IEEE 802 Tutorial: Cut-Through Forwarding (CTF) among Ethernet networks

Johannes Specht, Jordon Woods, Paul Congdon, Lily Lv,
Henning Kaltheuner, Genio Kronauer, Alon Regev

Overview

Cut-Through Forwarding (CTF) is a known method to improve the delay performance in bridged Ethernet networks.

CTF is already implemented in many commercial products and is therefore technically feasible. Standardizing CTF in IEEE 802.1 and IEEE 802.3 would enable interoperable implementations.

The goal of this tutorial is to motivate standardizing CTF. The tutorial introduces CTF on a technical level, explains application areas, markets and use-cases for CTF, and addresses aspects of standardizing CTF.

This tutorial has been developed within the IEEE 802 Nendica CTF Study Item.

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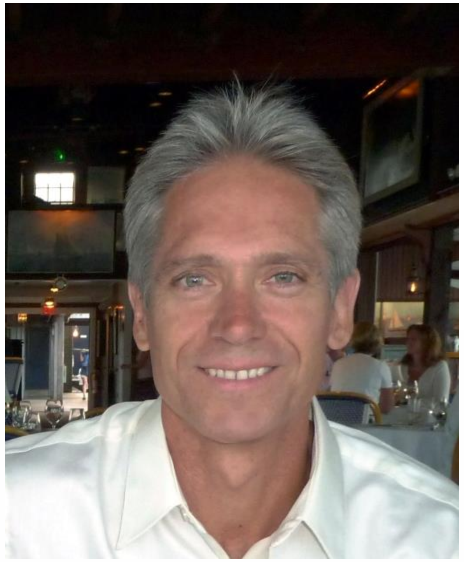
Speakers

Johannes Specht

Jordon Woods

Paul Congdon



Henning Kaltheuner

Alon Regev

Speakers' Biographies

Johannes Specht is a consultant and a researcher. His research area is the real-time traffic scheduling aspects of TSN. He holds a diploma in applied computer science and is currently finishing his PhD at the University of Duisburg-Essen (Germany).
He has been the technical editor of the IEEE P802.1Qcr - Asynchronous Traffic Shaping (ATS) project, and an active technical contributor to several IEEE 802.1 TSN standardization projects on real-time traffic scheduling, reliability, fault tolerance, time synchronization, and configuration since joining IEEE 802.1 nine years ago.
Johannes has been providing expert consulting to General Motors (USA) on using Ethernet for safety-critical applications since 2012. His professional career started in 2003 in the automotive industry, where he contributed to several projects on communication systems, testing, and functional safety.

Jordon Woods is a strategic technologist for Analog Devices Industrial Ethernet Technology Group (IET). IET enables seamless and secure connection of customer products across the entire landscape of Industrial IoT. Woods has 35 years of experience in the semiconductor industry. He is familiar with a variety of Ethernet-based Industrial protocols including Profinet, EtherNet/IP, as well as IEEE TSN standards. He is also a voting member of the IEEE 802 working group defining new Ethernet standards for Time Sensitive Networks and the editor of the IEC/IEEE 60802 Time-Sensitive Networking Profile for Industrial Automation.

Paul Congdon is a co-founder and is the Chief Technology officer (CTO) of Tallac Networks. He has over 34 years of experience in the networking industry and has become a widely esteemed inventor and leader in the networking industry. Prior to Tallac Networks, Paul was a Fellow at Hewlett Packard's Networking and Communications Labs with responsibility for HP's research in mobility, wireless and SDN network infrastructure. Paul has led, chaired, and is currently contributing widely to industry standards in the IEEE and IETF. Paul has a PhD in Computer Science from the University of California, Davis.

Henning Kaltheuner is Head of Business Development and Market Intelligence at d&b audiotechnik since December 2013. He knows the pro audio industry inside and out, having worked in positions ranging from Front of House to senior manufacturing roles. Before joining d&b Henning worked e.g. for brands like Riedel and Yamaha. Besides both his hands-on and managing experience in the pro audio and broadcast industry Henning's main expertise is market research based on his master degree in psychology at University of Cologne with a specialization on media psychology and qualitative research. His work has concentrated on gaining insights into market trends, brand perceptions and customer expectations in the pro audio industry. Since 2004 a special focus for him has been on trends and expectations for network systems in the field of ProAV.

Alon Regev is a system architect fluent in both the hardware and software domains who has innovated in network communications for over 30 years. For the last 20 years Alon has worked at Ixia and Keysight Technologies. Alon has founded 2 companies and has over 60 patents granted. Alon has led, participated, and is contributing to multiple standardization efforts with a focus on Industrial and Automotive network systems, Time Synchronization and Time Sensitive Networks. Alon is the chair of the Avnu testability task group, a voting member of IEEE 802.3. BSCS, California State University, Northridge (USA).

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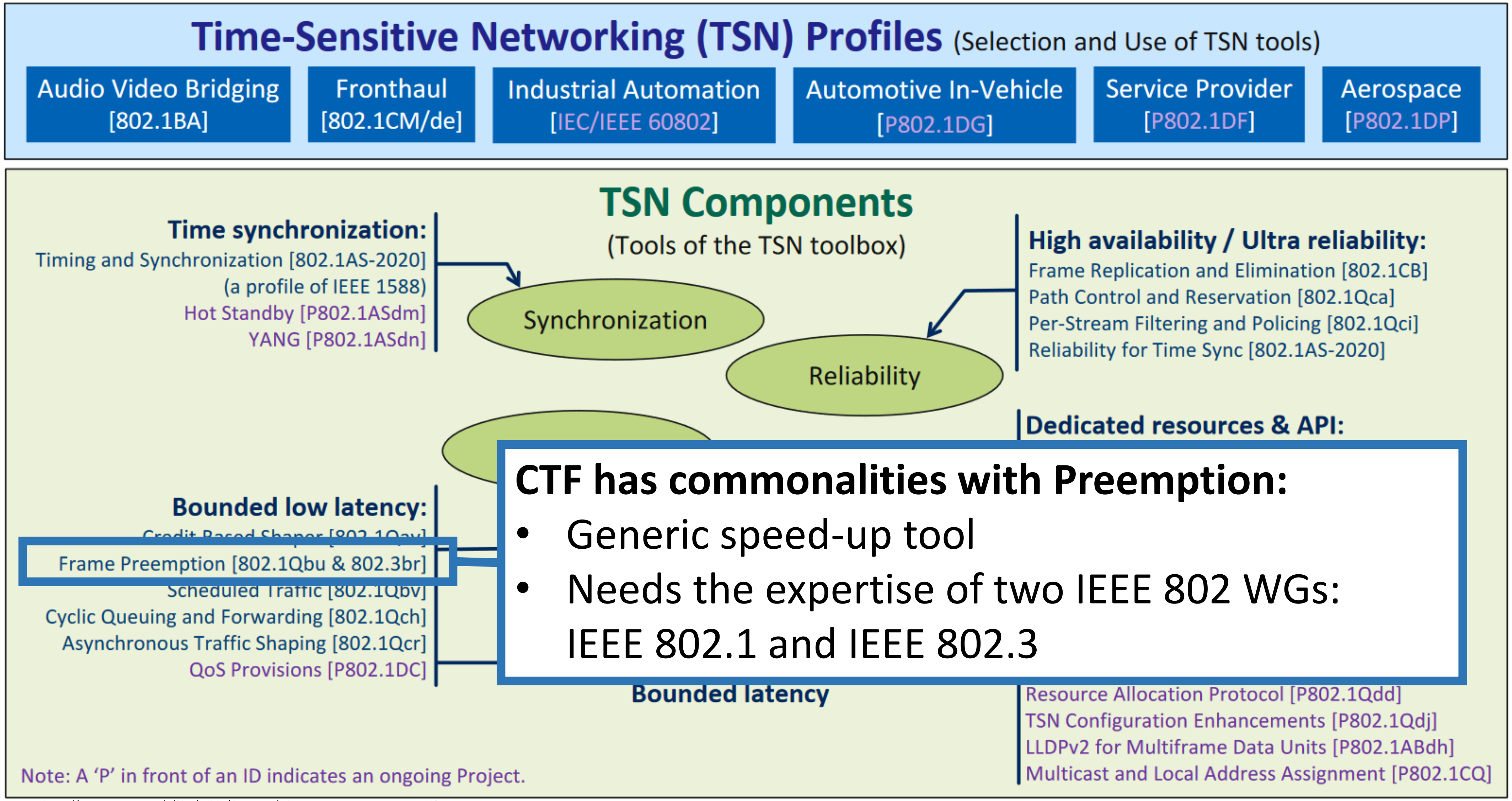
Please state your **questions** in the **chat**, including the slide number (e.g., ***"6: <your question>"***).
The questions are answered during the Q&A section at the end of this tutorial.

Introduction

Johannes Specht

Please state your **questions** in the **chat**, including the slide number (e.g., ***“7: <your question>”***).
The questions are answered during the Q&A section at the end of this tutorial.

CTF in the TSN Context



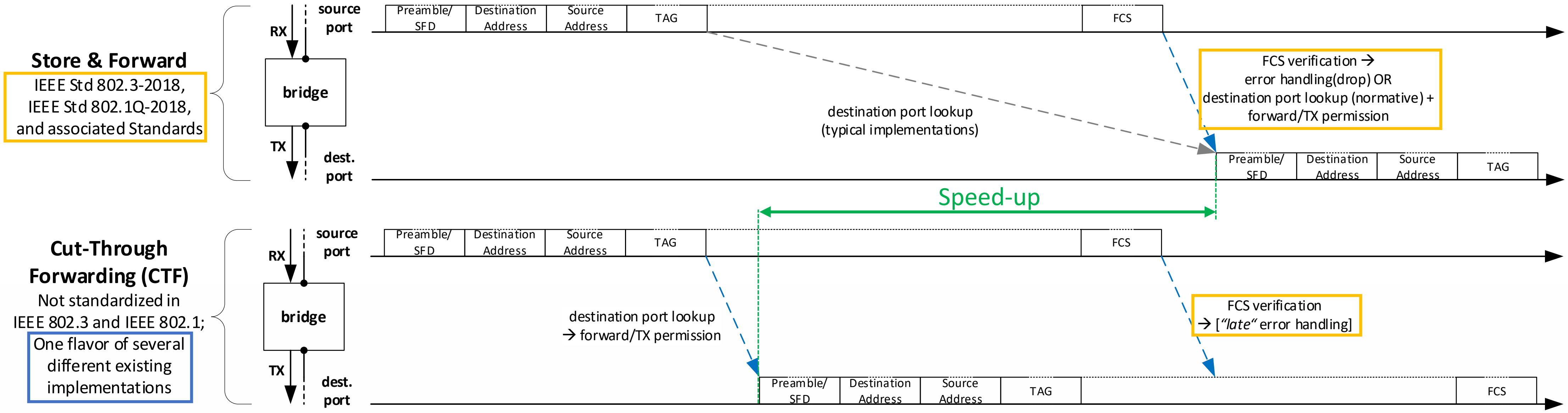
CTF has commonalities with Preemption:

- Generic speed-up tool
- Needs the expertise of two IEEE 802 WGs: IEEE 802.1 and IEEE 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



Enhanced delay performance

- Reduced residence times of frames in bridges ("speed-up").
- Reduced frame length dependent jitter/delay variation.

Challenges

- Forwarding and transmission of erroneous frames under reception:
  - ➢ Potentially to the wrong destination port(s) and/or traffic classes.
  - ➢ Limited handling options after subsequent late error discovery (e.g., FCS verification).
- S&F operation manifested in IEEE 802.1 and 802.3 standards, at least to a certain extent.

Different flavors of CTF

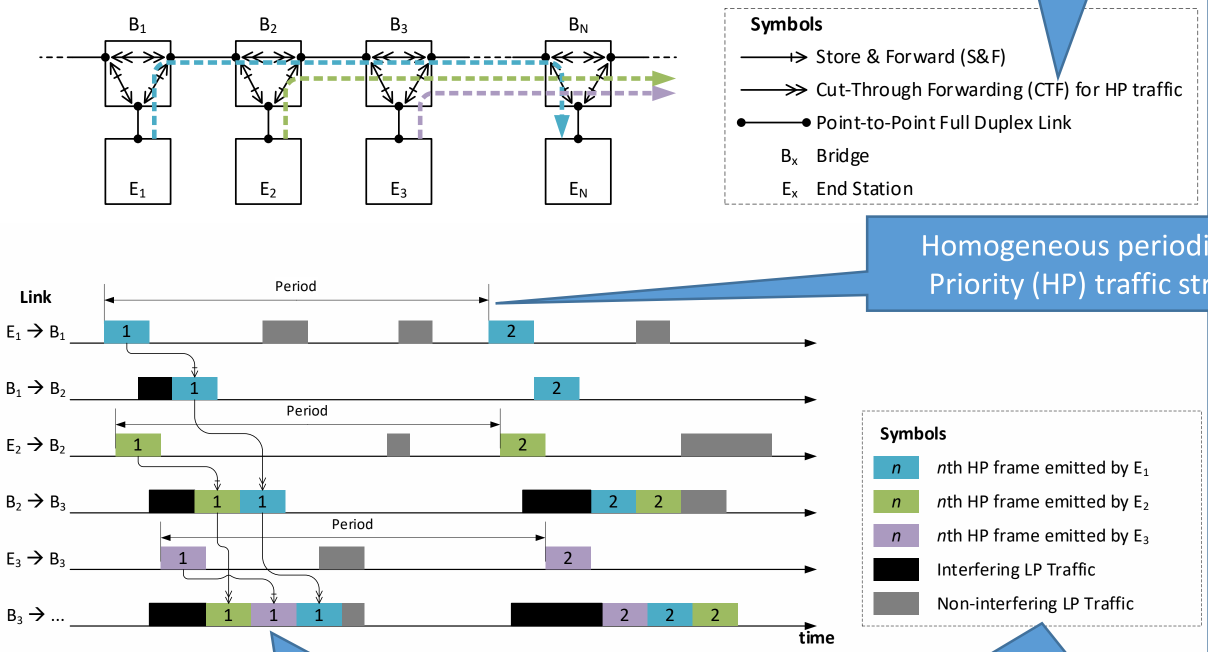
- Forwarding to destination port(s): After lookup v.s. after 64 octets
- Late error handling in destination port(s): Truncating v.s. (just) marking such frames
- …

➢ ***A good reason for standardizing CTF, regardless of the decisions which flavor(s) to standardize!***

CTF Speed-up in Max. End-to-End Delay: With Interference

Only in presence of CTF, S&F otherwise

Scenario: Uncoordinated transmissions



Homogeneous periodic High Priority (HP) traffic streams

HP streams may interfere with each other
(no preemption possible).

“Random” Low Priority traffic (always S&F) can interfere with HP traffic: delayed HP traffic transmissions.
HP traffic may preempt LP transmissions.

See the annex for more information (device, network, and traffic assumptions, math, more results, etc.)

CTF Speed-up in Max. End-to-End Delay: With Interference

High Priority (HP) frame length, incl. preamble, SFD and IPG

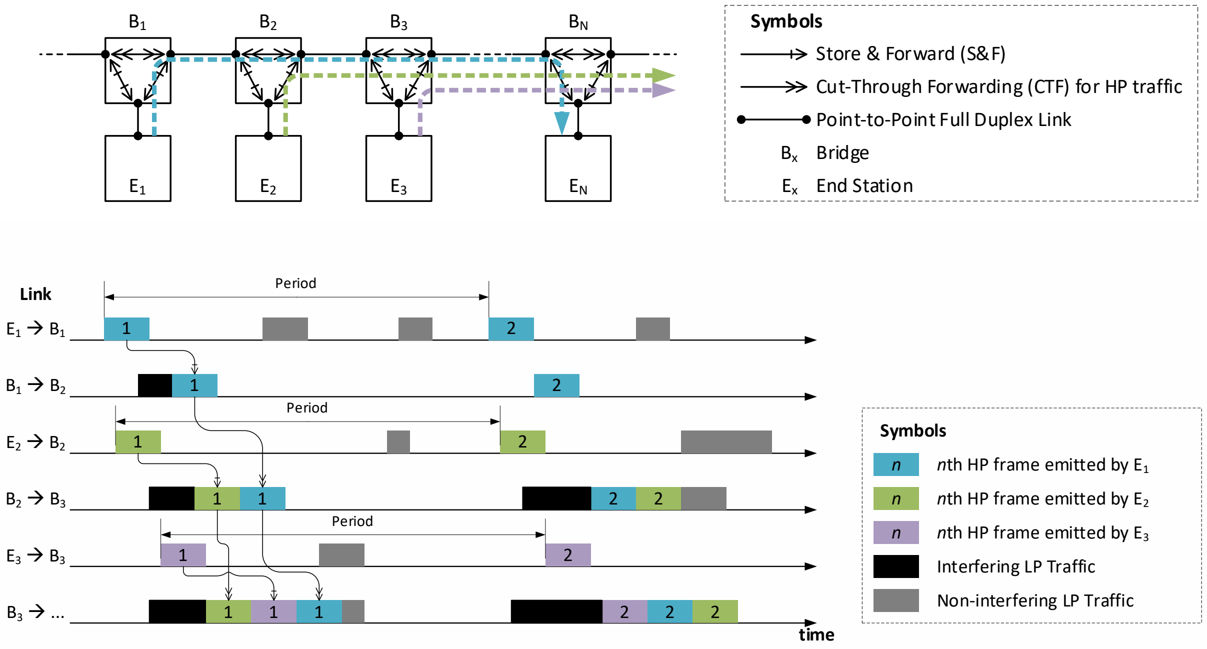
fwd. after VLAN-Tag

		CTF-to-S&F max. delay ratio (end-to-end)									
		Preemption unsupported					Preemption supported				
H	Link \ l_{HP}	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	96%	93%	87%	81%	78%	84%	77%	73%	70%	69%
4	100 Mbit/s	95%	91%	85%	78%	74%	80%	73%	67%	64%	63%
16	100 Mbit/s	95%	89%	82%	74%	69%	77%	68%	61%	57%	56%
64	100 Mbit/s	94%	89%	81%	73%	68%	76%	66%	60%	55%	54%
2	1 Gbit/s	97%	93%	88%	82%	79%	88%	80%	75%	71%	70%
4	1 Gbit/s	96%	92%	86%	78%	74%	85%	76%	69%	65%	64%
16	1 Gbit/s	96%	90%	83%	75%	70%	83%	72%	64%	59%	57%
64	1 Gbit/s	96%	90%	82%	73%	68%	82%	71%	62%	57%	55%
2	2,5 Gbit/s	98%	94%	89%	83%	79%	93%	85%	78%	73%	71%
4	2,5 Gbit/s	98%	93%	87%	80%	75%	92%	81%	73%	67%	65%
16	2,5 Gbit/s	97%	92%	85%	76%	71%	90%	78%	68%	61%	59%
64	2,5 Gbit/s	97%	92%	84%	75%	69%	90%	77%	66%	59%	57%

Hop-count (except first & last hop).

Link speeds (identical for all links).

Scenario: Uncoordinated transmissions



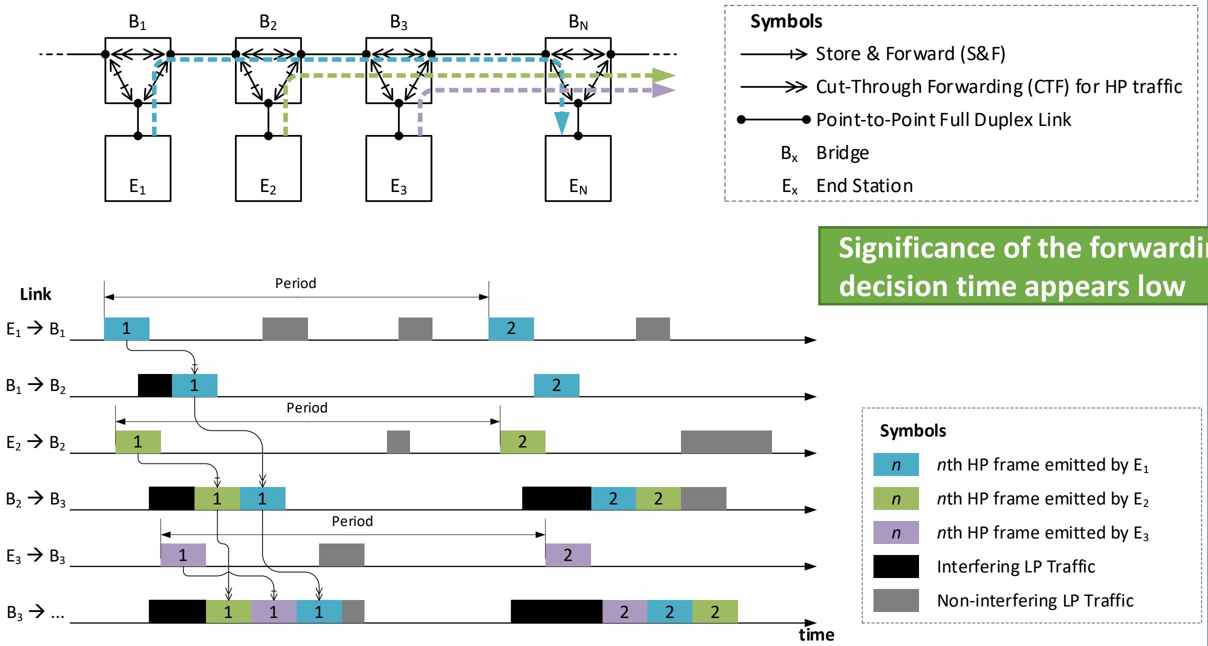
- **Lower numbers are better (examples):**
  - **68% → with CTF ~ 2/3rd of the max. end-to-end delay without CTF**
  - **98% → CTF significance is very low**
- **HP frame length dependent improvement**

- **Significance of LP interferences lowered by preemption**
- **54% @ 100 Mbit/s → ~ half max. end-to-end delays with CTF**

See the annex for more information (device, network, and traffic assumptions, math, more results, etc.)

CTF Speed-up in Max. End-to-End Delay: With Interference

Scenario: Uncoordinated transmission times



fwd. after VLAN-Tag

		CTF-to-S&F max. delay ratio (end-to-end)									
		Preemption unsupported					Preemption supported				
H	Link \ l_{HP}	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	96%	93%	87%	81%	78%	84%	77%	73%	70%	69%
4	100 Mbit/s	95%	91%	85%	78%	74%	80%	73%	67%	64%	63%
16	100 Mbit/s	95%	89%	82%	74%	69%	77%	68%	61%	57%	56%
64	100 Mbit/s	94%	89%	81%	73%	68%	76%	66%	60%	55%	54%
2	1 Gbit/s	97%	93%	88%	82%	79%	88%	80%	75%	71%	70%
4	1 Gbit/s	96%	92%	86%	78%	74%	85%	76%	69%	65%	64%
16	1 Gbit/s	96%	90%	83%	75%	70%	83%	72%	64%	59%	57%
64	1 Gbit/s	96%	90%	82%	73%	68%	82%	71%	62%	57%	55%
2	2,5 Gbit/s	98%	94%	89%	83%	79%	93%	85%	78%	73%	71%
4	2,5 Gbit/s	98%	93%	87%	80%	75%	92%	81%	73%	67%	65%
16	2,5 Gbit/s	97%	92%	85%	76%	71%	90%	78%	68%	61%	59%
64	2,5 Gbit/s	97%	92%	84%	75%	69%	90%	77%	66%	59%	57%

Significance of the forwarding decision time appears low

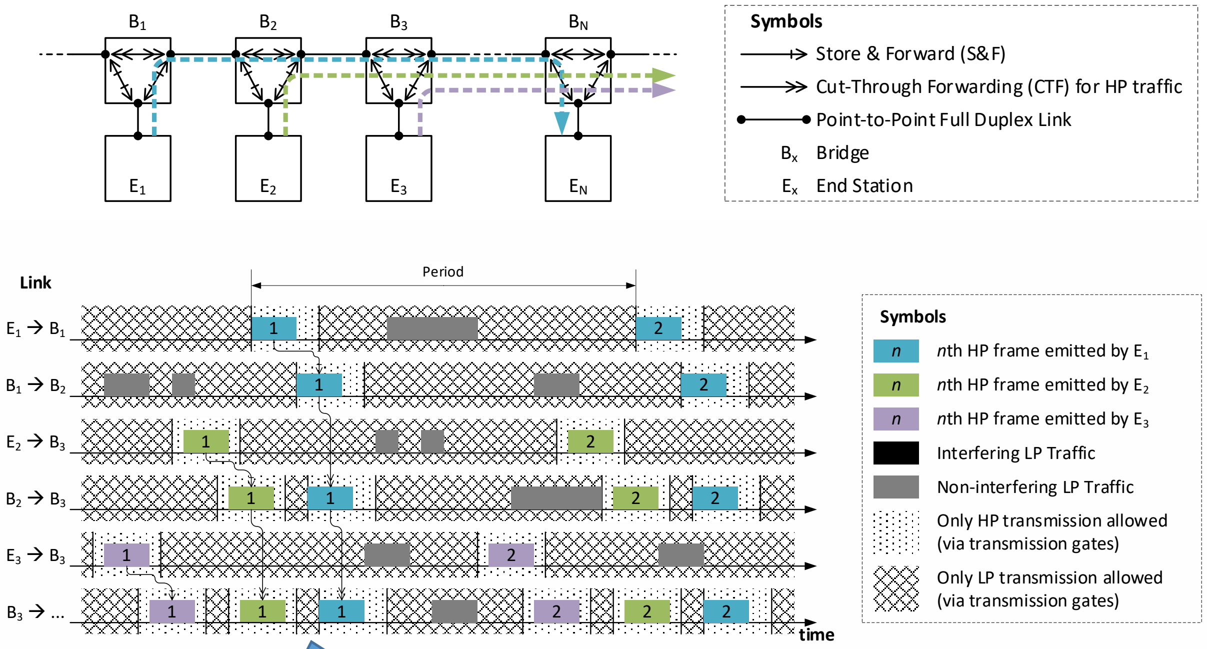
fwd. after 64 octets

		CTF-to-S&F max. delay ratio (end-to-end)									
		Preemption unsupported					Preemption supported				
H	Link \ l_{HP}	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	98%	94%	89%	82%	79%	91%	82%	75%	71%	70%
4	100 Mbit/s	98%	93%	86%	79%	75%	89%	78%	70%	66%	64%
16	100 Mbit/s	97%	92%	84%	75%	70%	87%	74%	65%	59%	57%
64	100 Mbit/s	97%	91%	83%	74%	69%	87%	73%	63%	58%	55%
2	1 Gbit/s	98%	94%	89%	83%	79%	92%	83%	76%	72%	70%
4	1 Gbit/s	98%	93%	87%	79%	75%	90%	79%	71%	66%	64%
16	1 Gbit/s	97%	92%	84%	75%	70%	88%	76%	66%	60%	58%
64	1 Gbit/s	97%	91%	83%	74%	69%	88%	74%	64%	58%	56%
2	2,5 Gbit/s	98%	94%	89%	83%	79%	93%	85%	78%	73%	71%
4	2,5 Gbit/s	98%	93%	87%	80%	75%	92%	81%	73%	67%	65%
16	2,5 Gbit/s	97%	92%	85%	76%	71%	90%	78%	68%	61%	59%
64	2,5 Gbit/s	97%	92%	84%	75%	69%	90%	77%	66%	59%	57%

See the annex for more information (device, network, and traffic assumptions, math, more results, etc.)

CTF Speed-up in Max. End-to-End Delay: Without Interference

Scenario: Full time division multiplexing



All interferences suppressed (via 802.1Qbv in this scenario)

fwd. after VLAN-Tag

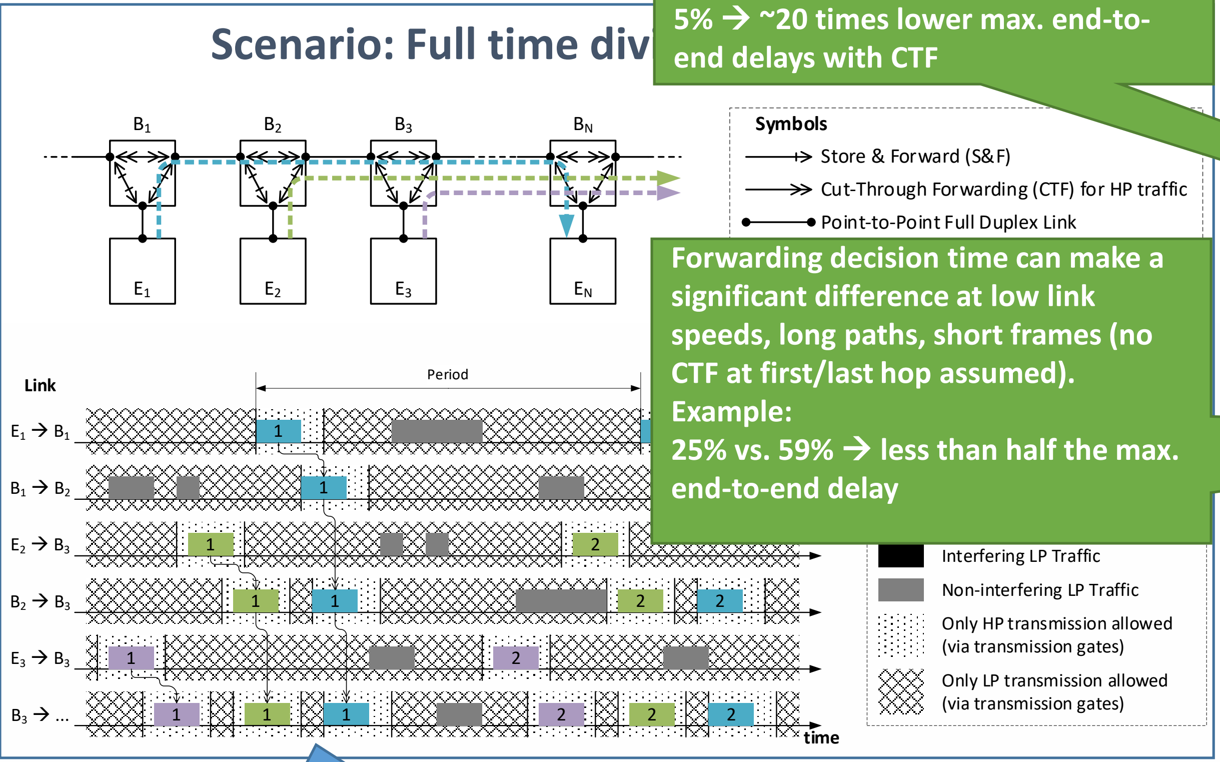
H	Link \ l_{HP}	128	256	512	1024	1542
		CTF-to-S&F max. delay ratio (end-to-end) Preemption supported or not				
2	100 Mbit/s	61%	56%	53%	51%	51%
4	100 Mbit/s	48%	41%	37%	35%	35%
16	100 Mbit/s	31%	21%	16%	14%	13%
64	100 Mbit/s	25%	14%	9%	6%	5%
2	1 Gbit/s	75%	64%	58%	54%	53%
4	1 Gbit/s	67%	52%	43%	39%	37%
16	1 Gbit/s	56%	36%	25%	18%	16%
64	1 Gbit/s	52%	31%	18%	11%	8%
2	2,5 Gbit/s	88%	74%	64%	58%	55%
4	2,5 Gbit/s	84%	66%	52%	44%	40%
16	2,5 Gbit/s	79%	55%	36%	25%	21%
64	2,5 Gbit/s	77%	50%	31%	18%	13%

fwd. after 64 octets

H	Link \ l_{HP}	128	256	512	1024	1542
		CTF-to-S&F max. delay ratio (end-to-end) Preemption supported or not				
2	100 Mbit/s	79%	65%	57%	54%	52%
4	100 Mbit/s	72%	53%	43%	38%	37%
16	100 Mbit/s	62%	37%	24%	18%	15%
64	100 Mbit/s	59%	31%	17%	10%	8%
2	1 Gbit/s	83%	69%	60%	55%	54%
4	1 Gbit/s	78%	59%	47%	40%	38%
16	1 Gbit/s	70%	45%	29%	20%	17%
64	1 Gbit/s	68%	40%	23%	13%	10%
2	2,5 Gbit/s	88%	74%	64%	58%	55%
4	2,5 Gbit/s	84%	66%	52%	44%	40%
16	2,5 Gbit/s	79%	55%	36%	25%	21%
64	2,5 Gbit/s	77%	50%	31%	18%	13%

See the annex for more information (device, network, and traffic assumptions, math, more results, etc.)

CTF Speed-up in Max. End-to-End Delay: Without Interference



In general, CTF becomes quite significant if interferences are avoided.
Example:
5% → ~20 times lower max. end-to-end delays with CTF

Forwarding decision time can make a significant difference at low link speeds, long paths, short frames (no CTF at first/last hop assumed).
Example:
25% vs. 59% → less than half the max. end-to-end delay

All interferences suppressed (via 802.1Qbv in this scenario)

fwd. after VLAN-

H	Link \ l_{HP}	128	256	512	1024	1542
		CTF-to-S&F max. delay ratio (end-to-end) – Preemption supported or not				
2	100 Mbit/s	61%	56%	53%	51%	51%
4	100 Mbit/s	48%	41%	37%	35%	35%
16	100 Mbit/s	31%	21%	16%	14%	13%
64	100 Mbit/s	25%	14%	9%	6%	5%
2	1 Gbit/s	75%	64%	58%	54%	53%
4	1 Gbit/s	67%	52%	43%	39%	37%
16	1 Gbit/s	56%	36%	25%	18%	16%
[illegible]	1 Gbit/s	52%	31%	18%	11%	8%
2	[illegible] Gbit/s	88%	74%	64%	58%	55%
4	2,5 Gbit/s	84%	66%	52%	44%	40%
16	2,5 Gbit/s	79%	55%	36%	25%	21%
64	2,5 Gbit/s	77%	50%	31%	18%	13%

fwd. after 64 octets

H	Link \ l_{HP}	128	256	512	1024	1542
		CTF-to-S&F max. delay ratio (end-to-end) – Preemption supported or not				
2	100 Mbit/s	79%	65%	57%	54%	52%
4	100 Mbit/s	72%	53%	43%	38%	37%
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64	2,5 Gbit/s	77%	50%	31%	18%	13%

See the annex for more information (device, network, and traffic assumptions, math, more results, etc.)

Reasons for standardizing CTF in IEEE 802

Interoperable and deterministic data plane

- When to forward frames under reception
- Late error handling
  - Truncate erroneous frames?
  - Mark erroneous frames?
  - Do nothing?
- Distinguish CTF traffic from S&F traffic
  - TAGs, Addresses, Ports, …?
- Behavior of existing 802.1 Bridge mechanisms for CTF traffic
  - Transmission selection algorithms?
  - 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 configuration (e.g., centralized network controller [802.1Qcc-2018])

Application and limitations of CTF in Networks

- Quality of Service[1,2]
- Security Considerations[1]
- Resulting Network Requirements/Recommendations

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

Use-Cases: Industrial Automation

Jordon Woods

Use Case 1 - Control Applications (line topologies)

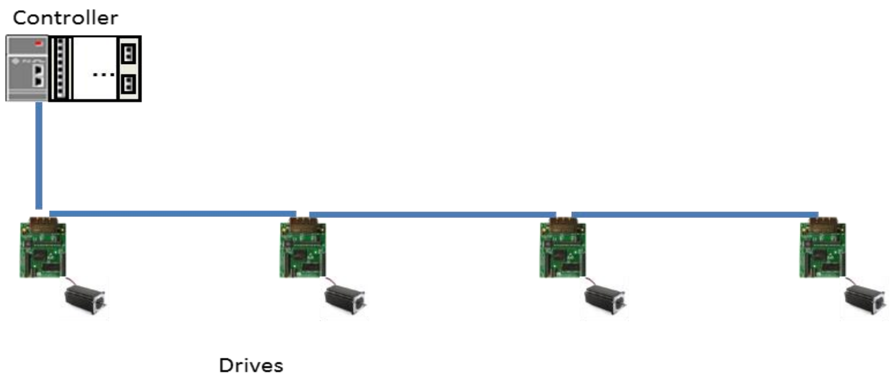
Control Applications (line topologies)

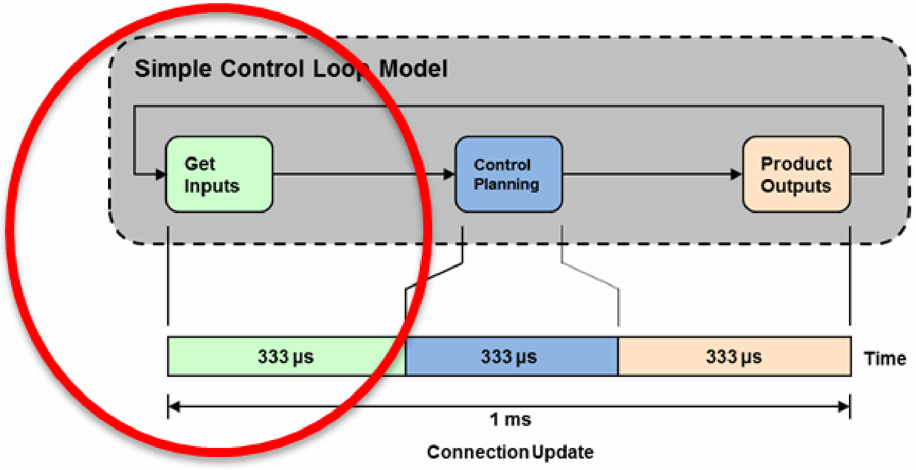
- Utilization of line topologies is prevalent in motion applications utilizing embedded switch technology
- There can be many hops along the line (64 hops or greater)
- Switch latency along these hops accumulates, eating into the time available for updates.

Store and forward delays quickly consumes the available control loop cycle

- Assuming a 500-byte control packet at 100 Mbit/s:
  - 1ms control loop: (1ms/3)/(500*80 ns/byte) = 8.325 hops.
  - 125 us control loop: (125 us/3)/(500*80 ns/byte) < 1 hops.

CTF is the only means to address the accumulated latency problem





Gigabit data rates are not sufficient to solve the problem

Combined store & forward, bridge delay and PHY delay exceed timing budgets. For instance, in a line topology of 64 hops, accumulated latency would exceed a 100 µs control loop even at Gigabit speeds.

- See http://www.ieee802.org/3/ad_hoc/ngrates/public/18_01/woods_nea_01a_0118.pdf

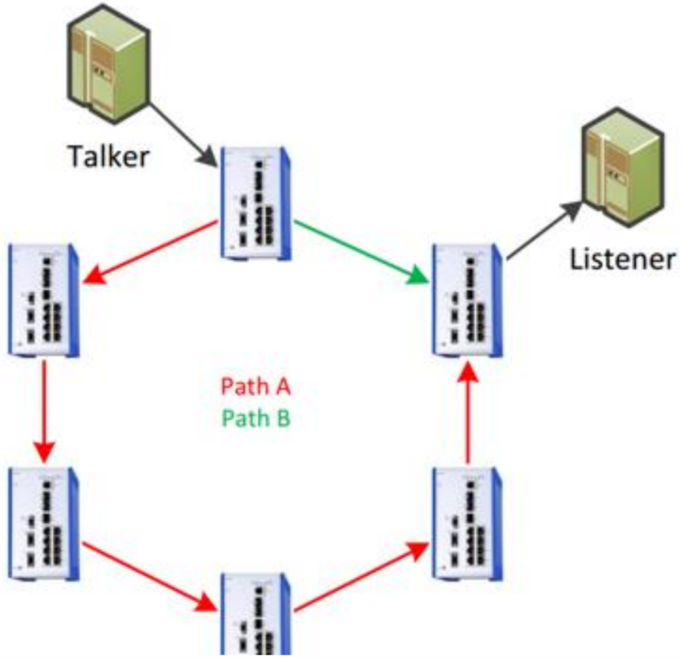
These industrial automation systems often have environmental constraints (power, space, radiated emissions, etc.) which make lower data rates desirable. There is a desire in some applications to support brown-field wiring. Often, these devices are resource, power and cost-constrained. For these applications 100Mbit/s rates are desired.

Why Line Topologies?

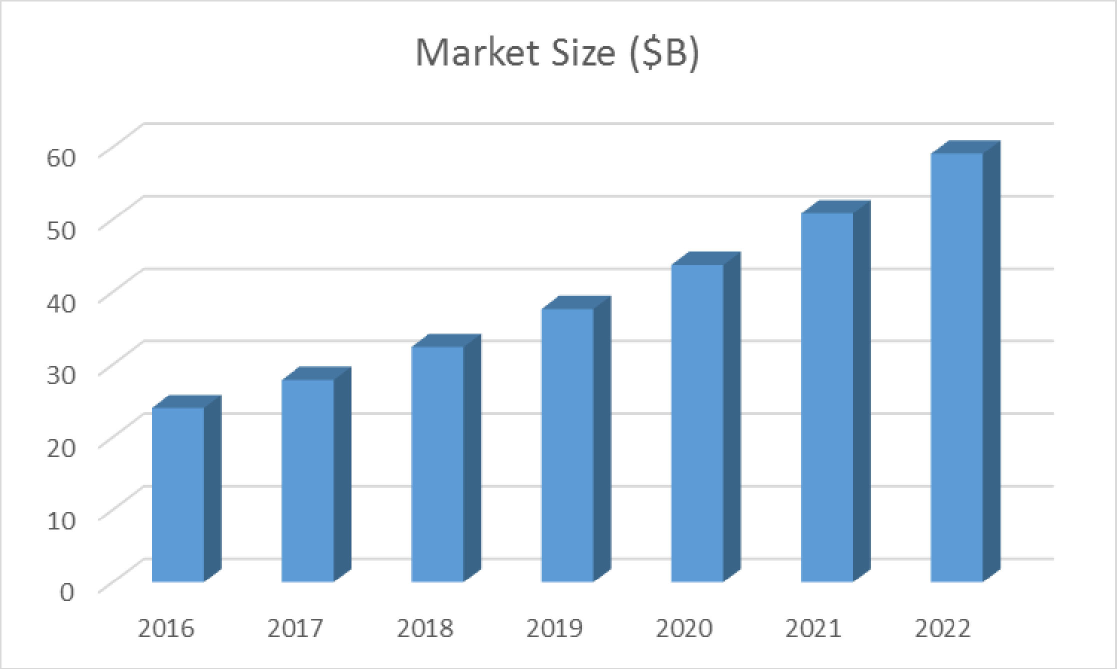
- Physical constraints make cabling for star topologies impractical
- The construction of the application naturally lends itself to point-to-point connectivity
- They are, after all, assembly "lines"

Use Case 2 - Redundancy (ring topologies)

- Typical topology for redundancy in industrial networks is a ring:
  - Inherently different packet latency on the network along the different routes
  - Depending on the setup, packet latency on the two paths can have extreme deviation
  - Depending on the allowed reception window of redundancy mechanisms, ring size is limited
  - For instance, for a 300 byte packet and 100 us packet deviation:
    - At 100 Mbit/s: the max. tolerable difference in the path is consumed in 4 hops
    - At 1 Gbit/s: the max. tolerable difference in the path is consumed in 34 hops



Industrial Network Growth



Industrial automation market > $123B in 2019

- Source: Control Global - https://www.controlglobal.com/articles/2020/top-50-automation-companies-of-2019-under-siege/

Connectivity portion is growing

- Fieldbus (58%), 7% growth
- Ethernet (38%), 20% growth
- Limited wireless adoption

With the advent of a common layer 2 (TSN), Industrie 4.0, China 2025, etc., strong growth is expected.

- Global industrial Ethernet market valued at USD $24B in 2016
- Expected to grow to $58.98 billion by 2022
- CAGR of slightly above 16.20% (2017 and 2022)
  - Source: Zion Market Research, 2017 - https://www.zionmarketresearch.com/news/global-industrial-ethernet-market

Use-Cases: Professional Audio/Video

Henning Kaltheuner, Genio Kronauer

ProAV perspectives

Ethernet is actually becoming the dominant media and control infrastructure in all **functional** Audio/Video applications

- Functional = Audio and Video serve a purpose within a relevant context

  - ‘Classic’ ProAV applications: **(Performance oriented systems)**

    - Live Concerts, shows, events (mobile, temporary)
    - Installations for live events in theatres, live clubs, concert halls, …. (fixed, permanently)

  - Commercial installation: **(non- performance oriented systems)**

    - Conference centers
    - Corporate buildings
    - Casinos, Hotels, Theme parks
    - Cruise Ships
    - Sport venues
    - Transportation
    - Education
    - Malls, shopping

ProAV perspectives

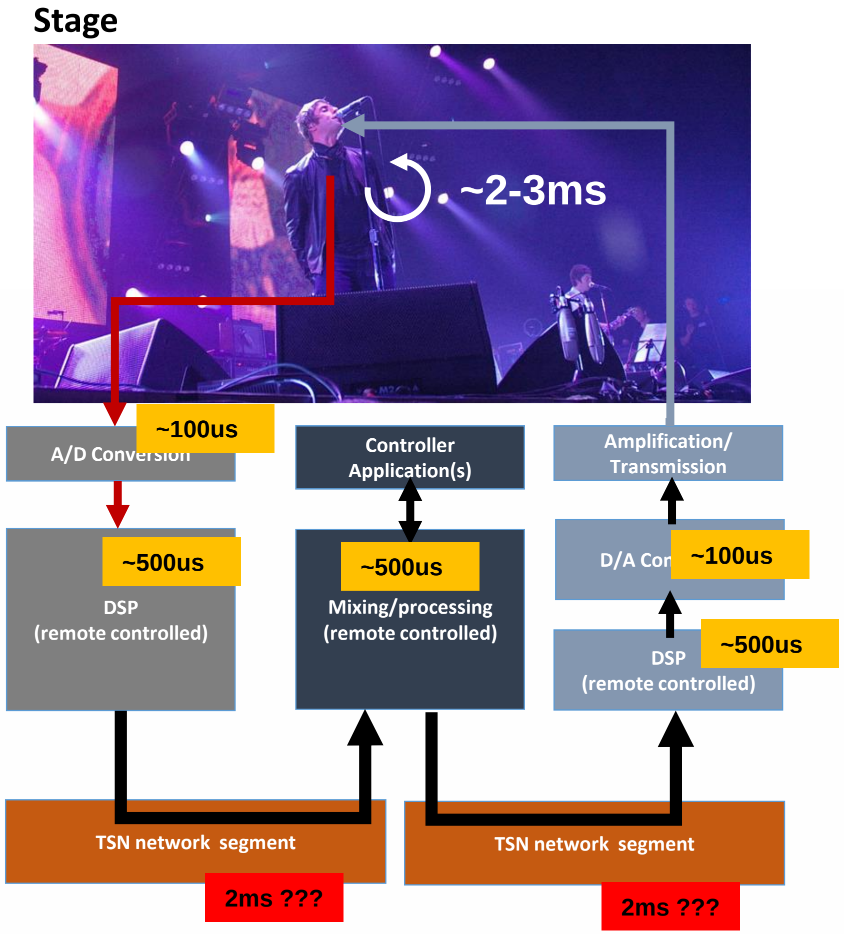
Important trends:

- Traditional borders between applications disappear
  - **Venue multi-functionality**
    - One room/hall to serve many purposes (Club, Conf. room, Corp. event space, HoW, Musical, Cinema in one space)
    - Maximum of versatility expected
    - Minimum setup/conversion time
  - **Audio and Video content becoming part of many buildings**
    - Experience culture everywhere
    - BYOD interaction
  - **Hybrid event formats**
    - ‘Live’ interaction of audience with content On – site or remotely
    - Multi-campus venue structures (HoW, Conference)
    - ‘Gamification’ means ‘real-time’ interaction
- Expectations for future ProAV systems go to an extreme of ‘intelligent’, very low latency networked digitalization.

ProAV perspectives

Everything will be networked – but so far everything is a compromise:

- ProAv doesn't get the low latencies that are needed
- **Real-time ProAV applications have very similar requirements as industrial applications (see Industrial Automation use-cases and IEC/IEEE 60802)**
  - Max. 2-3ms of latency through the entire signal chain can be tolerated.
- **BUT:**
  - **This often includes cascades of networks**
  - Signal capturing, processing, transmission requires time!
- **Even for the self-contained ProAV applications network structures can not be fast enough.**

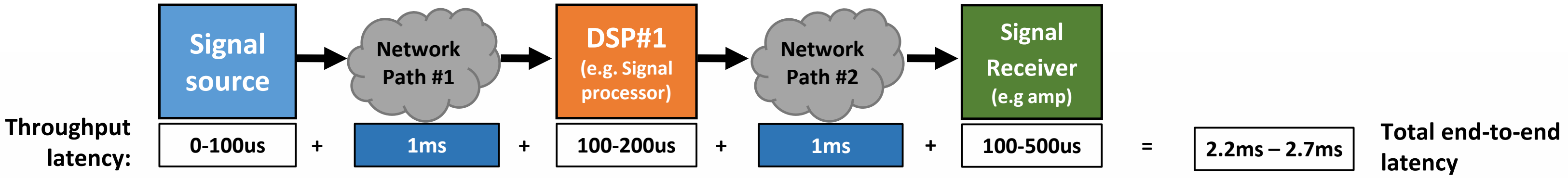


ProAV perspectives

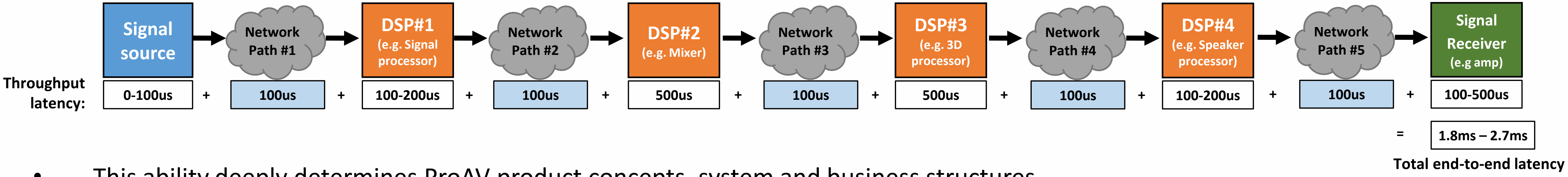
Everything will be networked – so far everything is a compromise:

- <u>Network latency has deep impact on ProAV system structures</u>

- **Example:** If network latency is 1ms and max. 3ms total end-to-end latency is accepted then the system structure is limited to 2 network connections within the signal path:



- **Desired structure:** Ability to have multiple network paths within a signal path:



- This ability deeply determines ProAV product concepts, system and business structures
- @100us per network path enable distributed hybrid signal processing environments

ProAV perspectives

From Stonehenge to 21st century:

- Most public or functional buildings include PA/VA systems (Public Address / Voice Alarm)

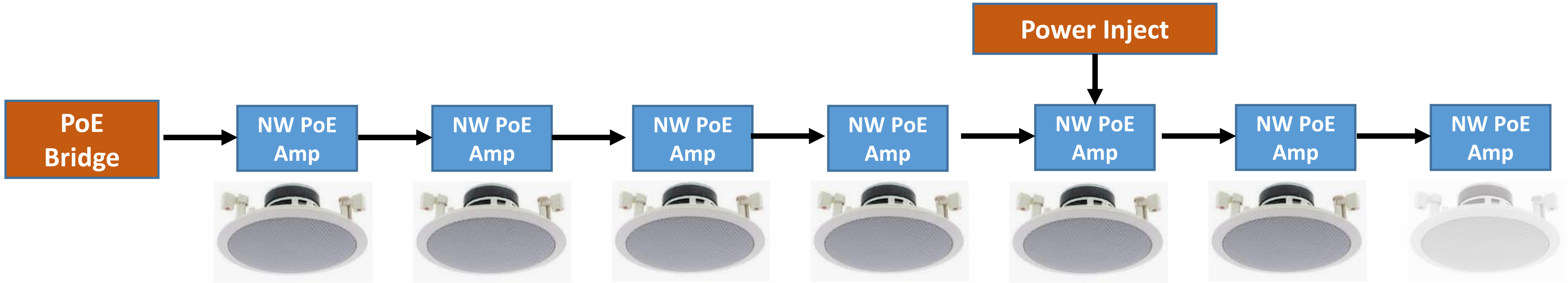
- Subject to fire/security regulations
- System / component status must be monitored / ensured
- Full redundancy required **(A/B system structures)**

- So far almost **no** digitalization !
- 99% Daisy-chained structures

ProAV perspectives

From Stonehenge to 21st century:

- Most public or functional buildings include PA/VA systems (Public Address / Voice Alarm)



Future expectations:

- Full remote monitoring of every component
- **Flexible integration with other AV/Event systems**
- Intelligent zoning

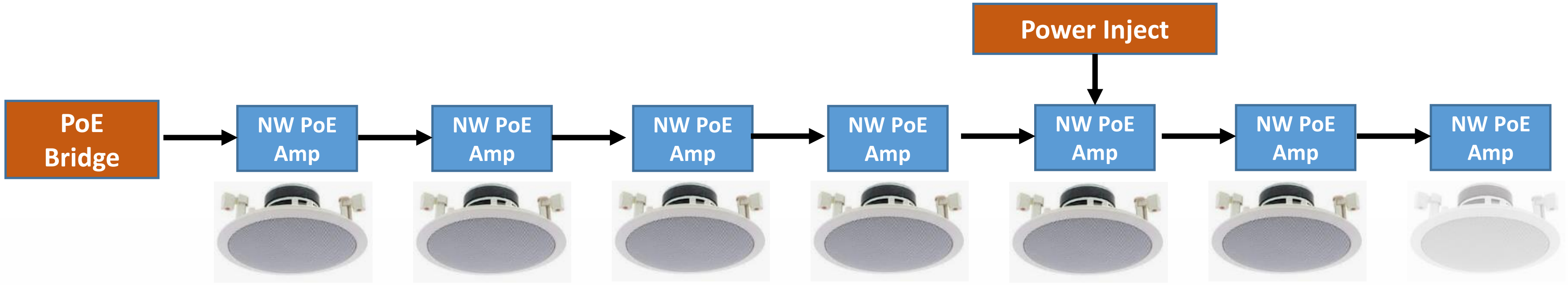
Requirement:

- Consistent low latency independent from length of chain for ensuring consistent performance
- Addressability per component
- Integrating other functionality
  (microphones, immersive sound, smart ceilings, interactive functionalities)

ProAV perspectives

From Stonehenge to 21st century:

- Most public or functional buildings include PA/VA systems (Public Address / Voice Alarm)



Forecast:

- We will have these structures in **all** functional buildings: Corporate, Government, Education, Hotel, Leisure, HoW, Airports, Transportation …….
- # of components (end stations): Cruise Ship: 50.000
  Casino: 12.000
  Airport: 10.000-30.000
- **So far the network has been the bottleneck to full building integration with audio and video content**

- There are many other use-cases for such daisy-chained structures in ProAV.
- CTF can be enabling technology

ProAV perspectives

Conclusions:

- ProAV becomes a part of many contexts in many different buildings
- Markets for intelligent systems with expanded functionalities are expanding fast

- Current NW topologies and properties have hindered full digitalization of building and event system structures

- Latency is critical to all live and/or interactive applications and to consistent performance in spaces with distributed systems.

- **Considering cascaded network structures in many system architectures and requirements for real-time interactive systems <u>a latency of roughly 100us over up to 100 hops seems an optimal design</u>.**
- **<u>However: < 100us for 50 hops could very well be a reasonable target.</u>**

- These numbers count for 1Gbit/s. For 100Mbit/s higher latencies can be considered (tbd).

Use-cases: Data Center Networks

Paul Congdon, Lily Lv

High Performance Applications Growth in the Data Center

High Performance Computing (HPC), AI (Artificial Intelligence)/Big Data and Cloud Computing are hot growth areas.

The convergence of these 3 areas is currently a trend in the data center.

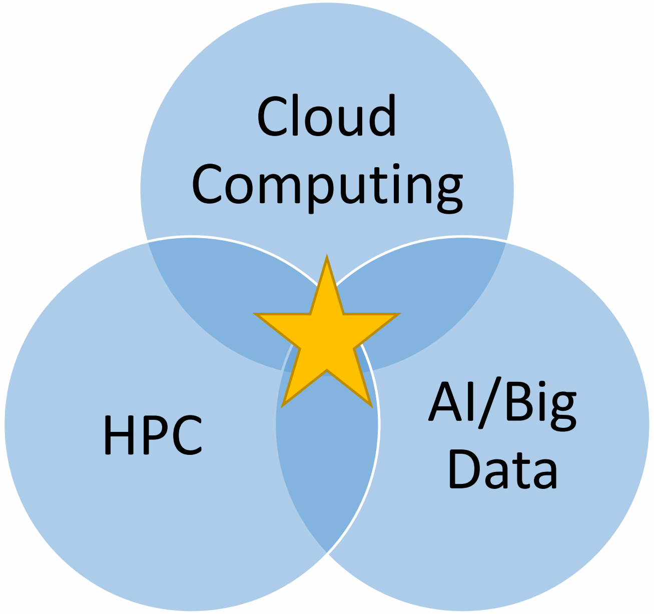
- HPC is available as a cloud service in many public offerings (AWS, Azure, Alibaba etc); growing 17.6% CAGR (Compound annual growth rate) , 2.5 times faster than on-premise HPC.
- HPDA (High performance data analytics) and HPC-based AI are fast emerging markets, with 16% and 31% CAGR respectively.

	2019	2020	2021	2022	2023	2024	CAGR
HPC cloud	$2,466	$3,910	$4,300	$5,300	$6,400	$8,800	17.6%
On-Premise HPC	$27,678	$23,981	$26,774	$31,872	$36,138	$38,214	6.7%

Source: Hyperion Research, November 2020

	2019	2020	2021	2022	2023	2024	CAGR
HPC Server Revenues	$13,713	$11,846	$13,295	$15,817	$17,942	$19,044	6.8%
HPDA Server Revenues	$3,598	$3,932	$4,737	$5,457	$6,480	$7,479	15.8%
HPC-Based AI	$918	$1,094	$1,399	$1,810	$2,745	$3,555	31.1%

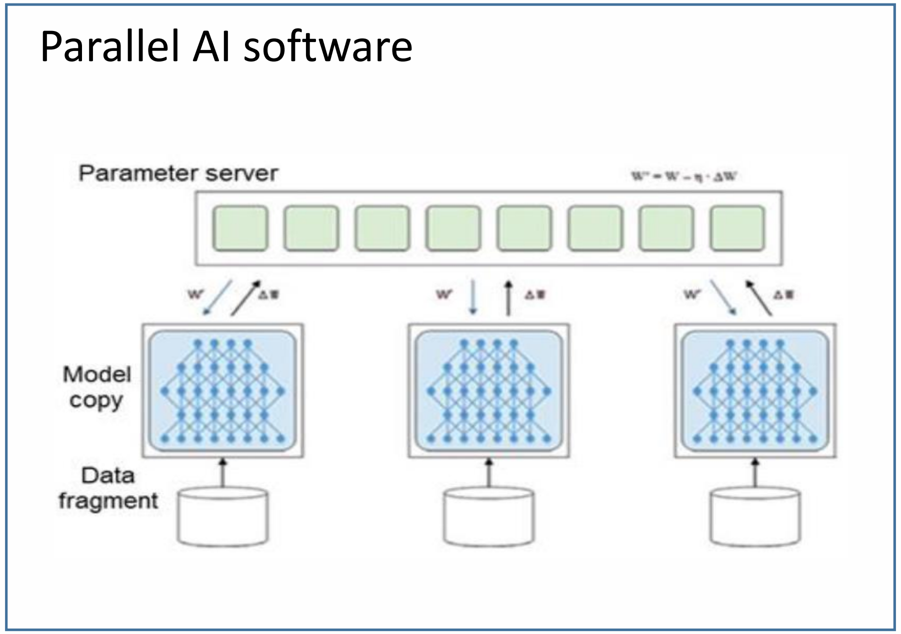
Source: Hyperion Research, November 2020

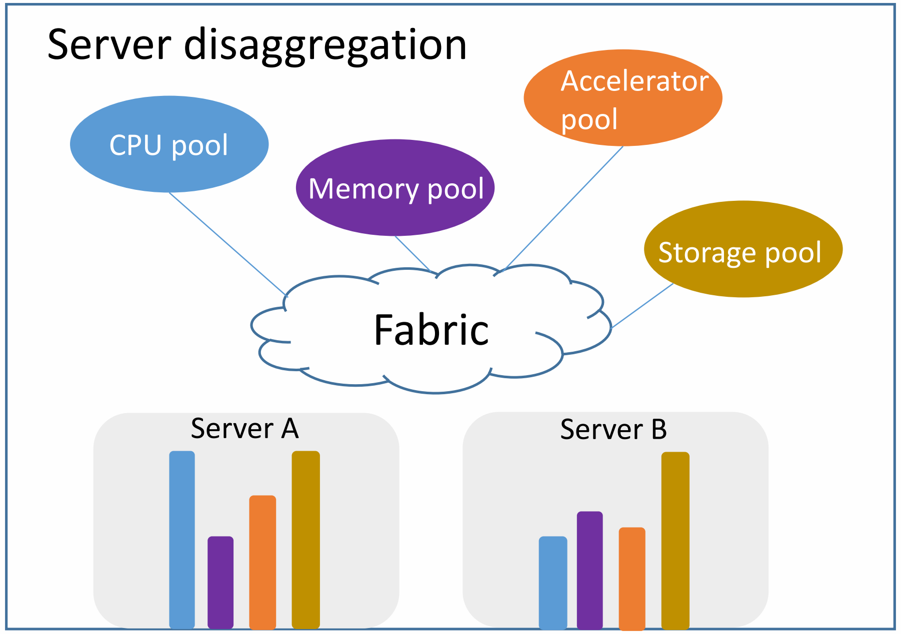


Latency is Critical in Data Center Networks (1)

High performance applications are driving change in data center, putting pressure on end-to-end latency.

- System scale is increasing significantly, with much more end points and a larger network.
- Synchronization in large parallel applications is critical to job completion time.
- New hardware architectures, such as server disaggregation, require extremely low-latency fabric.

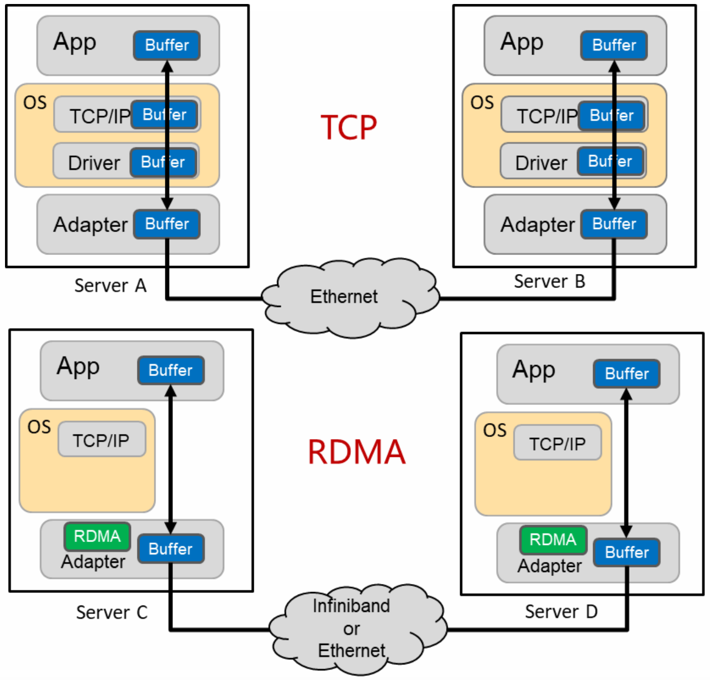


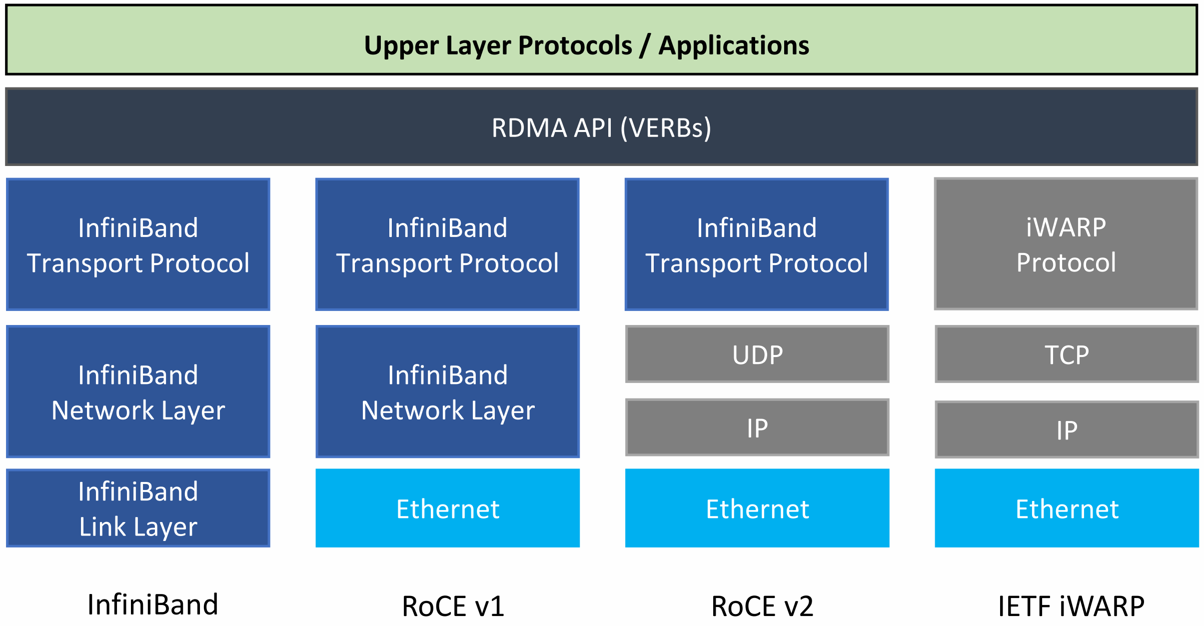


Latency is Critical in Data Center Networks (2)

New technologies are emerging to reduce system latency.

- **RDMA (Remote Direct Memory Access)**
  - RDMA enables direct memory access from one server to another, bypassing the TCP/IP stack handling in OS.
  - RDMA runs over InfiniBand or Ethernet.
    - InfiniBand, like Ethernet, is a networking technology, but customized for high throughput and low latency.
  - RDMA improves message transfer time by 5x compared with TCP/IP.

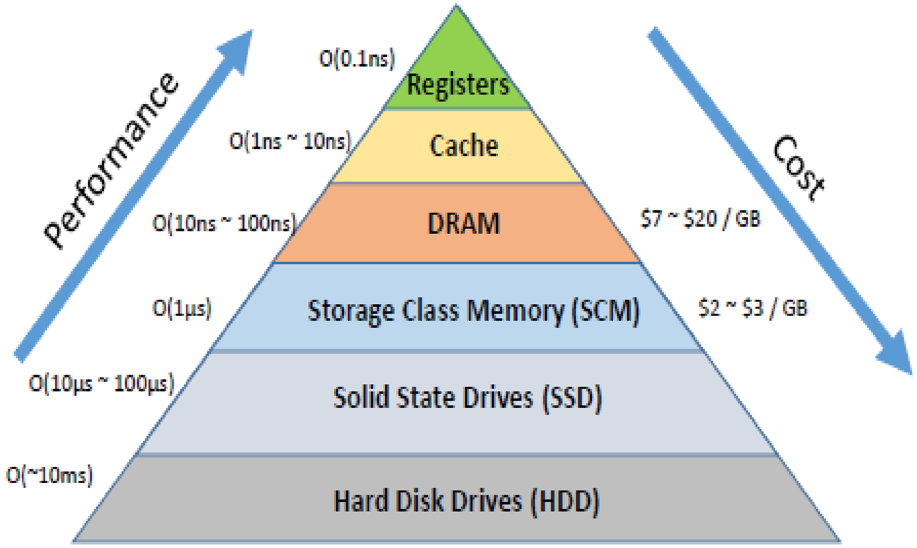




Latency is Critical in Data Center Networks (3)

New technologies are emerging to reduce storage latency.

- **Faster storage media**
  - Persistent storage latencies are approaching memory latencies with the latest Storage Class Memory (SCM) technology.
- **NVMe (Non-Volatile Memory express)**
  - NVMe is a storage interface specification defining communication between host software and PCIe SSD.
  - “The NVMe specification was designed from the ground up for SSDs. It is a much more efficient interface, providing lower latency, and is more scalable for SSDs than legacy interfaces, like serial ATA (SATA). ” (https://nvmexpress.org/)
  - NVMeoF (NVMe over Fabrics) enables “networked” fast storage (SSD/SCM) however without networking enhancements, the network becomes the largest part of end-to-end latency.



Network latency becomes the bottleneck!

Latency is Critical in Data Center Networks (4)

Types of latency in data center networks: dynamic and static

Dynamic latency = queuing delay + retransmission delay

- Mainly caused by congestion
  - In-cast congestion from parallel applications.
  - In-network congestion from ineffective load balancing.

- Mainly cause by packet loss due to congestion
  - Priority-based Flow Control (PFC) guarantees no loss
  - PFC has deployment challenges: configuration, deadlocks, head-of-line blocking, congestion spreading

Static latency = switch forwarding + packet processing + link latency

- Impacted by forwarding table lookup delay, frame reception delay (if store and forwarding) and switching delay

- Impacted by header processing and packet modification

- Propagation delay impacted by distance and speed

- Dynamic latency is the major component and attracts a lot of the industry's attention: See
  - 802 Nendica - The Lossless Network for Data Centers - https://mentor.ieee.org/802.1/dcn/18/1-18-0042-00-ICne.pdf
  - 802 Nendica - Intelligent Lossless Data Center Networks - https://mentor.ieee.org/802.1/dcn/20/1-21-0004-00.pdf
- However, Static latency becomes significant in high performance scenarios, such as HPC.

Benefits of Cut-Through Forwarding in the HPC Networks

HPC network operates at the nanosecond level

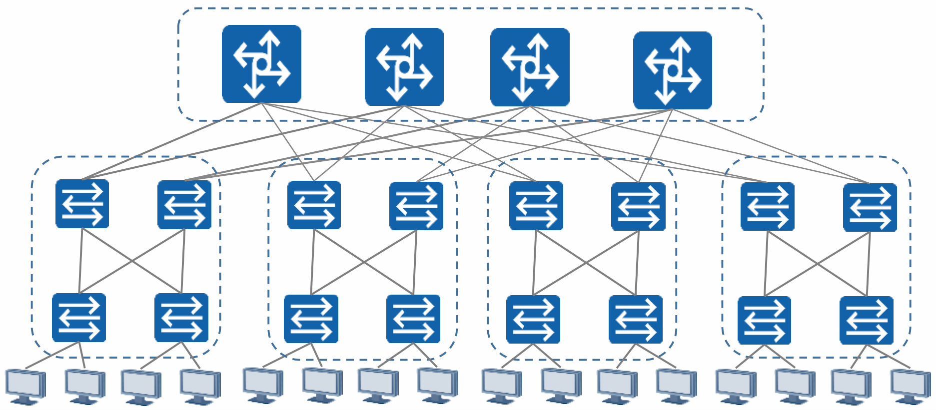
- E2E network latency is only several micro-seconds.
- Per hop latency is required as low as possible, hundreds of nano seconds, or even lower.

CTF is applicable in the HPC network

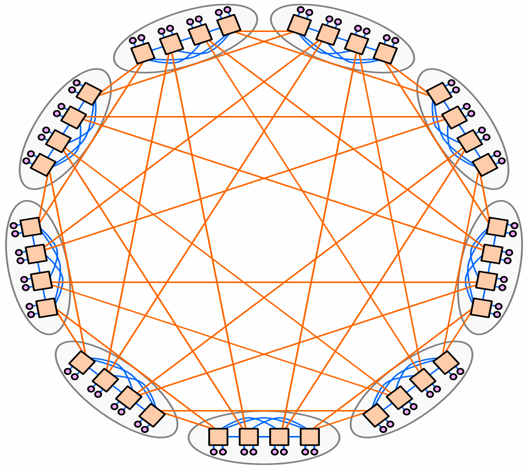
- Traffic loads can be predictable, leading to congestion avoidance techniques in switches.
- Data center topologies are well structured with similar type of switches.

Regular Topologies: Two typical HPC networks

Fat Tree is a rearrangeably non-blocking structure, which provides an oversubscription ratio of 1:1 to all servers.

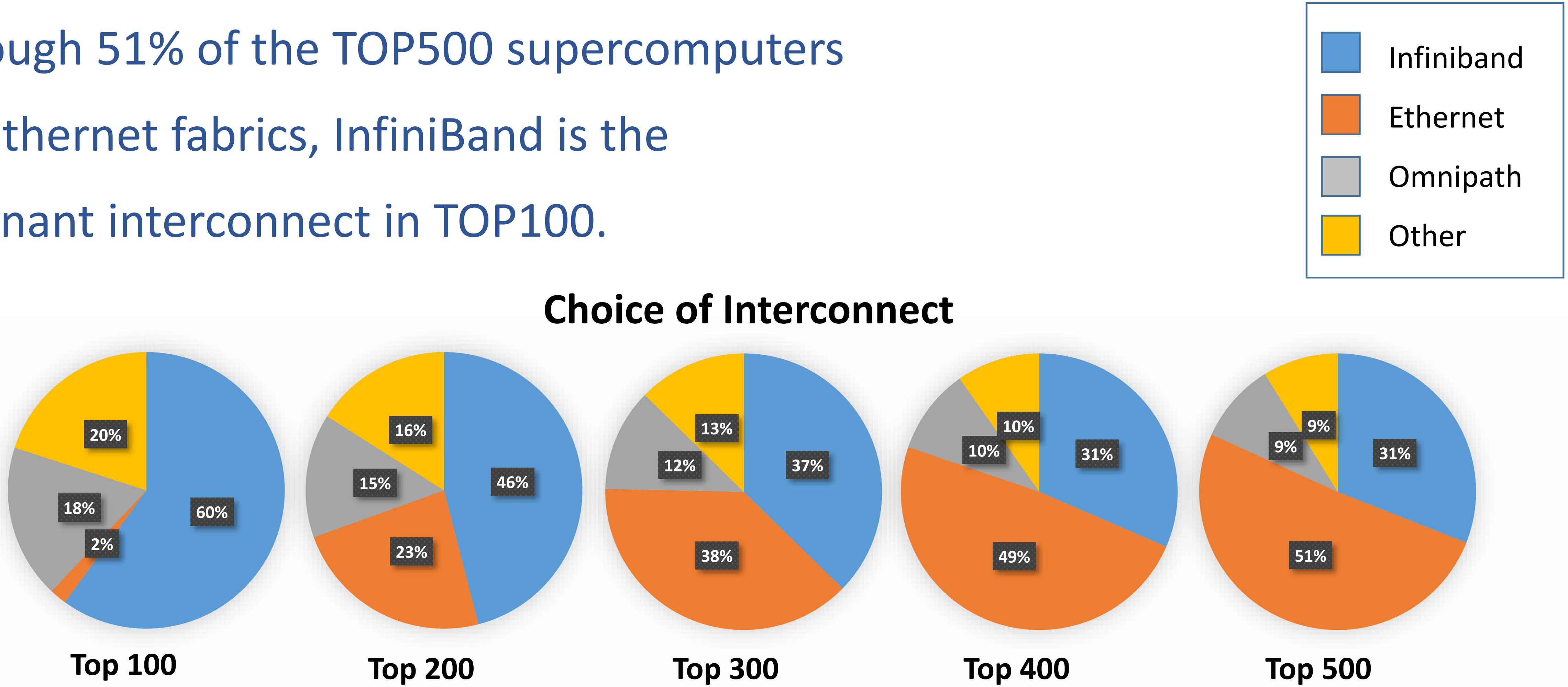


Dragonfly is a well-balanced network with no oversubscription.



InfiniBand is the ‘first-choice’ in HPC Today (1)

Although 51% of the TOP500 supercomputers use Ethernet fabrics, InfiniBand is the dominant interconnect in TOP100.



InfiniBand is the 'first-choice' in HPC Today (2)

InfiniBand switch per hop latency is much lower than Ethernet

- Ethernet switching chipset latency can be greater than 100s of ns.
- Latency increases with frame size using store-and-forward.
- InfiniBand switching chipset latency can be less than 100ns.
- Cut-through is an important feature for InfiniBand to keep per hop latency low.

Ethernet (non-CTF)

	BRCM THK
Port	128*25G

One 25GbE Port to One 25GbE Port Test

Frame Size(Bytes)	64	128	256	512	1024	1280	1518	2176	4096	9216
Latency(ns)	511	528	556	567	717	793	872	1082	1694	3334

Source: Tolly, February 2016

IB (with CTF)

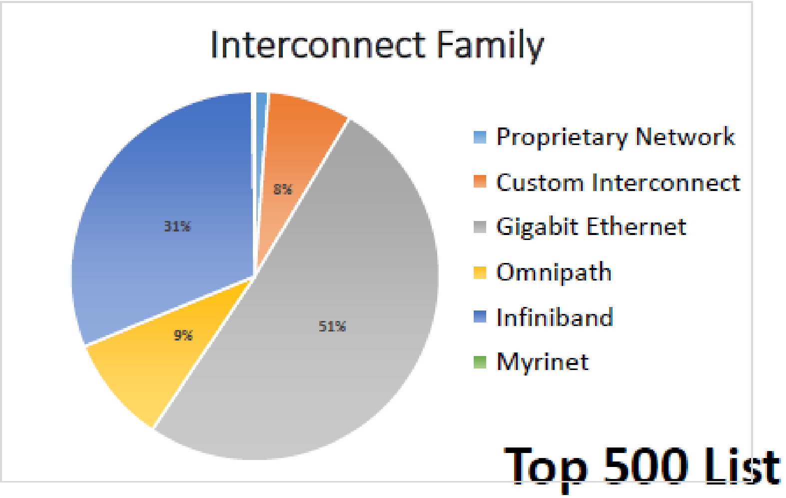
	MLNX Switch-IB	**MLNX Switch-IB2**
Port	144*25G	144*25G
Latency	90ns	90ns

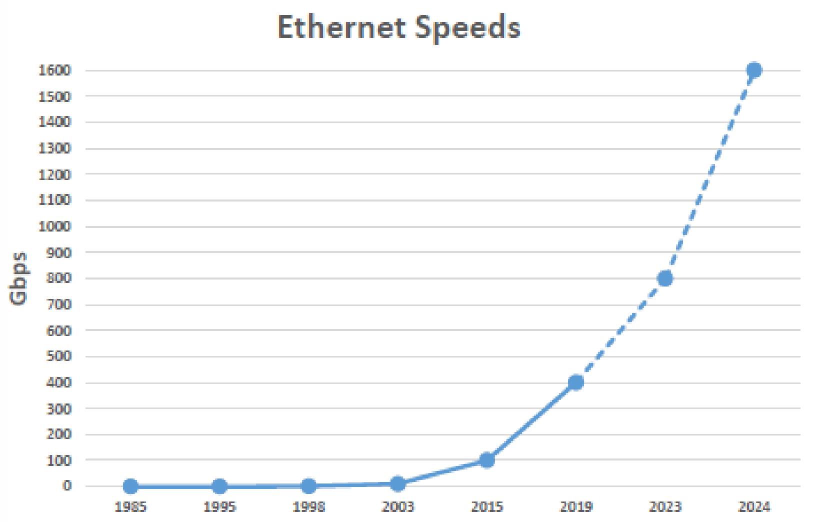
Source: https://www.mellanox.com/news/press_release/

Ethernet needs CTF to further penetrate HPC

Ethernet has great opportunity to become more competitive in HPC market.

- TOP 500 shows Ethernet Interconnects already takes the largest share (51%)
- Ethernet has its own advantages
  - Ethernet is ubiquitous technology.
    - Cost-effective solution
    - Relatively easy to deploy and manage
    - Leading technology development
  - Ethernet provides large bandwidth connectivity
    - up to 400G, 100G for single lane
    - towards 800G, 200G for single lane





The obvious gap of Ethernet is latency

- Per hop latency gap is significant compared with InfiniBand
- CTF is a good method to improve per hop latency

Summary: Goals and Objectives

Summary: Goals and Objectives

The delay performance needed by the use-cases requires bridges to start frame transmission before complete reception (core principle of CTF):

- **Preemption is no alternative to CTF**
  - Preemption vs. CTF
    - Preemption: Reduces delays *critical frames* experience from other interfering frames.
    - CTF: Reduces delays of the *critical frames* themselves.
      (regardless whether interference by other frames is present or not)
  - Nonetheless, it is desirable to combine CTF with protocols from existing IEEE 802.1/802.3 standards, including preemption.
- **Higher link speeds are no alternative to CTF**
  - Inapplicable where lower link speeds are desirable
    → Cost, environmental constraints, brown field installations (Industrial Automation)
  - Even at high link speeds, the delay performance enabled by CTF is needed (DCN)
- **Different topologies are no alternative to CTF**
  - Inapplicable where daisy chain and ring topologies are inevitable
    → Cost, physical constraints/pre-defined structures (Industrial Automation)
  - Even in optimized topologies, the delay performance enabled by CTF is needed (DCN)

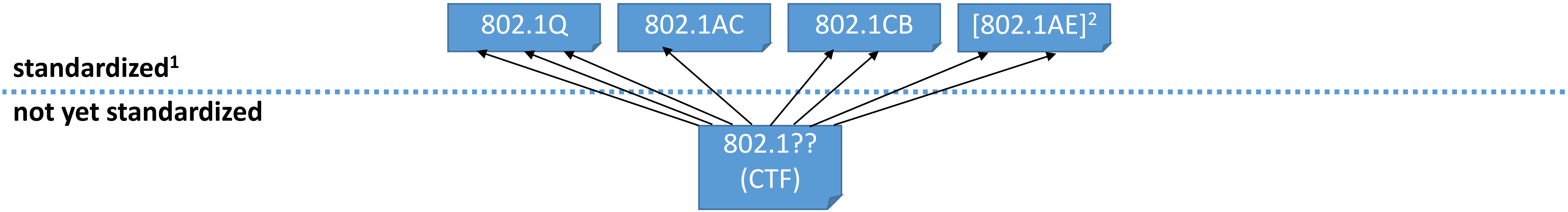
→ **Existing IEEE 802.1/802.3 standards do not provide this performance.**

→ **Standardizing CTF is desirable to enable a common management approach and ensure interoperability.**

IEEE 802.1 Considerations

Johannes Specht

Proposed Location in IEEE 802.1 Standards



Separate stand alone IEEE 802.1 base standard for CTF

- **Single document**
  Avoids distribution of CTF across existing standards (compared to multiple amendment projects).
- **Exclusion, inclusion/re-use and adjustment of existing protocols**
  - Existing protocols not referred to are basically beyond specification.
  - If no adjustments for CTF are needed:
    Inclusion by reference (e.g., *"as specified in x.y.z of IEEE Std 802.1Xxx-20XX"*) can be sufficient.
  - If adjustments for CTF are needed:
    - Additional description of the differences can be sufficient.
    - Adjustments apply for CTF only; no side effects on existing protocols in absence of CTF support.

1) The latest published base standards, corrigenda, and a subset of the published amendments.
2) See later slide on security/privacy.

Proposed Content Categories and (some) Contents[1]

CTF in Networks

- Application and Limitations[2]:
  - Quality of Service
  - Security Considerations
  - Resulting Network Requirements/Recommendations
- Usage/Performance aspects[3]
- …

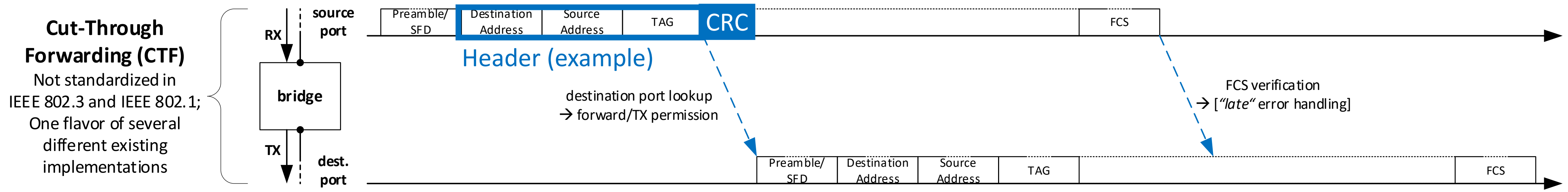
CTF in Bridges

- Bridge relay behavior
  - MAC Relay Entity/Forwarding Process
  - Bridge Port Transmit and Receive[4]
- Managed Objects/YANG
- …

Considered throughout the next slides

1) Illustration of technical contents, not a clause structure.
2) Issues introduced by CTF (cmp. https://ieee802.org/1/files/public/docs2017/new-tsn-thaler-cut-through-issues-0117-v01.pdf and ttps://www.ieee802.org/1/files/public/docs2019/new-seaman-cut-through-scissors-0119-v01.pdf) that can be addressed on a network level.
3) See the introduction of this slide set.
4) To the extent possible in IEEE 802.1.

CTF in Networks: Application and Limitations



The Basic Issue

- Erroneous frame under reception are forwarded to the wrong destination port(s), associated with the wrong traffic class, or both.

Option: "Header CRCs"

- Add CRCs over frame headers, forward only after verification to avoid wrong forwarding decisions.
- Several issues (e.g., compatibility/interoperability, frame overheads, loose header definition).

Could be analyzed during Stds activities …

Option: Analyze

Identify the resulting issues and analyze these issues individually.

Circulating frames

Erroneous frames can circulate for "for a while" in topological loops.

Additional congestion

Erroneous frames can cause additional congestion for other traffic in transmission ports.

Security/Privacy

Payload of erroneous frames become visible on links where it shouldn't be seen.

Next slides

CTF in Networks: Circulating Erroneous Frames

Issue

Erroneous frames can circulate for "for a while" in topological loops.

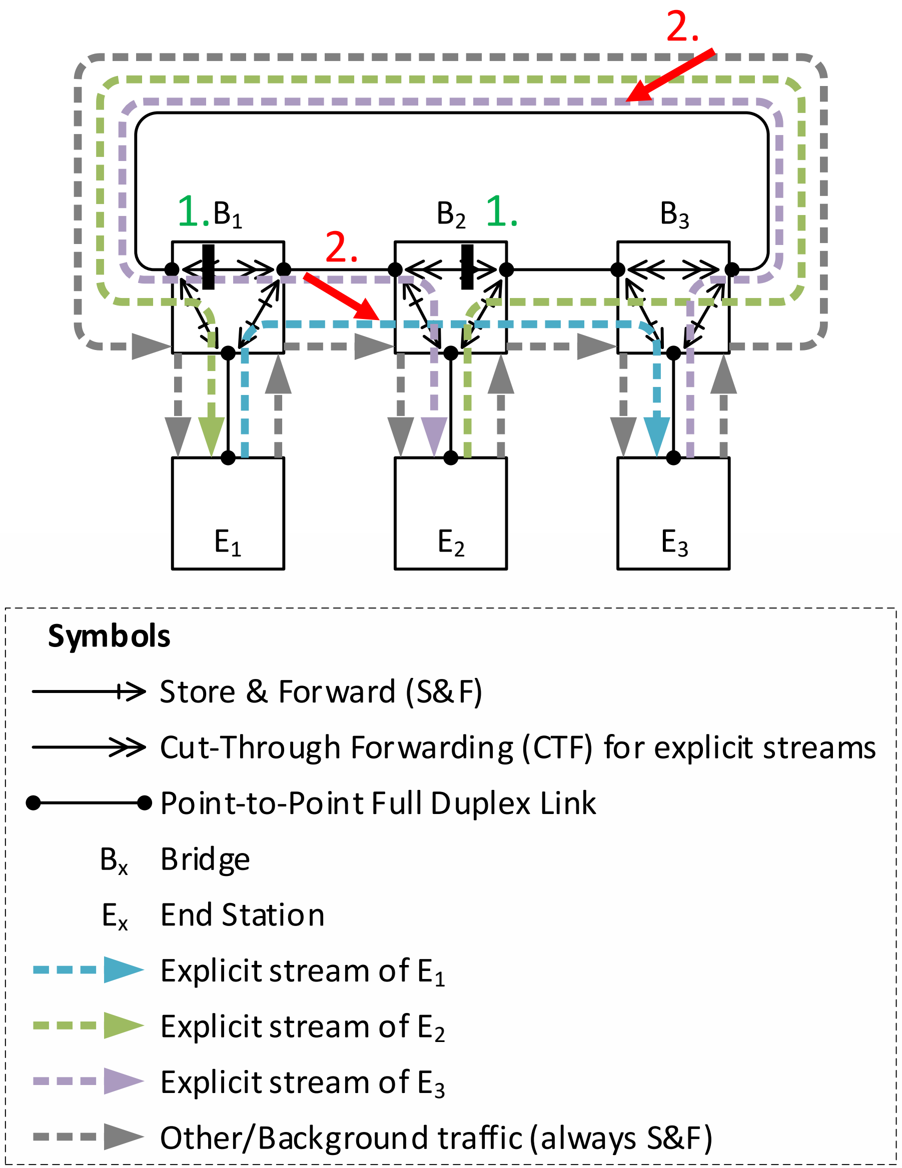
Goal

Solution(s) depend on the definition of a goal:

An erroneous frame shall circulate longer than one round in a topological loop if FCS verification can discover the error in this frame.

Solutions (Alternatives)

1. **Selective S&F-only hops** for all traffic in each topological loop (robust/default choice).
2. **Constrained FDB setups** (explicit unicast/multicast entries only), assuming a frame experiences corruption at most on one link.
3. **Frame truncation**, in topological loops with sufficient hops and in combination with upper bounds on frame lengths.



CTF in Networks: Additional Congestion

Issue

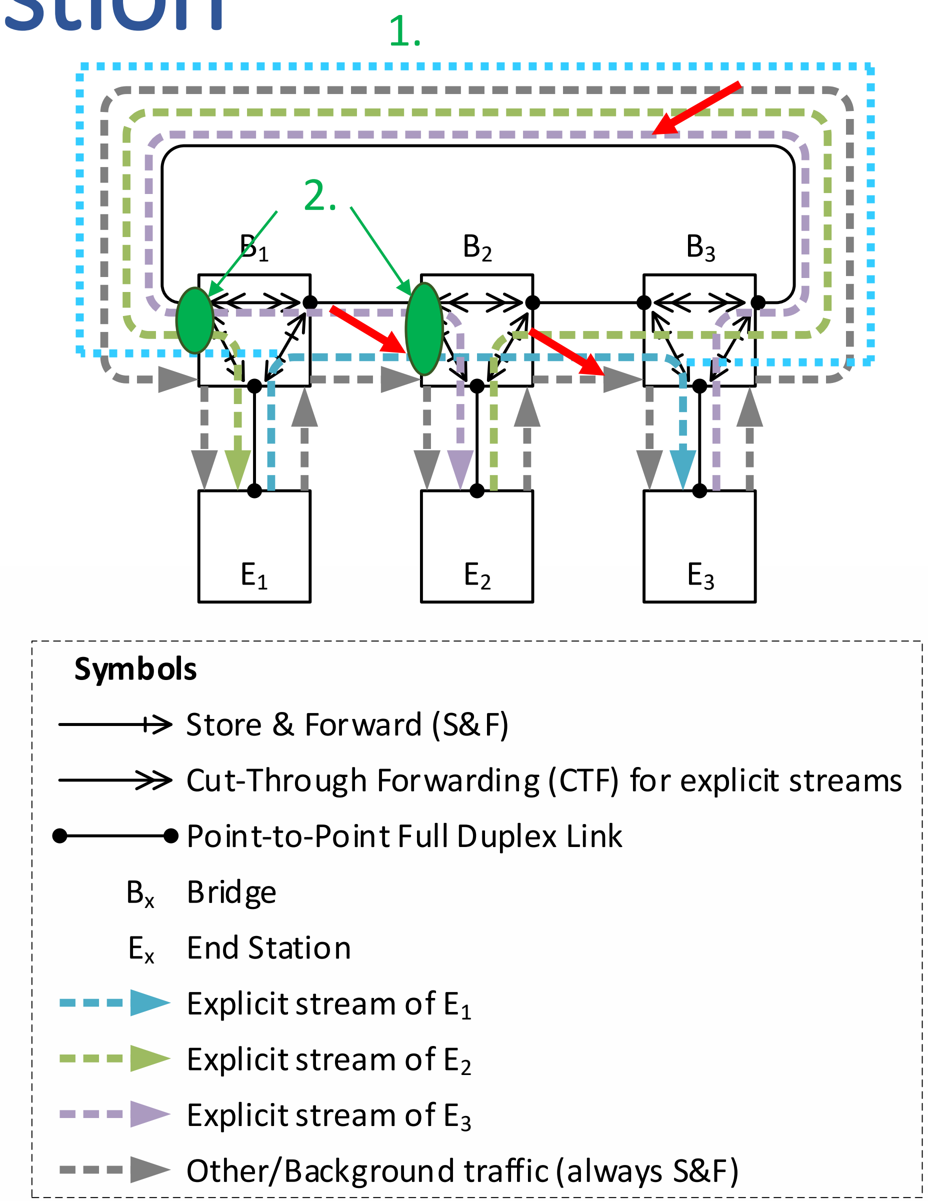
Erroneous frames can cause additional congestion for other traffic in transmission ports.

→Extra delays by additional interference

→Bandwidth reduction

Solutions

1. Disjoint redundant paths via Frame Replication and Elimination for Reliability (**FRER**).
2. Per-Stream Filtering and Policing (**PSFP**) functions.
3. **Planning** for additional delays/bandwidth reduction.
4. **Frame truncation** of erroneous frames.



CTF in Networks: Security/Privacy

Issue

Payload of erroneous frames become visible on links where it shouldn't be seen[1].

Solution

Dependent on the security under consideration.

Security with/without cryptography

Without Cryptography

- CTF may be an issue.
- **One Possible Solution**
  - Don't use CTF on the relevant links.
  - Document the issue when using CTF (e.g., security considerations).

With Cryptography

- Closer examination needed.
- See the next column (middle) …

Security with cryptography on layer 2/above layer 2

Above Layer 2

- CTF seems to be no issue (examples)
  - Web security (TLS), IPSec
  - OPC security (UASC, TLS, PubSub Security)
  - IEC 61125 (CIPSecurity [ODVA], ProfiNet security)

On Layer 2[2]

- Closer examination needed.
- See the next column (right) …

Security with cryptography on layer 2 with/without confidentiality

Without Confidentiality

- CTF seems to be no issue, in absence of path assumptions.
- **Additional considerations for CTF with MACsec**[3]
  - Transparently forward protected frames under CTF (i.e., no special handling).
  - Integrity check based propagation limitation via frame truncation.

With confidentiality

- CTF may be an issue, but probably not a new one (tbd).
- **One Possible Solution**
  - Don't use CTF on the relevant links.
  - Document the issue when using CTF (e.g., security considerations).

1) See also https://ieee802.org/1/files/public/docs2017/new-tsn-thaler-cut-through-issues-0117-v01.pdf
2) Cmp. IEEE Std 802.1AE-2018
3) See also https://www.ieee802.org/1/files/public/docs2019/new-seaman-cut-through-scissors-0119-v01.pdf

Proposed Content Categories and (some) Contents

CTF in Networks

- Application and Limitations[1]:
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- …

CTF in Bridges

- Bridge relay behavior
  - MAC Relay Entity/Forwarding Process
  - Bridge Port Transmit and Receive[3]
- Managed Objects/YANG
- …

An outline of a potential model on the next slides

1) Issues introduced by CTF (cmp. https://ieee802.org/1/files/public/docs2017/new-tsn-thaler-cut-through-issues-0117-v01.pdf and ttps://www.ieee802.org/1/files/public/docs2019/new-seaman-cut-through-scissors-0119-v01.pdf).
2) See the introduction of this slide set.
3) To the extent possible in IEEE 802.1.

CTF in Bridges: Initial Feature Set

Required

1. 802.1Q[1]:"Basic" VLAN/MAC Bridge operations [initial text in 5.4 and 5.12 of IEEE Std 802.1Q-2018]
2. Extensions of the relay model for CTF

Options/within spec[1]

1. 802.1Qci: Per-Stream Filtering and Policing (PSFP)
2. P802.1Qcz: Congestion Isolation (CI)
3. 802.1Qbv: Enhancements for Scheduled Traffic (EST)
4. 802.1Qaz: Enhanced Transmission Selection (ETS)
5. 802.1CB: Frame Replication and Elimination for Reliability (FRER)
6. 802.1Qbu: Preemption

Common Elements (Superset)
- Stream Filters
- Maximum SDU size filtering
- Stream Gates
- MEF 10.3 Flow Meters

Common Element
- Transmission Gates

1) With adjustments for CTF, as necessary.

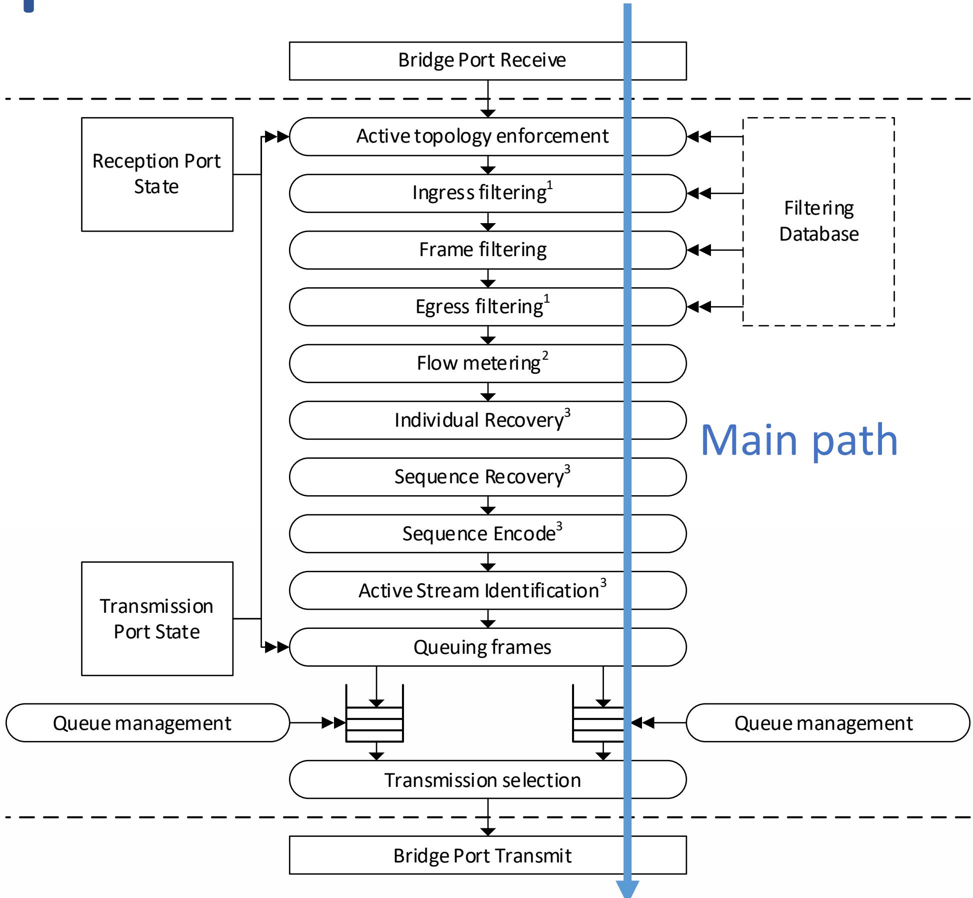
CTF in Bridges: Relay with CTF Support

Coexistence of CTF & S&F

- **Traffic separation**
  - Decoded priority (VLAN-Tags, IPV assignment)
  - Ports/traffic classes (FDB & decoded priority)
- **Enabling/disabling CTF**
  - Per reception port (the entire port)
  - Per transmission port per traffic class

The standardized model extended

- **Flow**
  (Incomplete) frames pass through processing stages, remain visible to earlier stages.
- **Stalls (incomplete frames)**
  Waiting for more data of an incomplete frame before passing it to the next stage.
- **Stall until completed (incomplete frames)**
  Stalling incomplete frames until completed before passing it to the next stage → Fallback to S&F
- **Late errors (incomplete frames)**
  - Causes (earlier stage)
  - Handling (same or later stage)



Cmp. 8.6 of IEEE Std 802.1Q-2018 and clause 8 of IEEE Std 802.1CB-2017.
1) Not present in MAC Bridges
2) Not present if PSFP and CI are unsupported
3) Not present if FRER is unsupported

CTF in Bridges: Fallbacks to S&F

1. On the main relay path

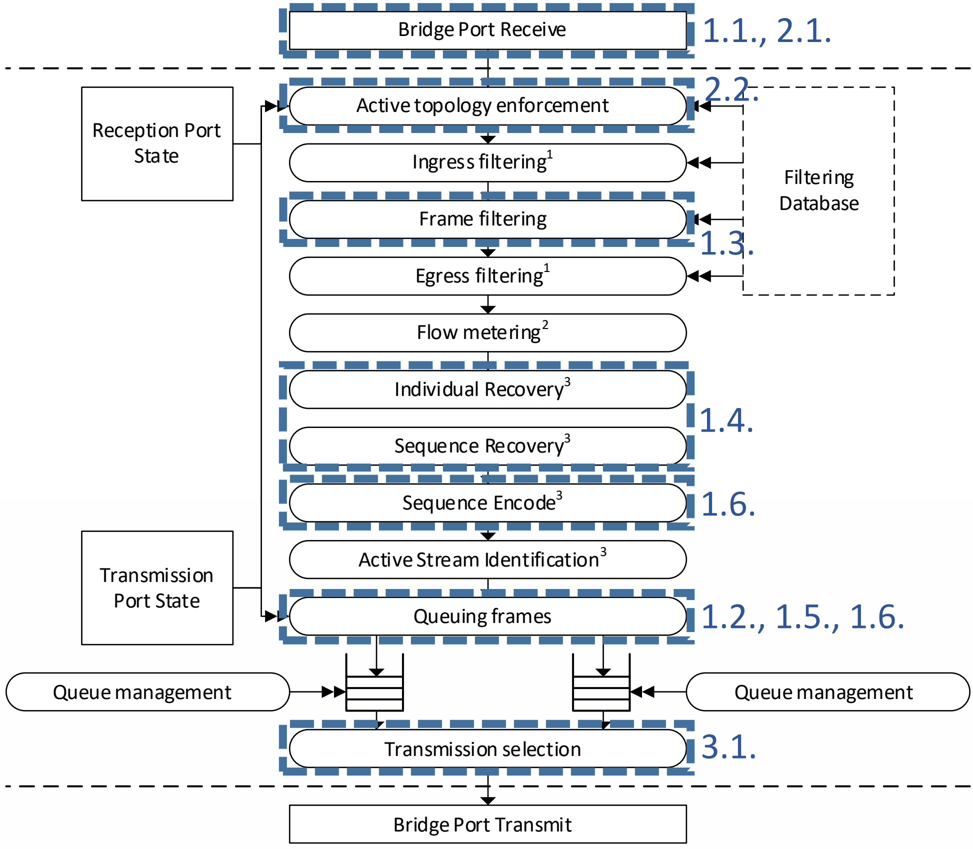
1. CTF reception is disabled on a reception port.
2. CTF is disabled/unsupported for/by a traffic class on a transmission port.
3. No matching filtering entry in the FDB (i.e., flooding).
4. Association of a frame under reception with a FRER recovery function.
5. Slow-to-fast link speed transitions.
6. Frame length changes (e.g., TAG removal).

2. Leaving the main relay path

1. To Higher Layer Entities
2. To FDB for learning

3. Implicit

1. Interfering frames



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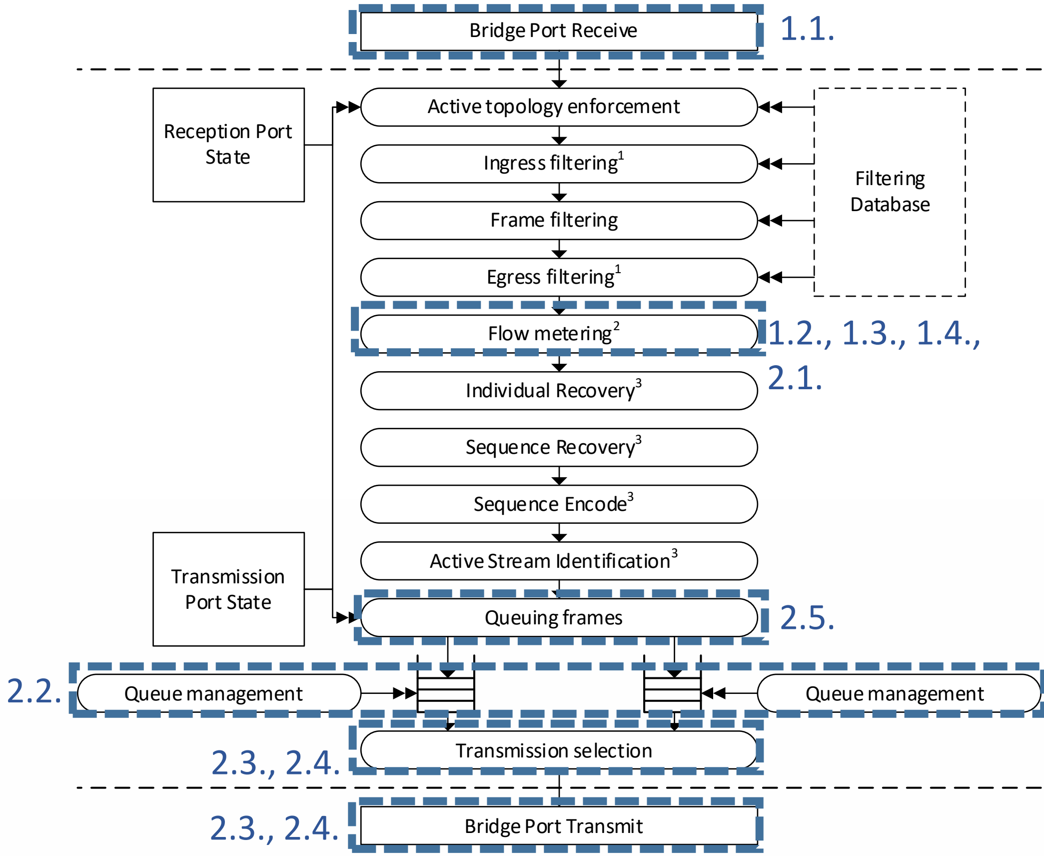
CTF in Bridges: Late Errors

1. Causes
   1. Errors discovered by FCS verification.
   2. Maximum SDU size filtering limit reached during reception.
   3. Stream gates transition to closed state[1].
   4. Flow meters run out of tokens.
   5. Frame exceeds the maximum SDU size of transmission gates.
2. Handling
   1. Treat late errors as end of the associated frame maximum SDU size filtering, stream gates and flow meters.
   2. Remove the frame from all queues, at least if not under transmission.
   3. Truncate the end of frame, if possible.
   4. Mark the end of erroneous frames (e.g., with a special FCS).



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1) Not present in MAC Bridges
2) Not present if PSFP and CI are unsupported
3) Not present if FRER is unsupported

1) In contrast to stream gates, it appears reasonable to not consider closing EST transmission gates during ongoing transmission as a late error (see 8.6.8.4 of IEEE Std 802.1Q-2018)

802.1 Considerations: Summary

Topics

- Proposed aspects for a potential future 802.1 standard for CTF
- Addressing issues introduced by CTF

General Proposal: stand alone IEEE 802.1 base standard for CTF

- Centralized
- Lightweight
- Compatibility (non-CTF/already standardized Bridges)

Issues introduced by CTF …

- Circulating erroneous frames in topological loops
- Additional congestion by erroneous frames
- Security/Privacy

… and Solutions

- Network level
- CTF-specific features

Extended Relay Model

- Coexistence of CTF and S&F traffic
- Additions for CTF, late error handling, fallbacks to S&F

IEEE 802.3 Considerations

Alon Regev, Johannes Specht

Problem Statements: Introduction

Background

- It is intended to move forward towards standardizing CTF in IEEE WG 802.1.
- We now dive into 802.3 and its interface with IEEE 802.1.

Potential Problem Summary

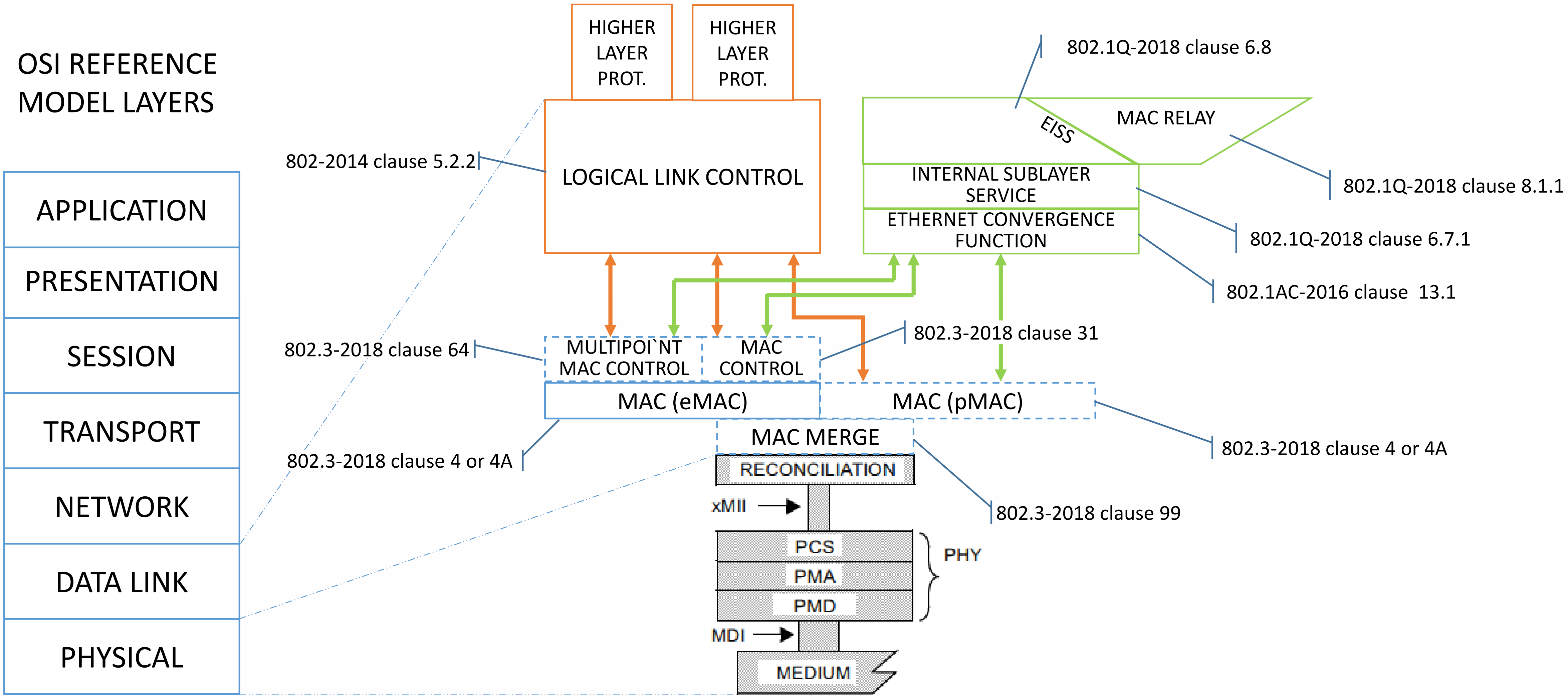
It is unclear whether particular elements of the MAC are in conflict with CTF at all. If yes, it is unclear how these conflicts can be resolved. Aspects identified so far:

1. Frame-level synchronous operations of the MAC service interface.
2. Invalid MAC frame handling, in particular in presence of the optional MAC Control sublayer.
3. The minimum frame size.
4. Normative statements are not always clear (where the style guidelines are not strictly followed).

Refinement

- The subsequent slides detail these aspects further.

Layering



OSI REFERENCE MODEL LAYERS
APPLICATION
PRESENTATION
SESSION
TRANSPORT
NETWORK
DATA LINK
PHYSICAL
HIGHER LAYER PROT.
HIGHER LAYER PROT.
LOGICAL LINK CONTROL
802-2014 clause 5.2.2
802.1Q-2018 clause 6.8
MAC RELAY
EISS
802.1Q-2018 clause 8.1.1
INTERNAL SUBLAYER SERVICE
802.1Q-2018 clause 6.7.1
ETHERNET CONVERGENCE FUNCTION
802.1AC-2016 clause 13.1
802.3-2018 clause 31
802.3-2018 clause 64
MULTIPOI`NT MAC CONTROL
MAC CONTROL
MAC (eMAC)
MAC (pMAC)
802.3-2018 clause 4 or 4A
MAC MERGE
802.3-2018 clause 4 or 4A
RECONCILIATION
802.3-2018 clause 99
xMII
PCS
PMA
PMD
PHY
MDI
MEDIUM

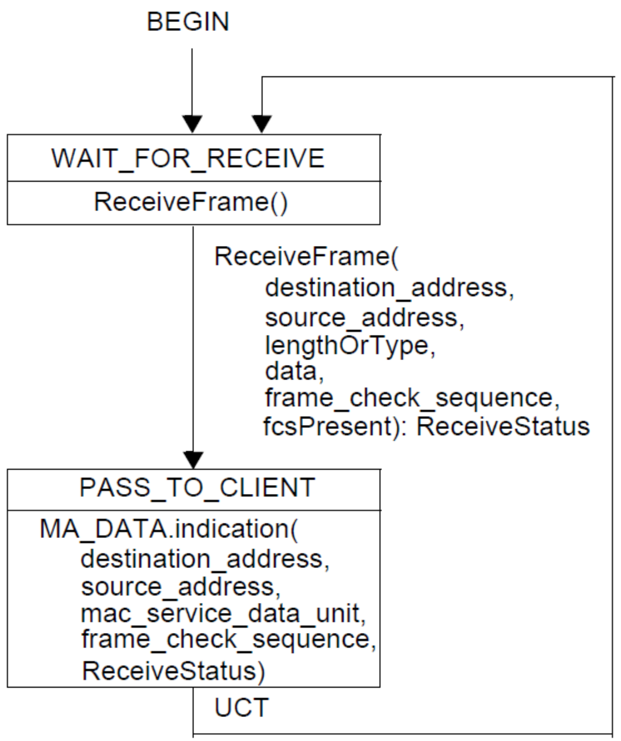
IEEE 802.3 Considerations: MAC Service Interface

Background

- The MAC service interface is specified in IEEE Std 802.1AC-2016 making use of ISO/IEC 10731 : 1994 [3.2 and 13.1 of IEEE Std 802.1AC-2016].
- A service primitive is to be regarded as taking place as an *instantaneous event* [6.2, 7.2, and Figure 5 of ISO/IEC 10731 : 1994], which appears to be the case at least in IEEE Std 802.3-2018 [Figure 1-3 of IEEE Std 802.3-2018].
- Moreover, it appears that the ordering relationship between service primitive invocation and the precise specification of CSMA/CD MAC method and precise specification of MAC method of the simplified full duplex MAC suggest a sequential ordering between service primitive invocation and associated Pascal procedure call of [Figure 4-6, Figure 4-7, Figure 4A-3, Figure 4A-4 of IEEE Std 802.3-2018] based on associated state diagram conventions:

  Labels on transitions are qualifiers that ***must*** *be fulfilled before the transition* ***will*** *be taken* [1.2.1 of IEEE Std 802.3-2018].

  Each primitive has a set of zero or more parameters, representing data elements that ***shall*** *be passed to qualify the functions invoked by the primitive* [1.2.1.1 of IEEE Std 802.3-2018].



Source: Figure 4A-4 of IEEE Std 802.3-2018.

Concern

- **It is not clear if the MAC service interface and the relationship to the precise MAC specifications allow Cut-Through Forwarding**
- **However, implementations are conformant so long as their externally visible behavior is identical to the model…**

IEEE 802.3 Considerations: Implementation vs. Model

Background

IEEE Std 802.3-2018 differentiates between an implementation and the model in state machines and the procedural models:

- *It is important to distinguish, however, between the model and a real implementation. The model is optimized for simplicity and clarity of presentation, while any realistic implementation* ***shall*** *place heavier emphasis on such constraints as efficiency and suitability to a particular implementation technology or computer architecture* [4A.2.2 of IEEE Std 802.3-2018].
- *It is the functional behavior of any unit that* ***must*** *match the standard, not its internal structure. The internal details of the model are useful only to the extent that they specify the external behavior clearly and precisely* [1.2.1 of IEEE Std 802.3-2018].
- *it is the behavior of any MAC sublayer implementations that* ***shall*** *match the standard, not their internal structure. The internal details of the procedural model are useful only to the extent that they help specify that behavior clearly and precisely* [item b) in 4.2.2.1 and 4A.2.2.1 of IEEE Std 802.3-2018].
- *The handling of incoming and outgoing frames is rather stylized in the procedural model, in the sense that frames are handled as single entities by most of the MAC sublayer and are only serialized for presentation to the Physical Layer. In reality, many implementations* ***will*** *instead handle frames serially on a bit, octet or word basis. This approach has not been reflected in the procedural model, since this only complicates the description of the functions without changing them in any way.* [item c) in 4.2.2.1 and 4A.2.2.1 of IEEE Std 802.3-2018].

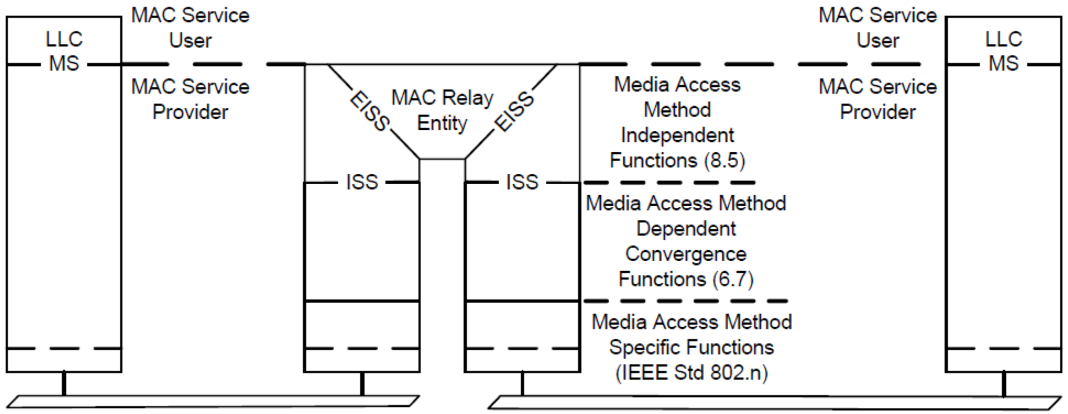
Observations

- The requirement for implementations is conformance to the externally visible behavior, not the specified structure, in certain areas of IEEE Std 802.3-2018 (but not all).
- It seems to be a statement of fact that many implementations would not be limited to the S&F operation implied by the MAC service interface.

IEEE 802.3 Considerations: Invalid MAC frames

Background

- *During reception, the contents of invalid MAC frames (e.g., frames that would fail FCS verification)* ***shall*** *not be passed to LLC and MAC control sublayers* [3.4 of IEEE Std 802.3-2018].
- There are other similar statements in IEEE Std 802.3-2018, although not using normative language (e.g., clause 2.3.2.3).
- The Pascal pseudocode and state machine DO pass invalid MAC frames to higher layers [4.2.9, 4A.2.9, 4.3.2.2 and 4A.3.2.2 of IEEE Std 802.3-2018]
- The MAC control sublayer is optional and located between MAC client (i.e., Bridge) and MAC transparently [4.1.1 and 4A.1.1 of IEEE Std 802.3-2018]. It is thus on the path from ingress to egress in a Bridge. In contrast, the LLC is not on this path [clause 6 in IEEE Std 802.1Q-2018] and excluded from further consideration.



Source: Figure 6-1 of IEEE Std 802.1Q-2018.

Concern

- The requirement stated in 3.4 of IEEE Std 802.3-2018 is normative, but it appears to be a requirement for the model specified in IEEE Std 802.3-2018 (not for implementations).
- Implementations of the associated state machines [clause 31 of IEEE Std 802.3-2018] only need to match the external visible behavior, not the internal structure (previous slide).
- **However, in the case this requirement does actually apply for implementations, it could imply a conflict if MAC control sublayer(s) are present.**

IEEE 802.3 Considerations: Minimum Frame Size

Background

The minimum frame size of 64 octets is required for CSMA/CD operation of a CSMA/CD MAC [clause 4 IEEE Std 802.3-2018] and by the simplified full duplex MAC [clause A4 IEEE Std 802.3-2018].

Observations

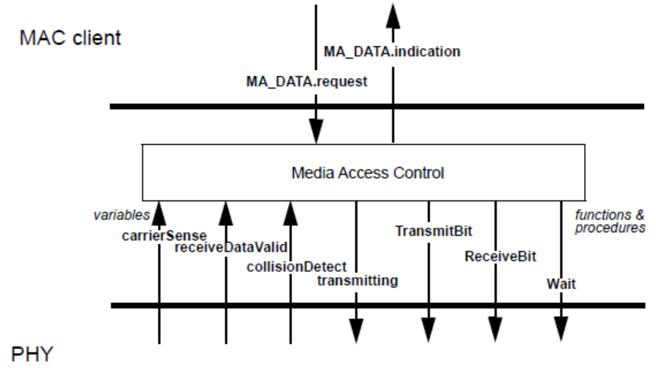
- Both clause 4 and 4A MACs enforce a 64 octet minimum frame size on both Rx (smaller frames discarded) and Tx (smaller frames padded) [ReceiveLinkMgmt in 4.2.9 and 4A.2.9 of IEEE Std 802.3-2018] [dataSize definition in 4.2.7.1 and 4A.2.7.1 of IEEE Std 802.3-2018].
- The MAC merge sublayer is likewise ensuring that the minimum frame size constraint requirement is satisfied [Figure 99-4, 99.3.5 and 99.4.4 of 802.3-2018].

Concern

- If a frame is forwarded before 64 octets are received…
  - On the Rx side, **forwarding a frame before 64 octets are received may violate the 802.3 MAC RecieveLinkMgmt procedure** in clause 4.2.9 if the received frame is an undersized fragment (in which case the frame should have been dropped)
  - On the Tx side, padding a forwarded frame to 64 octets may delay further frames. This could be additive if multiple such fragments are encountered.
  - Conversely, if forwarded frames are not padded to 64 octets, **this may be a violation of the 802.3 MAC clauses 4.2.3.3 and 4A.2.3.2.4**.
- **Forwarding frames only when at least 64 octets are received may not meet latency requirements**

IEEE 802.3 Considerations: Summary

- Cut-Through Forwarding involves layers spanning both IEEE 802.3 and IEEE 802.1
- There are open questions regarding on items in IEEE 802.3 that apply to Cut-Through Forwarding including
  - The MAC service interface
  - Invalid MAC frame handling
  - MAC control frame interactions
  - Minimum frame size
- IEEE 802.3 and IEEE 802.1 working together will yield the best results as the requirements and interfaces will be understood by both sides



MA_DATA.request (
destination_address,
source_address,
mac_service_data_unit,
frame_check_sequence
)

MA_DATA.indication (
destination_address,
source_address,
mac_service_data_unit,
frame_check_sequence,
reception_status
)

Source: Clause 2 of IEEE Std 802.3-2018

Call for Actions

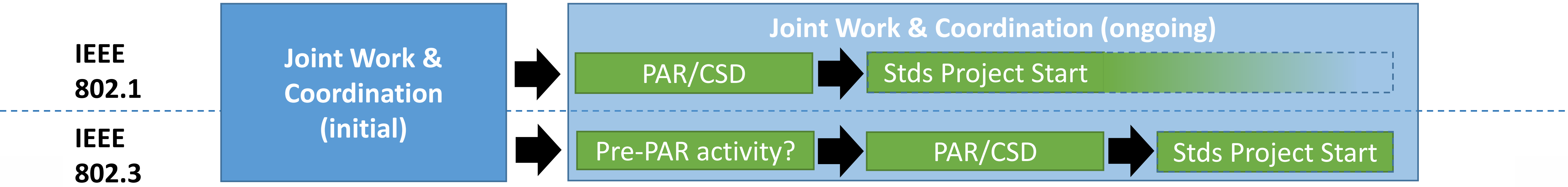
Johannes Specht

Summary of this Tutorial

- **Goal of this tutorial**
  Motivate standardizing CTF in IEEE 802.1 and IEEE 802.3.
- **Feasibility of CTF**
  CTF is already implemented in many commercial products.
- **Standardizing CTF**
  Interoperability/flavors of CTF, unified management, Network aspects.
- **Use-cases and markets**
  - Industrial Automation
  - Professional Audio/Video
  - Data Center Networks
- **IEEE WG 802.1 and IEEE WG 802.3**
  Proposals and aspects for consideration by both WGs.

Call for Actions

Moving Forward Proposal



Joint work & coordination

- CTF needs the expertise of two IEEE 802 WGs.
- It appears vital to have some level of joint work & coordination on technical aspects and logistics (interfaces, meetings, etc.).
- A possible forum for initial joint work & coordination: IEEE 802 Nendica.

Administrative discussion (separate meeting)

- Topics
  - Which pre-standards activities can and should be done in a (significant) initial joint work & coordination phase?
  - What are the logistics?
  - …
- Meeting identified to plan followup: IEEE 802 Nendica weekly call schedule for **August 5, 2021 09:00-11:00 ET (tentatively)**, pending **finalization on July 20, 2021**.

→ ***If you are interested in this discussion you are very welcome!***

Questions & Answers

Section	Speaker
1. Introduction	Johannes Specht
2. Use-Cases	
Industrial Automation	Jordon Woods
Professional Audio/Video	Henning Kaltheuner
Data Center Networks	Paul Congdon
3. Summary: Goals and Objectives	Johannes Specht
4. IEEE 802.1 Considerations	Johannes Specht
5. IEEE 802.3 Considerations	Alon Regev
6. Call for Actions	Johannes Specht
7. Q & A	All

Thank you for your Attention!

From all of us!

Annex (for offline reading): Material related to the CTF Speed-up Comparison

Johannes Specht

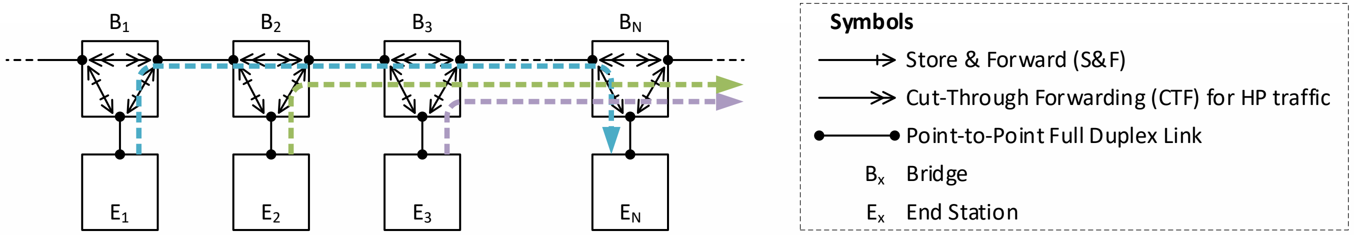
CTF Speed-up Analysis: Assumptions (1)

Purpose

- The following assumptions assemble a simplified model to focus on a simple speed-up analysis:
  - Some 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 link propagation delays
- CTF possible 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



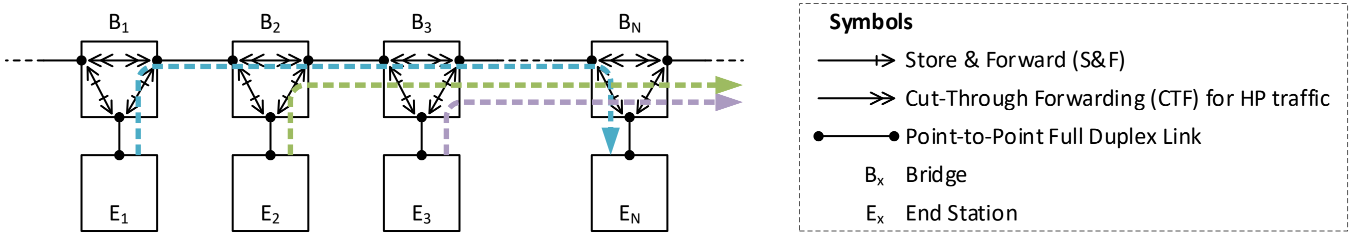
Errors

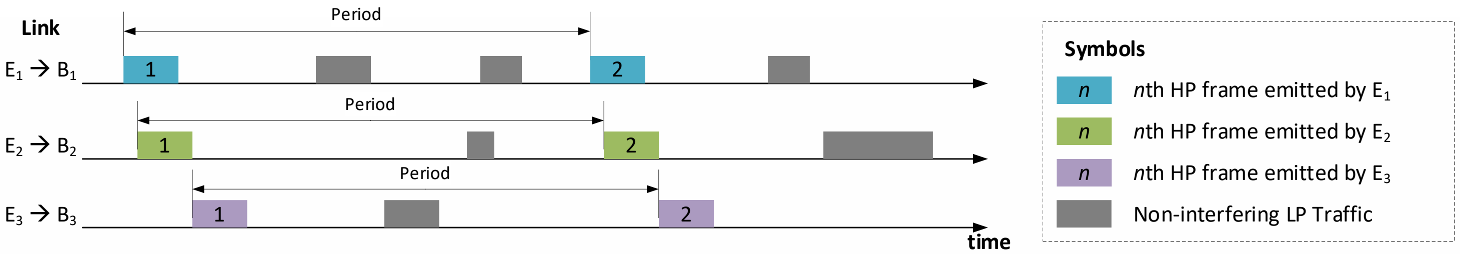
- Error free environment → no data corruption in frames
- However, errors, including late error handling, is addressed later in this tutorial

CTF Speed-up Analysis: Assumptions (2)

Traffic – Focus on Bounded Latency

- High Priority (HP): Focus of the Analysis
  - At most one stream sent by each end station, and each end station receives HP streams from at most one direction of the chain
  - Constant frame length[1]
  - Periodic (same period for all streams)
  - Period < maximum end-to-end latency
  - Nominal transmission times at sending end stations

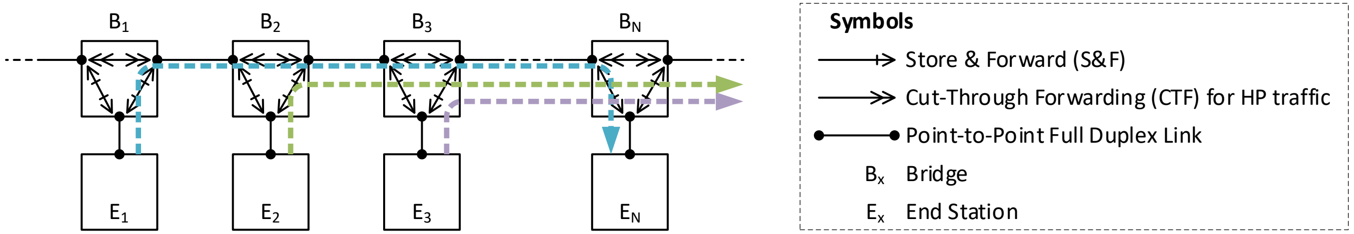




- Low Priority (LP): Background
  - Always Store & Forward
  - Interferes with HP traffic
    - Without preemption: 1542 octets (max. LP frame[1,2])
    - With preemption: 155 octets (max. non-preemptible LP frame[1,3])

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 Analysis: Math



Delay until forwarding to destination port(s). 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.

$$d_{S\&F}^{max} = (H+2)\left(\max\{l_{HP}d_{Oct}, l_{LU}d_{Oct} + d_{LU}\} + d_Q\right) + \left((H+1)l_{LP} + Hl_{HP}\right)d_{Oct}$$

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).

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

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
$d_{S\&F}^{max}$	Maximum end-to-end delay without CTF of HP frames, in μs.
d_{CTF}^{max}	Maximum end-to-end delay with CTF of HP frames, in μs.
H	Number of possible CTF interconnections along the path (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. Assumption: • 1542 octets without preemption • 155 octets with preemption
l_{LU}	Initially received frame fraction prior to destination port lookup, in octets. Assumption: 24 octets (preamble, …, VLAN-Tag).
l_{FWD}	Initially received frame fraction prior to forwarding to the transmission port(s), in octets. Two flavors considered in the following[1,2]: 1. 0 octets (immediately after destination port lookup). 2. 72 octets (preamble, SFD, 64 octets).
d_{Oct}	Nominal duration of an octet reflecting the link speed, in μs.
d_{LU}	Destination port lookup duration (after l_{LU} octets were received), in μs. Assumption[1]: 0.16 μs (e.g., 20 clock cycles @ 125 MHz).
d_Q	Interference-independent queuing delay (MAC delay, PHY delay, etc.), in μs. Assumption[1]: 0.32 μs (e.g., 40 clock cycles @ 125 MHz).

1) Cmp. https://www.ieee802.org/1/files/public/docs2017/new-woods-cutthroughconsiderations-0518-v01.pdf
2) Cmp. https://www.ieee802.org/1/files/public/docs2019/60802-Ademaj-et-al-CutThrough-0919-v11.pdf

Max. End-to-End Delays with Interference

Forwarding after VLAN-Tag

		S&F max. delay (end-to-end)										CTF max. delay (end-to-end)									
		Preemption unsupported					Preemption supported					Preemption unsupported					Preemption supported				
H	l_{HP} / Link	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	432,80 us	494,24 us	617,12 us	862,88 us	1111,52 us	99,92 us	161,36 us	284,24 us	530,00 us	778,64 us	416,48 us	457,44 us	539,36 us	703,20 us	868,96 us	83,60 us	124,56 us	206,48 us	370,32 us	536,08 us
4	100 Mbit/s	721,12 us	823,52 us	1028,32 us	1437,92 us	1852,32 us	166,32 us	268,72 us	473,52 us	883,12 us	1297,52 us	688,48 us	749,92 us	872,80 us	1118,56 us	1367,20 us	133,68 us	195,12 us	318,00 us	563,76 us	812,40 us
16	100 Mbit/s	2451,04 us	2799,20 us	3495,52 us	4888,16 us	6297,12 us	564,72 us	912,88 us	1609,20 us	3001,84 us	4410,80 us	2320,48 us	2504,80 us	2873,44 us	3610,72 us	4356,64 us	434,16 us	618,48 us	987,12 us	1724,40 us	2470,32 us
64	100 Mbit/s	9370,72 us	10701,92 us	13364,32 us	18689,12 us	24076,32 us	2158,32 us	3489,52 us	6151,92 us	11476,72 us	16863,92 us	8848,48 us	9524,32 us	10876,00 us	13579,36 us	16314,40 us	1636,08 us	2311,92 us	3663,60 us	6366,96 us	9102,00 us
2	1 Gbit/s	44,43 us	50,58 us	62,86 us	87,44 us	112,30 us	11,14 us	17,29 us	29,58 us	54,15 us	79,02 us	43,09 us	47,18 us	55,38 us	71,76 us	88,34 us	9,80 us	13,90 us	22,09 us	38,47 us	55,05 us
4	1 Gbit/s	73,84 us	84,08 us	104,56 us	145,52 us	186,96 us	18,36 us	28,60 us	49,08 us	90,04 us	131,48 us	71,15 us	77,30 us	89,58 us	114,16 us	139,02 us	15,67 us	21,82 us	34,10 us	58,68 us	83,54 us
16	1 Gbit/s	250,29 us	285,10 us	354,74 us	494,00 us	634,90 us	61,66 us	96,47 us	166,10 us	305,37 us	446,26 us	239,54 us	257,97 us	294,83 us	368,56 us	443,15 us	50,90 us	69,34 us	106,20 us	179,93 us	254,52 us
64	1 Gbit/s	956,08 us	1089,20 us	1355,44 us	1887,92 us	2426,64 us	234,84 us	367,96 us	634,20 us	1166,68 us	1705,40 us	913,07 us	980,66 us	1115,82 us	1386,16 us	1659,66 us	191,83 us	259,42 us	394,58 us	664,92 us	938,42 us
2	2,5 Gbit/s	18,54 us	21,00 us	25,91 us	35,74 us	45,69 us	5,23 us	7,68 us	12,60 us	22,43 us	32,37 us	18,20 us	19,83 us	23,11 us	29,66 us	36,29 us	4,88 us	6,52 us	9,80 us	16,35 us	22,98 us
4	2,5 Gbit/s	30,69 us	34,78 us	42,98 us	59,36 us	75,94 us	8,50 us	12,59 us	20,78 us	37,17 us	53,74 us	30,00 us	32,45 us	37,37 us	47,20 us	57,15 us	7,80 us	10,26 us	15,18 us	25,01 us	34,95 us
16	2,5 Gbit/s	103,57 us	117,50 us	145,35 us	201,06 us	257,41 us	28,12 us	42,04 us	69,90 us	125,60 us	181,96 us	100,81 us	108,18 us	122,92 us	152,42 us	182,25 us	25,35 us	32,73 us	47,47 us	76,96 us	106,80 us
64	2,5 Gbit/s	395,10 us	448,35 us	554,85 us	767,84 us	983,33 us	106,61 us	159,86 us	266,35 us	479,34 us	694,83 us	384,04 us	411,08 us	465,15 us	573,28 us	682,68 us	95,55 us	122,58 us	176,65 us	284,78 us	394,19 us

Forwarding after 64 octets

		S&F max. delay (end-to-end)										CTF max. delay (end-to-end)									
		Preemption unsupported					Preemption supported					Preemption unsupported					Preemption supported				
H	l_{HP} / Link	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	432,80 us	494,24 us	617,12 us	862,88 us	1111,52 us	99,92 us	161,36 us	284,24 us	530,00 us	778,64 us	423,84 us	464,80 us	546,72 us	710,56 us	876,32 us	90,96 us	131,92 us	213,84 us	377,68 us	543,44 us
4	100 Mbit/s	721,12 us	823,52 us	1028,32 us	1437,92 us	1852,32 us	166,32 us	268,72 us	473,52 us	883,12 us	1297,52 us	703,20 us	764,64 us	887,52 us	1133,28 us	1381,92 us	148,40 us	209,84 us	332,72 us	578,48 us	827,12 us
16	100 Mbit/s	2451,04 us	2799,20 us	3495,52 us	4888,16 us	6297,12 us	564,72 us	912,88 us	1609,20 us	3001,84 us	4410,80 us	2379,36 us	2563,68 us	2932,32 us	3669,60 us	4415,52 us	493,04 us	677,36 us	1046,00 us	1783,28 us	2529,20 us
64	100 Mbit/s	9370,72 us	10701,92 us	13364,32 us	18689,12 us	24076,32 us	2158,32 us	3489,52 us	6151,92 us	11476,72 us	16863,92 us	9084,00 us	9759,84 us	11111,52 us	13814,88 us	16549,92 us	1871,60 us	2547,44 us	3899,12 us	6602,48 us	9337,52 us
2	1 Gbit/s	44,43 us	50,58 us	62,86 us	87,44 us	112,30 us	11,14 us	17,29 us	29,58 us	54,15 us	79,02 us	43,54 us	47,63 us	55,82 us	72,21 us	88,78 us	10,25 us	14,34 us	22,54 us	38,92 us	55,50 us
4	1 Gbit/s	73,84 us	84,08 us	104,56 us	145,52 us	186,96 us	18,36 us	28,60 us	49,08 us	90,04 us	131,48 us	72,05 us	78,19 us	90,48 us	115,06 us	139,92 us	16,57 us	22,71 us	35,00 us	59,58 us	84,44 us
16	1 Gbit/s	250,29 us	285,10 us	354,74 us	494,00 us	634,90 us	61,66 us	96,47 us	166,10 us	305,37 us	446,26 us	243,12 us	261,55 us	298,42 us	372,14 us	446,74 us	54,49 us	72,92 us	109,78 us	183,51 us	258,10 us
64	1 Gbit/s	956,08 us	1089,20 us	1355,44 us	1887,92 us	2426,64 us	234,84 us	367,96 us	634,20 us	1166,68 us	1705,40 us	927,41 us	994,99 us	1130,16 us	1400,50 us	1674,00 us	206,17 us	273,75 us	408,92 us	679,26 us	952,76 us
2	2,5 Gbit/s	18,54 us	21,00 us	25,91 us	35,74 us	45,69 us	5,23 us	7,68 us	12,60 us	22,43 us	32,37 us	18,20 us	19,83 us	23,11 us	29,66 us	36,29 us	4,88 us	6,52 us	9,80 us	16,35 us	22,98 us
4	2,5 Gbit/s	30,69 us	34,78 us	42,98 us	59,36 us	75,94 us	8,50 us	12,59 us	20,78 us	37,17 us	53,74 us	30,00 us	32,45 us	37,37 us	47,20 us	57,15 us	7,80 us	10,26 us	15,18 us	25,01 us	34,95 us
16	2,5 Gbit/s	103,57 us	117,50 us	145,35 us	201,06 us	257,41 us	28,12 us	42,04 us	69,90 us	125,60 us	181,96 us	100,81 us	108,18 us	122,92 us	152,42 us	182,25 us	25,35 us	32,73 us	47,47 us	76,96 us	106,80 us
64	2,5 Gbit/s	395,10 us	448,35 us	554,85 us	767,84 us	983,33 us	106,61 us	159,86 us	266,35 us	479,34 us	694,83 us	384,04 us	411,08 us	465,15 us	573,28 us	682,68 us	95,55 us	122,58 us	176,65 us	284,78 us	394,19 us

Max. End-to-End Delays with LP Interference only

Forwarding after VLAN-Tag

		S&F max. delay (end-to-end)										CTF max. delay (end-to-end)									
		Preemption unsupported					Preemption supported					Preemption unsupported					Preemption supported				
H	Link \ l_{HP}	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	412,32 us	453,28 us	535,20 us	699,04 us	864,80 us	79,44 us	120,40 us	202,32 us	366,16 us	531,92 us	396,00 us	416,48 us	457,44 us	539,36 us	622,24 us	63,12 us	83,60 us	124,56 us	206,48 us	289,36 us
4	100 Mbit/s	680,16 us	741,60 us	864,48 us	1110,24 us	1358,88 us	125,36 us	186,80 us	309,68 us	555,44 us	804,08 us	647,52 us	668,00 us	708,96 us	790,88 us	873,76 us	92,72 us	113,20 us	154,16 us	236,08 us	318,96 us
16	100 Mbit/s	2287,20 us	2471,52 us	2840,16 us	3577,44 us	4323,36 us	400,88 us	585,20 us	953,84 us	1691,12 us	2437,04 us	2156,64 us	2177,12 us	2218,08 us	2300,00 us	2382,88 us	270,32 us	290,80 us	331,76 us	413,68 us	496,56 us
64	100 Mbit/s	8715,36 us	9391,20 us	10742,88 us	13446,24 us	16181,28 us	1502,96 us	2178,80 us	3530,48 us	6233,84 us	8968,88 us	8193,12 us	8213,60 us	8254,56 us	8336,48 us	8419,36 us	980,72 us	1001,20 us	1042,16 us	1124,08 us	1206,96 us
2	1 Gbit/s	42,38 us	46,48 us	54,67 us	71,06 us	87,63 us	9,10 us	13,19 us	21,38 us	37,77 us	54,34 us	41,04 us	43,09 us	47,18 us	55,38 us	63,66 us	7,75 us	9,80 us	13,90 us	22,09 us	30,38 us
4	1 Gbit/s	69,74 us	75,89 us	88,18 us	112,75 us	137,62 us	14,26 us	20,41 us	32,70 us	57,27 us	82,14 us	67,06 us	69,10 us	73,20 us	81,39 us	89,68 us	11,58 us	13,62 us	17,72 us	25,91 us	34,20 us
16	1 Gbit/s	233,90 us	252,34 us	289,20 us	362,93 us	437,52 us	45,27 us	63,70 us	100,57 us	174,30 us	248,89 us	223,15 us	225,20 us	229,30 us	237,49 us	245,78 us	34,52 us	36,57 us	40,66 us	48,86 us	57,14 us
64	1 Gbit/s	890,54 us	958,13 us	1093,30 us	1363,63 us	1637,14 us	169,30 us	236,89 us	372,06 us	642,39 us	915,90 us	847,54 us	849,58 us	853,68 us	861,87 us	870,16 us	126,30 us	128,34 us	132,44 us	140,63 us	148,92 us
2	2,5 Gbit/s	17,72 us	19,36 us	22,64 us	29,19 us	35,82 us	4,41 us	6,04 us	9,32 us	15,88 us	22,51 us	17,38 us	18,20 us	19,83 us	23,11 us	26,43 us	4,06 us	4,88 us	6,52 us	9,80 us	13,11 us
4	2,5 Gbit/s	29,05 us	31,51 us	36,42 us	46,25 us	56,20 us	6,86 us	9,32 us	14,23 us	24,06 us	34,01 us	28,36 us	29,18 us	30,82 us	34,09 us	37,41 us	6,17 us	6,99 us	8,62 us	11,90 us	15,22 us
16	2,5 Gbit/s	97,02 us	104,39 us	119,14 us	148,63 us	178,46 us	21,56 us	28,94 us	43,68 us	73,17 us	103,01 us	94,25 us	95,07 us	96,71 us	99,99 us	103,30 us	18,80 us	19,62 us	21,26 us	24,53 us	27,85 us
64	2,5 Gbit/s	368,89 us	395,92 us	449,99 us	558,12 us	667,53 us	80,39 us	107,43 us	161,49 us	269,63 us	379,03 us	357,83 us	358,65 us	360,29 us	363,56 us	366,88 us	69,33 us	70,15 us	71,79 us	75,07 us	78,38 us

Forwarding after 64 octets

		S&F max. delay (end-to-end)										CTF max. delay (end-to-end)									
		Preemption unsupported					Preemption supported					Preemption unsupported					Preemption supported				
H	Link \ l_{HP}	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	412,32 us	453,28 us	535,20 us	699,04 us	864,80 us	79,44 us	120,40 us	202,32 us	366,16 us	531,92 us	403,36 us	423,84 us	464,80 us	546,72 us	629,60 us	70,48 us	90,96 us	131,92 us	213,84 us	296,72 us
4	100 Mbit/s	680,16 us	741,60 us	864,48 us	1110,24 us	1358,88 us	125,36 us	186,80 us	309,68 us	555,44 us	804,08 us	662,24 us	682,72 us	723,68 us	805,60 us	888,48 us	107,44 us	127,92 us	168,88 us	250,80 us	333,68 us
16	100 Mbit/s	2287,20 us	2471,52 us	2840,16 us	3577,44 us	4323,36 us	400,88 us	585,20 us	953,84 us	1691,12 us	2437,04 us	2215,52 us	2236,00 us	2276,96 us	2358,88 us	2441,76 us	329,20 us	349,68 us	390,64 us	472,56 us	555,44 us
64	100 Mbit/s	8715,36 us	9391,20 us	10742,88 us	13446,24 us	16181,28 us	1502,96 us	2178,80 us	3530,48 us	6233,84 us	8968,88 us	8428,64 us	8449,12 us	8490,08 us	8572,00 us	8654,88 us	1216,24 us	1236,72 us	1277,68 us	1359,60 us	1442,48 us
2	1 Gbit/s	42,38 us	46,48 us	54,67 us	71,06 us	87,63 us	9,10 us	13,19 us	21,38 us	37,77 us	54,34 us	41,49 us	43,54 us	47,63 us	55,82 us	64,11 us	8,20 us	10,25 us	14,34 us	22,54 us	30,82 us
4	1 Gbit/s	69,74 us	75,89 us	88,18 us	112,75 us	137,62 us	14,26 us	20,41 us	32,70 us	57,27 us	82,14 us	67,95 us	70,00 us	74,10 us	82,29 us	90,58 us	12,47 us	14,52 us	18,62 us	26,81 us	35,10 us
16	1 Gbit/s	233,90 us	252,34 us	289,20 us	362,93 us	437,52 us	45,27 us	63,70 us	100,57 us	174,30 us	248,89 us	226,74 us	228,78 us	232,88 us	241,07 us	249,36 us	38,10 us	40,15 us	44,25 us	52,44 us	60,73 us
64	1 Gbit/s	890,54 us	958,13 us	1093,30 us	1363,63 us	1637,14 us	169,30 us	236,89 us	372,06 us	642,39 us	915,90 us	861,87 us	863,92 us	868,02 us	876,21 us	884,50 us	140,63 us	142,68 us	146,78 us	154,97 us	163,26 us
2	2,5 Gbit/s	17,72 us	19,36 us	22,64 us	29,19 us	35,82 us	4,41 us	6,04 us	9,32 us	15,88 us	22,51 us	17,38 us	18,20 us	19,83 us	23,11 us	26,43 us	4,06 us	4,88 us	6,52 us	9,80 us	13,11 us
4	2,5 Gbit/s	29,05 us	31,51 us	36,42 us	46,25 us	56,20 us	6,86 us	9,32 us	14,23 us	24,06 us	34,01 us	28,36 us	29,18 us	30,82 us	34,09 us	37,41 us	6,17 us	6,99 us	8,62 us	11,90 us	15,22 us
16	2,5 Gbit/s	97,02 us	104,39 us	119,14 us	148,63 us	178,46 us	21,56 us	28,94 us	43,68 us	73,17 us	103,01 us	94,25 us	95,07 us	96,71 us	99,99 us	103,30 us	18,80 us	19,62 us	21,26 us	24,53 us	27,85 us
64	2,5 Gbit/s	368,89 us	395,92 us	449,99 us	558,12 us	667,53 us	80,39 us	107,43 us	161,49 us	269,63 us	379,03 us	357,83 us	358,65 us	360,29 us	363,56 us	366,88 us	69,33 us	70,15 us	71,79 us	75,07 us	78,38 us

Max. End-to-End Delays with HP Interference only

Forwarding after VLAN-Tag

		S&F max. delay (end-to-end)										CTF max. delay (end-to-end)									
		Preemption unsupported					Preemption supported					Preemption unsupported					Preemption supported				
H	Link \ l_{HP}	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	62,72 us	124,16 us	247,04 us	492,80 us	741,44 us	62,72 us	124,16 us	247,04 us	492,80 us	741,44 us	46,40 us	87,36 us	169,28 us	333,12 us	498,88 us	46,40 us	87,36 us	169,28 us	333,12 us	498,88 us
4	100 Mbit/s	104,32 us	206,72 us	411,52 us	821,12 us	1235,52 us	104,32 us	206,72 us	411,52 us	821,12 us	1235,52 us	71,68 us	133,12 us	256,00 us	501,76 us	750,40 us	71,68 us	133,12 us	256,00 us	501,76 us	750,40 us
16	100 Mbit/s	353,92 us	702,08 us	1398,40 us	2791,04 us	4200,00 us	353,92 us	702,08 us	1398,40 us	2791,04 us	4200,00 us	223,36 us	407,68 us	776,32 us	1513,60 us	2259,52 us	223,36 us	407,68 us	776,32 us	1513,60 us	2259,52 us
64	100 Mbit/s	1352,32 us	2683,52 us	5345,92 us	10670,72 us	16057,92 us	1352,32 us	2683,52 us	5345,92 us	10670,72 us	16057,92 us	830,08 us	1505,92 us	2857,60 us	5560,96 us	8296,00 us	830,08 us	1505,92 us	2857,60 us	5560,96 us	8296,00 us
2	1 Gbit/s	7,42 us	13,57 us	25,86 us	50,43 us	75,30 us	7,42 us	13,57 us	25,86 us	50,43 us	75,30 us	6,08 us	10,18 us	18,37 us	34,75 us	51,33 us	6,08 us	10,18 us	18,37 us	34,75 us	51,33 us
4	1 Gbit/s	12,16 us	22,40 us	42,88 us	83,84 us	125,28 us	12,16 us	22,40 us	42,88 us	83,84 us	125,28 us	9,47 us	15,62 us	27,90 us	52,48 us	77,34 us	9,47 us	15,62 us	27,90 us	52,48 us	77,34 us
16	1 Gbit/s	40,58 us	75,39 us	145,02 us	284,29 us	425,18 us	40,58 us	75,39 us	145,02 us	284,29 us	425,18 us	29,82 us	48,26 us	85,12 us	158,85 us	233,44 us	29,82 us	48,26 us	85,12 us	158,85 us	233,44 us
64	1 Gbit/s	154,24 us	287,36 us	553,60 us	1086,08 us	1624,80 us	154,24 us	287,36 us	553,60 us	1086,08 us	1624,80 us	111,23 us	178,82 us	313,98 us	584,32 us	857,82 us	111,23 us	178,82 us	313,98 us	584,32 us	857,82 us
2	2,5 Gbit/s	3,74 us	6,20 us	11,11 us	20,94 us	30,89 us	3,74 us	6,20 us	11,11 us	20,94 us	30,89 us	3,39 us	5,03 us	8,31 us	14,86 us	21,49 us	3,39 us	5,03 us	8,31 us	14,86 us	21,49 us
4	2,5 Gbit/s	6,02 us	10,11 us	18,30 us	34,69 us	51,26 us	6,02 us	10,11 us	18,30 us	34,69 us	51,26 us	5,32 us	7,78 us	12,70 us	22,53 us	32,47 us	5,32 us	7,78 us	12,70 us	22,53 us	32,47 us
16	2,5 Gbit/s	19,69 us	33,61 us	61,47 us	117,17 us	173,53 us	19,69 us	33,61 us	61,47 us	117,17 us	173,53 us	16,92 us	24,29 us	39,04 us	68,53 us	98,37 us	16,92 us	24,29 us	39,04 us	68,53 us	98,37 us
64	2,5 Gbit/s	74,37 us	127,62 us	234,11 us	447,10 us	662,59 us	74,37 us	127,62 us	234,11 us	447,10 us	662,59 us	63,31 us	90,34 us	144,41 us	252,54 us	361,95 us	63,31 us	90,34 us	144,41 us	252,54 us	361,95 us

Forwarding after 64 octets

		S&F max. delay (end-to-end)										CTF max. delay (end-to-end)									
		Preemption unsupported					Preemption supported					Preemption unsupported					Preemption supported				
H	Link \ l_{HP}	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	62,72 us	124,16 us	247,04 us	492,80 us	741,44 us	62,72 us	124,16 us	247,04 us	492,80 us	741,44 us	53,76 us	94,72 us	176,64 us	340,48 us	506,24 us	53,76 us	94,72 us	176,64 us	340,48 us	506,24 us
4	100 Mbit/s	104,32 us	206,72 us	411,52 us	821,12 us	1235,52 us	104,32 us	206,72 us	411,52 us	821,12 us	1235,52 us	86,40 us	147,84 us	270,72 us	516,48 us	765,12 us	86,40 us	147,84 us	270,72 us	516,48 us	765,12 us
16	100 Mbit/s	353,92 us	702,08 us	1398,40 us	2791,04 us	4200,00 us	353,92 us	702,08 us	1398,40 us	2791,04 us	4200,00 us	282,24 us	466,56 us	835,20 us	1572,48 us	2318,40 us	282,24 us	466,56 us	835,20 us	1572,48 us	2318,40 us
64	100 Mbit/s	1352,32 us	2683,52 us	5345,92 us	10670,72 us	16057,92 us	1352,32 us	2683,52 us	5345,92 us	10670,72 us	16057,92 us	1065,60 us	1741,44 us	3093,12 us	5796,48 us	8531,52 us	1065,60 us	1741,44 us	3093,12 us	5796,48 us	8531,52 us
2	1 Gbit/s	7,42 us	13,57 us	25,86 us	50,43 us	75,30 us	7,42 us	13,57 us	25,86 us	50,43 us	75,30 us	6,53 us	10,62 us	18,82 us	35,20 us	51,78 us	6,53 us	10,62 us	18,82 us	35,20 us	51,78 us
4	1 Gbit/s	12,16 us	22,40 us	42,88 us	83,84 us	125,28 us	12,16 us	22,40 us	42,88 us	83,84 us	125,28 us	10,37 us	16,51 us	28,80 us	53,38 us	78,24 us	10,37 us	16,51 us	28,80 us	53,38 us	78,24 us
16	1 Gbit/s	40,58 us	75,39 us	145,02 us	284,29 us	425,18 us	40,58 us	75,39 us	145,02 us	284,29 us	425,18 us	33,41 us	51,84 us	88,70 us	162,43 us	237,02 us	33,41 us	51,84 us	88,70 us	162,43 us	237,02 us
64	1 Gbit/s	154,24 us	287,36 us	553,60 us	1086,08 us	1624,80 us	154,24 us	287,36 us	553,60 us	1086,08 us	1624,80 us	125,57 us	193,15 us	328,32 us	598,66 us	872,16 us	125,57 us	193,15 us	328,32 us	598,66 us	872,16 us
2	2,5 Gbit/s	3,74 us	6,20 us	11,11 us	20,94 us	30,89 us	3,74 us	6,20 us	11,11 us	20,94 us	30,89 us	3,39 us	5,03 us	8,31 us	14,86 us	21,49 us	3,39 us	5,03 us	8,31 us	14,86 us	21,49 us
4	2,5 Gbit/s	6,02 us	10,11 us	18,30 us	34,69 us	51,26 us	6,02 us	10,11 us	18,30 us	34,69 us	51,26 us	5,32 us	7,78 us	12,70 us	22,53 us	32,47 us	5,32 us	7,78 us	12,70 us	22,53 us	32,47 us
16	2,5 Gbit/s	19,69 us	33,61 us	61,47 us	117,17 us	173,53 us	19,69 us	33,61 us	61,47 us	117,17 us	173,53 us	16,92 us	24,29 us	39,04 us	68,53 us	98,37 us	16,92 us	24,29 us	39,04 us	68,53 us	98,37 us
64	2,5 Gbit/s	74,37 us	127,62 us	234,11 us	447,10 us	662,59 us	74,37 us	127,62 us	234,11 us	447,10 us	662,59 us	63,31 us	90,34 us	144,41 us	252,54 us	361,95 us	63,31 us	90,34 us	144,41 us	252,54 us	361,95 us

Note: Preemption does not make a difference in absence of low priority interference.

Max. End-to-End Delays without Interference

Forwarding after VLAN-Tag

		S&F max. delay (end-to-end)										CTF max. delay (end-to-end)									
		Preemption unsupported					Preemption supported					Preemption unsupported					Preemption supported				
H	l_{HP} / Link	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	42,24 us	83,20 us	165,12 us	328,96 us	494,72 us	42,24 us	83,20 us	165,12 us	328,96 us	494,72 us	25,92 us	46,40 us	87,36 us	169,28 us	252,16 us	25,92 us	46,40 us	87,36 us	169,28 us	252,16 us
4	100 Mbit/s	63,36 us	124,80 us	247,68 us	493,44 us	742,08 us	63,36 us	124,80 us	247,68 us	493,44 us	742,08 us	30,72 us	51,20 us	92,16 us	174,08 us	256,96 us	30,72 us	51,20 us	92,16 us	174,08 us	256,96 us
16	100 Mbit/s	190,08 us	374,40 us	743,04 us	1480,32 us	2226,24 us	190,08 us	374,40 us	743,04 us	1480,32 us	2226,24 us	59,52 us	80,00 us	120,96 us	202,88 us	285,76 us	59,52 us	80,00 us	120,96 us	202,88 us	285,76 us
64	100 Mbit/s	696,96 us	1372,80 us	2724,48 us	5427,84 us	8162,88 us	696,96 us	1372,80 us	2724,48 us	5427,84 us	8162,88 us	174,72 us	195,20 us	236,16 us	318,08 us	400,96 us	174,72 us	195,20 us	236,16 us	318,08 us	400,96 us
2	1 Gbit/s	5,38 us	9,47 us	17,66 us	34,05 us	50,62 us	5,38 us	9,47 us	17,66 us	34,05 us	50,62 us	4,03 us	6,08 us	10,18 us	18,37 us	26,66 us	4,03 us	6,08 us	10,18 us	18,37 us	26,66 us
4	1 Gbit/s	8,06 us	14,21 us	26,50 us	51,07 us	75,94 us	8,06 us	14,21 us	26,50 us	51,07 us	75,94 us	5,38 us	7,42 us	11,52 us	19,71 us	28,00 us	5,38 us	7,42 us	11,52 us	19,71 us	28,00 us
16	1 Gbit/s	24,19 us	42,62 us	79,49 us	153,22 us	227,81 us	24,19 us	42,62 us	79,49 us	153,22 us	227,81 us	13,44 us	15,49 us	19,58 us	27,78 us	36,06 us	13,44 us	15,49 us	19,58 us	27,78 us	36,06 us
64	1 Gbit/s	88,70 us	156,29 us	291,46 us	561,79 us	835,30 us	88,70 us	156,29 us	291,46 us	561,79 us	835,30 us	45,70 us	47,74 us	51,84 us	60,03 us	68,32 us	45,70 us	47,74 us	51,84 us	60,03 us	68,32 us
2	2,5 Gbit/s	2,92 us	4,56 us	7,83 us	14,39 us	21,02 us	2,92 us	4,56 us	7,83 us	14,39 us	21,02 us	2,57 us	3,39 us	5,03 us	8,31 us	11,62 us	2,57 us	3,39 us	5,03 us	8,31 us	11,62 us
4	2,5 Gbit/s	4,38 us	6,84 us	11,75 us	21,58 us	31,53 us	4,38 us	6,84 us	11,75 us	21,58 us	31,53 us	3,69 us	4,51 us	6,14 us	9,42 us	12,74 us	3,69 us	4,51 us	6,14 us	9,42 us	12,74 us
16	2,5 Gbit/s	13,13 us	20,51 us	35,25 us	64,74 us	94,58 us	13,13 us	20,51 us	35,25 us	64,74 us	94,58 us	10,37 us	11,19 us	12,83 us	16,10 us	19,42 us	10,37 us	11,19 us	12,83 us	16,10 us	19,42 us
64	2,5 Gbit/s	48,15 us	75,19 us	129,25 us	237,39 us	346,79 us	48,15 us	75,19 us	129,25 us	237,39 us	346,79 us	37,09 us	37,91 us	39,55 us	42,83 us	46,14 us	37,09 us	37,91 us	39,55 us	42,83 us	46,14 us

Forwarding after 64 octets

		S&F max. delay (end-to-end)										CTF max. delay (end-to-end)									
		Preemption unsupported					Preemption supported					Preemption unsupported					Preemption supported				
H	l_{HP} / Link	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542	128	256	512	1024	1542
2	100 Mbit/s	42,24 us	83,20 us	165,12 us	328,96 us	494,72 us	42,24 us	83,20 us	165,12 us	328,96 us	494,72 us	33,28 us	53,76 us	94,72 us	176,64 us	259,52 us	33,28 us	53,76 us	94,72 us	176,64 us	259,52 us
4	100 Mbit/s	63,36 us	124,80 us	247,68 us	493,44 us	742,08 us	63,36 us	124,80 us	247,68 us	493,44 us	742,08 us	45,44 us	65,92 us	106,88 us	188,80 us	271,68 us	45,44 us	65,92 us	106,88 us	188,80 us	271,68 us
16	100 Mbit/s	190,08 us	374,40 us	743,04 us	1480,32 us	2226,24 us	190,08 us	374,40 us	743,04 us	1480,32 us	2226,24 us	118,40 us	138,88 us	179,84 us	261,76 us	344,64 us	118,40 us	138,88 us	179,84 us	261,76 us	344,64 us
64	100 Mbit/s	696,96 us	1372,80 us	2724,48 us	5427,84 us	8162,88 us	696,96 us	1372,80 us	2724,48 us	5427,84 us	8162,88 us	410,24 us	430,72 us	471,68 us	553,60 us	636,48 us	410,24 us	430,72 us	471,68 us	553,60 us	636,48 us
2	1 Gbit/s	5,38 us	9,47 us	17,66 us	34,05 us	50,62 us	5,38 us	9,47 us	17,66 us	34,05 us	50,62 us	4,48 us	6,53 us	10,62 us	18,82 us	27,10 us	4,48 us	6,53 us	10,62 us	18,82 us	27,10 us
4	1 Gbit/s	8,06 us	14,21 us	26,50 us	51,07 us	75,94 us	8,06 us	14,21 us	26,50 us	51,07 us	75,94 us	6,27 us	8,32 us	12,42 us	20,61 us	28,90 us	6,27 us	8,32 us	12,42 us	20,61 us	28,90 us
16	1 Gbit/s	24,19 us	42,62 us	79,49 us	153,22 us	227,81 us	24,19 us	42,62 us	79,49 us	153,22 us	227,81 us	17,02 us	19,07 us	23,17 us	31,36 us	39,65 us	17,02 us	19,07 us	23,17 us	31,36 us	39,65 us
64	1 Gbit/s	88,70 us	156,29 us	291,46 us	561,79 us	835,30 us	88,70 us	156,29 us	291,46 us	561,79 us	835,30 us	60,03 us	62,08 us	66,18 us	74,37 us	82,66 us	60,03 us	62,08 us	66,18 us	74,37 us	82,66 us
2	2,5 Gbit/s	2,92 us	4,56 us	7,83 us	14,39 us	21,02 us	2,92 us	4,56 us	7,83 us	14,39 us	21,02 us	2,57 us	3,39 us	5,03 us	8,31 us	11,62 us	2,57 us	3,39 us	5,03 us	8,31 us	11,62 us
4	2,5 Gbit/s	4,38 us	6,84 us	11,75 us	21,58 us	31,53 us	4,38 us	6,84 us	11,75 us	21,58 us	31,53 us	3,69 us	4,51 us	6,14 us	9,42 us	12,74 us	3,69 us	4,51 us	6,14 us	9,42 us	12,74 us
16	2,5 Gbit/s	13,13 us	20,51 us	35,25 us	64,74 us	94,58 us	13,13 us	20,51 us	35,25 us	64,74 us	94,58 us	10,37 us	11,19 us	12,83 us	16,10 us	19,42 us	10,37 us	11,19 us	12,83 us	16,10 us	19,42 us
64	2,5 Gbit/s	48,15 us	75,19 us	129,25 us	237,39 us	346,79 us	48,15 us	75,19 us	129,25 us	237,39 us	346,79 us	37,09 us	37,91 us	39,55 us	42,83 us	46,14 us	37,09 us	37,91 us	39,55 us	42,83 us	46,14 us

Note: Preemption does not make a difference in absence of low priority interference.