Real-Time Ethernet in the Automotive Systems

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SAFety and secURity by dEsign for interconnected mixed-critical cyber-physical systems

Standard Ethernet Summary

- State of the art
  - Standard Ethernet, IEEE802.1
    - Weighted Round Robin: alternating transmission
  - Ethernet Quality of Service (QoS), IEEE802.1Q
    - Static priority non-preemptive: priority based transmission
  - Audio/Video Bridgeing, IEEE802.1Qas
    - Credit based shaper: bandwidth guarantees for traffic classes
- Mixed critical traffic → provide isolation between streams
- Desired improvements
  - Isolation / freedom from interference
  - Low and bounded latencies
  - Simple verification
  - Handling of transmission errors

Real-time Ethernet – TSN

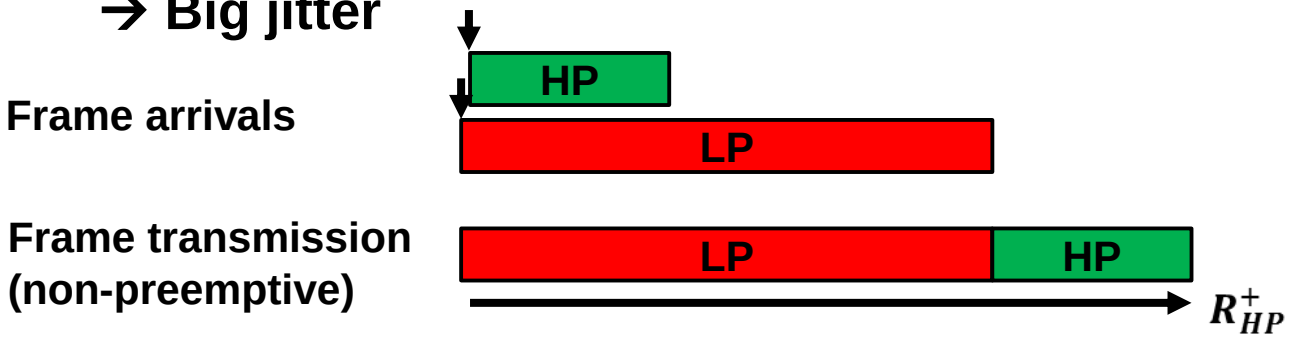
- Ethernet TSN (Time-Sensitive Networks)
  - Continuation of the AVB group
  - Set of standards (partially and fully completed)
  - Accurate time synchronisation
  - QoS (bounded latency, improved reliability)
  - Protection (against derouted and rogue traffic)
  - Scheduled traffic

- SAFURE relevant TSN efforts:
  - Traffic shapers, IEEE802.1Qbv
    - Burst limiting shaper
    - Time aware shaper
    - Peristaltic shaper
  - Frame preemption, IEEE802.1Qbu
  - Frame replication, IEEE802.1CB
  - Stream filtering, IEEE802.1Qci

Limitations of non-preemptive transmission schemes

- **Standard Ethernet:** Non-preemptive transmissions
  - Lower priority (LP) blocking
  - Longest Ethernet frame: 1500 Byte
  - Long blocking times: **120µs** @ 100Mbit/s per switch

    → **Big jitter**

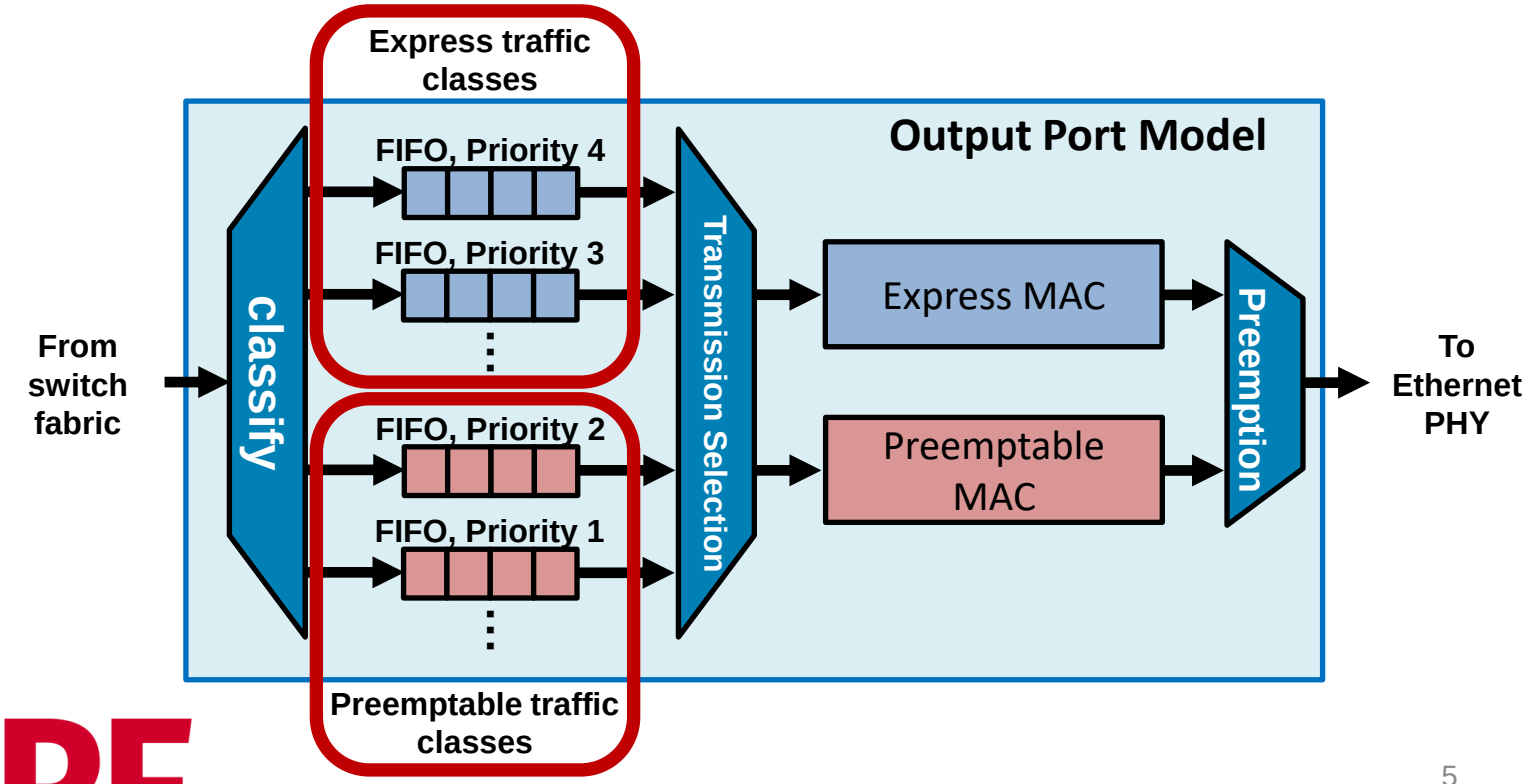


Solution:
Allow preemption of low priority frames

Frame preemption 1/2

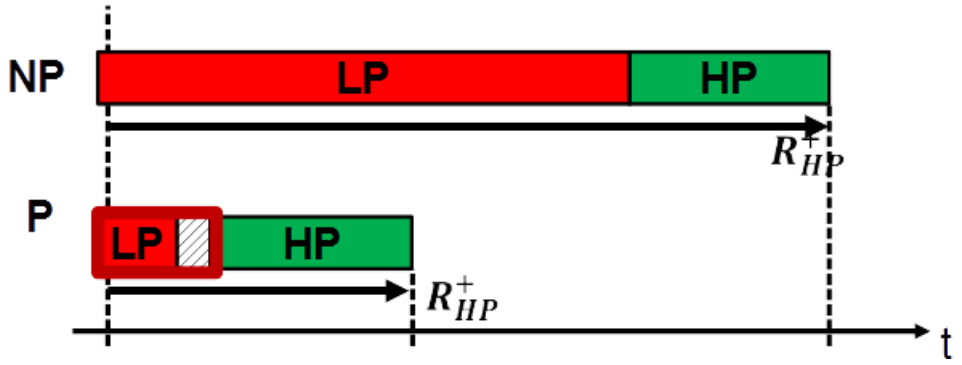
IEEE 802.3br and IEEE 802.1Qbu introduce frame preemption to Ethernet

- Two MAC interfaces Express and preemptable
- Only one level of preemption



Frame preemption 2/2

- Priority based transmission (IEEE802.1Q)



Performance gain due to frame preemption*

12µs vs 120µs @ 100Mbit/s per switch

→ Factor 10 improvement

* Thiele and Ernst. "Formal Worst-Case Performance Analysis of Time-Sensitive Ethernet with Frame Preemption". *ETFA 2016*

Ethernet TSN – Time-Aware Shaper (TSN/TAS)

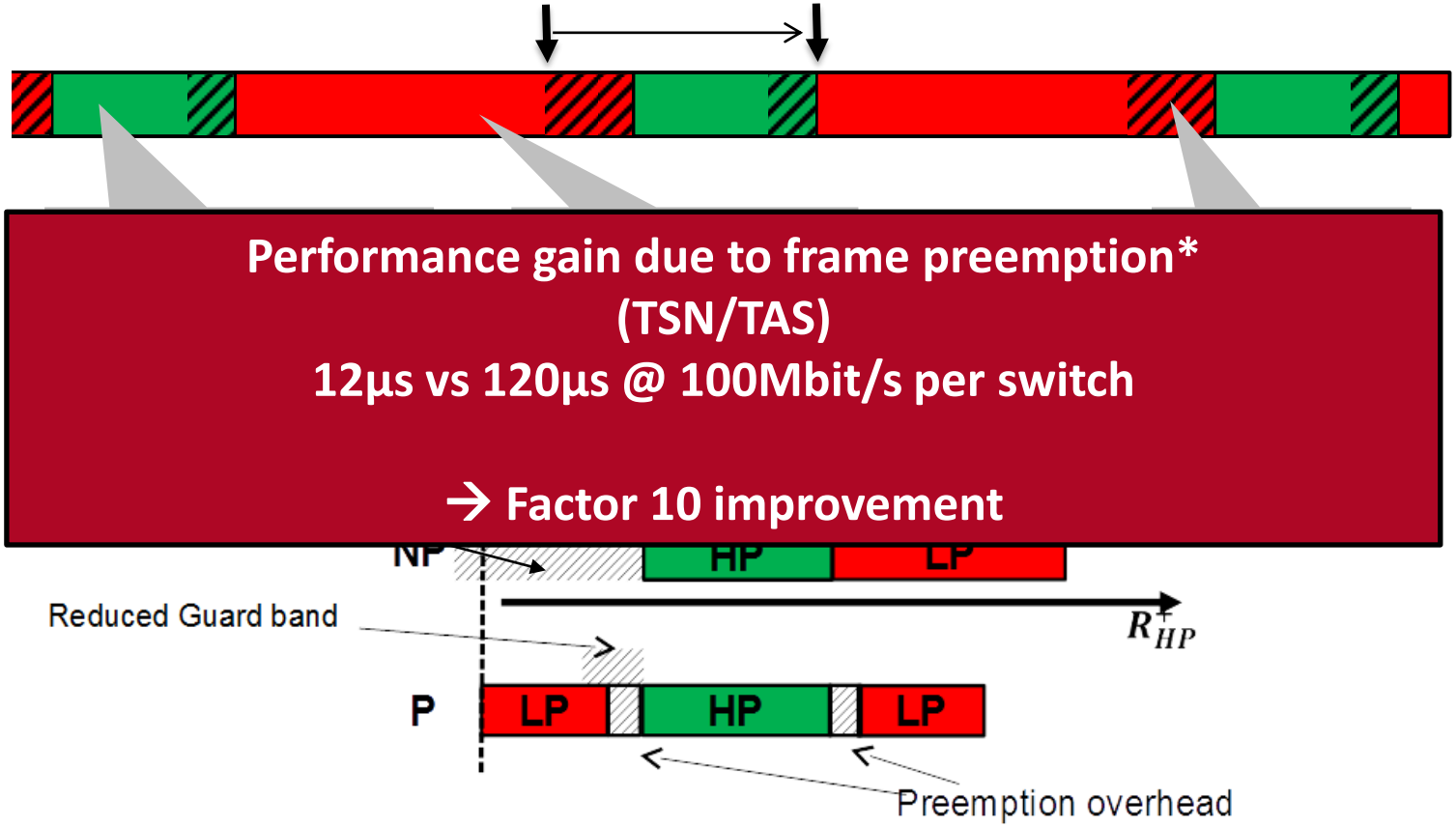
Temporal isolation of two traffic classes via time segments

- **Critical traffic** scheduled in time-triggered segments
  - FIFO order
  - Guard bands prevent segment violations
    - Guard band length equal to longest possible frame size
- **Non-critical traffic** scheduled during remaining time
  - Fixed-priority based and FIFO within same priority class
- Switch synchronization necessary for good performance
- Formal worst-case timing analysis performed*

* Thiele et al., "Formal Worst-Case Timing Analysis of Ethernet TSN's Time-Aware and Peristaltic Shapers". *VNC 2015*

TSN/TAS – Frame Preemption

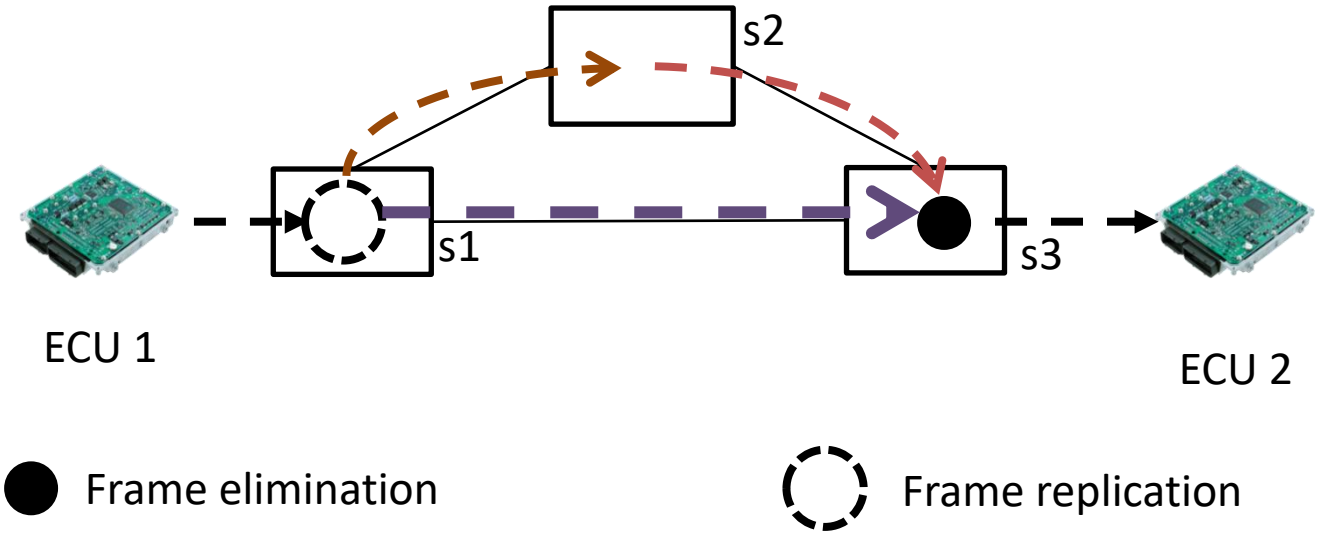
- TAS/TSN (IEEE802.1Qbv)



* Thiele and Ernst, "Formal Worst-Case Performance Analysis of Time-Sensitive Ethernet with Frame Preemption". *ETFA 2016*

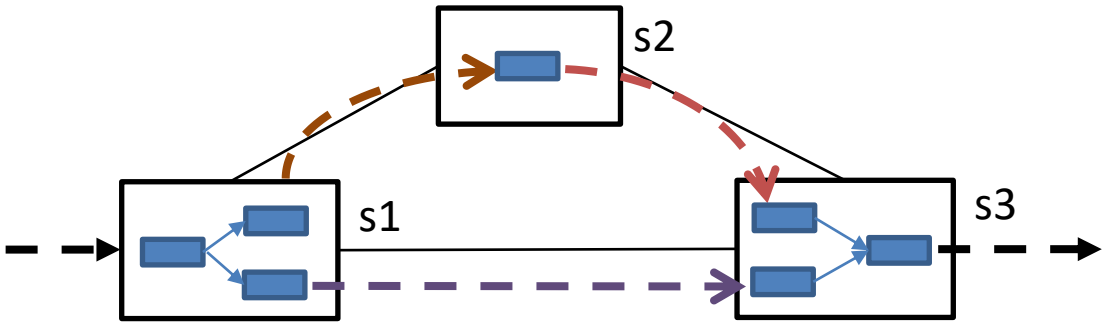
FRER

- Frame replication and elimination for increased reliablity (FRER)
- TSN standard under IEEE802.1CB
- Increased reliablity and reduced packet loss rate under transmission errors



FRER principle

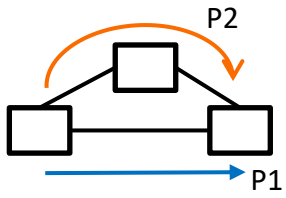
1. Network element receives FRER-proctected stream
2. Replication of stream in traversed element
3. Sending frame copies via redundant paths
4. Merge streams / Elimination of copies
5. Forwarding a single frame

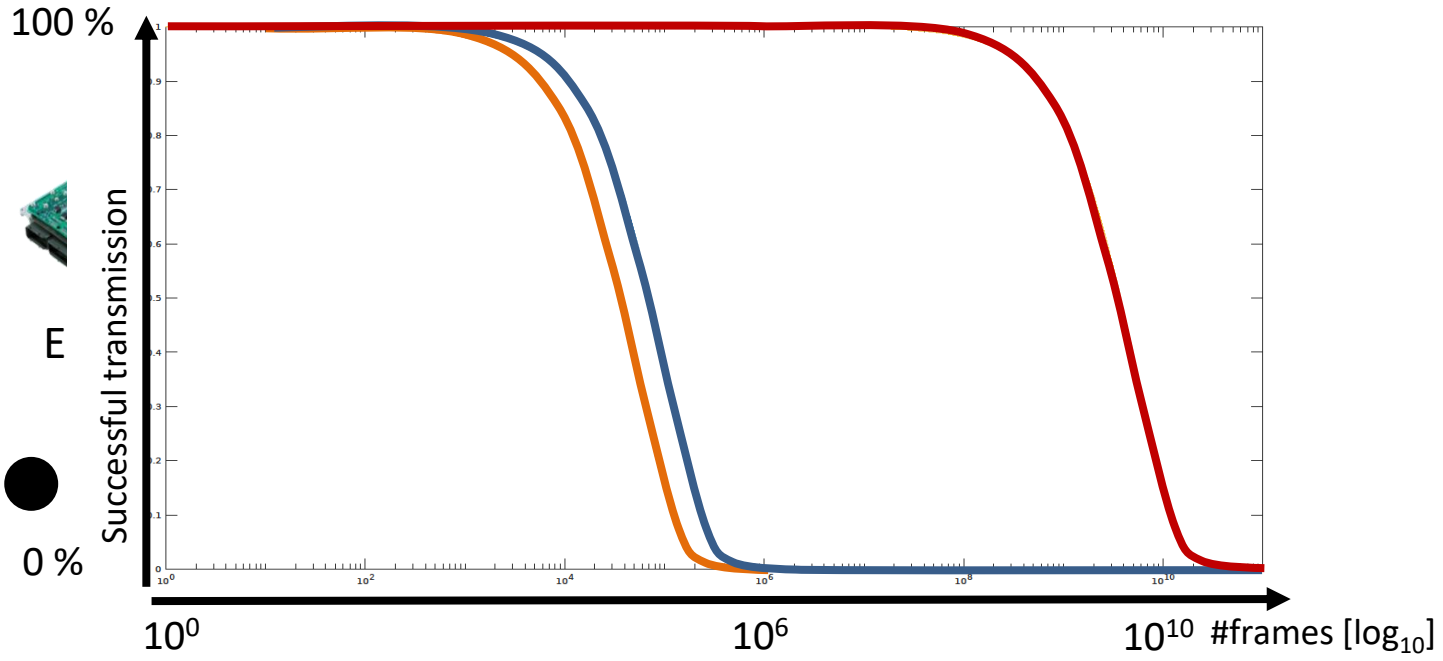


Hofmann et al. „Formal Worst-case Analysis of TSN Ethernet Frame Replication and Elimination for Reliabilty", *Under submission*

FRER – benefits

- Error rate: 10e-10 BER
- Transmission speed: 100Mb/s
- Frame size: 1200 Byte

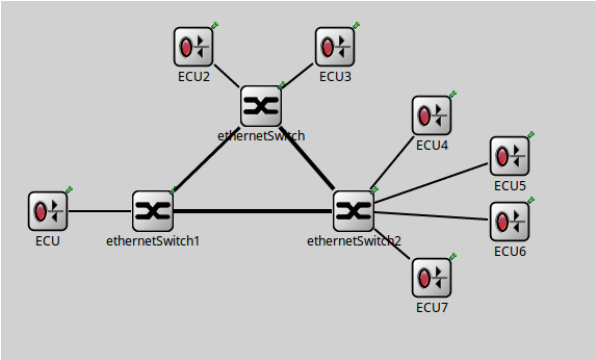


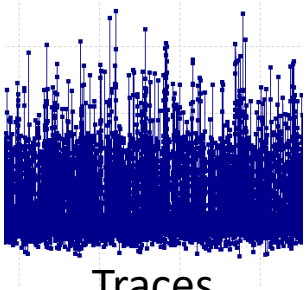


Analysis and simulation tools

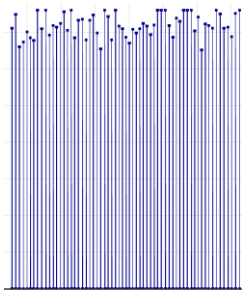
- Formal worst-case timing analysis: pyCPA
- Simulation environment: OMNeT++

- All features implemented in either pyCPA or OMNET.
  - Some in both

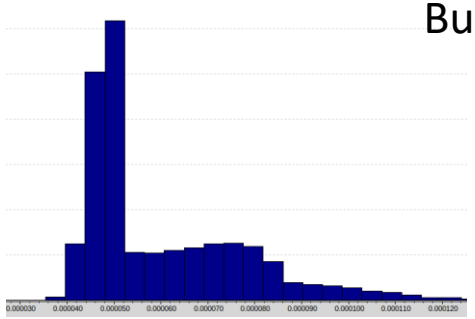




Traces



Buffer levels



End-to-end delay distributions

Future work

- Desired features for next-generation networks
  - Dynamic behaviour
  - Improved safety (resilience to failures)
  - Improved security (intrusion detection)
- TSN lacks solutions to handle dynamics
- Software defined networking (SDN) a promising approach
  - Centralalised network runtime management
  - Already successfully applied in other domains (e.g. OpenFlow)
- Ongoing research topic*
- Future research directions
  - Intrusion detection / run-time admission control
  - Fail-operational behaviour
  - Bootstrapping procedures

* Thiele and Ernst, “Formal Analysis Based Evaluation of Software Defined Networking for Time-Sensitive Ethernet”. *DATE 2016*

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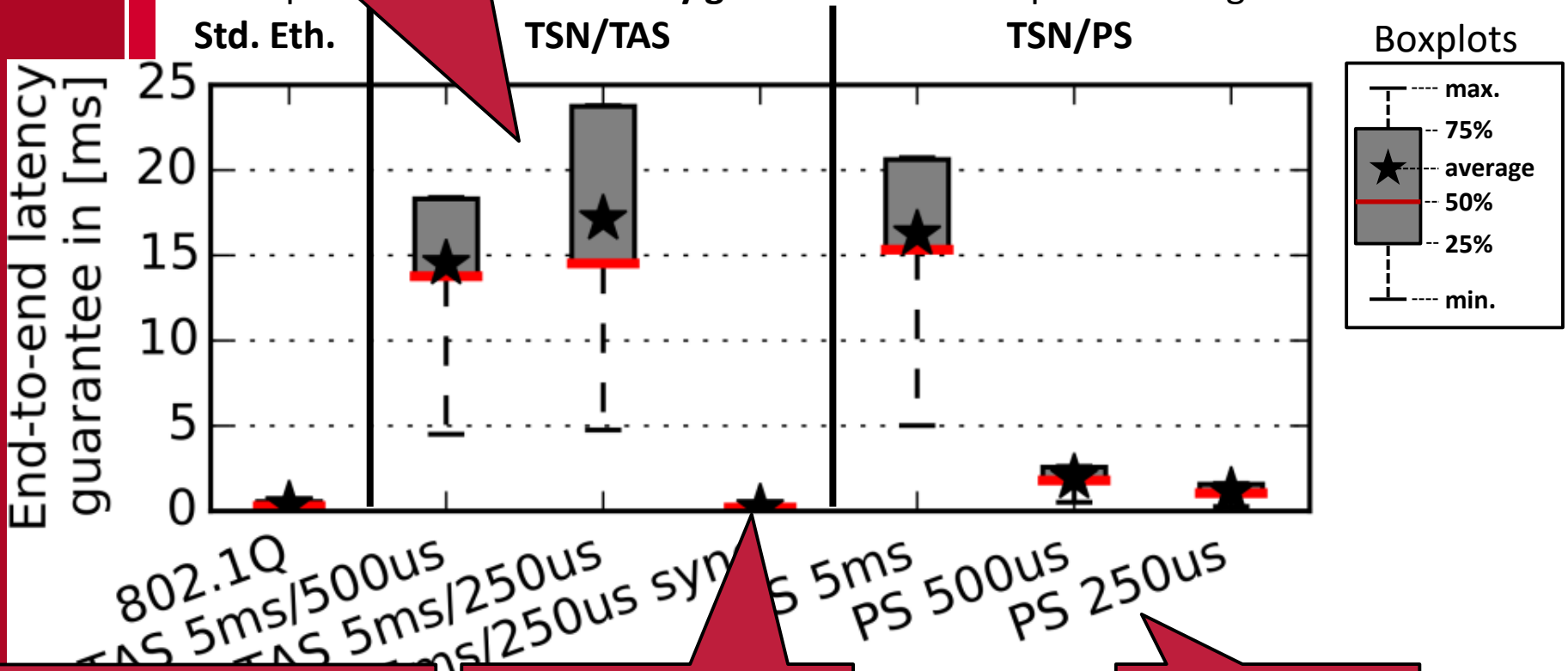
Back up slides

Back up slides – TSN/TAS

Evaluation of the Quad Star Topology – N-Shaped Traffic

- Compar[illegible] **end latency guarantees** on 121 paths through the network



TSN/TAS: significantly worse than std. Eth., if unsynchronized

Only use TSN/TAS with synchronization!

TSN/TAS: very low latencies, if synchronized

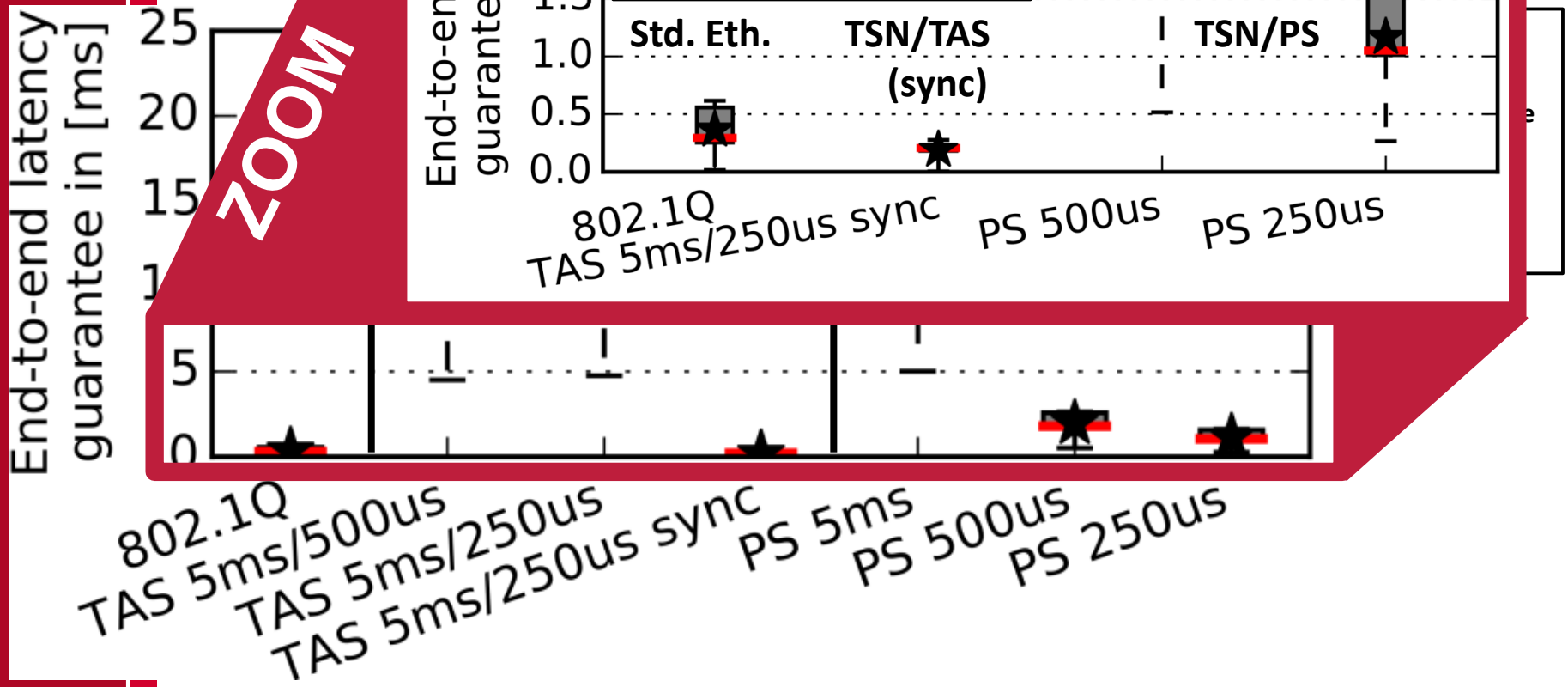
TSN/PS: always worse than std. Eth.

Evaluation of the Quad Star Topology –

Hig

- Compa

Std. Et



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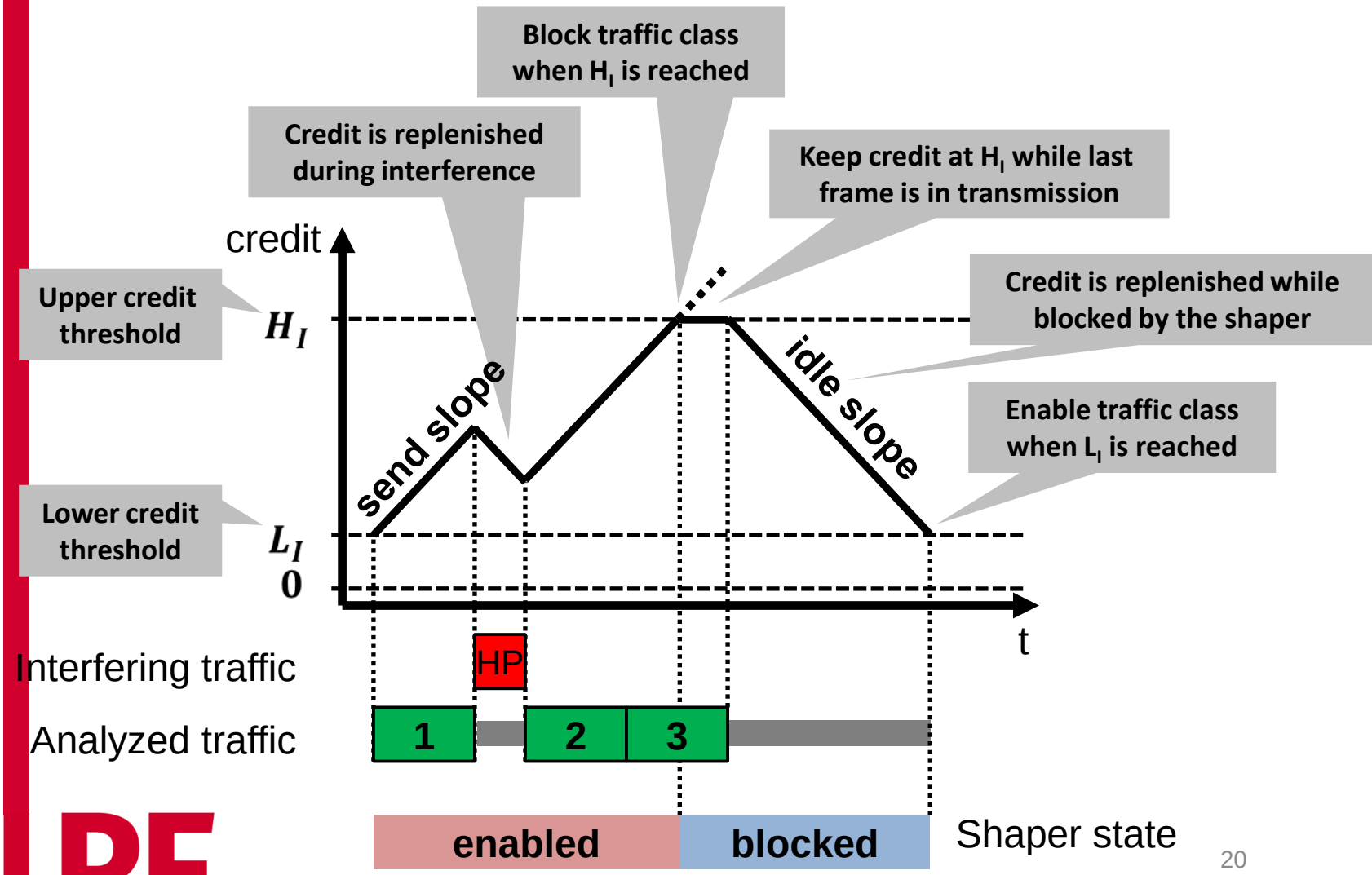
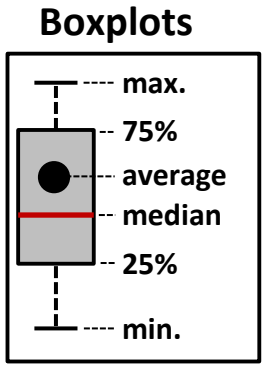
Back up BLS Shaper

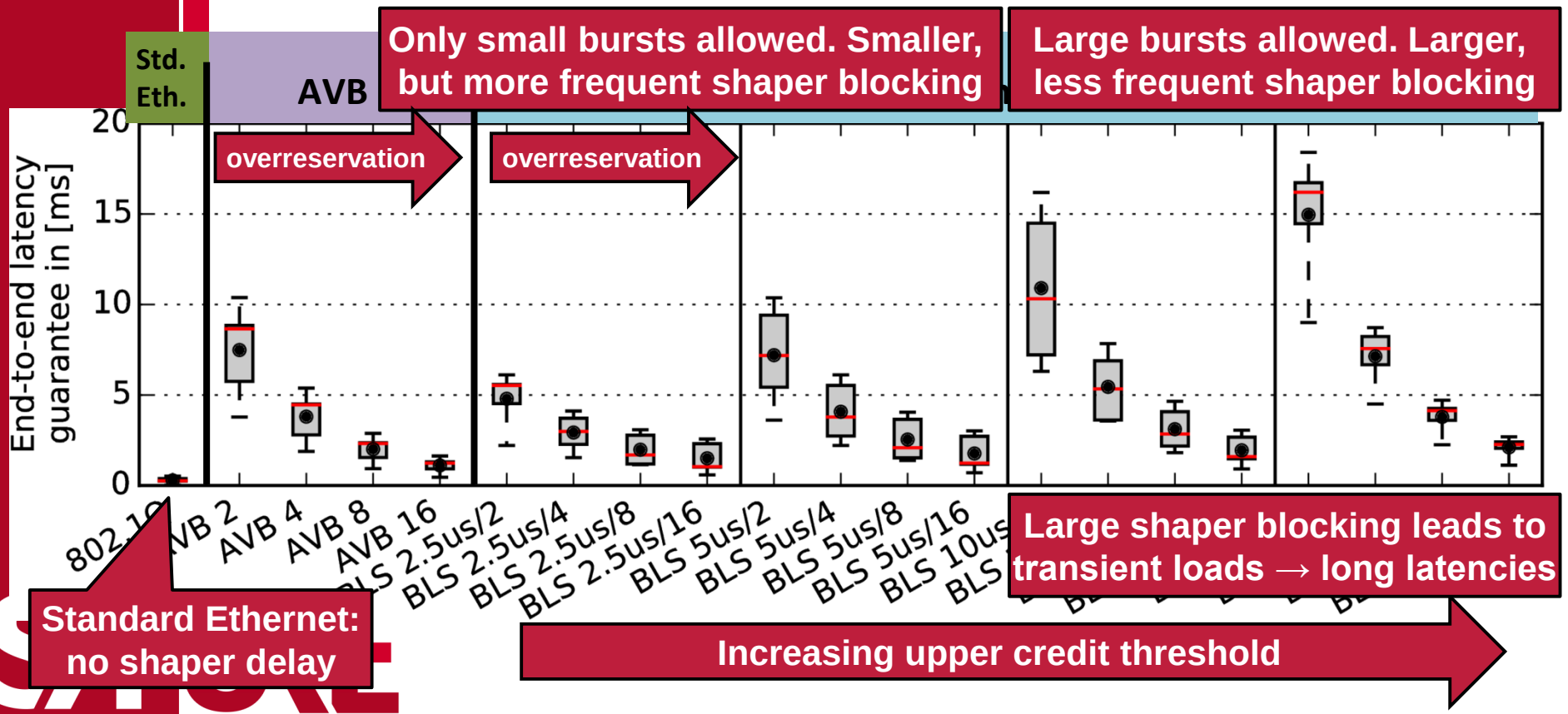
The Burst-Limiting Shaper 1/3



BLS 2/3

- Compare **worst-case end-to-end latency guarantees** of (all) 5 **latency-critical traffic streams**
  - TSN/BLS can give comparable worst-case guarantees as AVB
  - Allowing large bursts in TSN/BLS → large replenishment intervals → longer shaper blocking





BLS 3/3

- Ethernet TSN's burst-limiting shaper
  - **Enforce bandwidth** limits
  - **Allow bursts** of certain size
- Presented **complete formal worst-case analysis** for Ethernet TSN/BLS
  - **End-to-end latencies,** buffer sizes (not part of this presentation)
- Key takeaways for TSN/BLS
  - TSN/BLS allows **better shaper control than AVB**
  - **No advantage of using TSN/BLS over AVB** from a worst-case perspective
    - Shaper delay proportional to the bandwidth limit
  - **Shaping has significant impact on worst-case guarantees**

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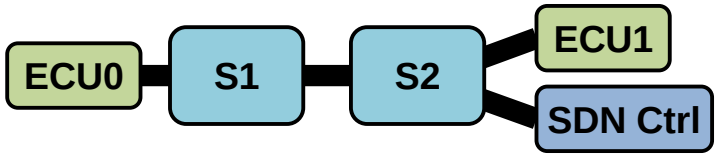
Back up Slides - SDN

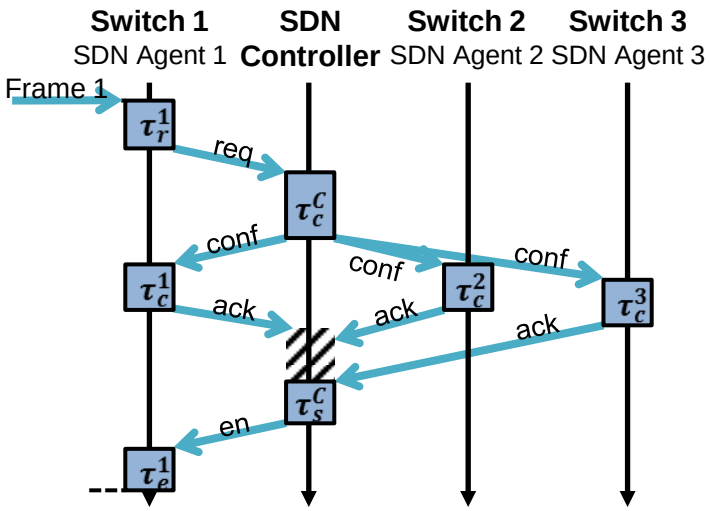
SDN 1/4

- Goal: derive timing guarantees
- Model SDN in **compositional performance analysis** framework [Henia2005]

Topology

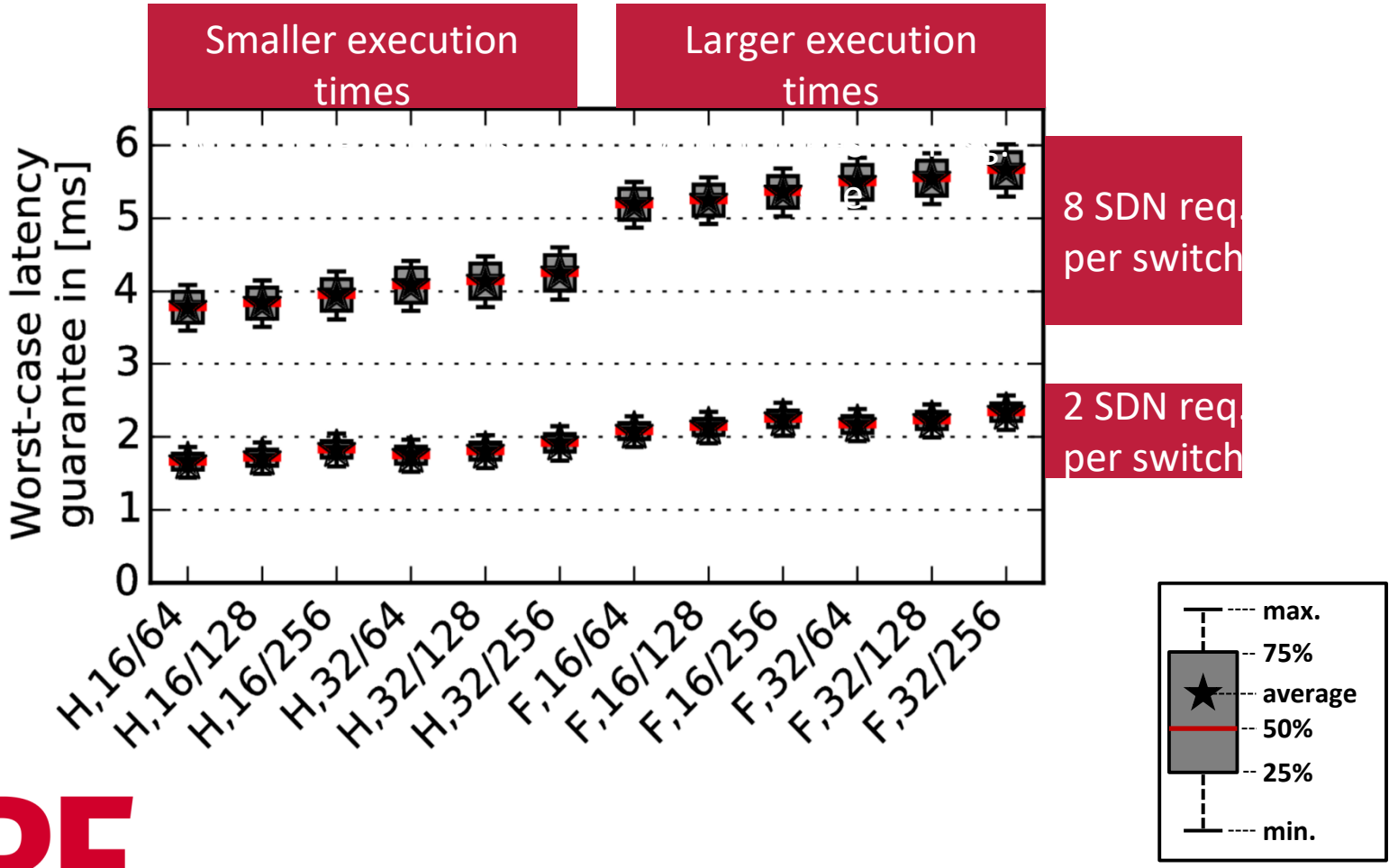


SDN Traffic



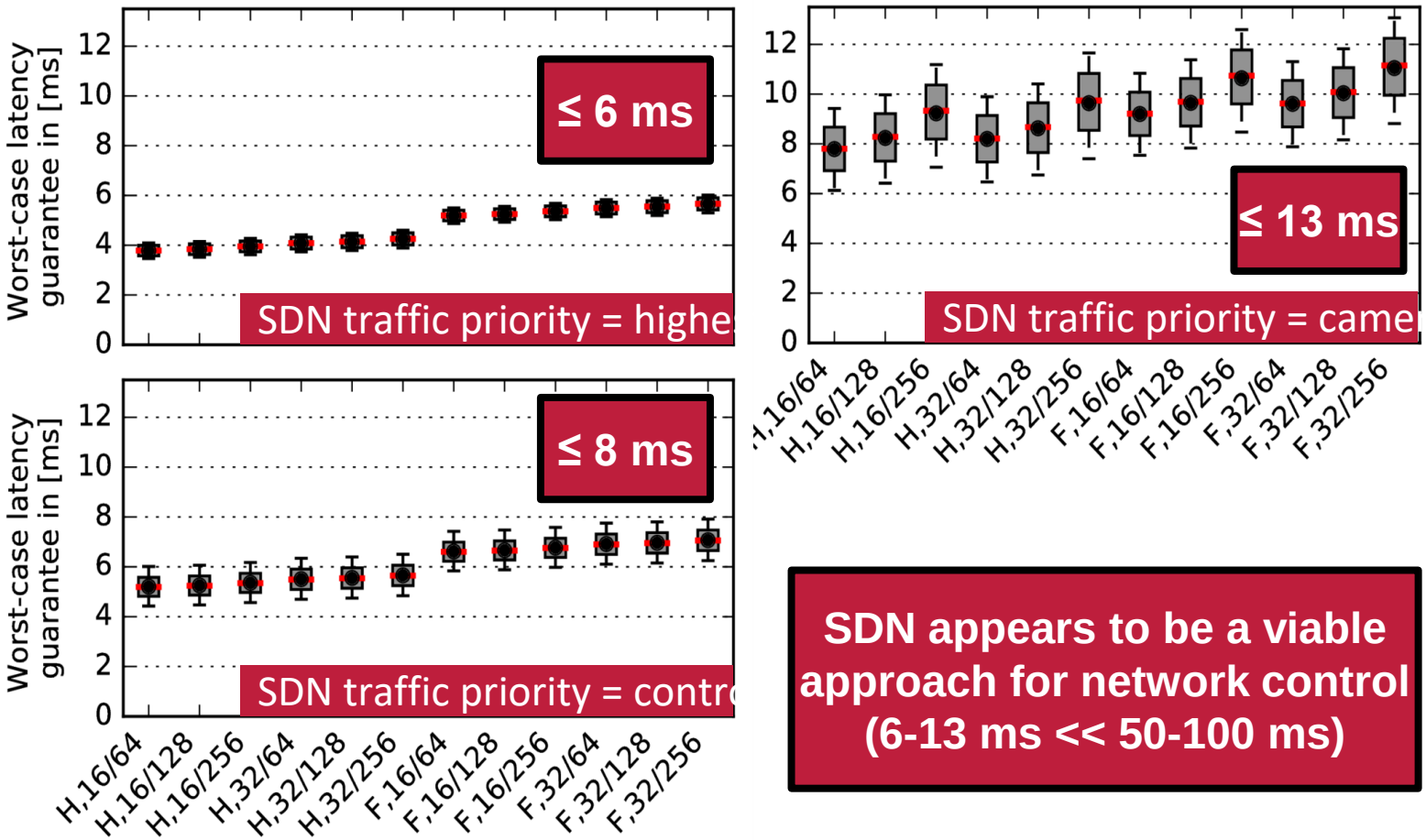
SDN 2/4

- Setup: SDN traffic on highest priority, **variable number SDN requests, request sizes, and execution times**



SDN 3/4

- Setup: **variable SDN traffic priority**, 8 SDN requests per switch, variable request sizes and execution times



SDN appears to be a viable approach for network control (6-13 ms << 50-100 ms)

SDN 4/4

- **Software Defined Networking** is an **interesting** approach to solve the **requirements of future automotive networks**
  - **Freedom from interference** (ISO 26262)
  - **Redundancy** control

- Evaluated the **general suitability of SDN for real-time applications**
  - Typical **automotive setup**
  - SDN **network reconfiguration** times are less than 13 ms
  - **Impact on normal traffic** latencies are less than 3 ms (not shown here)

- **Key takeaways**
  - **Formal timing analysis** of SDN is **possible**
  - **SDN is fast enough** for real-time networks

- Towards **SDN for automotive networks** (SAFURE project, www.safure.eu)
  - Protocol design
  - SDN controller is single point of failure
  - …

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