Tutorial: Cut-Through Forwarding (CTF) in Bridges and Bridged Networks

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Purpose of this slide set

The following slides (not including this slide) contain material proposed for inclusion into the planned 802 tutorial on CTF (see https://mentor.ieee.org/802.1/dcn/21/1-21-0015-04-ICne-ctf-study-item-planning-proposal.pdf).

The current version of this slide set contains the proposed introduction to the topic, intended to be followed by existing (and potential upcoming) use-case presentations. The existing use-case presentations are the following ones:

- Industrial Automation
  https://mentor.ieee.org/802.1/dcn/21/1-21-0018-00-ICne-ctf-industrial-use-case.pdf
- Data Center Networks
  https://mentor.ieee.org/802.1/dcn/21/1-21-0019-01-ICne-ctf-for-dcn.pdf

Abstract

Cut-Through Forwarding (CTF) is a known method to increase the delay performance in Bridged Networks. In contrast to the store and forward operation of standardized switched Ethernet, CTF allows frame transmission in Bridges before reception is completed. Although not standardized in IEEE 802, CTF is already implemented in existing Bridge implementations. It is therefore technical feasible, but different implementations face interoperability problems that can be resolved by standardizing CTF in IEEE 802.

This tutorial introduces CTF on a technical level, explains application areas, markets and use-cases for CTF, and describes one possible integration of CTF into switched Ethernet.

Disclaimer

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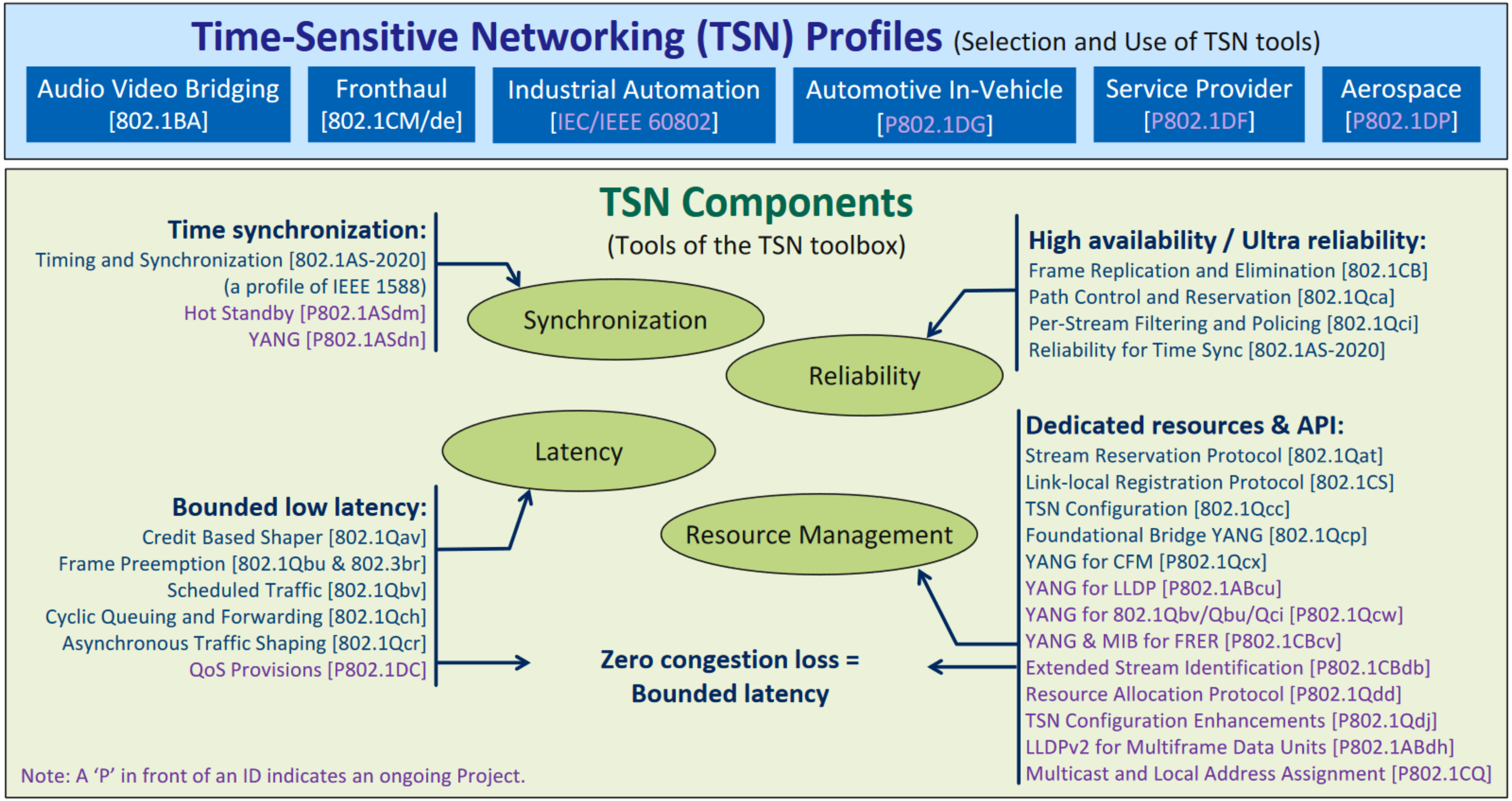
Introduction

Johannes Specht

IEEE 802.1 TSN Context, Basic CTF Operation Guaranteed Latency, CTF Performance, Reasons for standardizing CTF

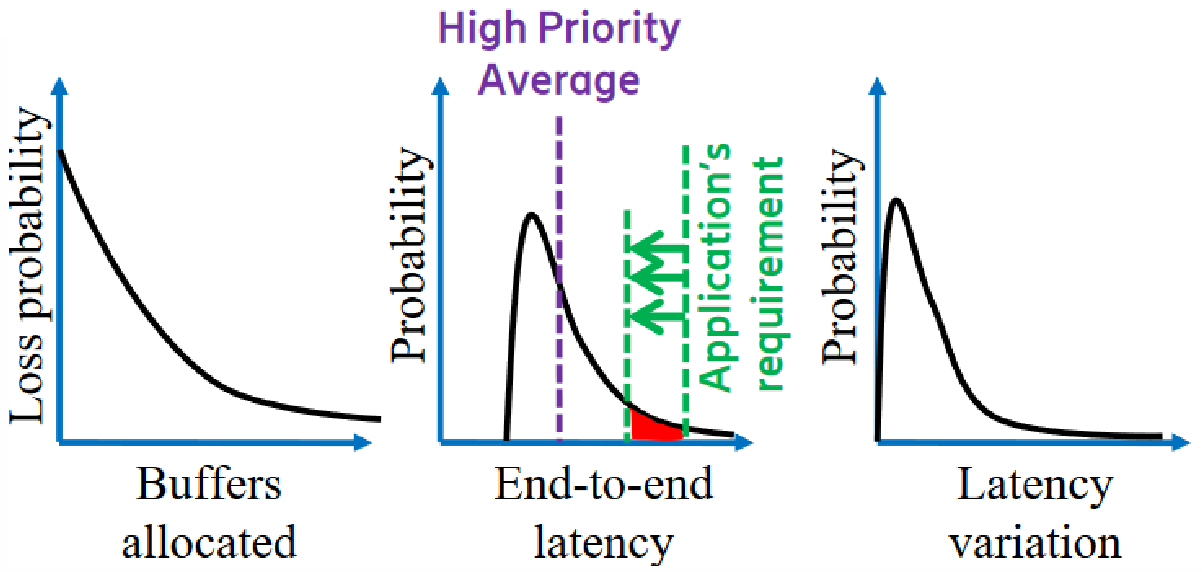
TSN Context

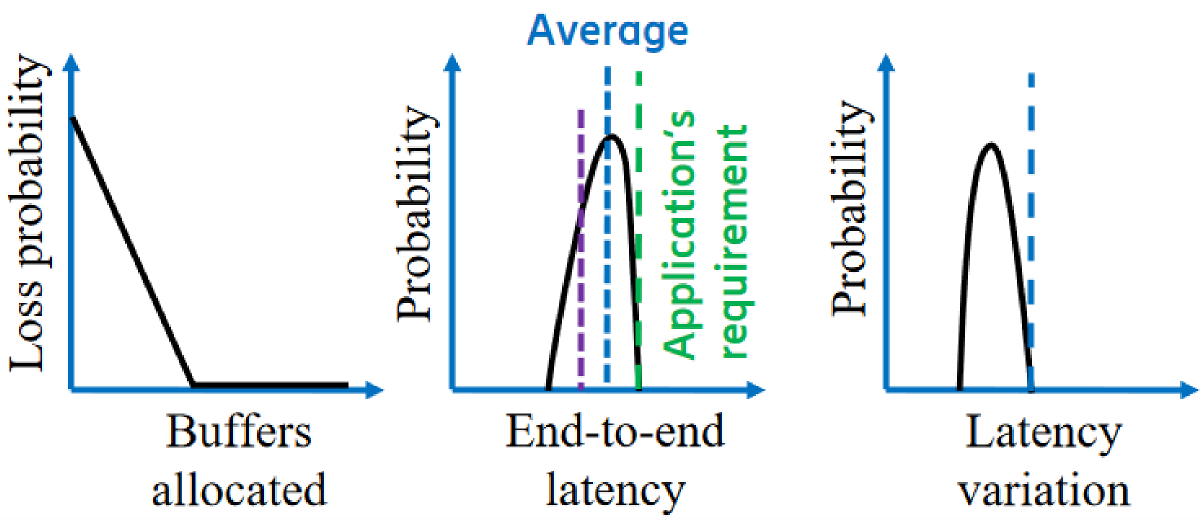


Source: https://www.ieee802.org/1/files/public/docs2021/admin-tsn-summary-0221-v01.pdf

Traditional and Deterministic Services

- Traditional Service
  - Curves have long tail
  - Average latency is good
  - Lowering the latency means losing packets (or overprovisioning)
- Deterministic Service
  - Packet loss is at most due to equipment failure (zero congestion loss)
  - Bounded latency, no tails
  - The right packet at the right time





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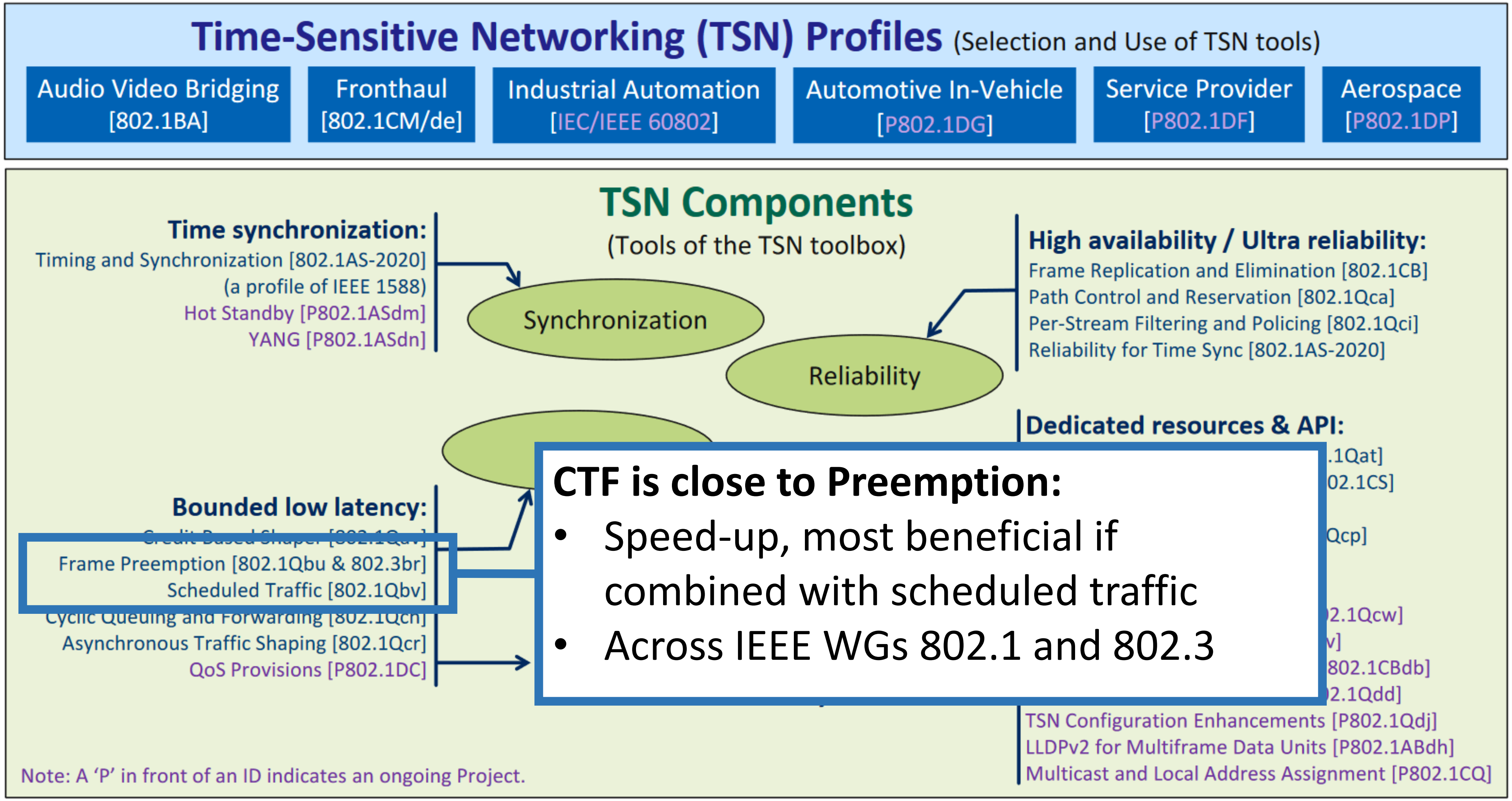
CTF in the TSN Context



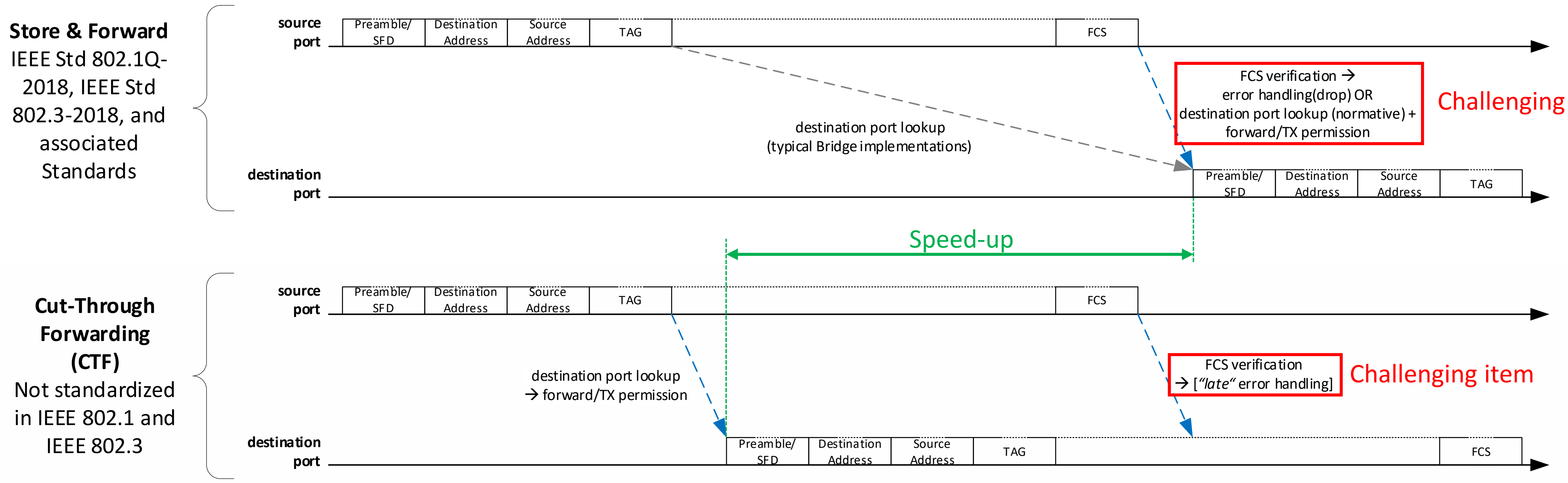
CTF is close to Preemption:

- Speed-up, most beneficial if combined with scheduled traffic
- Across IEEE WGs 802.1 and 802.3

Source: https://www.ieee802.org/1/files/public/docs2021/admin-tsn-summary-0221-v01.pdf

Basic CTF Operation

CTF is an alternative forwarding method to Store & Forward (S&F) in Bridges



Delay performance enhancements

- Reduced residence times of frames in Bridges (“speed-up”)
- Reduced frame length dependent jitter/delay variation

(Main) Challenges

- Transmission of frames with errors discovered by FCS verification, and the associated consequences
- S&F operation “deeply” manifested in IEEE 802.1 and 802.3 Standards

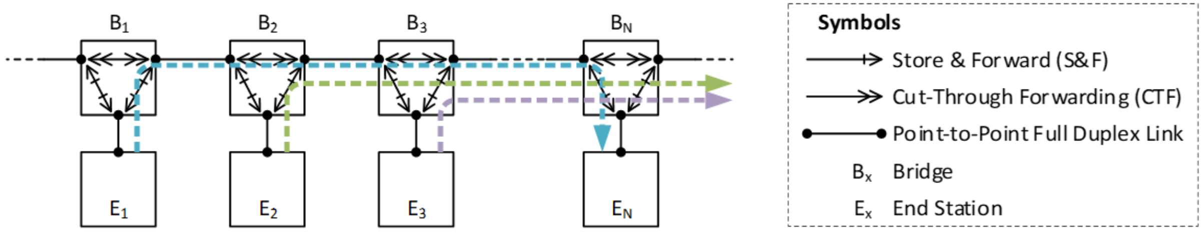
CTF Speed-up: Assumptions (1)

Purpose

- Subsequent assumptions are made to simplify analysis:
  - These assumptions can be valid for some real systems, while being invalid for others.
  - The assumptions here are not intended as requirements or limitations for real systems with CTF.

Topology/Network

- Chain Network/Network segment
- Identical Link Speeds, Full-Duplex, negligible propagation delays
- CTF on all interconnections *except* from/to end stations (i.e., S&F at first and last hops)
- Strict Priority Transmission Selection Algorithm, optional with Enhancements for Scheduled Traffic



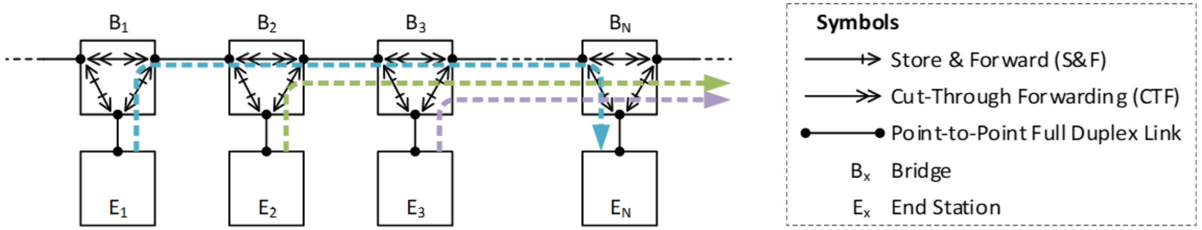
Errors

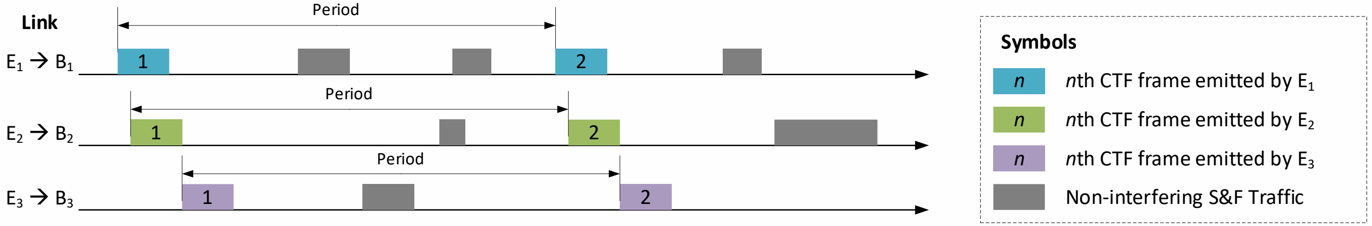
- Error free environment → no data corruption in frames
- However, errors, including late error handling, is addressed later in this tutorial

CTF Speed-up: Assumptions (2)

Traffic – Focus on Bounded Latency

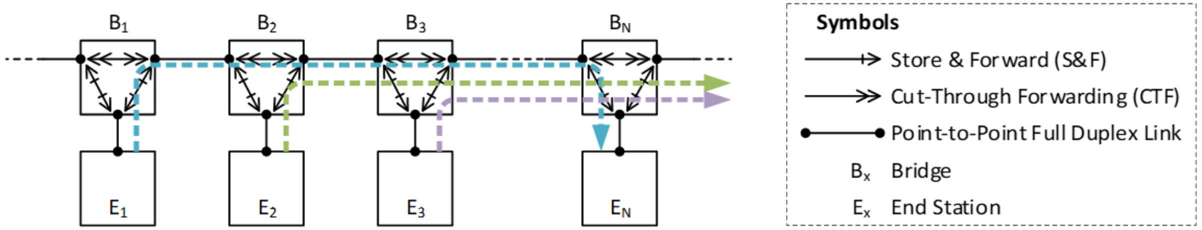
- CTF Traffic: High Priority (HP)
  - At most one stream sent by each end station
  - Constant frame length[1]
  - Periodic (same period for all streams)
  - Period < maximum end-to-end latency
  - Nominal transmission times at sending end stations
- Background Traffic: Low Priority (LP)
  - Always Store & Forward
  - Interferes with CTF traffic
    - Without preemption: 1542 octets (max. LP frame[1,2])
    - With preemption: 155 octets (max. non-preemptible LP frame[1,3])





1) Includes all media-dependent overhead for IEEE 802.3 point-to-point full duplex media (Preamble, SFD, minimal Interpacket Gap).
2) Upper limit of 1500 octets payload in a tagged frame.
3) Defined upper limit for addFragSize=0 (cmp. 99.4.8 of IEEE Std 802.3br-2016).

CTF Speed-up: Math



Delay until forwarding to destination ports happens. Assumed that the lookup starts after l_{Hdr} octets and finishes after d_{LU} µs. Note that the lookup can finish after frame completion during reception.

$$d_{SFF}^{max} = (H+2)\left(\max\{l_{HP}d_{Oct}, l_{Hdr}d_{Oct} + d_{LU}\} + d_Q\right) + (H+1)\left(l_{HP} + l_{Lp}\right)d_{Oct}$$

Maximum interference by crossing high priority traffic (l_{HP}) and crossing low priority traffic (l_{LP}). Dependent on the subsequently introduced communication schemes, either one or both types of interference exist or not (e.g., full TDM avoids both).

$$d_{CTF}^{max} = 2\left(\max\{l_{HP}d_{Oct}, l_{Hdr}d_{Oct} + d_{LU}\} + d_Q\right) + H\left(l_{Hdr}d_{Oct} + d_{LU} + d_Q\right) + (H+1)\left(l_{HP} + l_{Lp}\right)d_{Oct}$$

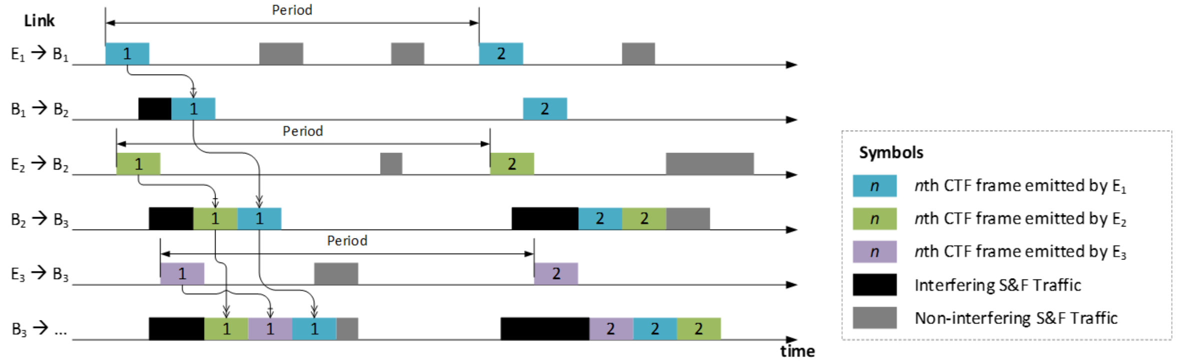
Separates the H interconnections (CTF) from the first and last ones (S&F). Note that, if the lookup finishes after frame completion during reception, then CTF provides no lower delay than S&F. The other way around, if the lookup is "fast enough", then CTF provides lower delays than S&F.

Symbol	Description
d_{SFF}^{max}	Maximum end-to-end delay without CTF, in μs.
d_{CTF}^{max}	Maximum end-to-end delay with CTF, in μs.
H	Number of possible CTF interconnections (e.g., N-2 for the stream of E_1).
l_{HP}	Frame size of high priority traffic (i.e., the traffic that can be subject to CTF), including all media dependent overhead, in octets.
l_{LP}	Frame size of low priority traffic (always S&F), including all media dependent overhead, in octets. <u>Assumption:</u> 1542 octets without preemption, 155 octets with preemption.
l_{Hdr}	Header length required for destination port lookup in Bridges, in octets. <u>Assumption:</u> 24 octets (preamble, start of frame delimiter, DA, SA, VLAN-Tag).
d_{Oct}	Nominal duration of an octet reflecting the link speed, in μs.
d_{LU}	Destination port lookup duration after l_{Hdr} octets were received, in μs. <u>Assumption:</u> 0.16 μs (e.g., 20 clock cycles @ 125 MHz).
d_Q	Interference-independent queuing delay (MAC delay, PHY delay, etc.), in μs. <u>Assumption:</u> 1 μs.

CTF Speed-up: Both Extremes

Uncoordinated

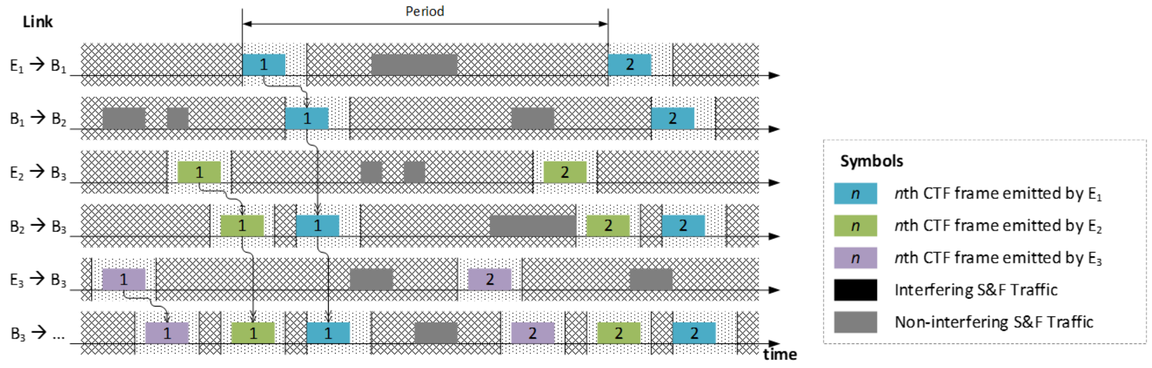
Interference by low priority and other high priority (CTF) traffic



		SFF-to-CTF ratio									
		Preemption unsupported					Preemption supported				
H	Link \ l_{HP}	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbps	96%	93%	88%	83%	80%	85%	80%	76%	74%	73%
4	100 Mbps	96%	91%	85%	79%	75%	82%	75%	70%	67%	66%
16	100 Mbps	95%	90%	82%	74%	70%	77%	68%	62%	59%	57%
64	100 Mbps	94%	89%	81%	73%	68%	76%	66%	60%	56%	54%
2	1 Gbps	97%	94%	89%	84%	81%	89%	82%	78%	75%	74%
4	1 Gbps	96%	92%	86%	80%	76%	86%	78%	72%	68%	67%
16	1 Gbps	96%	91%	83%	75%	70%	83%	72%	65%	60%	58%
64	1 Gbps	96%	90%	82%	74%	69%	82%	71%	62%	57%	55%
2	2,5 Gbps	98%	95%	90%	84%	81%	94%	86%	80%	76%	75%
4	2,5 Gbps	98%	93%	87%	81%	77%	92%	83%	75%	70%	68%
16	2,5 Gbps	97%	92%	85%	76%	71%	90%	78%	69%	62%	60%
64	2,5 Gbps	97%	92%	84%	75%	70%	90%	77%	67%	60%	57%

Full Time Division Multiplexing

No Interference



		SFF-to-CTF ratio									
		Preemption unsupported					Preemption supported				
H	Link \ l_{HP}	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbps	61%	56%	53%	51%	51%	61%	56%	53%	51%	51%
4	100 Mbps	48%	41%	37%	35%	35%	48%	41%	37%	35%	35%
16	100 Mbps	31%	21%	16%	14%	13%	31%	21%	16%	14%	13%
64	100 Mbps	25%	14%	9%	6%	5%	25%	14%	9%	6%	5%
2	1 Gbps	75%	64%	58%	54%	53%	75%	64%	58%	54%	53%
4	1 Gbps	67%	52%	43%	39%	37%	67%	52%	43%	39%	37%
16	1 Gbps	56%	36%	25%	18%	16%	56%	36%	25%	18%	16%
64	1 Gbps	52%	31%	18%	11%	8%	52%	31%	18%	11%	8%
2	2,5 Gbps	88%	74%	64%	58%	55%	88%	74%	64%	58%	55%
4	2,5 Gbps	84%	66%	52%	44%	40%	84%	66%	52%	44%	40%
16	2,5 Gbps	79%	55%	36%	25%	21%	79%	55%	36%	25%	21%
64	2,5 Gbps	77%	50%	31%	18%	13%	77%	50%	31%	18%	13%

Lower percent values indicate higher end to end delay performance gains of CTF over S&F.

Reasons for standardizing CTF in IEEE 802

Interoperable and deterministic data plane (examples)

- Distinguish CTF Traffic from S&F Traffic
  - TAGs, Addresses, Ports?
- “Late” error handling
  - Shorten/truncate erroneous frames?
  - Mark erroneous frames?
  - Do nothing?
- Behavior of existing 802.1 Bridge mechanisms for CTF traffic
  - Flow Metering (e.g. Max. SDU size filters, MEF 10.3)?
  - Transmission selection algorithms?
  - Transmission gates?
  - Link speed transitions?[1]

Unified Management

- Elements
  - Configuration Parameters
    (e.g., enable/disable CTF)
  - Device properties
    (e.g., timing)
  - Status Variables
    (e.g., erroneous CTF frame counters)
- Required, for example, for automated, efficient and consistent TDM configuration (e.g., centralized network controller [802.1Qcc-2018])

Application and limitations of CTF in Networks

- Quality of Service[1,2]
  Limit circulating erroneous frames in topological loops
- Security [1]
  Prevent exposure of traffic (CTF and S&F) to untrusted network segments

1) See also https://ieee802.org/1/files/public/docs2017/new-tsn-thaler-cut-through-issues-0117-v01.pdf
2) See also https://www.ieee802.org/1/files/public/docs2019/new-seaman-cut-through-scissors-0119-v01.pdf

Thank you for your Attention!

Questions, Opinions, Ideas?