System Level Simulation for the Design and Evaluation of Heterogeneous Ethernet, CAN, and FlexRay In-Car Networks

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Agenda

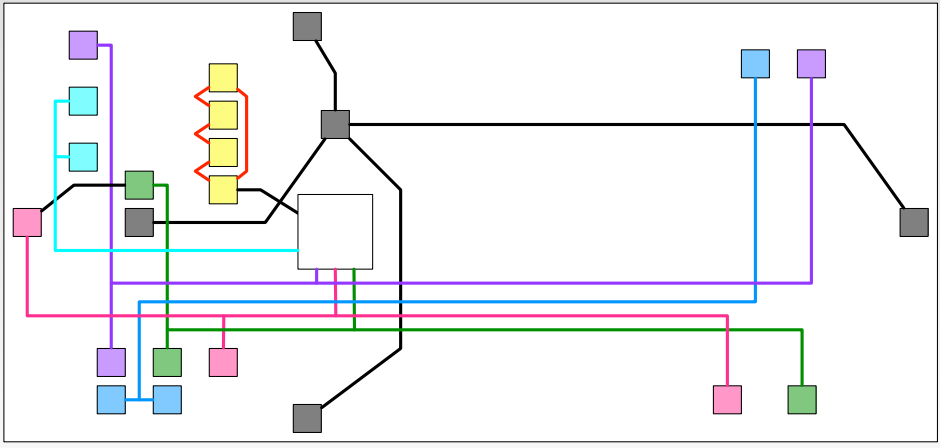
Ethernet for cars is not new!

- Series cars with ”Ethernet” commercially available

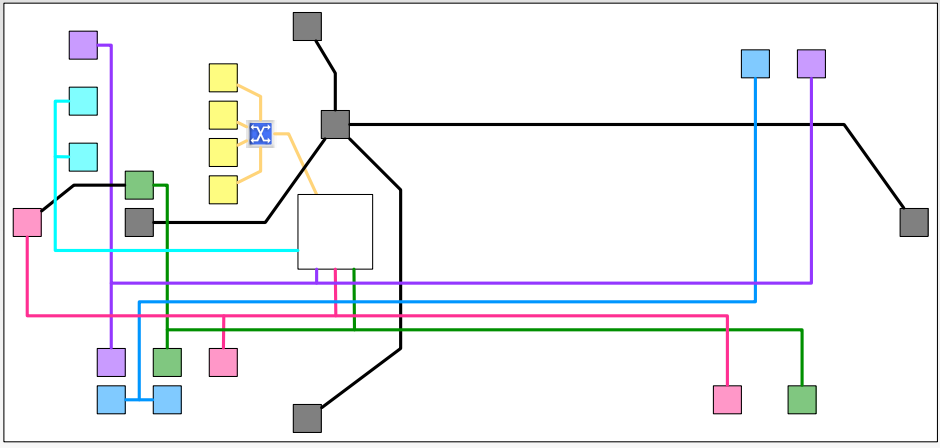
But:

- Not the Ethernet we are thinking of!
  - Dedicated links
  - Single purpose
  - No critical traffic
  - Only for bandwidth reasons?
  - ...

Ethernet in today's cars
Limited applications

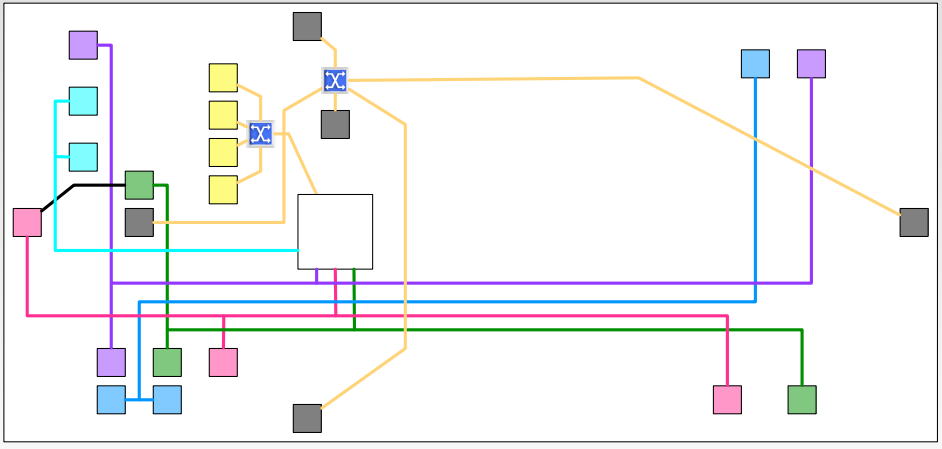


Ethernet in today's cars
Limited applications



Ethernet in today's cars

Limited applications

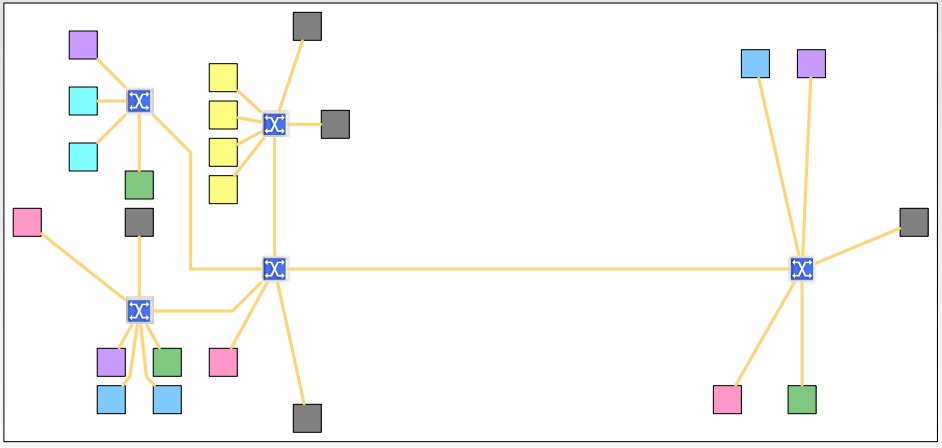


Let us look in the future! – Maybe 2020-2025?

- Homogenous Backbone build on Ethernet
- One single technology
- Switched network
- Reduced complexity
- Communication across domain boarders
- Reduced wiring harness?

Ethernet for tomorrow's cars

An Ethernet based backbone



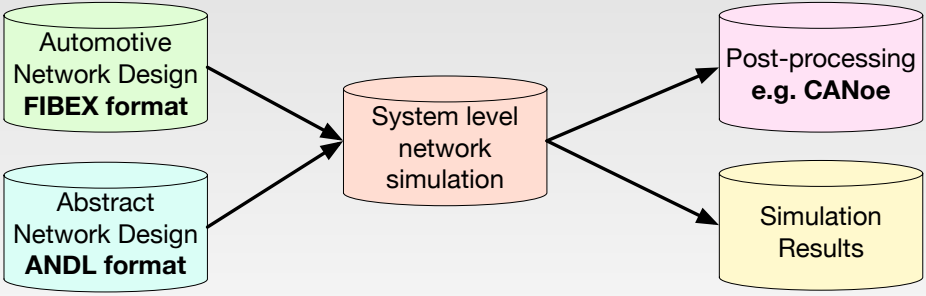
Some of the challenges of automotive Ethernet:

- Smooth transition from legacy busses to Ethernet required
- Automotive development is distributed
- Shared responsibilities
- Communication must be designed and specified early
- Traffic of different domains may interfere
- Paradigm change (Scaling bandwidth, no additional busses required)
- New design rules

Some typical questions to be answered:

- Assessment of quality of service with different traffic classes, protocols and media access strategies in parallel
- Design and configuration of gateways between legacy technologies and (real-time) Ethernet
- Evaluation of impact of concurrency – e.g. cross-traffic
- Prediction of hardware requirements for ECUs, switches, gateways, ...
- Analysis of expected behavior prior to prototyping

- Simulating communication of car on abstract level
- For early development phase:
  - Evaluation of protocols
  - Design of architectures
  - Configuration
  - Hardware requirement prediction
- Simulation makes problems visible (white-box)
- Supports debugging and understanding of a system
- Established technology (e.g. in computer or communication networks)
- No proof of worst cases, but strong prediction!


Automotive
Network Design
FIBEX format
Abstract
Network Design
ANDL format
System level
network
simulation
Post-processing
e.g. CANoe
Simulation
Results

Demo video

Agenda

1 Problem Statement & Motivation

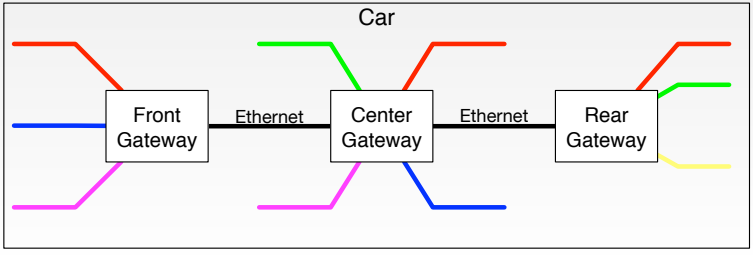
2 System Level Simulation

3 Network Simulation in Practice
- Gateway Strategies
- Cross Traffic
- Prototype

4 Conclusion & Outlook

- Several busses (e.g. CAN, FlexRay)
- Each bus hosts a specific domain
- Typically, one central gateway
- Gateway translates messages between the domains

- Interconnection of busses and Ethernet required (interim period)
- Many open questions, e.g.:
  - Representation of bus in Ethernet frame
  - Bandwidth efficiency (MTU problem)
  - Aggregation strategies of frames
  - Delay impact of aggregation strategies
  - Efficiency and multicast
  - ...



Why simulating gateway strategies?

- Early design decisions
- Simulation does not require to manipulate the system for measurement
- Simulation allows to assess huge parameter sets

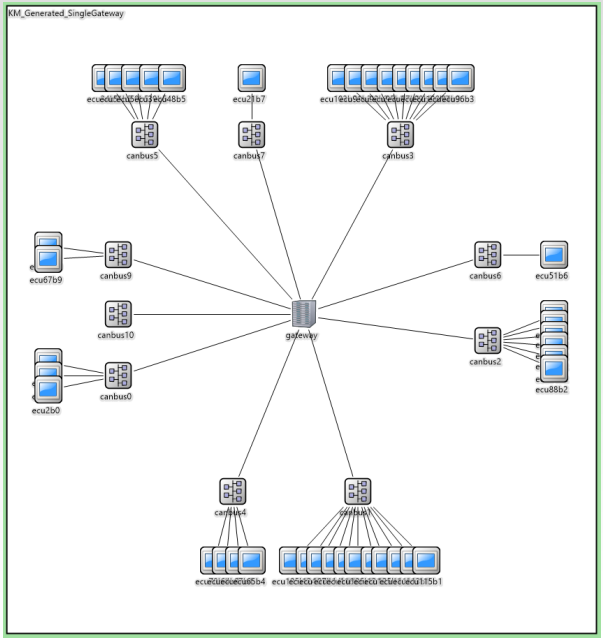
Simulating communication of series car using Ethernet backbone

- Volkswagen Golf 7
- 7 CAN busses
- Real world traffic streams
- replacing the central gateway with Ethernet backbone

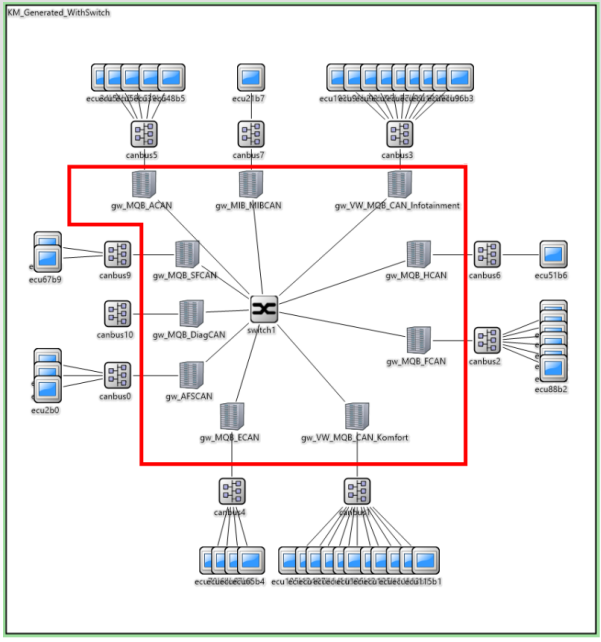
We are most interested in:

- Utilization, latency, jitter, queue lengths

Central Gateway



Central Gateway



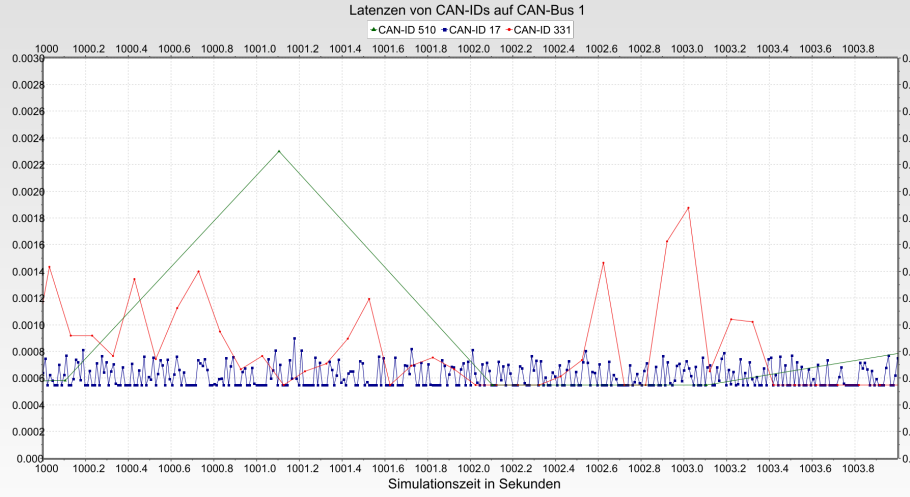
Configuration:

- Standard Ethernet traffic
- No prioritization on Ethernet
- One Ethernet frame per CAN message
- No multicast

Results:

- Utilized bandwidth below 1% of Ethernet link
- End-to-end latency increase below 10 %
- No noticeable jitter increase (below jitter due to arbitration)

Central Gateway
Latency Results



- Same traffic flows
- Aggregation with two message pools
  - Express traffic with short holdup time
  - Traffic with holdup time according to priority and period

CAN ID	Hold-up time	Pool
< 101	1 ms	Express
101 - 200	25 % of period	Default
201 - 300	50 % of period	Default
300 <	75 % of period	Default

- Significant latency increase (must be checked against requirements):

CAN-ID	No Aggregation [µs]	Aggregation [µs]
17	984	1987
331	8658	13643
510	18415	24470

- Significant jitter increase
- Bandwidth utilization reduced by more than 50%

Lessons learned:

- Even a low holdup time can significantly reduce required bandwidth
- Aggregation results in significantly higher latency and jitter
- The more knowledge of the applications that use the gateway are available, the better the configuration can be tuned

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   - Cross Traffic
   - Prototype
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What is Cross Traffic?

- 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 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
- 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)

Time-triggered Ethernet (AS6802)

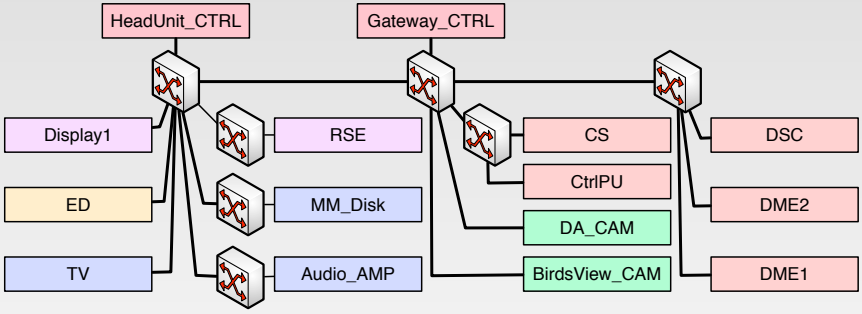
Mixed critical applications through IEEE 802 networks

- 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)

- Realistic traffic-flows derived from configuration of BMW series car
- In focus are: end-to-end latency and jitter

Type	Bandwidth [Mbit/s]	IEEE 802.1 AVB Class	TTEthernet Class (Priority)
Control	$(0.37\ldots73.6) \cdot 10^{-3}$	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

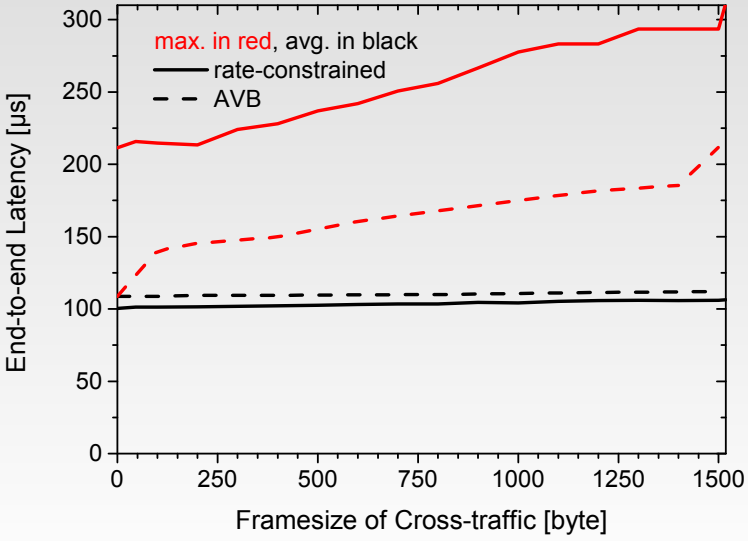
Topology
A tree based in-car network design by BMW



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

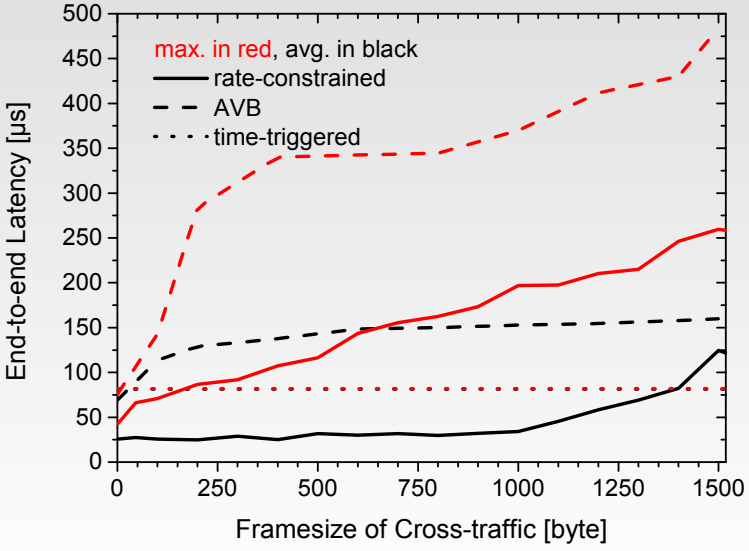
Real-time Camera Stream

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



Control Traffic

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



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

Performance Improvements

How to overcome limited performance when adding cross-traffic

Propositions to overcome performance limitations:

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

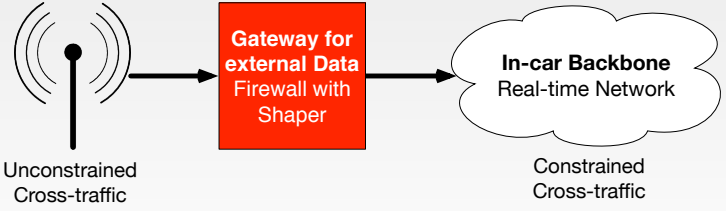
Not every strategy is applicable to all architectures!
Careful individual assessment required!
System level network simulation suites well for these assessments

Shaping Cross-traffic & Optimized System Design

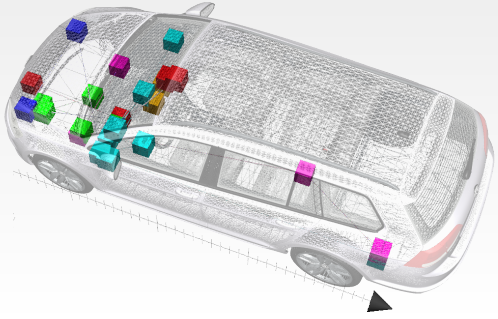
Applying static rules and dynamic shaping to control cross-traffic

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



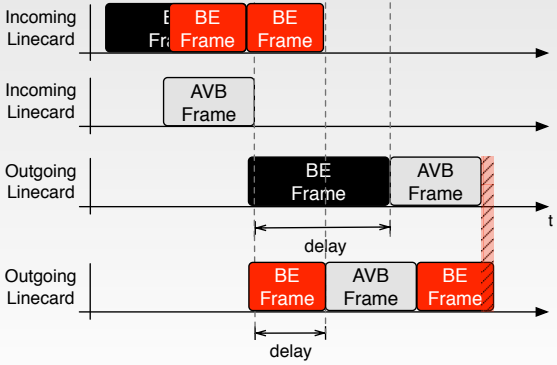
- Latency increase proportional to number of hops with concurrent cross-traffic
- Considering cross-traffic while designing network topology can significantly improve latency and jitter
- Entry of background messages near ECUs with most inbound cross-traffic
- Avoid daisy chains wherever possible



Limiting MTU

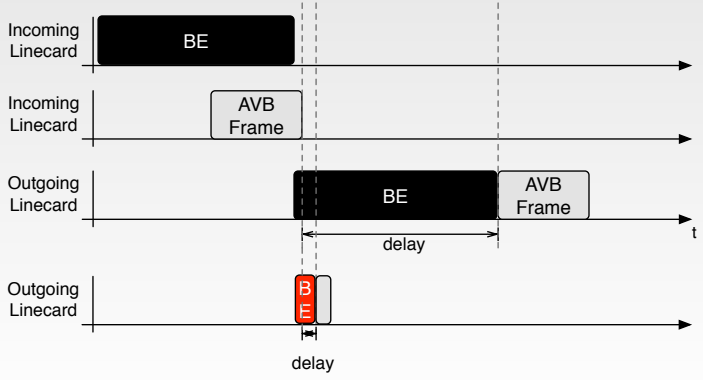
Attenuate the impact of frame congestion

- 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

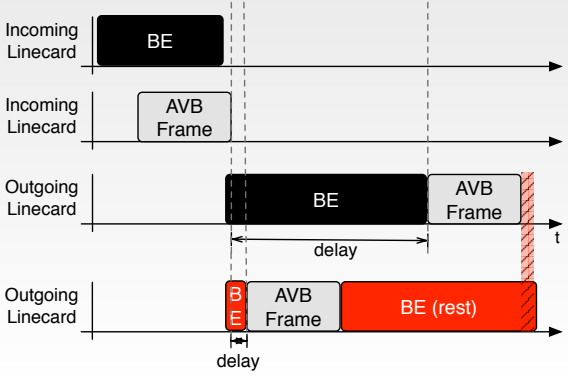
- Increased bandwidth not only allows to transfer more data, but also reduces delays of real-time messages
- ”Automotive” Gigabit Ethernet on its way: IEEE P802.3bp (RTPGE)
- Gigabit not only for saturated links, but also for time-critical paths



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



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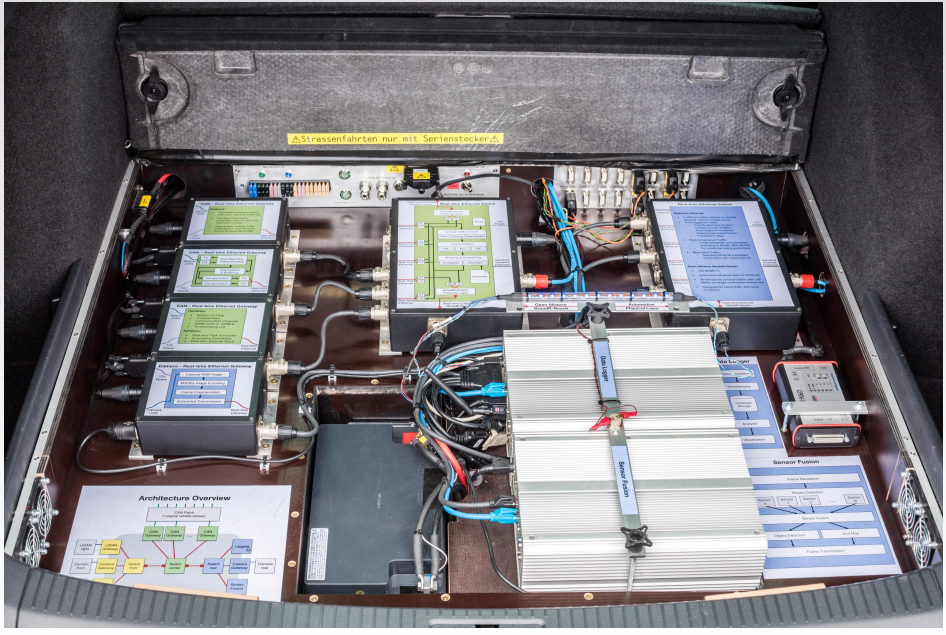
Prototype

Prototype



Prototype

Prototype

Prototype
Simulation to secure prototype development

- Correctly dimension hardware
- Assess expectations prior to deployment
- Debug new configurations in a white box environment
- Try protocol improvements in a safe environment

Agenda

Conclusion

- Automotive Ethernet is coming! Fast?
- New challenges (especially with Ethernet backbone)
- Simulation is a well suited tool for e.g.;
  - Design of protocols, network architectures and applications
  - Assessment of early designs
  - Analysis of future requirements
  - Configuration and debugging of prototypes

Now, it is your turn!

How can you get your hands on the simulation?

- Our simulation models are free and open source
- Platform independent
- Ready to use for everyone

But:

- Simulation requires expert knowledge
- We can support you to build up that knowledge:
  - Provide trainings and workshops
  - Support you during your simulation studies
  - Implement models specific to your use-case
  - Completely analyzing your networks and provide you with data

Thank you for your attention!
If you are interested in a short demo, meet us in the coffee break!

- 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 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.