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Contents

1 Introduction

1.1 Objectives

Time-Sensitive Networking (TSN) is a set of standards specified by [1, IEEE 802.1 TSN Task Group]. It provides end-to-end data transmission with extremely low latency and high reliability over Ethernet. As a result, TSN is considered as one of the key enabler for deterministic communication on standard Ethernet, which can further be used to accurate timing and guarantee data delivery for automotive Ethernet.

The purpose of this document is to give an overview on the relevant TSN features, and provide examples how to use them together with AUTOSAR platform.

1.2 Scope

This document provides explanatory information and help the automotive engineer to understand the fundamental TSN features, as well as the basic approach to design a deterministic network on automotive Ethernet.

The content of this document will address following topics:

- Constraints and Assumptions
- Overview
- Usage of Shapers
- Accuracy of Time Synchronization
- Measure Quality (Accuracy) of Time Synchronization

2 Definition of terms and acronyms

2.1 Acronyms and abbreviations

The glossary below includes acronyms and abbreviations relevant to FO_RS_IEEE1722 that are not included in the AUTOSAR TR Glossary.

Abbreviation / Acronym:	Description:
TSN	Time Sensitive Networking
TSpec	Traffic specification as defined by [2, IEEE Std 802.1Q-2018]
AVTP	Audio/Video Transport Protocol as defined by [3, IEEE Std 1722-2016]
AVTPDU	Audio/Video Transport Protocol Data Unit as defined by [3, IEEE Std 1722-2016]
IIDC	Instrumentation and Industrial Digital Camera as defined by [3, IEEE Std 1722-2016]
61883_IIDC	IEC 61883/IIDC format as defined by [3, IEEE Std 1722-2016]
AAF	AVTP Audio Format as defined by [3, IEEE Std 1722-2016]
CRF	Control Reference Format as defined by [3, IEEE Std 1722-2016]
TSCF	Time Sensitive Control Format as defined by [3, IEEE Std 1722-2016]
NTSCF	None Time Sensitive Control Format as defined by [3, IEEE Std 1722-2016]
ACF	AVTP Control Format as defined by [3, IEEE Std 1722-2016]
ACF_CAN	Controller Area Network (CAN)/CAN with Flexible Data-Rate (CAN FD) message as defined by [3, IEEE Std 1722-2016]
ACF_CAN_BRIEF	Abbreviated CAN/CAN FD message as defined by [3, IEEE Std 1722-2016]
ACF_LIN	LIN® message as defined by [3, IEEE Std 1722-2016]
RVF	Raw Video Format as defined by [3, IEEE Std 1722-2016]
gPTP	generalized Precision Time Protocol [4, IEEE Std 802.1AS]
PPS	Pulse Per Second physical signal
1PPS	1 Pulse Per Second physical line
GPS	Global Positioning System

Table 2.1: Acronyms and abbreviations used in the scope of this Document

2.2 Definition of terms

2.2.1 Ethernet packet

Definition: An "Ethernet packet" is an on wire format defined by [5, IEEE Std 802.3-2022] which includes the following parts: Preamble (7 bytes), SFD (start frame delimiter, 1 byte), Ethernet frame (up to 2000 bytes), IPG (inter package gap, 12 byte times)

2.2.2 Ethernet frame

Definition: An "Ethernet frame" is on wire format defined [5, IEEE Std 802.3-2022] which includes the following parts: MAC destination address field (6 bytes), MAC source address field (6 bytes), Type field (2 bytes), MAC client data field (include optional Q-Tag (4 bytes)) (up to 1982 bytes), optional PAD (padding bytes), FCS (frame check sequence, 4 bytes)

2.2.3 Stream

Definition: A "stream" represent multiple Ethernet frames which are grouped by similar frame attributes (e.g. MAC source address)

2.2.4 IEEE1722-based stream

Definition: A "IEEE1722-based stream" represent multiple Ethernet frames which have EtherType set to AVTP Ethertype (0x22F0) (see [3, IEEE Std 1722-2016])), carry an IEEE1722 specified AVTP header and an AVTP stream data subtype (e.g. AAF (AVTP Audio Format))

2.2.5 Stream data producer

Definition: A "stream data producer" represent an end node in an Ethernet network which (continuously) produces data. The data is transmitted via a stream and received by 1 or multiple end nodes (stream data consumer)

2.2.6 Stream data consumer

Definition: A "stream data consumer" represent an end node in an Ethernet network which (continuously) consumes data. The data is received via a stream.

2.2.7 AVTP presentation time

Definition: The "AVTP presentation time" is defined by [3, IEEE1722-2016]) and represents the globally synchronized time at which designated data within an AVTPDU payload is transferred to a time-sensitive application of an stream data consumer. Please note: AVTP presentation time is calculated as "TavtpPresentationTime" = "TcurrentGlobalTime" + "TmaxTransitTime".

2.2.8 Max transit time

Definition: "Max transit time" is defined by [3, IEEE1722-2016]) and represents the maximal acceptable delay when data of a stream data producer is added to its egress queue, transferred across the network via an IEEE1722-based stream and this data is forwarded from the ingress queue of the receiving stream data consumer to a time-sensitive application.

2.2.9 Media clock

Definition: "Media clock" is defined by [3, IEEE1722-2016]) and represents an entity which generates a periodic signal with a constant rate (e.g. precise hardware clock with a constant rate (e.g. 48kHz)). The media clock is hosted by the media clock provider.

2.2.10 Media clock provider

Definition: A "media clock provider" is an end node in the network which hosts an media clock. The media clock provider transmit an IEEE1722-based stream to 1 or multiple media clock consumer. The IEEE1722-based stream is of subtype Clock Reference Format (CRF) and contain several presentation timestamps which correlates to the media clock rate.

2.2.11 Media clock consumer

Definition: A "media clock consumer" is an end node in the network which receives a IEEE1722-based stream of subtype Clock Reference Format (CRF) from a media clock provider. The media clock consumer performs a recovery of its media clock (e.g. PLL) based on the received encapsulated data from the media clock provider.

3 Related Documentation

3.1 Input documents & related standards and norms

[1] IEEE 802.1 TSN Task Group
https://1.ieee802.org/tsn/

[2] IEEE 802.1Q-2018 - IEEE Standard for Local and Metropolitan Area Network - Bridges and Bridged Networks
https://ieeexplore.ieee.org/

[3] IEEE Standard 1722-2016 - IEEE Standard for a Transport Protocol for Time-Sensitive Applications in Bridged Local Area Networks

[4] IEEE Standard 802.1AS-2011

[5] IEEE 802.3-2022
https://www.ieee802.org/3/

[6] IEEE Standard for Local and metropolitan area networks-Virtual Bridged Local Area Networks-Amendment 12:Forwarding and Queuing Enhancements for Time-Sensitive Streams
https://ieeexplore.ieee.org/

[7] IEEE Standard for Local and metropolitan area networks – Bridges and Bridged Networks - Amendment 25:Enhancements for Scheduled Traffic
https://ieeexplore.ieee.org/

[8] IEEE Standard for Local and Metropolitan Area Networks–Bridges and Bridged Networks – Amendment 31:Stream Reservation Protocol (SRP) Enhancements and Performance Improvements
https://ieeexplore.ieee.org/

[9] P802.1Qcr - Bridges and Bridged Networks Amendment:Asynchronous Traffic Shaping

[10] Time Synchronization Protocol Specification
AUTOSAR_FO_PRS_TimeSyncProtocol

[11] Specification of Time Synchronization over Ethernet
AUTOSAR_CP_SWS_TimeSyncOverEthernet

[12] 802.1AS Recovered Clock Quality Testing
https://avnu.org/wp-content/uploads/2014/05/Avnu-Testability-802.1AS-Recovered-Clock-Quality-Measurement-1.0_Approved-for-Public-Release.pdf

4 Time Sensitive Network in AUTOSAR

4.1 Constraints and Assumptions

AUTOSAR does not support the following TSN features:

- time aware shapers
- active stream identification
- frame replication

AUTOSAR assumes that all Ethernet switches in the network are VLAN-aware. VLAN-unaware Ethernet switches are not supported.

4.2 Overview

TSN is a set of IEEE 802 standards based on Ethernet. It specifies functions to ensure the transmission with bounded low latency and high availability for applications in automotive or industrial control facilities. The deterministic transmission of time-critical frames may be achieved by using TSN features of high reliability, low delay, zero packet loss through traffic shaping, seamless redundant transmission, filtering, priority-based scheduling, ingress policing and rate limitation.

4.2.1 IEEE 802.1AS

The basis of TSN standards is global time synchronization. It specifies the clock synchronization mechanism with switches as key nodes based on the data link layer. IEEE 802.1AS [4, IEEE Std 802.1AS] was mainly extended from the simplified version of the IEEE 1588 (Precision Time Protocol) and it is more suitable for communication transmission scenarios that require high real-time precision in vehicle networks.

4.2.2 IEEE 802.1Qav

IEEE 802.1Qav [6, IEEE Std 802.Qav] can be used to ensure that traditional asynchronous Ethernet data traffic does not interfere with AVB's real-time audio and video streams. To avoid competition for network resources between ordinary data traffic and AVB traffic, the AVB switch differentiates time-sensitive audio and video streams from ordinary data streams, queues real-time frames and asynchronous frames separately, and assigns the highest priority to real-time frames. Therefore a so-called Credit Based Shaper (CBS) could be used for bandwidth limitation to convergence time-sensitive and time-insensitive traffic.

4.2.3 IEEE 802.1Qbv

IEEE 802.1Qbv [7, IEEE Std 802.Qbv] specifies the feature of time-aware shaping, which allows the scheduling of the transmission of frames with different priorities in time-triggered windows. Time-aware shaping divides time into fixed windows, and schedules the transmission of frames within these windows based on their priority. Time-critical frames are normally given with higher priority and transmitted in a separate window, while lower priority frames are transmitted in the remaining time.

4.2.4 IEEE 802.1Qcc

Most networks need to be configured while the network is down, which is not suitable for applications such as in industrial control and automotive network communication. IEEE 802.1Qcc [8, IEEE Std 802.Qcc] can be used to introduce a Centralized Network Configuration (CNC) and a Centralized User Configuration (CUC) to implement dynamic network configuration, and flexibly configure new devices and data flows when the network is running.

Table 4.1 gives an overview on the relevant TSN standards.

TSN Standards	Description
IEEE 802.1AS	Timing and synchronization.
IEEE 802.1Qav	Forwarding and Queuing Enhancements for Time-Sensitive Streams
IEEE 802.1Qbv	Scheduled Traffic
IEEE 802.1Qbu	Forwarding and queuing with frame preemption
IEEE 802.1Qbv	Forwarding and queuing with enhancements for scheduled traffic
IEEE 802.1Qca	Path control and reservation
IEEE 802.1Qcc	Central configuration method
IEEE 802.1Qci	Time-based ingress per-stream filtering and policing
IEEE 802.1CB	Seamless redundancy with frame replication and elimination for reliability

Table 4.1: List of TSN Standards

4.3 Usage of Shapers in the Network

4.3.1 Asynchronous Traffic Shaping

4.3.1.1 Overview

Asynchronous Traffic Shaping (ATS) is specified by [9, IEEE Std 802.1Qcr-2020] and provides a traffic shaping concept that can provide bounded latencies for data streams in a network. It avoids bursts and provides a fair usage of the egress port for streams arriving on different ingress ports. This is a main difference between the Credit Based Shaper (CBS) and ATS, as CBS only considers a particular traffic class of an egress port. The algorithm is loosely based on the token bucket algorithm and uses similar terminology for the configuration parameters.

ATS is divided into two major functional blocks, one, the ”ATS Eligibility Time Assignment” situated on the ingress side of a bridge, operating on streams identified by the stream filters using the stream_handle and priority, includes the computational part of the shaping function. This means it calculates an eligibility time for every frame received based on the ATS algorithm. The eligibility time is the time when a frame is eligible for transmission on the egress port. The other functional block, the ”ATS transmission selection algorithm” is situated on the egress side and shapes the traffic according to the results calculated by the ”ATS Eligibility Time Assignment”. As the eligibility times of frames of streams from different receive ports can be in non-decreasing order, ATS queues need to support non-FIFO queues.

4.3.1.2 Configuration parameters

Configuration parameters of the ATS Eligibility Time Assignment:

- Scheduler Instance Table (EthSwtAtsInstanceTable)
  - EthSwtAtsInstanceEntry
    - CommittedBurstSize (EthSwtPortATSCommitedBurstSize)
    - CommittedInformationRate (EthSwtPortATSCommitedInformationRate)
    - SchedulerGroupInstanceID (EthSwtPortAtsSchedulerGroupRef)
- Scheduler Group Instance Table (EthSwtAtsGroupInstanceTable)
  - EthSwtAtsGroupInstanceEntry
    - MaxResidenceTime (EthSwtAtsGroupMaximumResidenceTime)

Configuration parameters of the ATS transmission selection algorithm: There are no specific parameters to configure the ATS transmission selection algorithm, but the ATS transmission selection algorithm needs to be configured for the traffic class used to transmit the frames intended to be shaped using ATS.

4.3.1.3 Guidance on the configuration

1. Streams that are shaped using the ATS algorithm need to be identified on the ingress side of a bridge. Stream Filters are used to identify the frames of a stream and associate them with the relevant functions. To use the stream filters, stream identification functions need to be configured to identify the frames of a stream.

2. The stream filters can be used to configure a Maximum SDU size filter to protect the following processing stages from frames that are bigger than the maximum SDU size of a well-formed frame of the considered stream.
3. The stream filters can be used to remap the stream to a different traffic class using the IPV assignment provided by stream gates. This is optional and can be used to prioritize certain streams.
4. The stream filter assigns the Scheduler Instance for the stream, which is responsible to perform the computations to calculate the eligibility time for every frame of the stream.
   (a) The CommittedInformationRate is the rate of the ATS algorithm used to accumulate ”tokens” in bits/second and represents the average bit rate of the stream.
   (b) The CommittedBurstSize is the maximum number of ”tokens” that can be accumulated and therefore defines the maximum burst size. It needs to be set to a larger value than the maximum burst that can evolve due to interfering traffic.
   (c) The SchedulerGroupInstanceID references the EthSwtAtsGroupInstanceEntry the ”ATS Eligibility Time Assignment” is associated with. All streams received from one upstream port with the same traffic class need to be associated with the same SchedulerGroupInstanceID. This guarantees that frames of different streams sharing the same priority and that are received on the same port are transmitted in the arrival order.
   (d) The EthSwtAtsGroupInstanceEntry is also used to configure the EthSwtAtsGroupMaximumResidenceTime of the Scheduler Group. This parameter defines the latest point in time the calculated eligibility time can have. Frames that exceed the maximum residence time i.e., with a calculated eligibility time later than the sum of the arrival time and the EthSwtAtsGroupMaximumResidenceTime are discarded. The value can be derived from the maximum latency, and a frame of this scheduler group should experience in this bridge.
5. To use the ATS transmission selection algorithm on the egress side, the traffic class(es) used for ATS traffic need to be configured to use the ATS transmission selection. Therefore, EthSwtPortEgressQueueTransmissionSelectionAlgorithm needs to be set to ETHSWT_TRANSMISSION_SELECTION_ALGORITHM_ATS.

4.3.2 Credit Based Shaper

4.3.2.1 Overview

The Credit Based Shaper (CBS) is specified by [6, IEEE Std 802.Qav] and provides a traffic shaping concept for high priority, high data rate streams. It was specified as part of the Audio Video Bridging (AVB) standards. The behavior is similar to ATS, but the CBS is operating only on Traffic Classes on the egress side of a bridge. Therefore, there is no differentiation between individual streams within the traffic class as well as different ingress ports. As a consequence, the Credit Based Shaper is strictly operating on the order frames are received on all ports, there is no reordering of frames received on different ports. The Credit Based Shaper minimizes bursts and therefore protects lower priority traffic from the high priority CBS shaped traffic.

The CBS only exists as one functional block (per traffic class) that is located on the egress side of a bridge port and makes frames available for transmission selection based on a credit value. If there is zero or positive credit, frames are available for transmission, in case there is negative credit, frames of the associated traffic class are not available for transmission selection. The idleSlope is the main parameter that defines the rates with which credit is accumulated and reduced, and thereby it directly controls the data rate of the assigned traffic class on a port.

4.3.2.2 Configuration parameters

Configuration parameters of the Credit Based Shaper:

- idleSlope (EthSwtPortEgressQueueCreditBasedShaperIdleSlope)
- highCredit (EthSwtPortEgressQueueCreditBasedShaperUpperBoundary)
- lowCredit (EthSwtPortEgressQueueCreditBasedShaperLowerBoundary)

4.3.2.3 Guidance on the configuration

1. Frames associated with the CBS are identified by the priority. In case there are ports of the bridge that use the priority intended to be used for CBS traffic for other traffic, the priorities on those ports need to be remapped by configuring the priority regeneration table.
2. The idleSlope of the CBS is set according to the average bit rate of all streams sent with this traffic class on that specific port. A little bit of oversubscription is necessary to account for frequency differences of the oscillators of the different bridges in the network. Credit increases with the idleSlope and is reduced with sendSlope (sendSlope = idleSlope - portTransmitRate).
3. highCredit is set to the maximum amount of credit that can be accumulated in a queue. This value is calculated based on the maximum amount of interference by traffic from higher priority traffic classes and the idleSlope parameter.
4. lowCredit is the lowest possible amount of traffic, it can be derived from the maximum frame size supported by the traffic class and the sendSlope parameter.

5. To use the CBS algorithm the traffic class(es) used for CBS need to be configured to use the CBS transmission selection. Therefore, EthSwtPortEgressQueueTransmissionSelectionAlgorithm needs to be set to ETHSWT_TRANSMISSION_SELECTION_ALGORITHM_CBS.

4.4 Ensure Accuracy of Time Synchronization

4.4.1 Recommendations to support accuracy in an Ethernet network

4.4.1.1 Parts in Documents which Reflect Accuracy

In Time Synchronization Protocol Specification [10]:

Time Master and Time Slave shall work with a Time Base reference clock accuracy as defined in [4, IEEE 802.1 AS], ANNEX B.1.2 "Time measurement granularity".

In Specification of Time Synchronization over Ethernet [11]:

Automotive systems requiring a common Time Base for ECUs regardless of which bus system the ECUs are connected to.

4.4.1.2 System requirements

TSN uses gPTP protocol (IEEE 802.1AS) to get precise timestamps for the nodes in the Network. IEEE 802.1AS also targets at accuracy of +/-500ns between any two nodes over 7 hops for Audio Video Bridging using 100 Mb/s links. That means, the hardware has to support the global time on Ethernet with an end to end accuracy of +/- 500ns, where end to end describes a network path from a data producer to a data consumer (e.g. from audio source to an audio sink).

4.5 Measurement of the Time Synchronization Quality (Accuracy)

4.5.1 Overview

The quality of time synchronization needs to be measured in order to assess if devices meet requirements for gPTP recovered clock quality.

The traditional approach to measure the accuracy of the clock synchronization is the 1 Pulse Per Second (1PPS) method. The PPS signal must be driven by a hardware clock in all participating devices so that it generates a pulse every full second. If this is done for multiple hardware clocks in a distributed system their synchronization accuracy can be checked on a measurement device like a scope by measuring the distance of PPS pulses originating from different devices. After their clocks have been correctly synchronized, the PPS pulses triggered every second should only have a marginal time distance in a successful scenario.

However, the 1PPS method is not feasible for automotive environment, where using a separate output pin for generating the 1PPS signal on the ECU is considered costly. Furthermore, static offset in the internal clock of a slave may exist and can be canceled out by an opposite static offset in the logic that drives the 1PPS output. This will result in an error condition that cannot be observable by using 1PPS measurement method.

In order to mitigate the flaws from 1PPS measurement, Advance methods like Ingress Reporting Method and Reverse Sync Method may be considered for alternative measurement methods. More details for Ingress Reporting Method and Reverse Sync Method, please refer to [12, 802.1AS Recovered Clock Quality Testing].

4.5.2 Usage of PPS

4.5.2.1 Configuration of PPS within an Ethernet controller

AUTOSAR support to configure the generation of a PPS signal, if the hardware supports this feature. AUTOSAR support the following configuration options:

- support to configure the rate of a PPS (e.g. 1Hz, 2 Hz, 4 Hz ...)
- support to configure the duty cycle of a PPS (e.g. 50% == 500ms high an 500ms low if rate is configured for 1Hz)
- support to configure the starting point (either rising edge and falling edge) of a PPS (Please consider this point for the SysT)

4.5.2.2 Configuration of PPS by using OCU in combination with a PHC

If OCU is hardware driven, then a PPS could be generated as alternative to an existing PPS hardware unit in the Ethernet controller. Please note: It is recommended to use a PPS hardware unit, since the OCU approach could introduce inaccuracy.