use standard TSN hardware for industrial Ethernet. EtherNet/IP uses User Datagram Protocol (UDP) packets for data exchange. PROFINET supports a direct layer-2 buffer model for consumer and provider data supported by PRU-ICSS TSN solution. Both PROFINET and EtherNet/IP are compatible with the TSN switching layer and can benefit from the real-time enhancements.

The IEEE standardization of redundancy protocols were not included in the 802.1Q-2018 standard, and it remains to be seen whether 802.1CB will replace the redundancy protocols of PROFINET and EtherNet/IP, such as media redundancy protocol (MRP) and device level ring (DLR). The transition from existing industrial communication protocols to new standards typically spans many years. During the transition phase, old and new protocols are used concurrently in production systems.

In addition to greenfield systems based solely on TSN capable controllers and devices. functions that bridge between existing and new protocols will accelerate the introduction of TSN hardware for industrial communication. Possible applications include:

- Industrial fieldbus to TSN network gateway.
- An IO-Link master gateway to TSN network.
- The object linking and embedding for process control unified architecture (OPC UA) over TSN Ethernet.
- A combination of protocols at the field and control levels with an uplink into the cloud.
- Motion controller with tarditional industrial fieldbus controller, with device side TSN based interface for controller to controller communication **OPC UA FX**.

Texas Instruments **Sitara Processors** and **MCUs** can realize the applications from remote IO and network connected motor drives to the functions on this list. Industrial communication subsystems (PRU-ICSSG), an additional gigabit switch (CPSW3G, CPSW5G, CPSW9G) and the ability to interface to a Wi-Fi® module mean that the Sitara processors can support up to seven communication channels from a single device. Each PRU-ICSSG can implement either controller- or device-side industrial Ethernet protocols. Sitara AM64x supports up to 5 TSN ports capable of gigabit Ethernet and the related AM243x MCU brings this 5 port capability to microcontrollers. AM62x, and AM62A processors and AM263x MCU include two ports with TSN capable Ethernet.

Portfolio of TSN Capable Processors and MCUs shows the portfolio of TSN capable processors and MCUs at different levels in a production system.

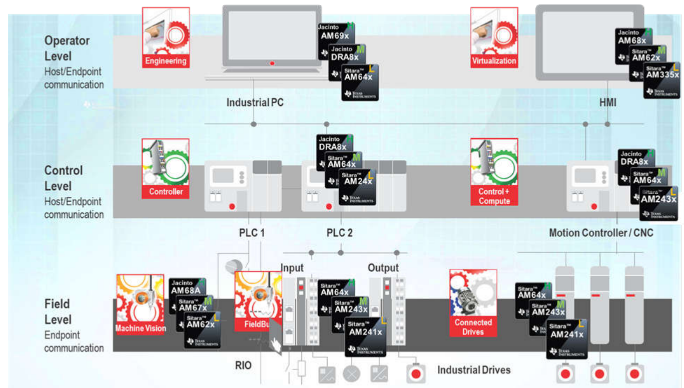

Figure 5. Portfolio of TSN capable processors and MCUs

To get started see the evaluation boards listed below.

Table 2 shows the software support for the TSN features.

Board	Number of TSN Interfaces	
AM64x EVM and **AM243x EVM**	3 with further 2 on the expansion header	Widest variety of interfaces exposed
AM64x SK and **AM62x SK** SK	2	Lowest cost Linux capable board with TSN switch support
AM243x LP	2	Low cost MCU board with TSN switch support
AM62A SK	1	Linux board with machine learning inference accelerator and TSN support

Table 2. Software support for TSN features

Feature	HW Support CPSW/ICSSG	Linux Native Drivers	FreeRTOS MCU-PLUS Drivers
802.1Q VLANs	Y/Y	Y	Y
802.1AS-2020 Time Synchronization	Y/Y	Linuxptp / ptp4l	gPTP in 9.0 SDK
802.1Qbv Enhancements Scheduled Traffic (EST): Time-Aware Shaper(TAS)	Y/Y	Y (tc qdisc)	Y

Feature	HW Support CPSW/ICSSG	Linux Native Drivers	FreeRTOS MCU-PLUS Drivers
802.1Qbu/ 802.3br Interspersed Express Traffic (IET): Frame Preemption	Y/Y	Y (tc qdisc) LLDP support in 2024	Y
802.1QavForward and Queing of Time Sensitive Streams (FQTSS) - previously known as eAVB (Ethernet Audio Video Bridging)	Y/Y	Y (tc qdisc)	Y
802.1Qci Per-Stream Filtering and Policing (PSFP)	Partial, on off gates not supported	Y (tc qdisc) for metering	N
802.1CB Frame Replication and Elimination for Reliability(FRER)	N/Y	ICSSG prototype in 2023	ICSSG prototype in 2023
802.1Qch Cyclic Queuing and Forwarding	N	Looking at configuration of the EST/Qbv scheduler to implement	Looking at configuration of the EST/Qbv scheduler to implement
802.1Qcr Asynchronous Traffic Shaping	N	N	N
802.1Qcat Stream Reservation Protocol (SRP)	Y/Y	Netconf included in 8.6 SDK	Netconf included in 9.0 SDK
802.1Qcc Enhancements to SRP	Y/Y	Netconf included in 8.6 SDK	Netconf included in 9.0 SDK
802.1BAAudio Video Bridging (AVB) Systems	Y/Y	libavtp	Evaluation version of commercial stack in 9.0 SDK
Cut-through switching (no approved IEEE standard)	Y/Y	Y	Y

Conclusion

TSN is moving in the right direction to provide a rich set of capabilities with which to stream packets through a larger industrial network with guaranteed latency. Leading industrial Ethernet organizations are adopting TSN technology and integrating it into existing engineering systems and application profiles.

Higher-layer control systems and other applications outside the factory may also work with central network configuration tools that are independent of the application. Manufacturing networks continue to evolve with the introduction of TSN features, however traditional industrial Ethernet (PROFINET, EtherCAT, EtherNet/IP, and so forth) continue to be supported by Sitara processors. Using Sitara processors with integrated cut-through TSN hardware switches can accelerate the transition from 100 Mb to 1 Gb industrial Ethernet.

References

1. Wired and Wireless Connectivity
2. Sitara processors
3. Sitara MCUs
4. Linux SDK NETCONF
5. Linux SDK time aware shaper (EST)
6. MCU+ SDK time aware shaper (EST)
7. AM64x Evaluation Board, AM243 Evaluation Board
8. AM64x Starter Kit AM62x Starter Kit
9. AM243x Launchpad
10. AM62A Launchpad
11. Time Sensitive Networking on AM64x

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