Beware of the Hidden!

How Cross-traffic Affects Quality Assurances of Competing Real-time Ethernet Standards for In-Car Communication

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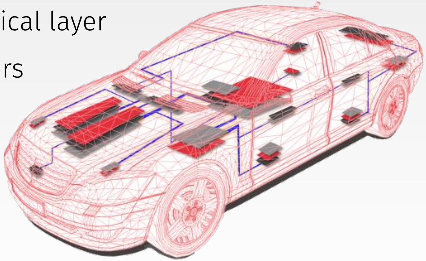
Agenda

Problem Statement

The heterogeneity of in-car networking or why we should consider Ethernet

- The in-car network grew over the past decades
- Continuous demand required introduction of new technologies
  - High bandwidth sensors (LIDAR, radar), high resolution cameras, ...
- Today, extremely heterogeneous network formed of domain specific technologies
  - CAN, FlexRay, MOST, ...
- Ethernet promises for in-car networks ...
  - A mature technology
  - High bandwidth and flexible physical layer
  - Huge knowledge among developers



Motivation & Challenge

Ethernet as a homogeneous backbone

- Ethernet as "one more" in-car communication technology only advances heterogeneity and complexity
- Full benefit in homogeneous Ethernet-based backbone design
- Previous work showed general feasibility for an in-car backbone[1]
- Upcoming applications demand low priority background traffic in parallel with real-time control messages
  - Software updates, diagnosis, update of databases (maps, metadata), offloading of tasks in the cloud, ...

Will background cross-traffic corrupt real-time guarantees?

[1] Till Steinbach, Hyung-Taek Lim, et al.:"Tomorrow's In-Car Interconnect? A Competitive Evaluation of IEEE 802.1 AVB and Time-Triggered Ethernet (AS6802)". Sept. 2012.

- Standard Ethernet not suitable for in-car real-time traffic
  - Requirements of contol-data: End-to-end latency down to ≈100 µs
  - Driver assistance: latency of video frame down to ≈25 ms
- Two competing real-time Ethernet approaches

Event-triggered:

- E.g. IEEE 802.1Qav, AFDX (rate-constrained), ...
- Strict priorities
- Shaping of bursts (e.g. credit based shaper)

Time-triggered:

- E.g. TTEthernet, PROFINET, IEEE 802.1Qbv, ...
- Strict priorities
- Scheduling (coordinated TDMA)

IEEE 802.1 Audio Video Bridging Protocol Suite

- Set of standards developed in the IEEE
- Provides Queuing and Forwarding Rules in IEEE 802.1Qav
- 3 traffic classes:
  - Stream Reservation Class A (SR A)
    Based on IEEE 802.1Q, credit based shaper, maximum latency of 2 ms over 7 hops
  - Stream Reservation Class B (SR B)
    Similar to (SR A) but maximum latency of 50 ms over 7 hops
  - Best-effort (BE)
    Lowest priority, standard Ethernet
- Dynamic Stream Reservation Protocol

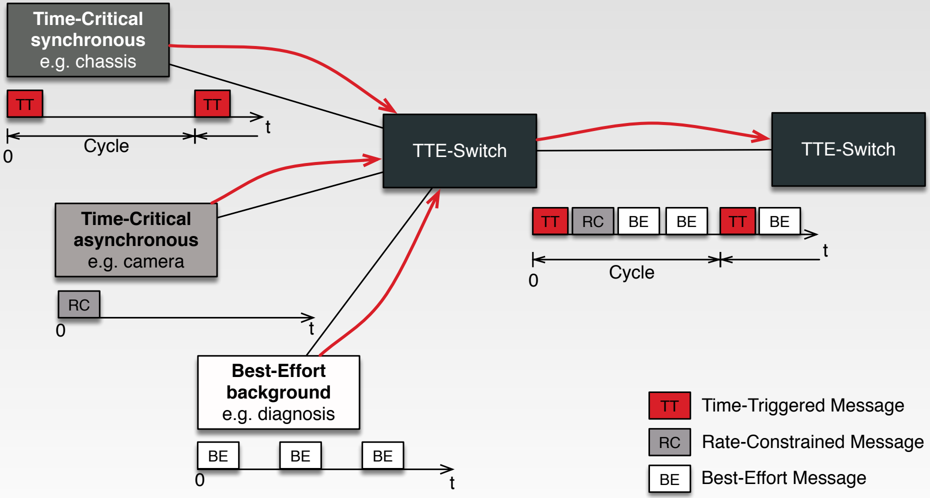
Time-triggered Ethernet (AS6802)

Mixed critical applications through IEEE 802 networks

- Extension to standard switched Ethernet
- SAE standardized in 2011 (AS6802)
- 3 traffic classes:
  - Time-triggered (TT)
    Highest priority, time-triggered, cyclic, offline planned, requires synchronized time
  - Rate-constrained (RC)
    Event-triggered, bandwidth-based (AFDX)
  - Best-effort (BE)
    Lowest priority, standard Ethernet
- Scheduled (time-triggered) Traffic currently worked on in IEEE TSN-Group (PAR 802.1Qbv - Enhancements for Scheduled Traffic)

Time-triggered Ethernet (AS6802)

Ethernet for mixed critical applications



- Discrete event based simulation
  - OMNeT++ network simulation framework
  - Models for TTEthernet[2] and Ethernet AVB[3]
- Realistic traffic-flows derived from configuration of BMW series car
- Tree based topology
- Analysis of real-time control-traffic, driver assistance camera streams, and multimedia
- In focus are: end-to-end latency and jitter

[2] Till Steinbach, Hermand Dieumo Kenfack, et al.:"An Extension of the OMNeT++ INET Framework for Simulating Real-time Ethernet with High Accuracy". Mar. 2011.

[3] Hyung-Taek Lim et al.:"Performance analysis of the IEEE 802.1 ethernet audio/video bridging standard". Mar. 2012.

Traffic Model

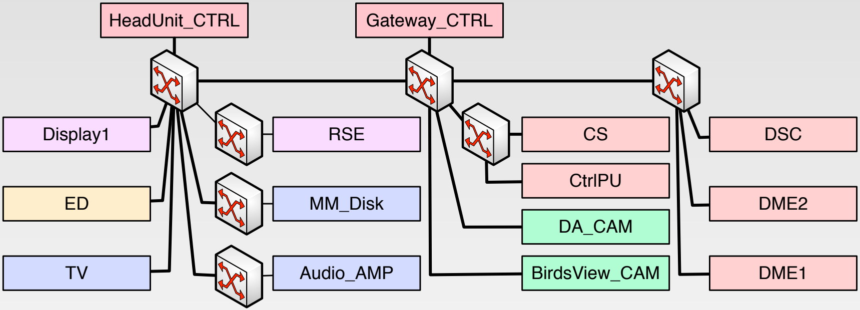
Traffic flows of in-car applications

Type	Bandwidth [Mbit/s]	IEEE 802.1 AVB Class	TTEthernet Class (Priority)
Control	$(0.37...73.6) \cdot 10^{-3}$	A	TT + RC (Prio 0...5)
Camera	25	A	RC (Prio 6)
TV	10...20	B	RC (Prio 7)
Media Audio	8	B	RC (Prio 7)
Media Video	40	B	RC (Prio 7)
Cross-traffic (1 MB bursts)	Bursts	Best-effort	Best-effort

- Control traffic: Low bandwidth, high timing requirements
- Driver assistance camera: High bandwidth, medium timing requirements
- Multimedia traffic: High bandwidth, low timing requirements
- Interspersing cross-traffic bursts: low timing requirements

Topology

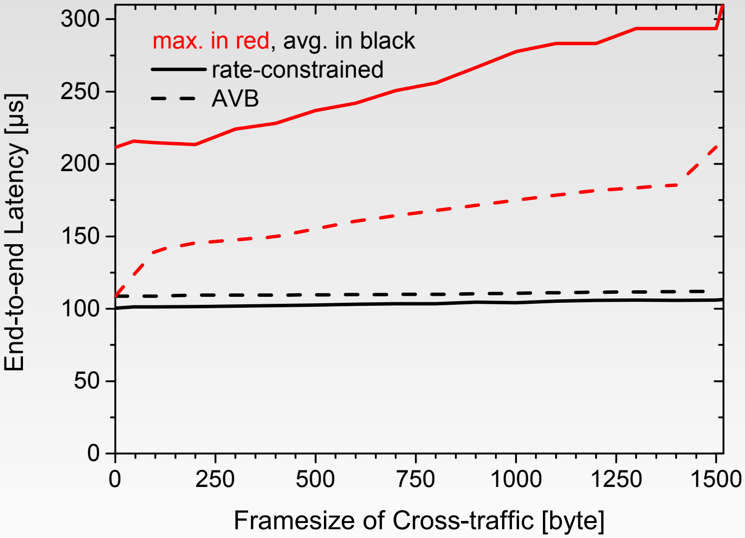
A tree based in-car network design by BMW



- 22 Nodes, 7 Switches, 21 Links
- Tree structure with one root switch
- Domain specific regions in the network

Real-time Camera Stream

End-to-end latency with varying cross-traffic frame sizes

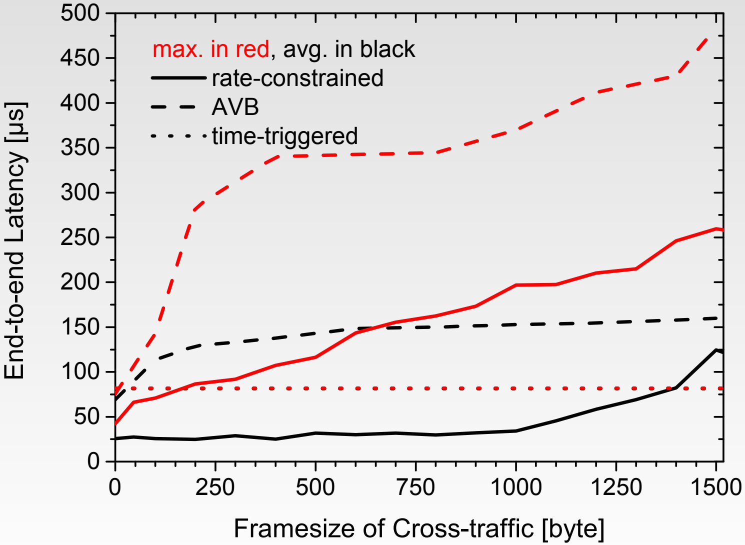


Real-time Camera Stream

Results in detail

Frame Size Cross-traffic [B]	IEEE 802.1 AVB Latency [µs]	IEEE 802.1 AVB Jitter [µs]	Rate-constrained Latency [µs]	Rate-constrained Jitter [µs]
0	108.71	17.51	211.34	111.43
100	140.27	20.75	214.75	114.83
800	167.77	38.87	255.98	156.06
1518	211.70	59.30	311.37	211.45

- Ethernet AVBs credit based shaper outperforms rate-constrained traffic
- Significant increase for both protocols, still well within application requirements



max. in red, avg. in black
rate-constrained
AVB
time-triggered
End-to-end Latency [µs]
Framesize of Cross-traffic [byte]
0
50
100
150
200
250
300
350
400
450
500
0
250
500
750
1000
1250
1500

Control Traffic
Results in detail

Size Cr. Tr. [B]	IEEE 802.1 AVB Latency [µs]	IEEE 802.1 AVB Jitter [µs]	Time-triggered Latency [µs]	Time-triggered Jitter [µs]	Rate-constrained Latency [µs]	Rate-constrained Jitter [µs]
0	75.69	7.23	82.02	1.17	42.26	19.12
100	142.97	10.58	82.03	1.16	70.95	47.81
800	344.64	69.60	82.02	1.15	162.57	139.43
1518	484.27	112.82	82.02	1.16	258.48	235.34

- Time-triggered control traffic admits excellent results
- AVB and rate-constrained traffic suffer heavily from cross-traffic

Discussion

Why time-triggered traffic is not always the best choice

- Best results for time-triggered class (no influence by cross-traffic)
- Time-triggered messages offer end-to-end latency under 100 μs
- Rate-constrained and AVB traffic suffers from cross-traffic
  - Latency up to 5 times higher
  - jitter up to 14 times higher

But:

- Time-triggered traffic ...
  - is not plug-and-play (requires static schedules)
  - wastes bandwidth (due to link reservation)
- It is desirable to use event-triggered messages for real-time tasks

Can we improve the network to transport cross-traffic and still have sufficient real-time guarantees for event-triggered messages?

Propositions to overcome performance limitations:

- Shaping cross-traffic & Optimized system design
- Adapting the topology to traffic flows
- Limiting MTU
- Increasing bandwidth
- Frame preemption

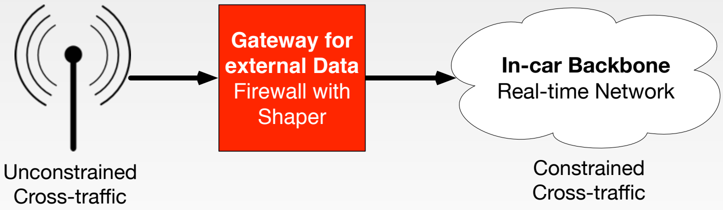
Not every strategy is applicable to all architectures!
Careful individual assessment required!

Shaping Cross-traffic & Optimized System Design

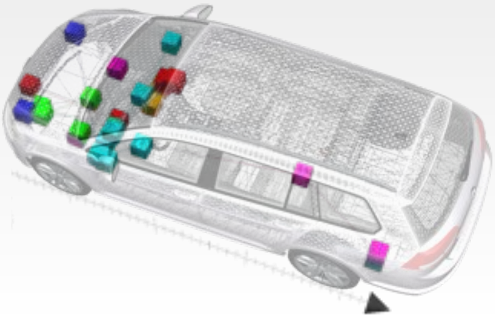
Applying static rules and dynamic shaping to control cross-traffic

Avoid performance degradation by artificially limiting cross-traffic:

- Design rules for cross-traffic applications:
  Static approach, rules for the developer when implementing communication
- Traffic shapers at entry points (gateways) of cross-traffic:
  Dynamic approach, implemented in the network

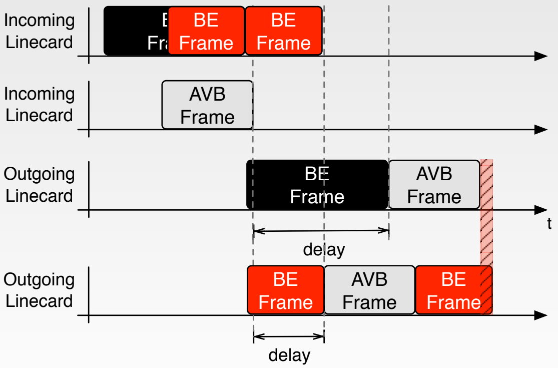


- Latency increase proportional to number of hops with concurrent cross-traffic
- Considering cross-traffic while designing network topology can significantly improve latency and jitter
- Entry of background messages near ECUs with most inbound cross-traffic
- Avoid daisy chains wherever possible



Limiting MTU
Attenuate the impact of frame congestion

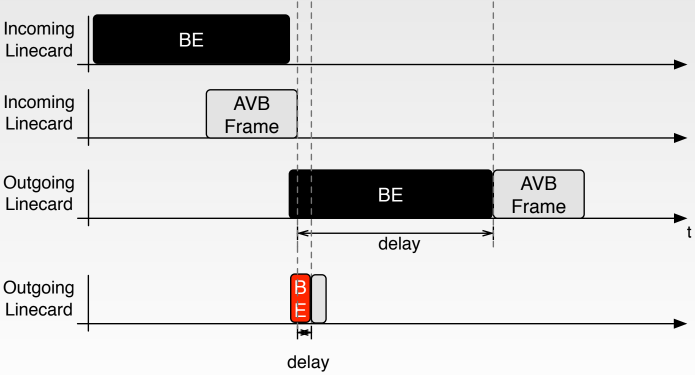
- Frame size of cross-traffic significantly impacts latency and jitter
- Cross-traffic bursts use large frames to reduce overhead
- Tradeoff between overhead and latency when reducing MTU



Increasing Bandwidth

Reducing delays by increasing capacity

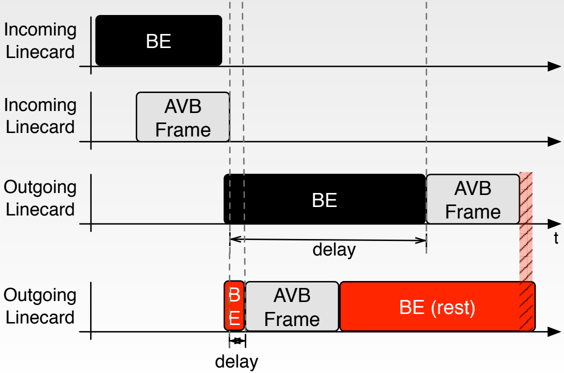
- Increased bandwidth not only allows to transfer more data, but also reduces delays of real-time messages
- "Automotive" Gigabit Ethernet on its way: IEEE P802.3bp (RTPGE)
- Gigabit not only for saturated links, but also for time-critical paths



Frame Preemption

On-demand splitting of large Ethernet frames

- Frame preemption is under development (IEEE TSN and 802.3 Groups) e.g. PAR 802.1.Qbu
- On-demand splitting frames into chunks of at least 64 B
- Largest unsplittable Frame is 127 B or 11.76 µs transmission time
- Comparable to delay of full size frame using 1 Gbit/s



- Real-time control traffic in parallel with best-effort cross-traffic will soon become reality in in-car networks
- We analyzed impact of cross-traffic on real-time Ethernet extensions considered for in-car backbones:
  - Time-triggered messages remain unaffected
  - Event-triggered classes (AVB, rate-constrained) have up to 5 times higher end-to-end latency and up to 14 times higher jitter
- Design optimizations and protocol improvements can reduce impact of concurrent cross-traffic

In our ongoing and future work we will ...

- Assess frame preemption (IEEE 802.1Qbu)
- Analyze heterogeneous Ethernet-Fieldbus designs
- Confirm our findings in our real-world prototype car

Outlook

Our real-world prototype

Outlook

Our real-world prototype

Outlook

Our real-world prototype

Outlook

Our real-world prototype

Thank you for your attention!

See you in the demo session!

- Website of CoRE research group:
`http://www.haw-hamburg.de/core`
- Website for Download of simulation models:
`http://core4inet.core-rg.de`

Literatur I

[1] Till Steinbach, Hyung-Taek Lim, et al. “Tomorrow’s In-Car Interconnect? A Competitive Evaluation of IEEE 802.1 AVB and Time-Triggered Ethernet (AS6802)”. In: *2012 IEEE Vehicular Technology Conference (VTC Fall)*. Piscataway, New Jersey: IEEE Press, Sept. 2012. DOI: `10.1109/VTCFall.2012.6398932`. ieeexplore: `6398932`.

[2] Till Steinbach, Hermand Dieumo Kenfack, et al. “An Extension of the OMNeT++ INET Framework for Simulating Real-time Ethernet with High Accuracy”. In: *Proceedings of the 4th International ICST Conference on Simulation Tools and Techniques*. Barcelona, Spain: ACM-DL, Mar. 2011, pp. 375–382. acmdl: `2151120`.

[3] Hyung-Taek Lim et al. “Performance analysis of the IEEE 802.1 ethernet audio/video bridging standard”. In: *Proceedings of the 5th International ICST Conference on Simulation Tools and Techniques*. Desenzano del Garda, Italy: ACM-DL, Mar. 2012, pp. 27–36.