Deterministic Ethernet for Safety-Critical Applications

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Electronic Robustness for a More Electric and Connected World

Real-Time Internet of Things

25+ Billion

Embedded and intelligent systems by 2020

Autonomous & Near Autonomous Operations

$1.9 Trillion

Economic impact of near autonomous cars by 2025

Every 2nd

Embedded device will be safety relevant by 2020

Safety & Reliability

What is Deterministic Networking?

Same as normal networking, but with the following features for **critical data streams**:

1. **Time synchronization** for network nodes and hosts to better than 1 µs.
2. Software for **resource reservation** for critical data streams (buffers and schedulers in network nodes and bandwidth on links), via configuration, management, and/or protocol action.
3. Software and hardware to ensure **extraordinarily low packet loss ratios**, starting at 10^{-6} and extending to 10^{-10} or better, and as a consequence, a **guaranteed end-to-end latency** for a reserved flow.
4. **Convergence** of critical data streams and other QoS features (including ordinary best-effort) on a single network, even when critical data streams are 75% of the bandwidth.

Slide source: DetNet Problem Statement, Norman Finn, Cisco Systems

Who needs Deterministic Networking?

Two classes of bleeding-edge customers, Industrial and Audio/Video. Both have moved into the digital world, and some are using packets, but now they all realize they must move to Ethernet, and most will move to the Internet Protocols.

1. **Industrial:** process control, machine control, and vehicles.
   - At Layer 2, this is IEEE 802.1 **Time-Sensitive Networking (TSN)**.
   - Data rate per stream very low, but can be large numbers of streams.
   - Latency critical to meeting control loop frequency requirements.
2. **Audio/video:** streams in live production studios.
   - At Layer 2, this is IEEE 802.1 **Audio Video Bridging (AVB)**.
   - Not so many flows, but one flow is 3 Gb/s now, 12 Gb/s tomorrow.
   - Latency and jitter are important, as buffers are scarce at these speeds.

(You won't find any more market justification in this deck.)

Why such a low packet loss ratio?

Back-of-the-envelope calculations:

1.Industrial:

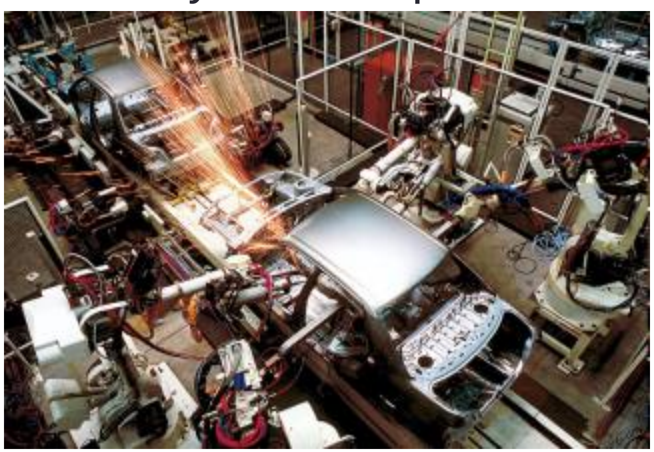
- Automotive factory floor: 1000 networks • 1000 packets/s/network • 100,000 s/day = 10^{11} packets/day.
- Machine fails safe when 2 consecutive packets are lost.
- At a random loss ratio of **10^{-5}**, 10^{-10} is chance of 2 consecutive losses.
- 10^{11} packets/day • 10^{-10} 2-loss ratio = **10 production line halts/day**.
- In extreme cases, lost packets can damage equipment or kill people.

2.Audio video production: (not distribution)

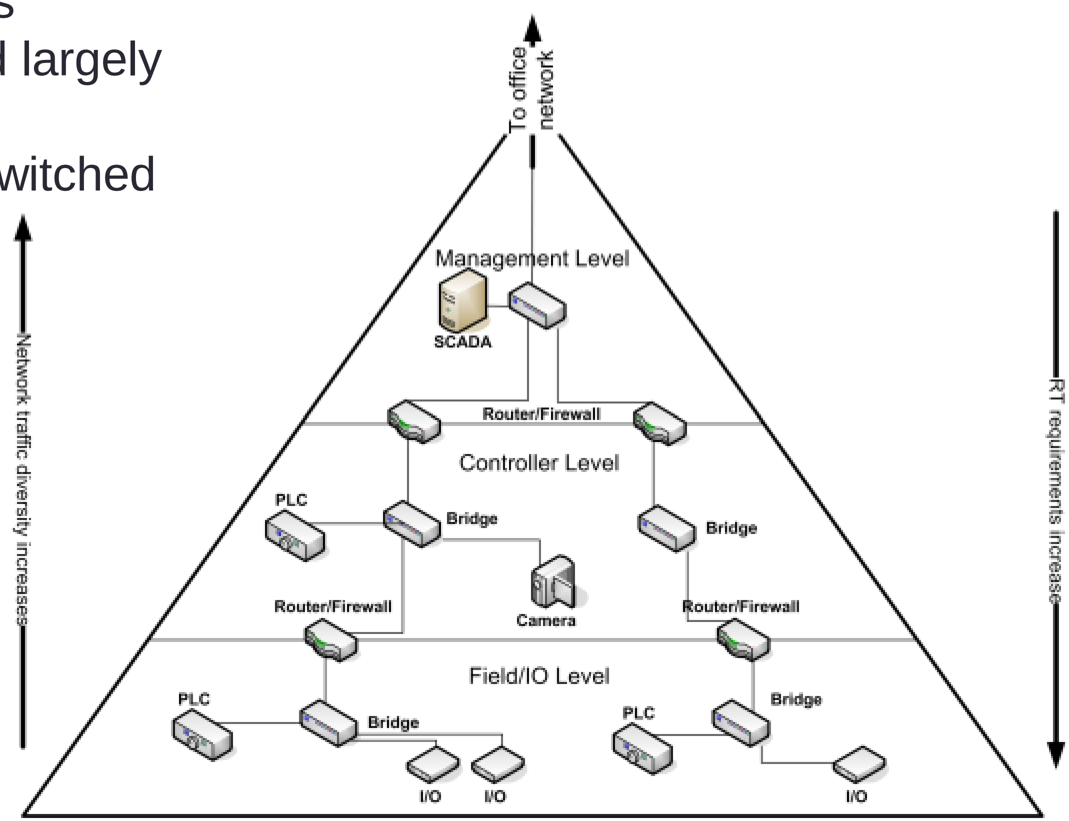
- 10^{10} b/s • 10 processing steps • 1000 s/show = 10^{14} bits = 10^{10} packets.
- Waiting for ACKs and retries = too many buffers, too much latency.
- Lost packets result in a **flawed master recording**, which is the user's end product.

History and Emerging Markets

- Early adopters outside IT: Industrial Automation (~1990s)
  - Higher Bandwidth than Fieldbusses
    (legacy automation network technologies, e.g. Profibus, Interbus, …)
  - Convergence with IT services
  - Widely available silicon could largely be re-used
  - Micro-Segmentation / Fully switched networks introduced first „deterministic Ethernet“
  - Easy fibre adoption



Manufacturing shop floor



Automation Pyramid

Slide source: Oliver Kleineberg, Belden / Hirschmann Automation & Control

History and Emerging Markets

- Early adopters outside IT: Professional and Home Audio and Video (early to mid 2000‘s)
  - High Performance
  - Good Price / Performance
  - High flexibility in wiring and media
  - Easily merges with existing home entertainment networks and Wireless LANs
  - In 2005, work in IEEE 802.3 (Residential Ethernet) started → Later moved to IEEE 802.1 as Audio and Video Bridging

Converged home networked services:
- File storage
- VoIP
- Audio and Video transmission (on demand)

Live Performances(*)

Home Theater PC(*)

(*) Source: Wikipedia

History and Emerging Markets

- Existing Technologies: IEEE and Non-IEEE
  - IEEE 802.1 Audio and Video Bridging
    - Of high interest in Professional and Home Audio and Video
    - Time Synchronization based on well-proven IEEE 1588 protocol
    - Bandwidth Reservation and Class-based QoS (Traffic Shaping)
    - Deterministic Real-Time Ethernet technology that fits the original use case very well
    - Already applicable to some of the emerging new market applications
  - IEEE 802.1 Shortest Path Briding
    - Providing resiliency to failures in the network infrastructure

- Where no IEEE standards were available, other specifications emerged, often driven by proprietary technologies:
  - Proprietary protocols for Professional Audio (e.g. Cobranet)
  - Proprietary protocols for Industrial Automation (e.g. ISO/IEC addressing Redundancy and Real-Time in ISO/IEC 62439 / 61158 / 61784 series)
  - Application-specific extensions of standard IEEE 802 technologies (e.g. ARINC Avionics Full-Duplex Switched Ethernet - AFDX)

→ High demand for a **converged IEEE 802 solution for deterministic Ethernet** to replace proprietary technology and fit the needs of existing and emerging markets.

Slide source: Oliver Kleineberg, Belden / Hirschmann Automation & Control

History and Emerging Markets

- Emerging Markets: Mission-critical networking
  - Emerges out of Industrial Automation, massively broadening the scope
  - Requirements (far) beyond standard IT equipment relating to determinism in time and protocol behaviour
  - Often used as transparent communication channel for End-to-End Safety Communication
  - Risk for Life and Limb if the system fails – High requirements to overall network, protocol and device robustness

…  …  …  …

Power Utility Automation

Traffic Control Systems

Transportation

Slide source: Oliver Kleineberg, Belden / Hirschmann Automation & Control

Use Case: Mission-critical Automation

- Railway: Rolling stock

- Ethernet in trains has applications in customer information and also infotainment

- Another application area lies in train control networks and video surveillance…

- …as well as passenger counters and detectors on the automatic train doors

Slide source: Oliver Kleineberg, Belden / Hirschmann Automation & Control

Use Case: Motion Control

Wind turbine: Synchronized rotor blade control actuators

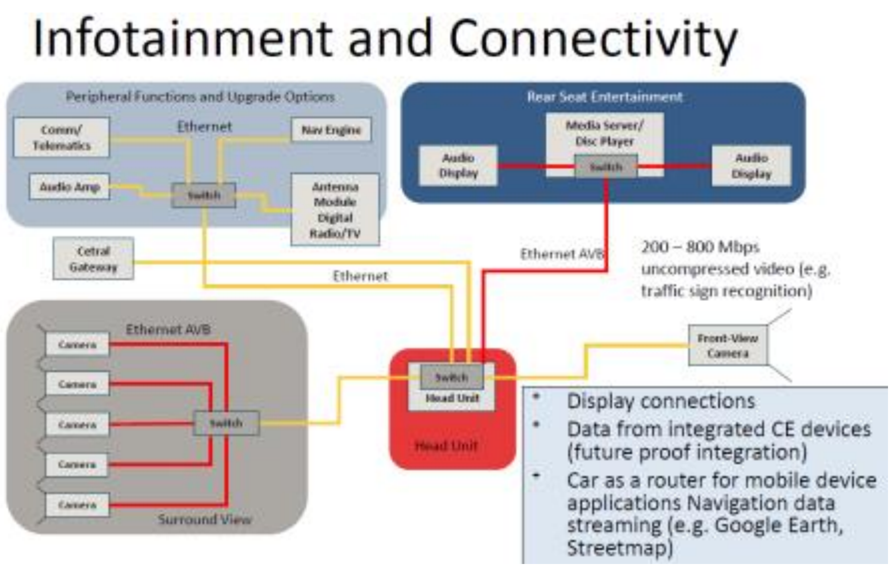
Printing machine: Large number of synchronized axles

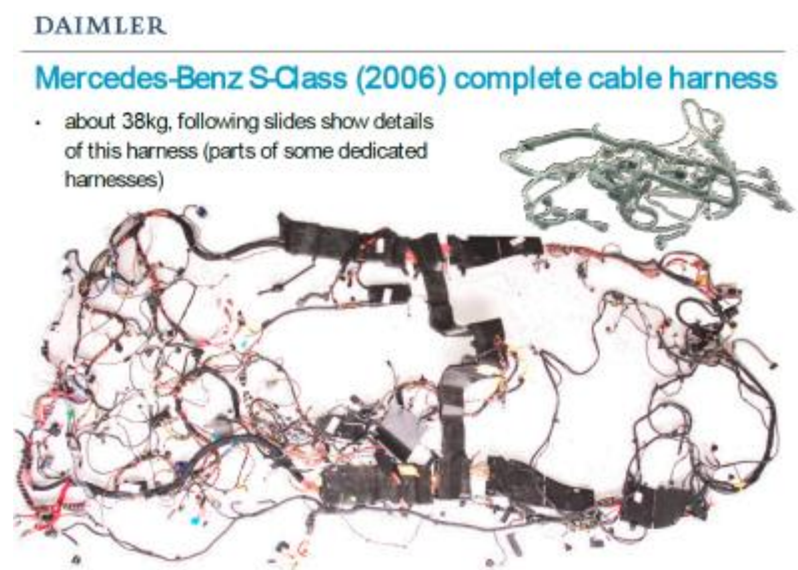
Applications where robots and humans closely interact:

•Robot-assisted manufacturing
•Robot-assisted surgery
•Robotic prostheses
•…

History and Emerging Markets

- Emerging Markets: Vehicular Networks
  - Reduced Wiring Harness → Reduced weight and cabling costs
  - Reduce overall costs by using standardized chips
  - Reduce risks of binding to one silicon/solution vendor
  - Unified solution for different application areas (e.g. Infotainment, Power Train, Driver Assistance, …)

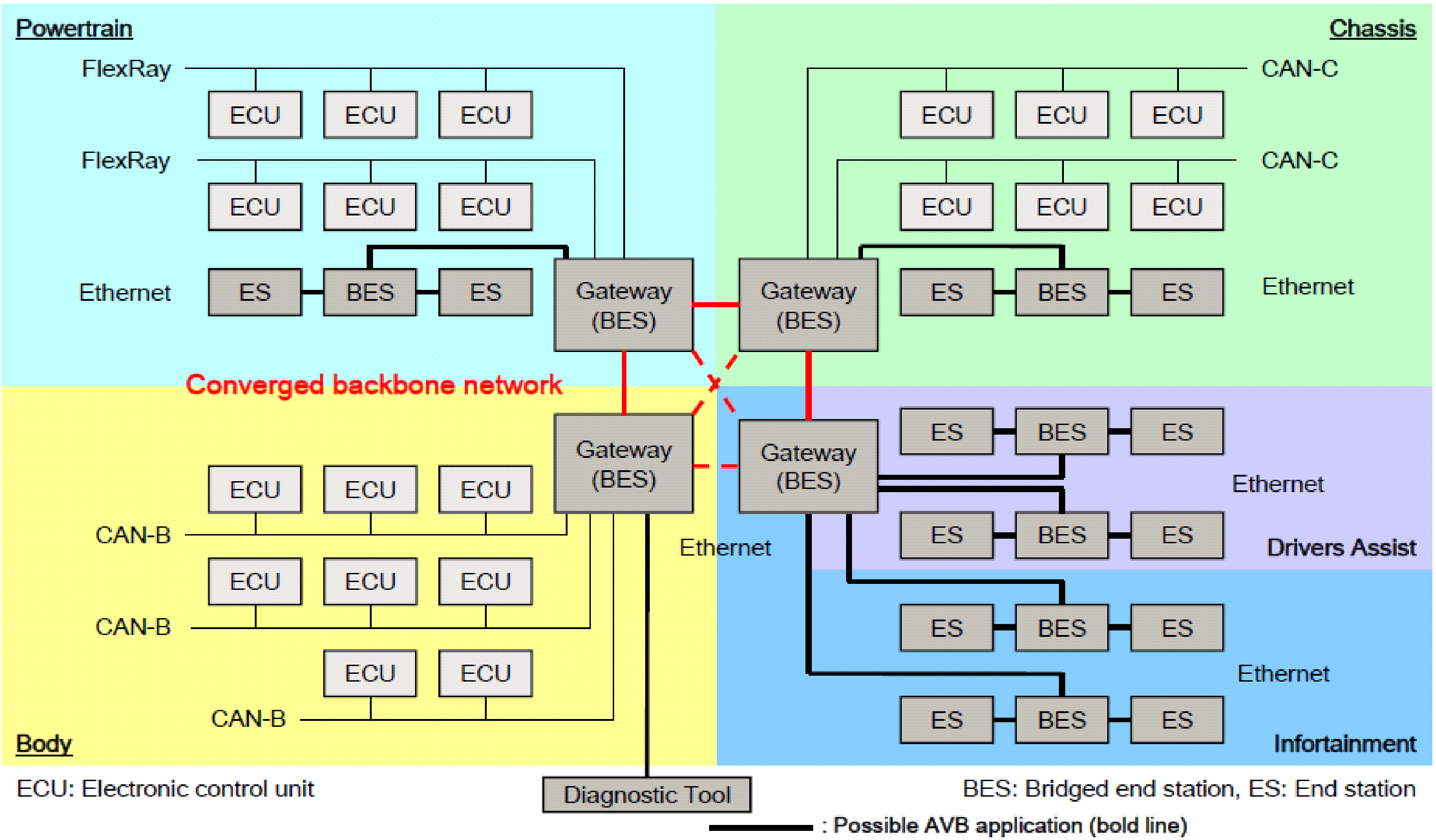




Picture Sources: IEEE 802.3 RTPGE SG

Use Case: Vehicular Network

- **An example converged backbone network for the domain architecture**



One possible application example of a future vehicular network

Source: IEEE 802.1 AVB TG presentation

History and Emerging Markets

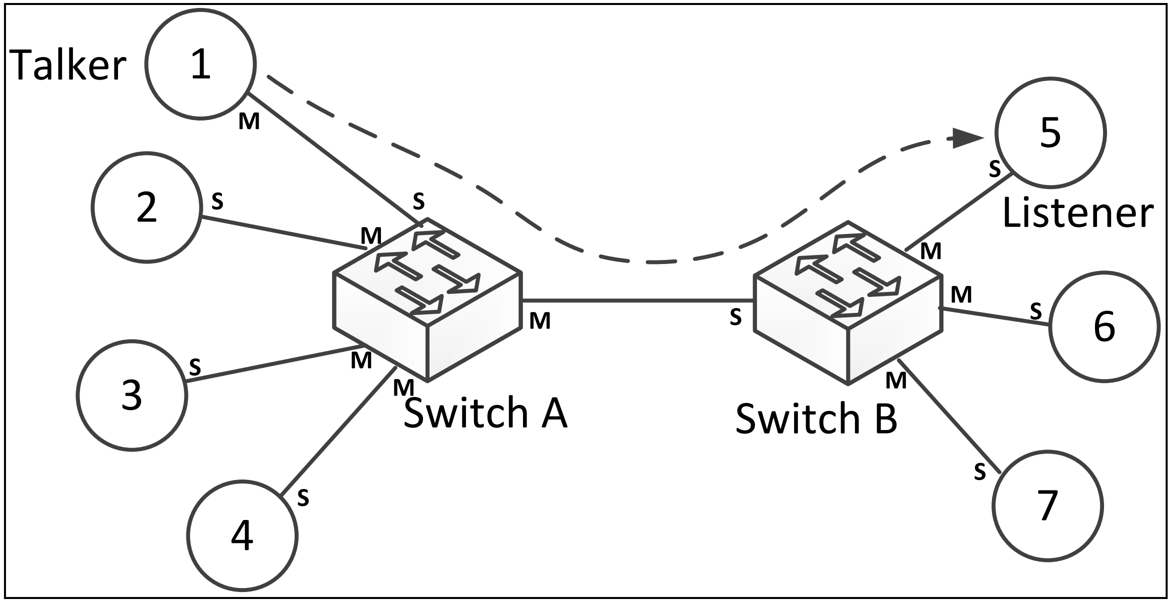
- One Step further - Added Requirements for a converged IEEE solution for Deterministic Ethernet:
  - There are many requirements already covered by 802.1 AVB and other IEEE 802 solutions, but the scope has broadened
  - Need to support larger network structures (long daisy-chains, interconnected rings…)
  - Very High EM resistance and low weight/cost of PHY‘s (see RTPGE)
  - Very low latency and jitter, exceeding the original AVB scope
  - Seamless fault-tolerance
  - Resilient Time Synchronization

802.1 and 802.3 are currently starting or have already started to address these market needs!

Basic Concepts and Example Network

7B	1B	6B	6B	4B	2B	42B – 1500B	4B	12B
Preamble	SOF	MAC Destination	MAC Source	802.1Q "VLAN" Tag	Ethertype/ Length	Payload	FCS	IFG

16 bits	3 bits	1 bit	12 bits
Tag Protocol Identifier	Priority Code Point	Drop Eligible Indicator	VLAN Identifier



TSN – Time-Sensitive Networks

802.1AS-RevTiming and Synchronization: Enhancements and Performance Improvements

802.1Qbv Enhancements for Scheduled Traffic: a basic form of time-triggered communication

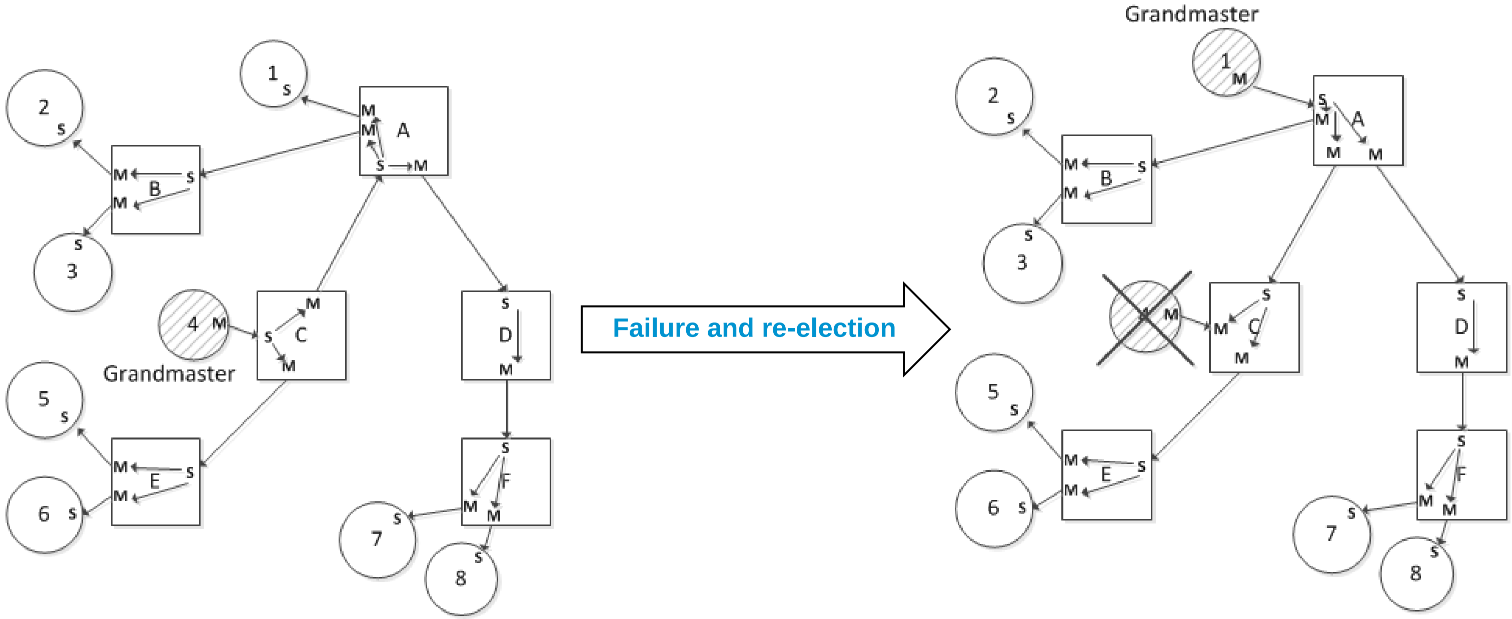
802.1Qca Path Control and Reservation: protocols and mechanisms to set up and manage the redundant communication paths in the network.

802.1CB Frame Replication and Elimination for Reliability: to eliminate redundant copies of frames transmitted over the redundant paths setup in 802.1Qca.

802.1Qcc – enhancements and improvements for stream reservation

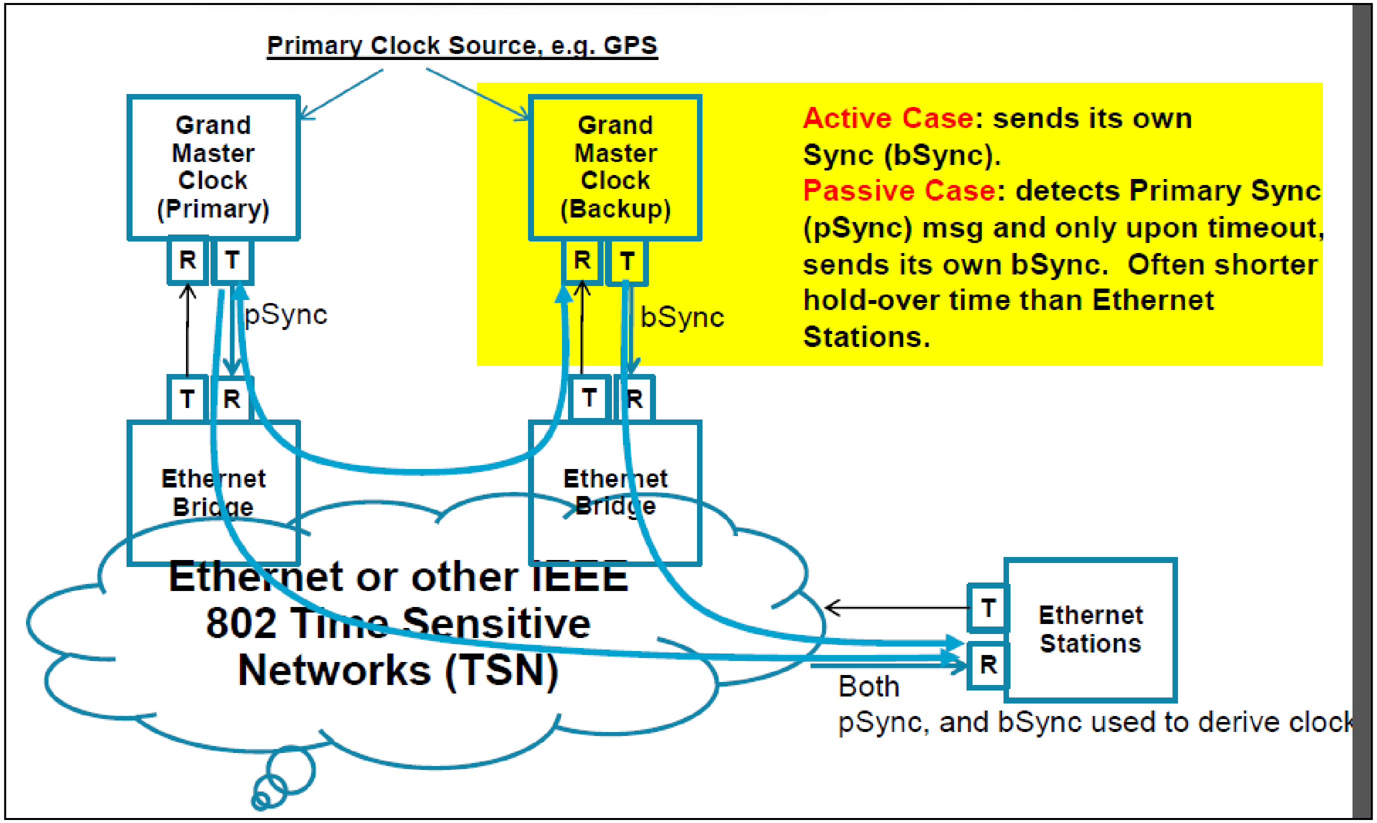
802.1Qbu Frame Preemption: a mechanism that allows to preempt a frame in transmit to intersperse another frame.

IEEE 802.1AS
Clock Synchronization



The clock synchronization protocol is a classical master-slave protocol.
The master is called the "grandmaster".
When the grandmaster fails, then a new grandmaster is elected.
Issues with this mechanism have been reported by industry.

802.1ASbt Clock Synchronization
Proposals for Improvements



http://www.ieee802.org/1/files/public/docs2013/ASbt-Spada-Kim-Fault-tolerant-grand-master-proposal-0513-v1.pdf

Other 802.1AS Improvements

Multiple Timescales

- Provision to support multiple timescales, e.g., working clock time and wall clock time.
- Working clock used, e.g., to schedule communication.
- Wall clock time used, e.g., to timestamp events.

Harmonization with IEEE 1588

- Ongoing coordination with the IEEE 1588 stakeholders to ensure future compatibility.
- Several IEEE 802.1 members are actively involved also in IEEE 1588.

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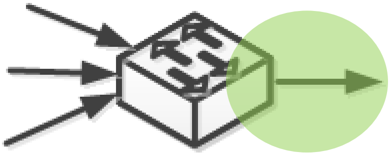
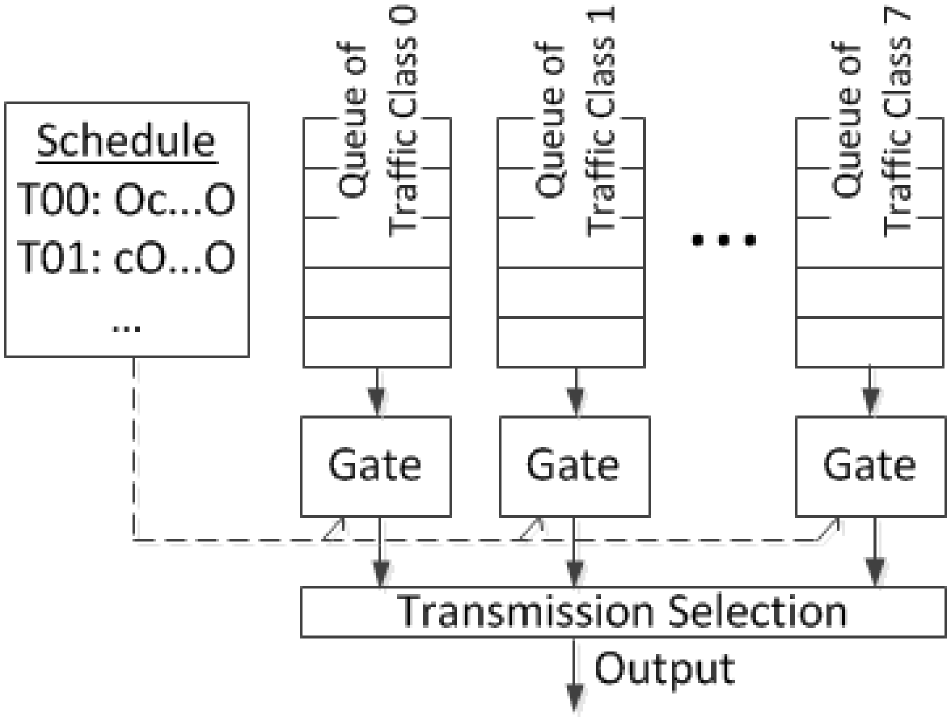
802.1Qbv
Time-Aware Shaper

- The time-aware shaper defines a time-triggered paradigm on a per-class level (opposed to on a per-flow level).
  - Background:
    - The class of a frame is determined by the priority of the VLAN tag.
    - The field is three bits long, hence there are eight priorities.
    - Thus, it is typical that switches implement eight “logical queues” per output port of a switch.
- It is planned that the time-aware shaper will allow to enable and to disable each of the queues based on a communication schedule.
- The execution of the communication schedules in the switches (and potentially also end systems) is synchronized using IEEE 802.1AS.

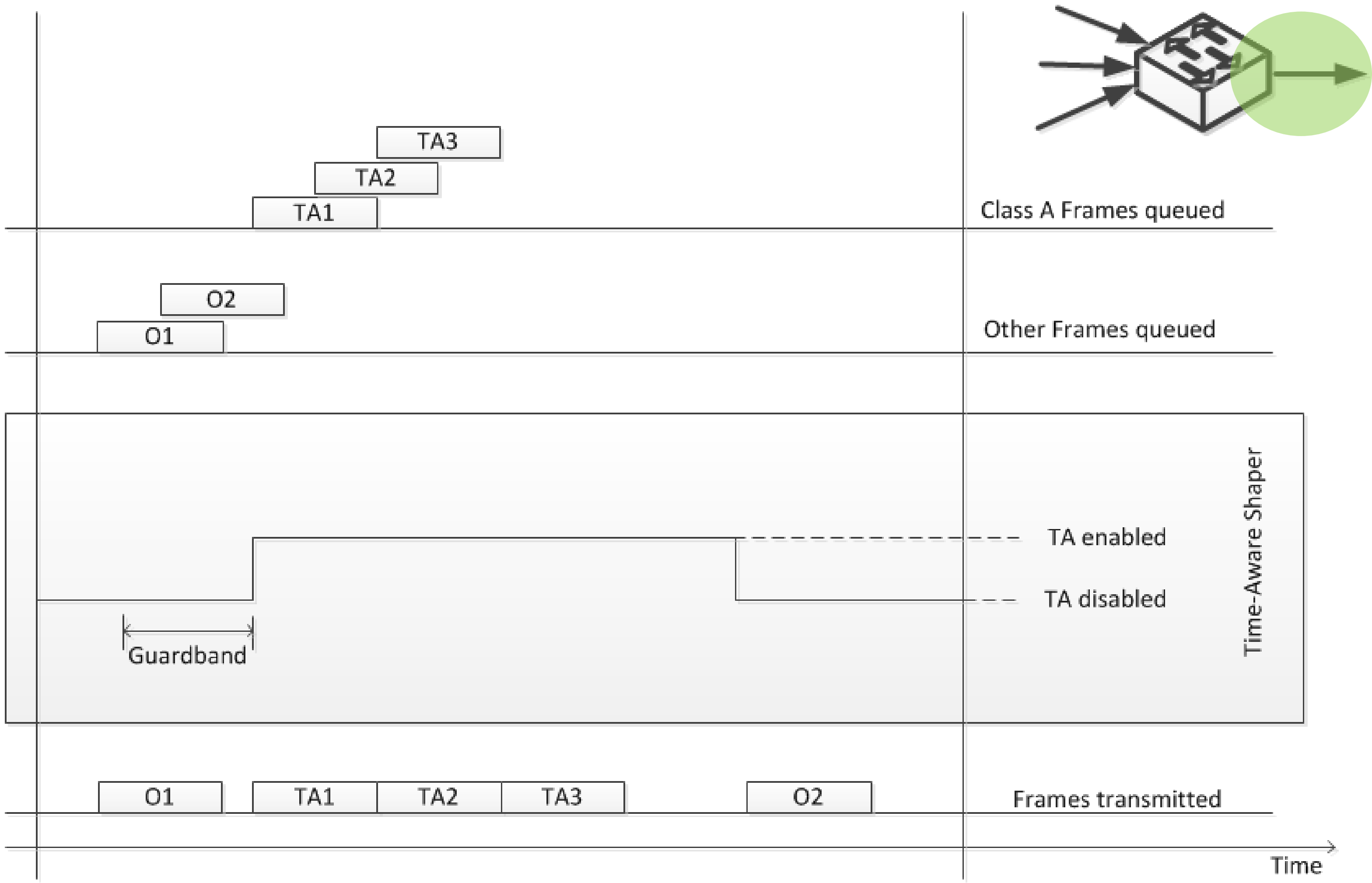
802.1Qbv
Time-Aware Shaper (cont.)





From the most recent draft standard IEEE 802.1Qbv-D.2.0

802.1Qbv
Time-Aware Shaper (cont.)



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802.1Qbu Frame Preemption: a mechanism that allows to preempt a frame in transmit to intersperse another frame.

Stream Reservation

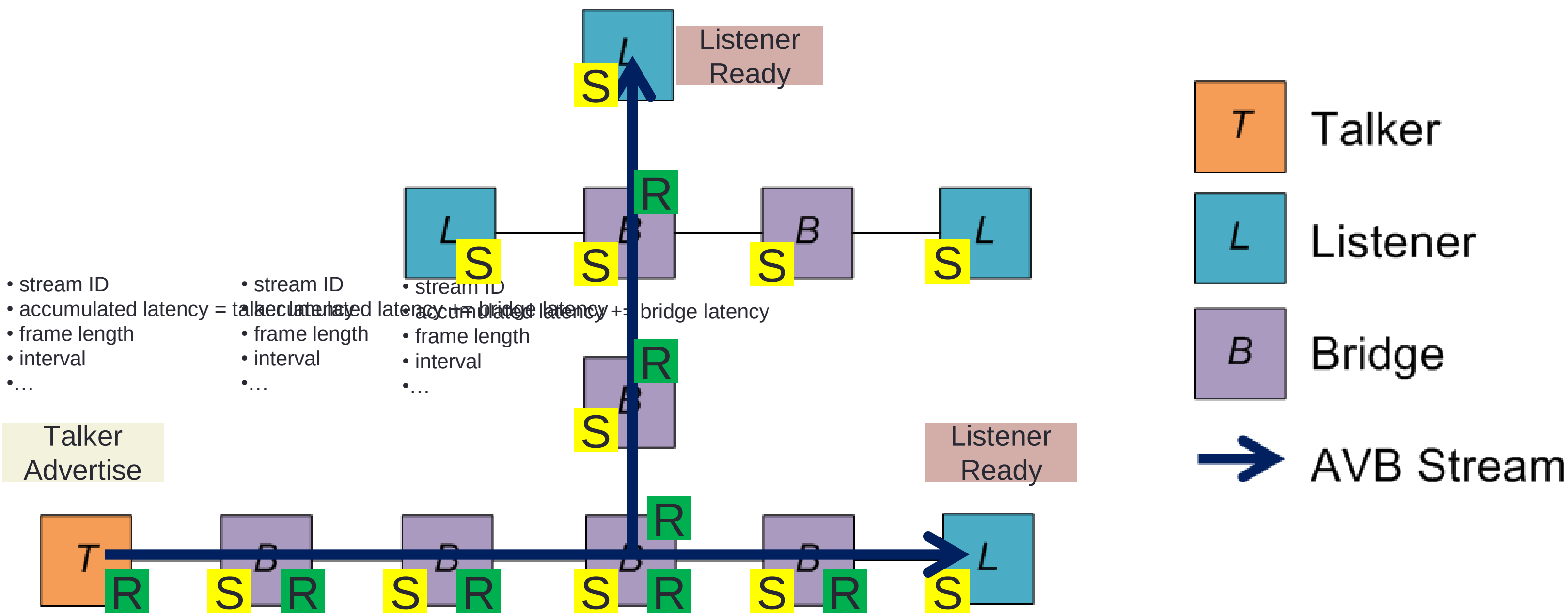
The Stream Reservation Protocol (SRP):

- Advertises streams in the whole network
- Registers the path of streams
- Calculates the "worst case latency"
- Specifies the forwarding rules for AVB streams
- Establishes an AVB domain
- Reserves the bandwidth for AVB streams

Especially the bandwidth reservation is important in order to:

- Protect the best effort traffic, as only 75% of the bandwidth can be reserved for SR class traffic
- Protect the SR class traffic as it is not possible to use more bandwidth for SR class traffic than 75% (this is an important factor in order to guarantee a certain latency)

Stream Reservation Example



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Frame Preemption

- Joint project between IEEE 802.1 and IEEE 802.3
- There will be a standardized way to preempt ongoing transmissions (e.g., of low priority frames) and to “intersperse express traffic”.
- Preempted transmissions will not be lost, but rather continued when the high-priority traffic has finished its transmission.

Summary

There is a native standardization body for Ethernet and it is the IEEE.

In particular, IEEE 802.3 develops and maintains the Ethernet PHY and MAC standards, IEEE 802.1 develops and maintains bridging (aka switching) standards.

With AVB, the IEEE has moved Ethernet into the real-time applications domain.

With TSN, the IEEE moves Ethernet into the hard real-time applications domain and improves Ethernet's robustness.

With the growing competences in the IEEE standards, products built on these standards increase their market potential.

RetNet

- Marie Sklodowska-Curie – European Industrial Doctorate (EID)
- Education & career paths of young researchers
- PhD training
- Project duration: Oct. 2013 – Sep. 2017
  - Researchers are funded for three years
- Two main partners
  - MDH Mälardalen University (Prof. Hansson): academic partner
  - TTTech: industrial partner
- Four associated partners
  - SWE: ABB, Ericsson,
    Volvo Construction Equipment
  - AT: TU Vienna

RETNET
Real-Time Networks

FP7-MSCA-EID

RetNet

- Deterministic Wireless Communication (Pablo Gutierrez Peon)
  - Apply the time-triggered paradigm to wireless communication media, e.g., IEEE 802.11 (WiFi)
- Configuration and Management (Francisco Pozo, Marina Gutierrez)
  - Scheduling and performance analysis of extremely large networks (e.g., smart cities)
  - Increase flexibility and reconfiguration capabilities of time-triggered systems
- Security (Elena Lisova)
  - Development of a generic threat model for wired/wireless time-triggered systems and integration of security mechanisms (e.g., IPsec).
- Deterministic Computer Vision (Ayhan Mehmed)
  - Improve determinism and safety of computer vision systems via offline safety measuring/assessment and online safety monitoring

Time-Triggered Ethernet

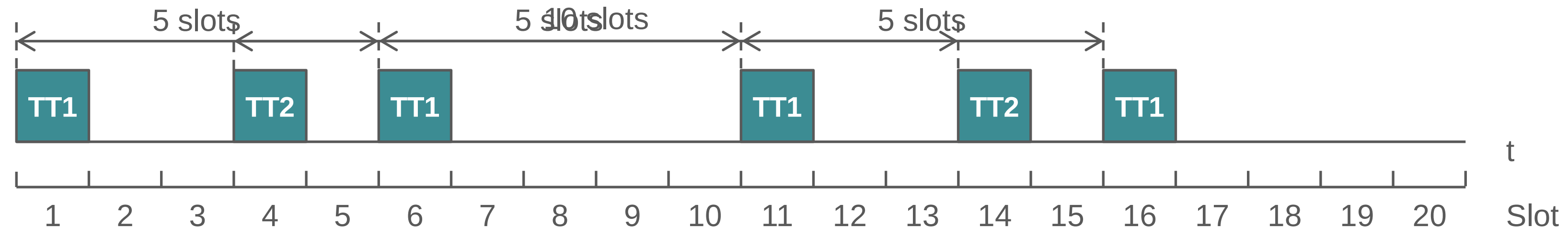
Ethernet technology
+ time-triggered communication paradigm
+ mixed-criticality traffic flows.

Time-Triggered (TT) traffic class

Messages sent at predefined points in time.

TT1 5 slots period.

TT2 10 slots period.



Time-Triggered Ethernet

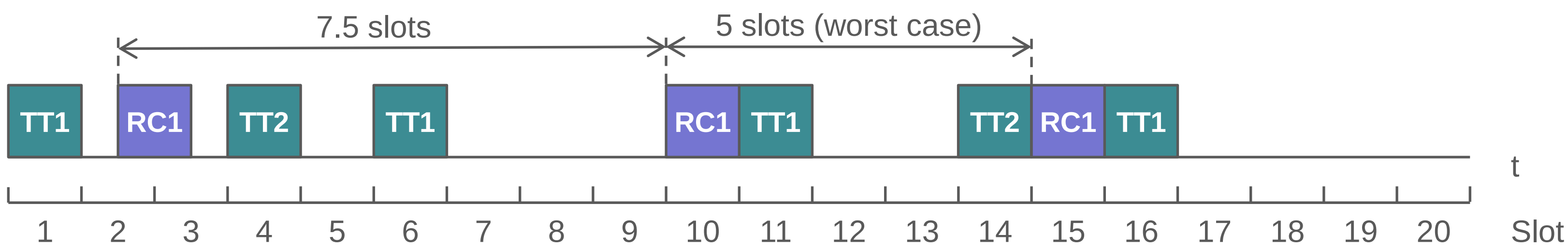
Ethernet technology
+ time-triggered communication paradigm
+ mixed-criticality traffic flows.

Time-Triggered (TT) traffic class

Rate-Constrained (RC) traffic class

Guaranteed minimum inter-arrival time.

RC1 Max. 1/5 slots rate.



Time-Triggered Ethernet

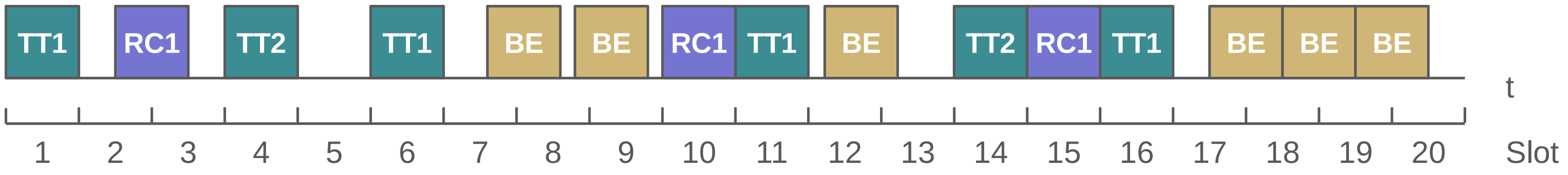
Ethernet technology
+ time-triggered communication paradigm
+ mixed-criticality traffic flows.

Time-Triggered (TT) traffic class

Rate-Constrained (RC) traffic class

Best-Effort (BE) traffic class

Random and not guaranteed.



Our proposal

Satisfy our requirements

Industrial control applications:
- High reliability.
- Predictable data delivery latency.

New application use cases:
- Wireless.

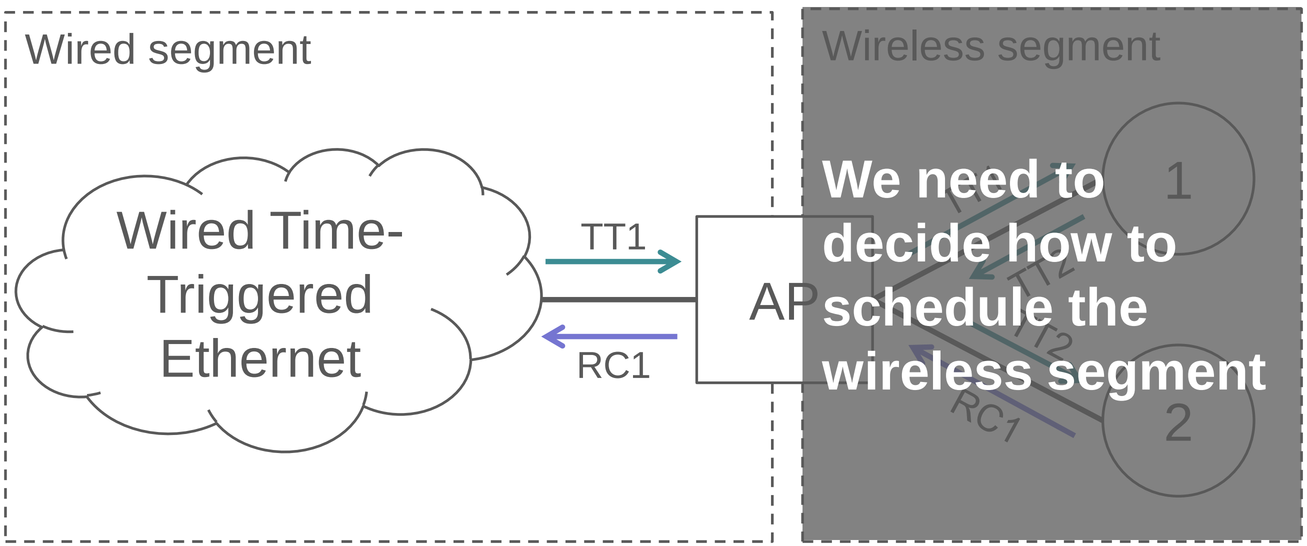
Through the combination of

Existing technology		Our contribution
Time-Triggered Ethernet	&	Wireless MAC protocol supporting heterogeneous data traffic

Our proposal

Traffic scenario

	Characteristics	Path
TT1	Period: 20 slots	Wired → AP → 1
TT2	Period: 10 slots	1→ AP → 2
RC1	Rate: max 1/5 slots	2→ AP → Wired
BE	Unknown pattern	-

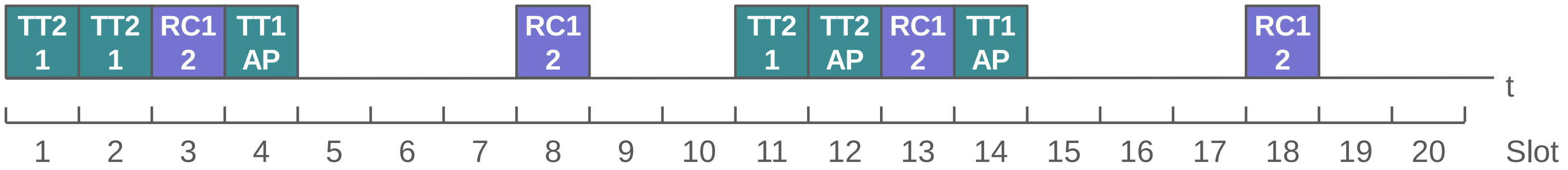


Our proposal

TT and RC traffic allocation

It is always given by the network scheduler.

	Characteristics	Path
TT1	Period: 20 slots	Wired → AP → 1
TT2	Period: 10 slots	1→ AP → 2
RC1	Rate: max 1/5 slots	2→ AP → Wired

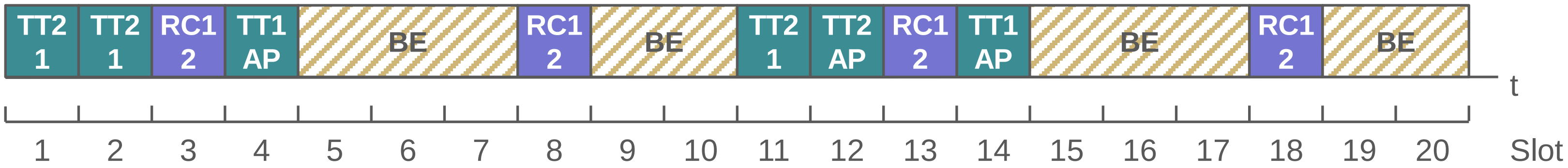


Our proposal

What happens with BE traffic?

Options on how to allocate are open.

	Characteristics	Path
BE	Unknown pattern	-

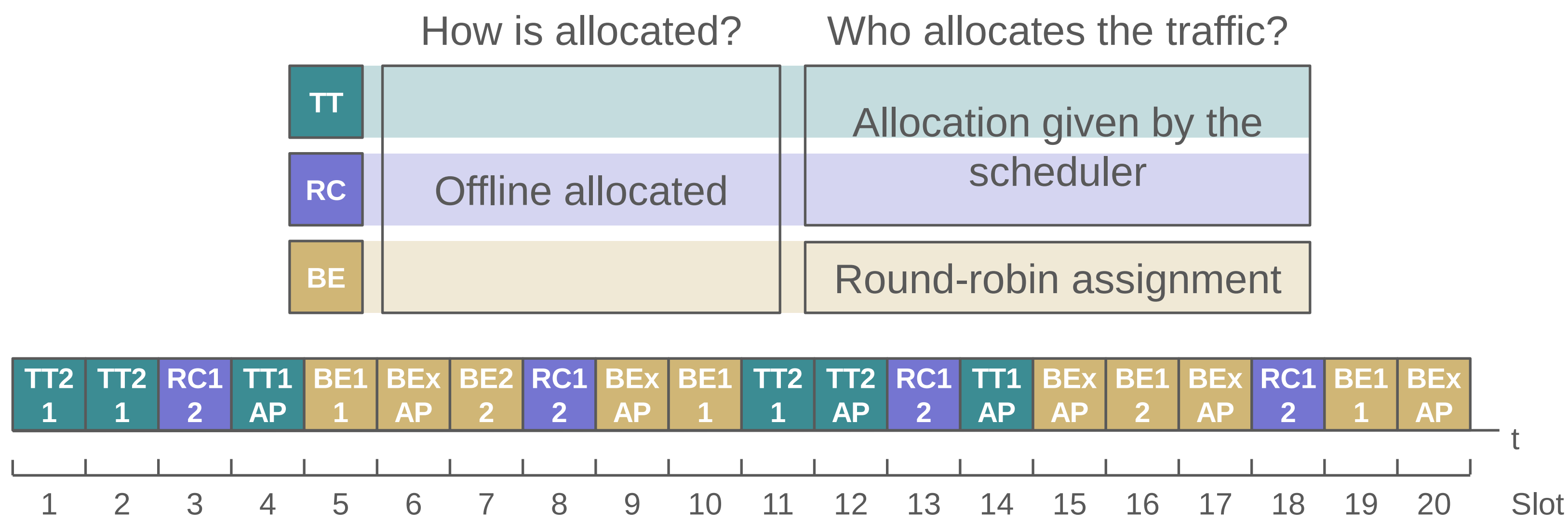


MAC proposal

3 wireless MAC protocols proposed and compared

Proposal 1

Pre-scheduled time-slots only.



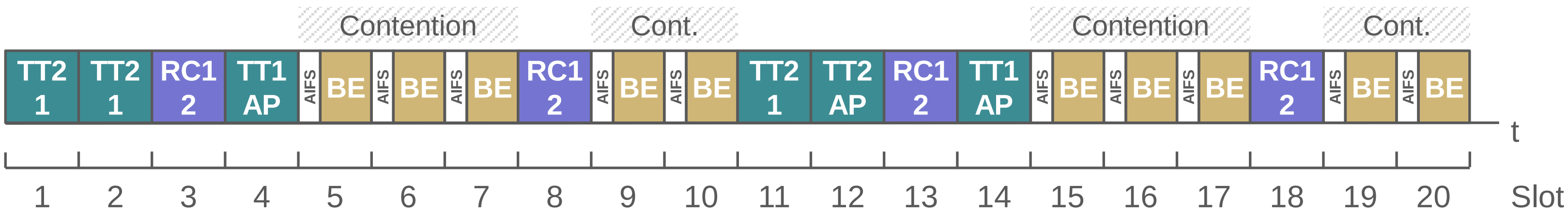
MAC proposal

TTTech

3 wireless MAC protocols proposed and compared
Proposal 1: Pre-scheduled time-slots only.

Proposal 2
Pre-scheduled time-slots and contention-based timeslots.

	How is allocated?	Who allocates the traffic?
TT	Offline allocated	Allocation given by the scheduler
RC	Offline allocated	Allocation given by the scheduler
BE	Contention-based	AIFS/Backoff One node (round-robin selected) does not add backoff



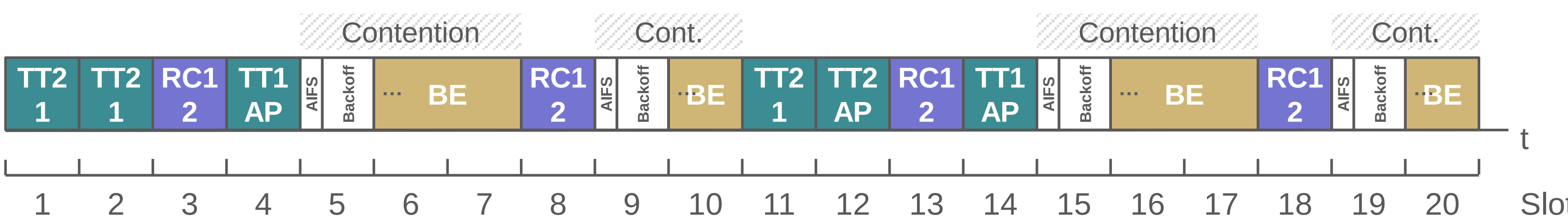
MAC proposal

TTTech

3 wireless MAC protocols proposed and compared
Proposal 1: Pre-scheduled time-slots only.
Proposal 2: Pre-scheduled time-slots and contention-based timeslots.

Proposal 3
Pre-scheduled time-slots and contention-based phase.

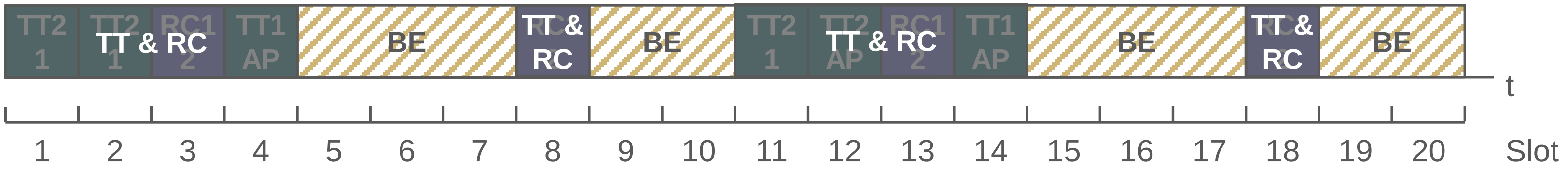
	How is allocated?	Who allocates the traffic?
TT	Offline allocated	Allocation given by the scheduler
RC	Offline allocated	Allocation given by the scheduler
BE	Contention-based	AIFS/Backoff



Protocol overhead and efficiency

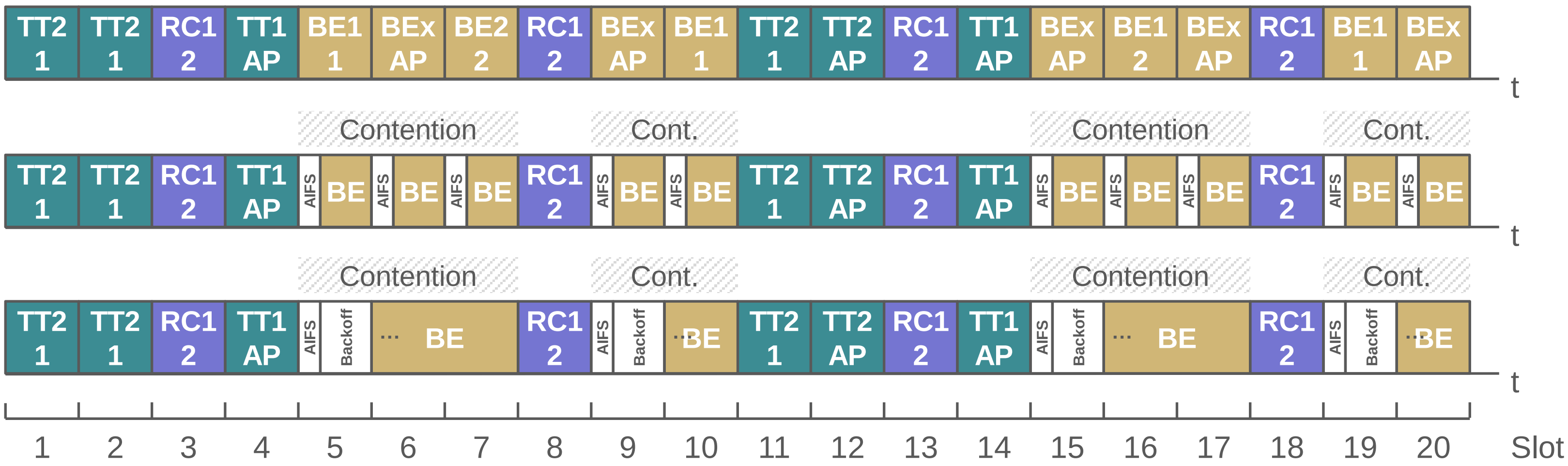
We would like to know…

- Time needed to schedule TT and RC. E.g. 10 slots.
- Time left for BE (excluding protocol overhead). E.g. ≤10 slots.



Channel access delay

TTTech



For TT and RC, known and constant.

For BE…

	Best	Worst
Proposal 1	0	$T_{BE\_worst\_delay\_1} = (S + N - 1)T_{transm}$
Proposal 2	T_{AIFS}	$T_{BE\_worst\_delay\_2} = (S + N - 1)(T_{transm} + T_{AIFS})$
Proposal 3	T_{AIFS}	Unbounded

S # of scheduled slots, N devices

Conclusion

TTTech

Proposal
Heterogeneous data traffic working in TTEthernet.
Extend this to wireless is desired.

One step forward in extending TTEthernet with wireless.

Three proposals for heterogeneous data traffic in wireless
Selecting one of them depends on the BE traffic pattern.
Proposal 1. High predictability.
Proposal 3. More flexible.

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