Technische Universität Braunschweig

INSTITUT FÜR DATENTECHNIK UND KOMMUNIKATIONS-NETZE

Automotive Ethernet – Opportunities and Pitfalls

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Overview

- automotive networks – the Ethernet promise
- Ethernet as a backbone - a closer look
- Ethernet – the safety perspective
- conclusion

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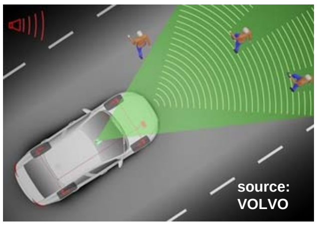
Automotive networks – The trends



- **Trend 1: New infotainment applications**
  - **networks with IP traffic via car-to-X communication**
  - ***primarily best effort***
- **Trend 2: Quickly growing sensor traffic**
  - **high resolution redundant image sensors for autonomous driving**
  - ***high bandwidth* communication using switched high speed network**
  - ***limited network latency (system response times)***
- **Trend 3: Complex low latency traffic**
  - **backbone function: legacy, future drives, highly interactive functions, ...**
  - ***low to medium volume, low latency traffic***
- ***the idea: Use Switched Ethernet!***

The Ethernet promise

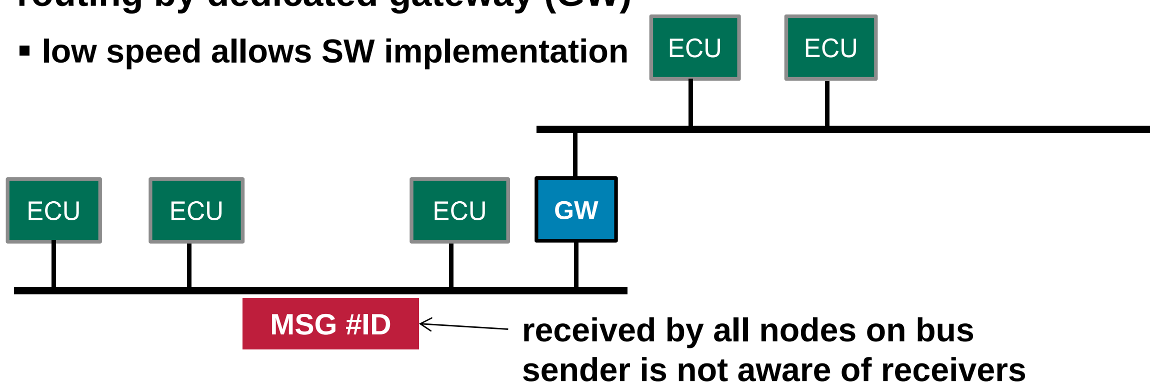
- bandwidth, bandwidth, bandwidth
  - for novel functions with high data rates, such as ADAS or infotainment
  - speed growing with technology 100Mb/s – 1Gb/s -10Gb/s - ...
- open network capabilities
  - open automotive networks towards IP protocol with approved technology
- shared technology cost
  - standard with high volume across industries
    - no headaches with next generation MOST, FlexRay, ...
  - huge engineering platform experience
    - avionics, industry, ...

but: how to efficiently design with Ethernet?

how to reach the required safety?

Where we come from: Bus-based communication

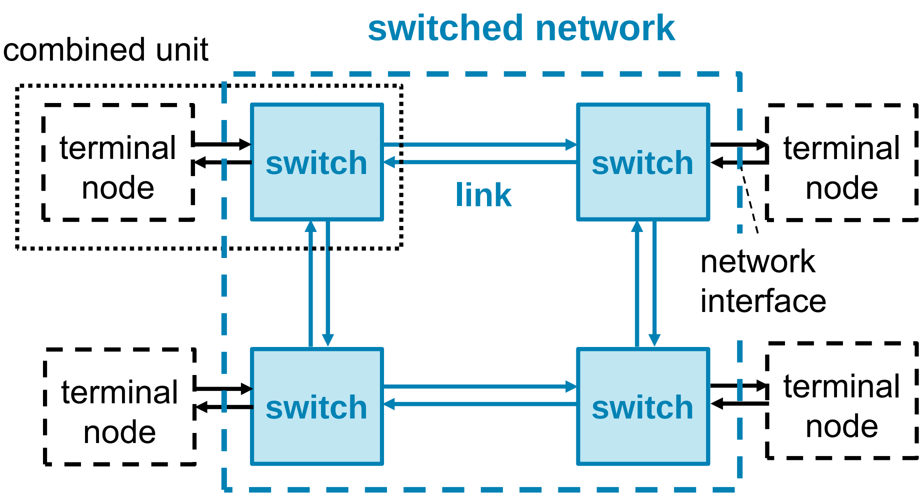
- straightforward support of publisher-subscriber mechanism
- several application specific standards, CAN, FlexRay, LIN, …
  - < 100kbit … 10Mbit (FlexRay, CAN FD) data rate
- predictable scheduling: fixed priority or TDMA or slotted ring (MOST)
- routing by dedicated gateway (GW)
  - low speed allows SW implementation



Ethernet is different

- switched network instead of bus
  - point-to-point connections with dynamic address handling
  - different scheduling mechanisms, flow control
  - *note: original Ethernet bus technology not suitable*
- different communication schemes
  - unicast, multicast, broadcast
  - different identifier assignment
  - not primarily developed for time-critical communication
- complex multi-level protocol alternatives
  - many configuration parameters
  - higher overhead than CAN
- *consequence for network properties and design?*

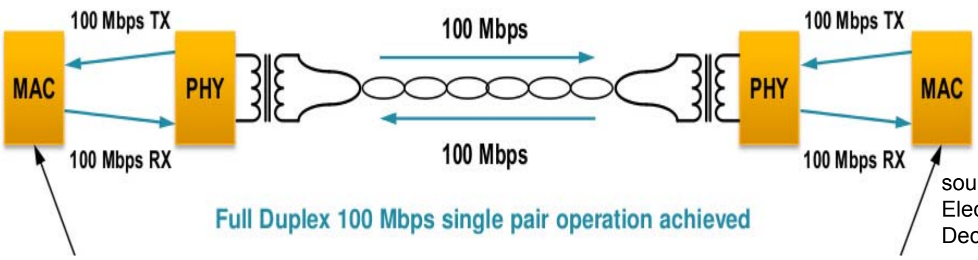
Switched Network – High Flexibility



- all traffic through bidirectional links – *fastest electrial solution*
- all arbitration in the switches – *flexible scheduling*
- arbitrary network topology – *adaptable performance & redundancy*

Bidirectional links for high speed

- automotive: OPEN alliance (BroadR Reach)
  - simple 2-wire physical medium – low cost
  - no link access arbitration necessary!



source:
Electronic Design
Dec 13, 2011

Adaptable traffic patterns

- variable frame sizes
  - 84 bytes (e.g. control messages) → 1500 bytes (e.g. camera frames)
  - resulting link latencies (non preemptable frames)
    - 100Mbit/s: short frames 6.72 µs → long frames 122 µs
- switch scheduling
  - WRR, static priority, time triggered, different shapers
  - TSN – many additional mechanisms

Ethernet IEEE 802.1Q – Standardization

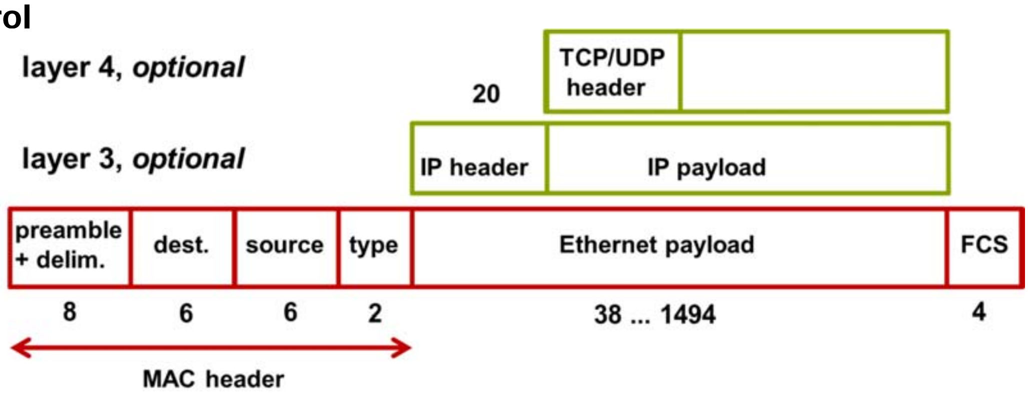
- **Standard Ethernet (IEEE 802.1Q)**
  - priority based
  - up to 8 priorities and 4096 VLANs
  - static priority scheduling
- **Ethernet AVB (IEEE 802.1Qav)**
  - originally defined for streaming applications
  - adds standardized traffic shaping to IEEE 802.1Q
  - 802.1AS: clock synchronization
- **Time-Sensitive Networking – TSN**
  - set of (draft) Ethernet standards addressing real-time requirements

TSN Arbitration and Shaping

- **frame preemption** (IEEE 802.1Qbu)
  - reduce blocking time by lower-priority fames
  - allow preemption of lower-priority frames (at certain points)
- **ingress filtering** (IEEE 802.1Qci)
  - ensure that traffic streams stay within predefined bounds (fault containm.)
- **timing and synchronization** (IEEE 802.1ASbt)
  - extensions to 802.1AS: redundancy, multiple time domains
- **time triggering** (IEEE 802.1Qbv)
  - time aware shaper for low latency, time sensitive traffic
- more shapers: peristaltic, burst limited, ...
- ***worst case timing analysis available for most standardized features***
  (pyCPA, SymTA/S) – see talk by Thiele et al. session T3.1

Higher-layer protocols – Network and Transport

- IP (layer 3)
  - IP adds routing support and compatibility
- UDP (layer 4)
  - adds software ports on top of IP - connectionless protocol
- TCP (layer 4)
  - adds software ports on top of IP - connection oriented, hand shake and flow control



Software stacks and Run-time Environment (RTE)

- SOME/IP
  - middleware standardizing data encapsulation in TCP or UDP packets
  - service discovery
- AUTOSAR Ethernet socked adapter
  - AUTOSAR: Automotive software standard
  - software adapter to embed Ethernet in AUTOSAR COM stack
  - achieves compatibility to other communication standards
    - more complex than in conventional buses

AUTOSAR Ethernet socket adapter

AUTOSAR PDU router
(Protocol Data Unit)

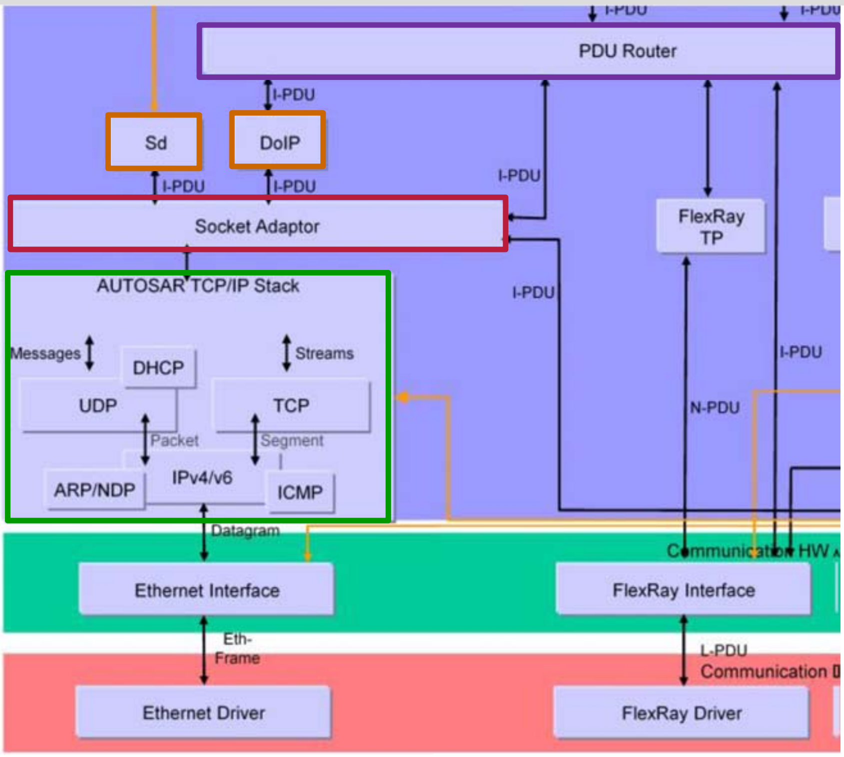
Service discovery (Sd)
Diagnostics over IP (DoIP)

Ethernet socket adapter

TCP/UDP/IP stack

communication HW abstraction

communication drivers



source. www.autosar.com

Design complexity and cost – a caveat

- **Ethernet: many more parameters and variants than in current networks**
  - **MAC address management, switch management, protocol selection, packaging, ...**
- **current standardarization addresses compatibility to existing architectures and standards**
  - **does not limit variety**
  - **variety easily leads to incompatibilities and inefficiencies – cost!**

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- **Ethernet as a backbone - a closer look**
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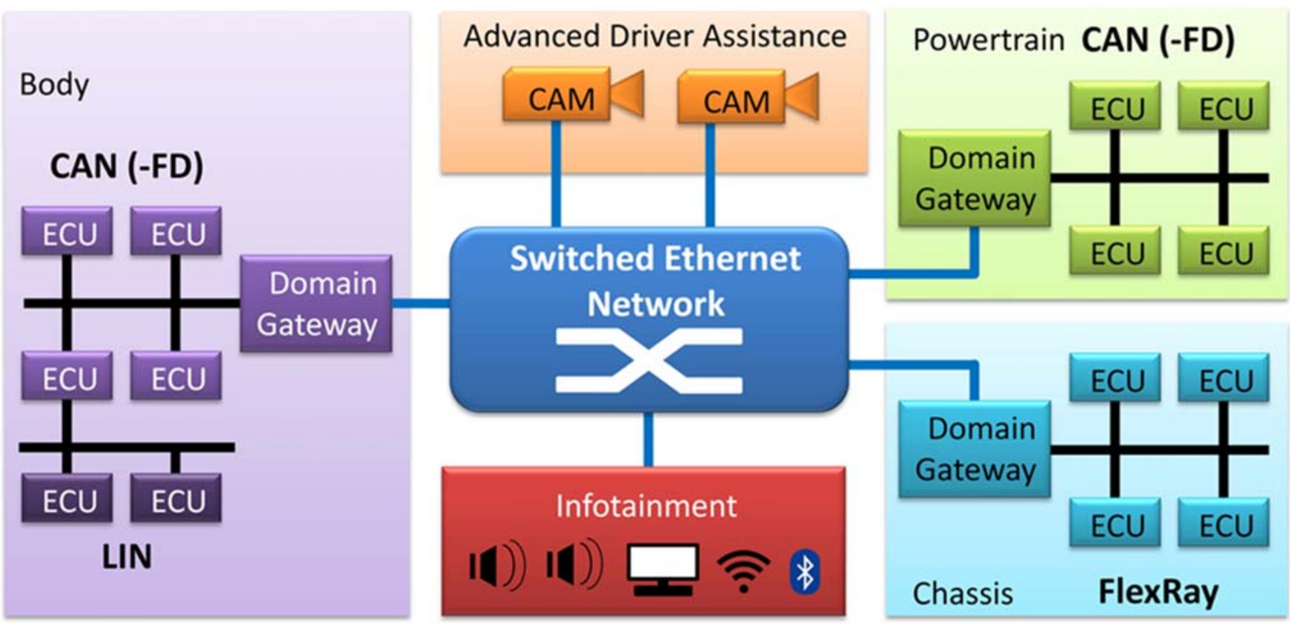
The Ethernet backbone idea

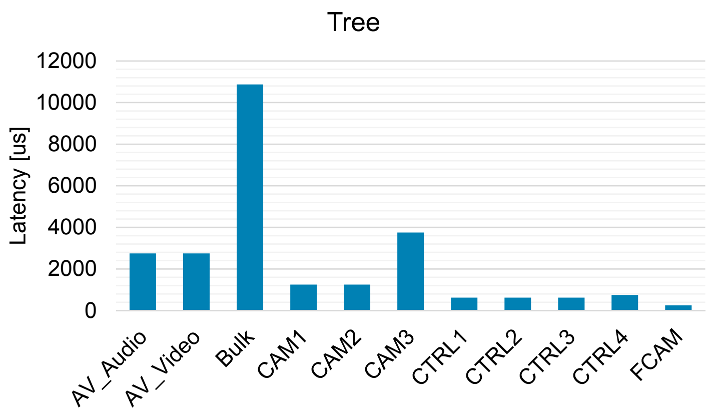


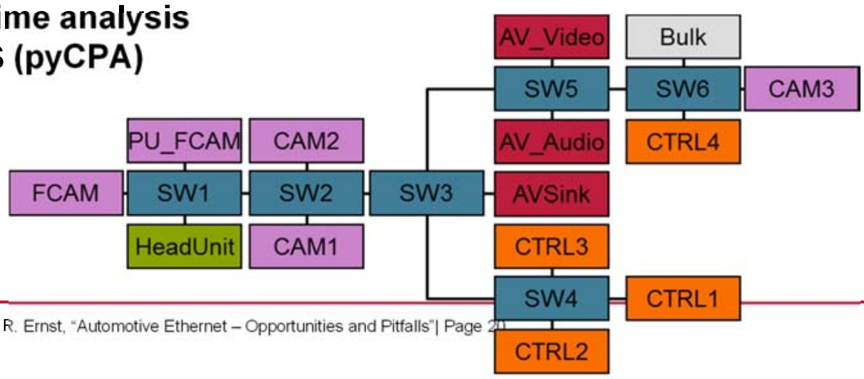
Evaluation: Design example

- use case
  - traffic pattern according to published BMW use-case [Lim2011]
- ECUs
  - 4 control units
    - each ~72 kbit/s → streamed to Head Unit
  - 4 cameras (Rear, Sides, Front)
    - each 26 Mbit/s (compressed) → streamed to Head Unit
  - rear seat entertainment
    - audio: 1.43 Mbit/s
    - DVD video: 12 Mbit/s
    - Internet data / bulk traffic: 11.52 Mbit/s

AVB experiments: Tree topology

- static priority w. shaping
  - latency critical traffic mapped to Class A disabled shaper
  - bandwidth critical traffic mapped to Class B shaper 10% overreservation
  - bulk/Internet traffic: lowest priority
  - WC response time analysis using SymTA/S (pyCPA)



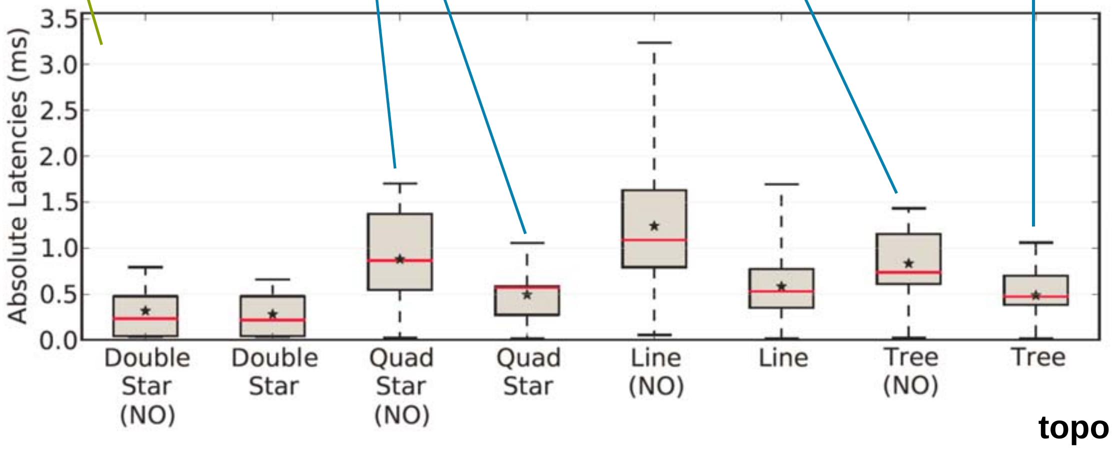


Larger system [Thiele14] – Results for control

period > latency
[5ms ..1s]

correlation has
strong influence
for control messages

stream correlation
not considered
(NO)
considered

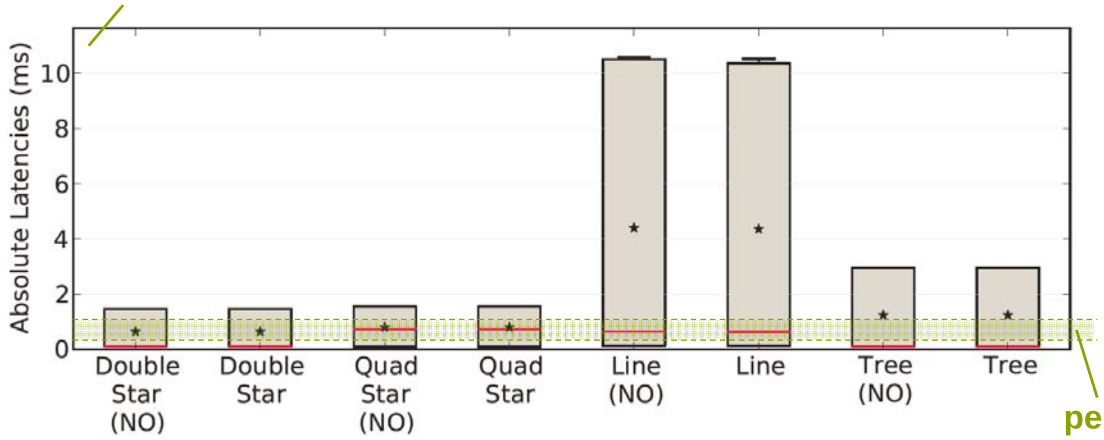


topology

→ control streams are NOT pipelined in any topology
→ no overwriting in Ingress transmit buffers

Experiments – Results for camera messages

frame period < latency
[0.1ms ..1ms]



periods

→ camera stream packets are pipelined
→ buffers for frames in switches needed!

Topology and bandwidth effects - Conclusion

- **high priority control traffic (class A)**
  - **no risk of message overwriting in transmit buffers**
    - **if sufficient switch buffer available and message density low**
  - **holds for all investigated topologies in example**
- **high priority camera traffic (class B)**
  - **risk of overwriting in transmit buffer – stream buffering needed**
  - **holds for all investigated topologies**

- ***Ethernet AVB scheduling appears sufficient***
  - ***no shaper for class A***

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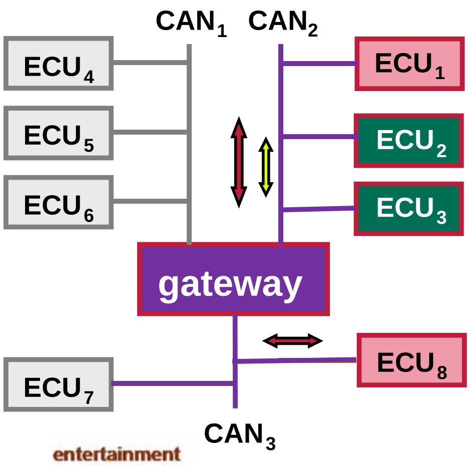
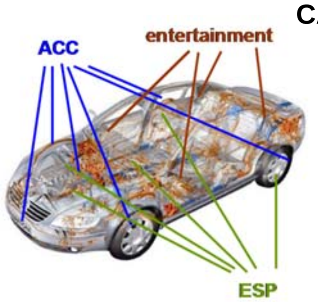
Current automotive network – protection





- application of safety standard ISO26262 affects large part of the system
  - *„freedom from interference!"*
- ***isolation on mixed critical buses required***

„Freedom from interference" on CAN

- WC design process
- WC frame timing independent of lower priority messages
- WC or other design process

- **use priorities to separate criticalities**
  - **„criticality as a priority"**
- **allow „occasional" loss of non (time) critical frames due to overload**
  - **„less than worst-case design" possible**

$\rightarrow$ ***mature solution to address ISO 26262 requirements***

- **comparable solutions for *FlexRay (TDMA)* and *MOST (reservation)***

Ethernet – The safety perspective

- isolation
  - how well does Ethernet isolate critical from other traffic?
    - „freedom from interference“
- delivery under transmission errors
  - what timing guarantees are possible under errors?
- fail operational
  - how well can network failures be compensated?

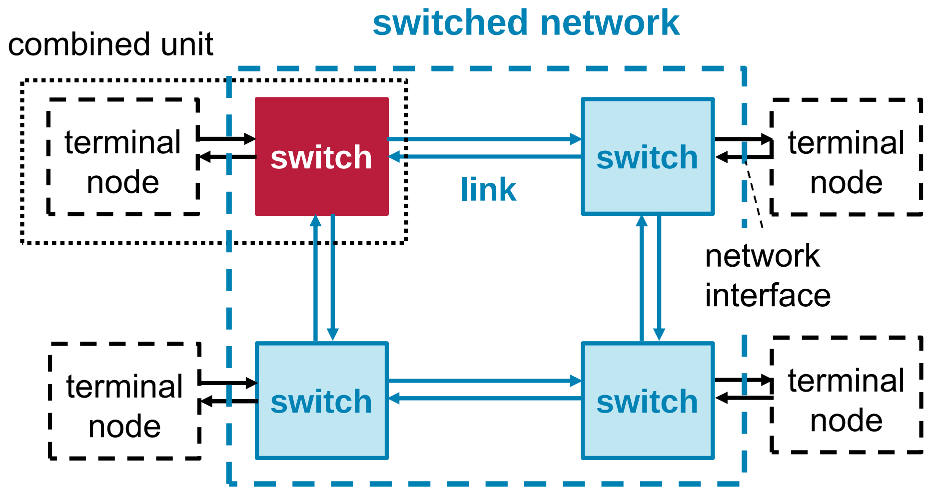
Ethernet generally supports similar techniques

- priority assignment according to traffic class
  - combine with shaping where needed (AVB or TSN)
  - supports combination of design styles

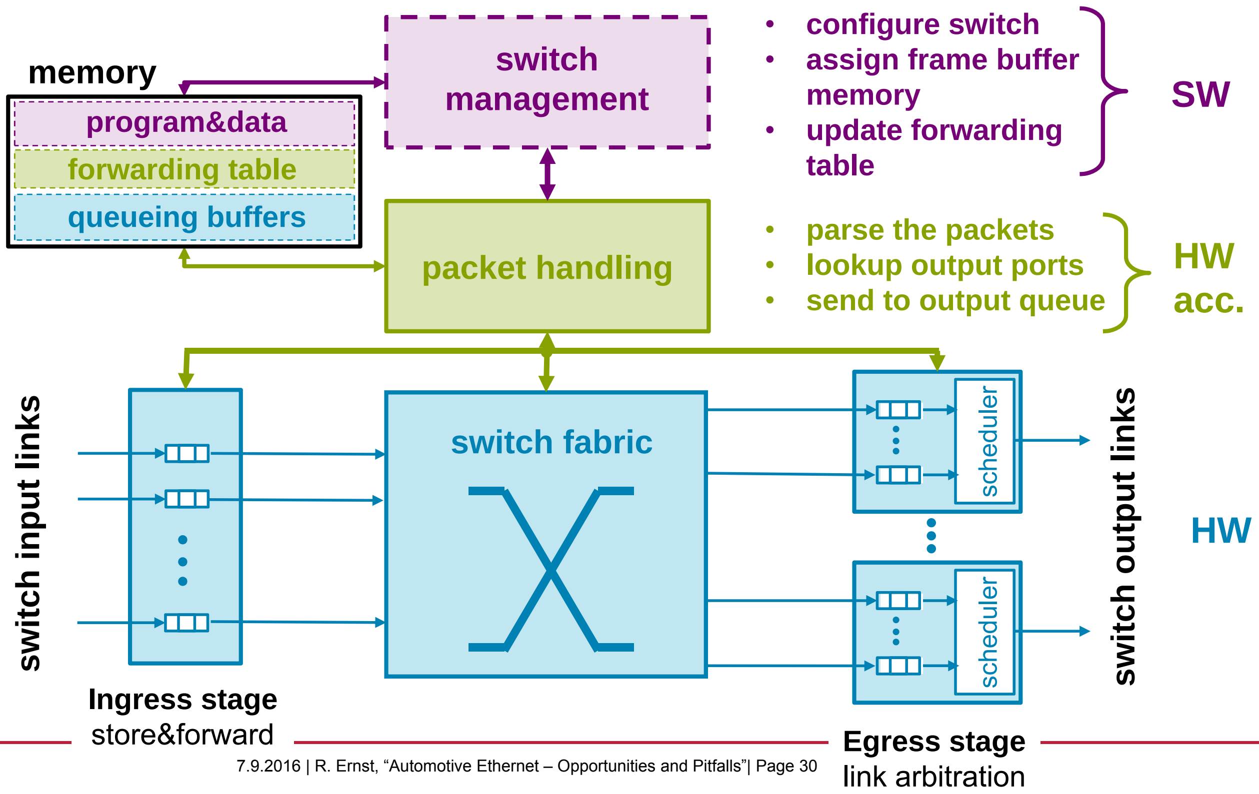
- other techniques: TSN time triggering (cp. FlexRay)

but: is the isolation effective?

Isolation – The switch matters

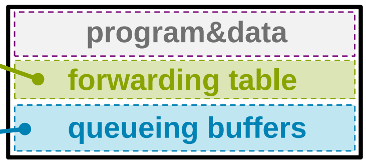


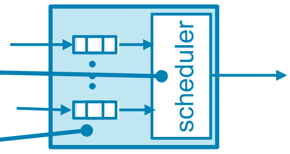
Ethernet switch structure



Switching interference challenges

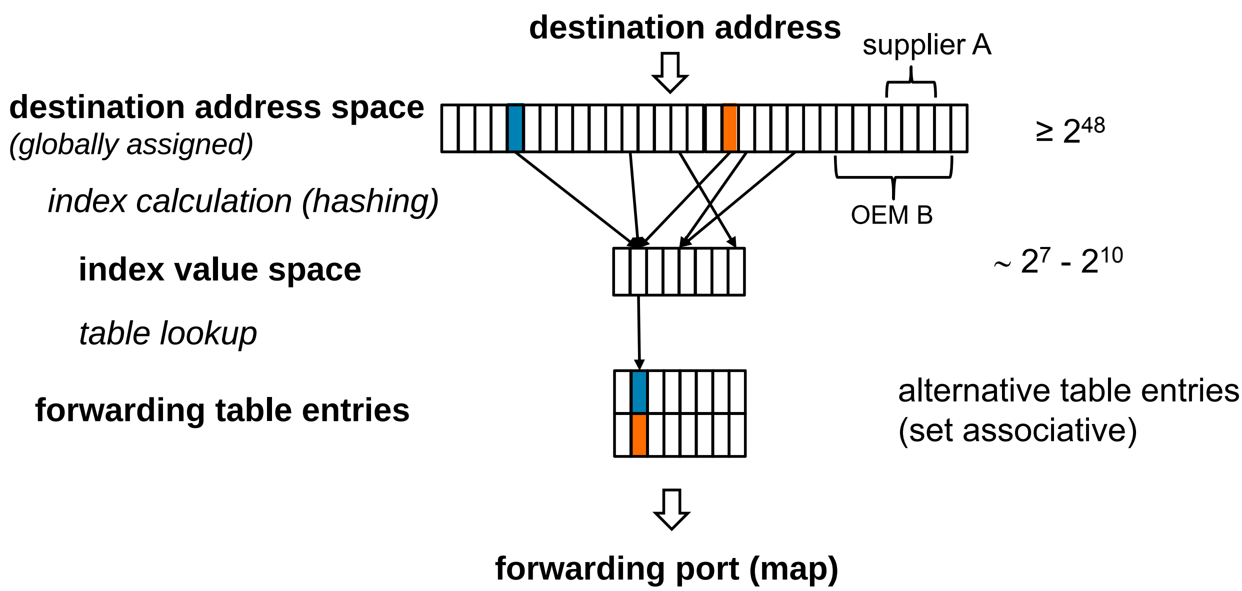
- forwarding table
  - limited index space leads to indexing conflicts
    - loss of timing, *interference*
  - requires appropriate MAC address management
- queueing buffers
  - limited buffer space
    - message drop, *interference*
  - flow control
    - same priority blocking, increased delay&buffer
  - few queues - few priorities
    - head-of-line-blocking, *interference*
  - queueing effects require system level end-to-end analysis





Ethernet switch – address mapping

- forwarding resolved via indexing



Ethernet switch – address mapping

- **forwarding resolved via indexing**

destination address space
(globally assigned)

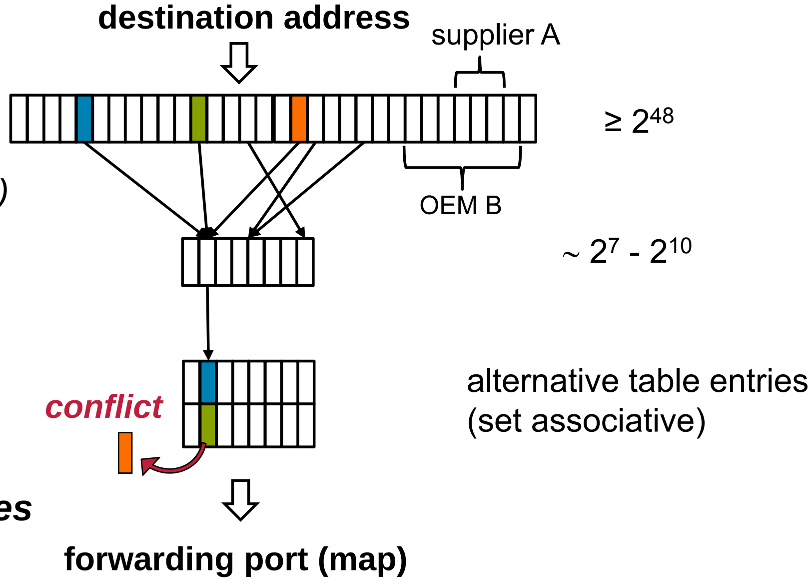
index calculation (hashing)

index value space

table lookup

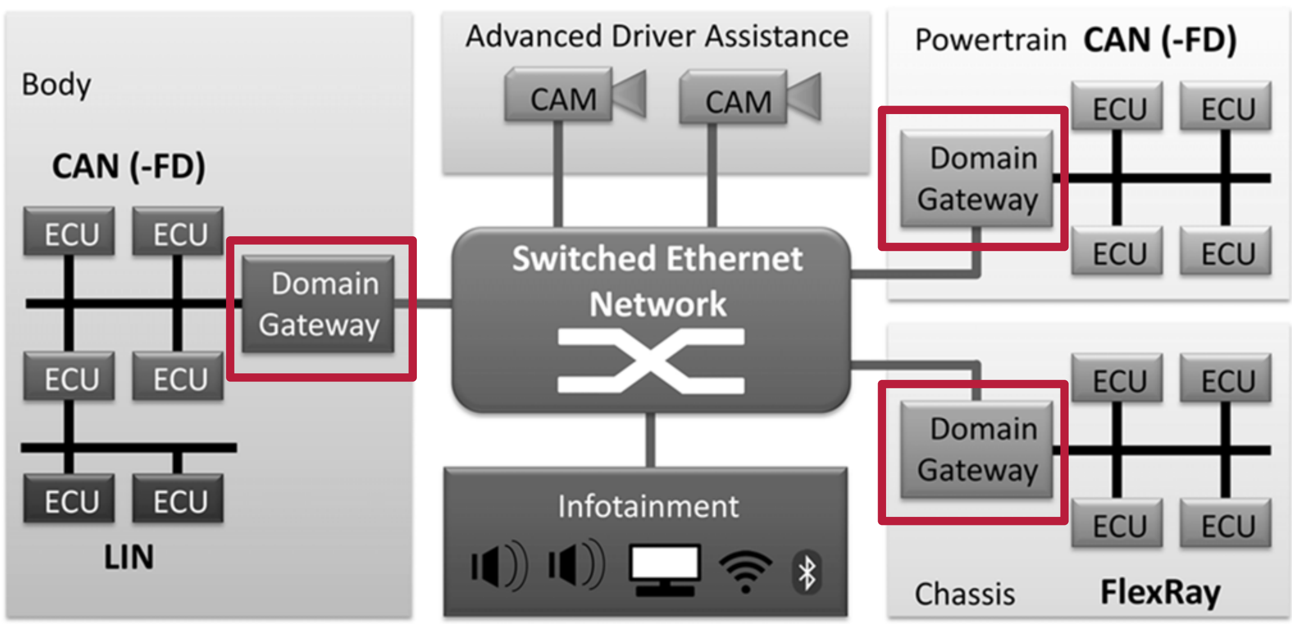
forwarding table entries

conflict
when all table entries for index are full



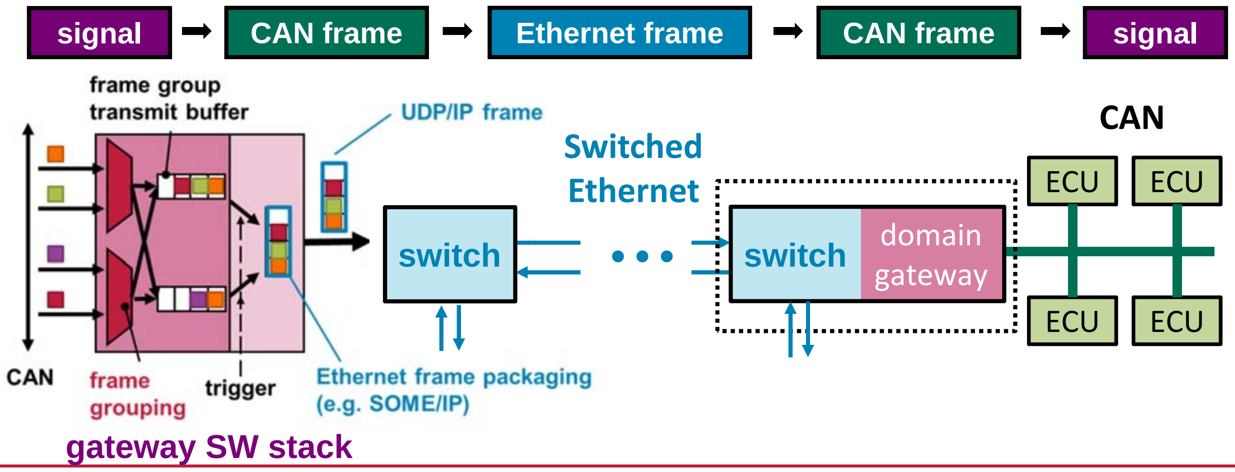
switch architecture and indexing usually not published

Isolation in a backbone – The gateway influence



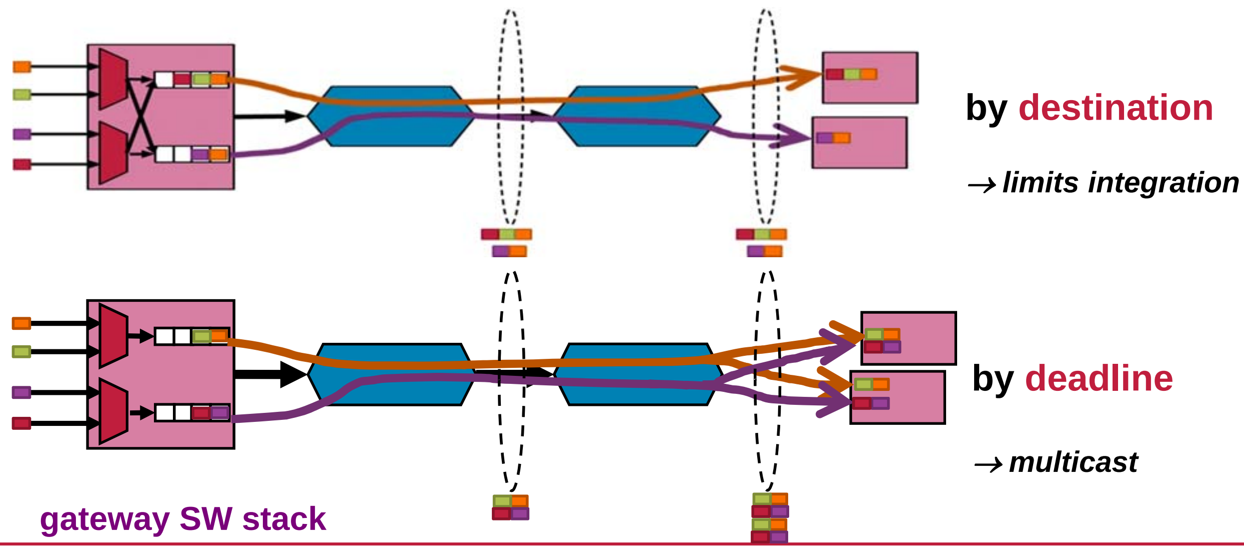
CAN frame packaging scenario - Backbone

- complex protocol choices
  - SOME/IP – UDP – IP – MAC
  - TCP – IP – MAC, ...
- packaging is further source of interference



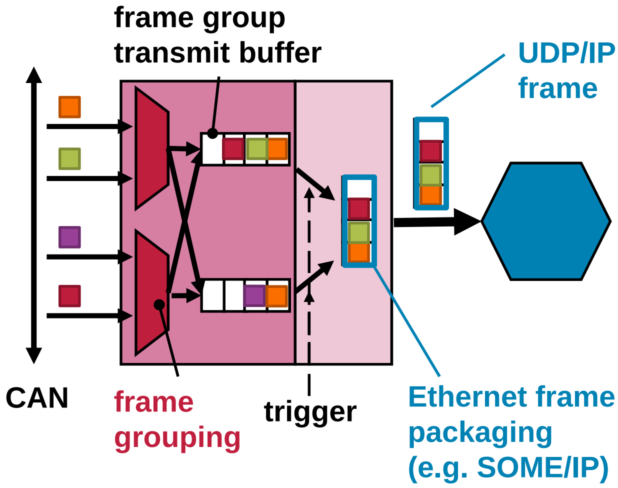
CAN-to-Ethernet-to-CAN – Frame grouping

- by destination - minimize multicast overhead
- by priority (e.g. CAN ID) – enable QoS for different traffic classes
- by period or deadline - minimize sampling delay



Frame grouping - Triggering and interference

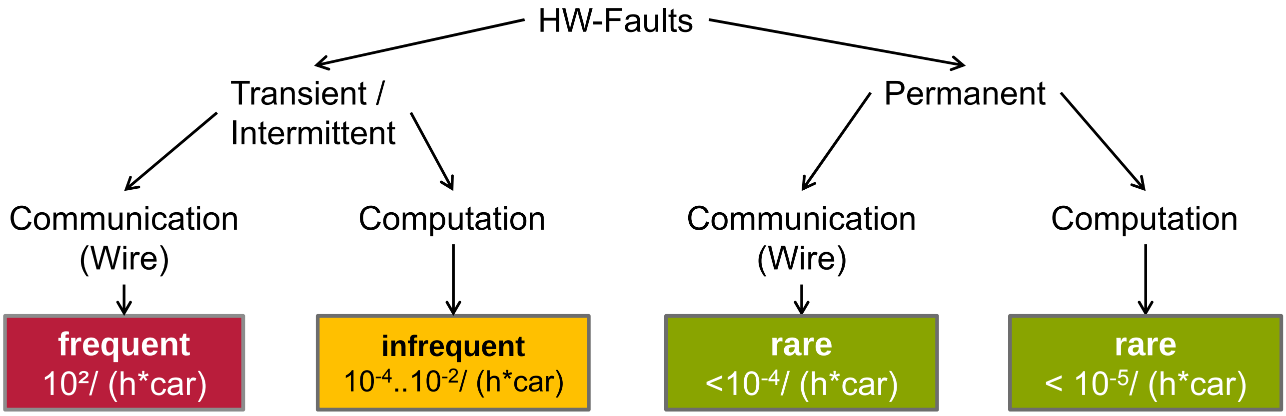
- buffer timeout (AUTOSAR)
  - frame is sent periodically
  - *no frame interference*
- buffer full event (AUTOSAR)
  - frame transmitted if buffer full
  - *interference*
- trigger frames (AUTOSAR)
  - certain CAN IDs immediately release frame
  - *interference*
- per-frame timeout
  - send upon single frame timeout



Interference in automotive Ethernet – Conclusion

- numerous sources of interference
  - switch operation, prioritization, frame grouping, triggering
  - no standardized solutions
  - partly based on non-disclosed parameters
- careful evaluation and design required
  - *don‘t rely on standards only!*

Ethernet under errors – HW fault probabilities

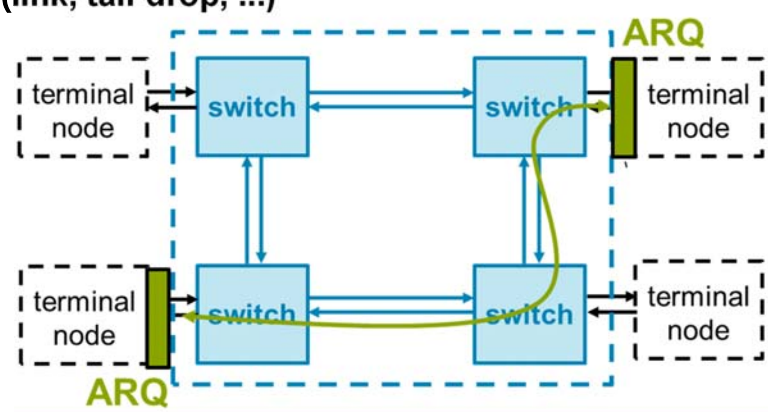


note: resulting computation errors strongly depend on state protection (memory)

- **system reaction must be tailored to requirements (performance & safety)**
- **transient communication faults dominate**
  - **transient error handling must be part of regular communication**

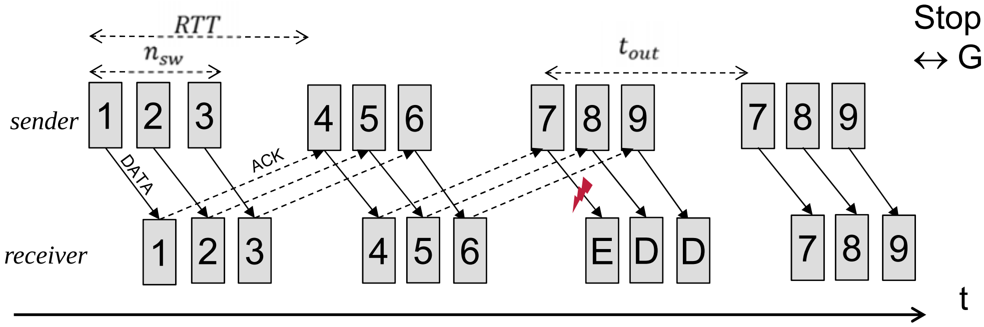
Communication under transient faults

- **system must be capable of real-time operation**
  - **even under occasional transmission errors (cp. CAN, FlexRay, ...)**
  - **transient error protocol timing must be part of regular operation**
- **suggest end-to-end error control**
  - **overhead can be limited to critical messages**
  - **covers all error types (link, tail-drop, ...)**
- **Automatic Repeat Request (ARQ)**



Automatic Repeat Request (ARQ)

- **various flavors of ARQ [Tanenbaum2002]**
  - **Stop and Wait ARQ** (e.g. CAN)
  - **Go-Back-N** (HDLC, X.25 used in wide-area packet switched networks)
  - **Selective Repeat** (TCP) – not considered here due to complexity

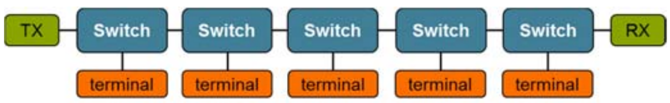


Stop and Wait ↔ Go-Back-1

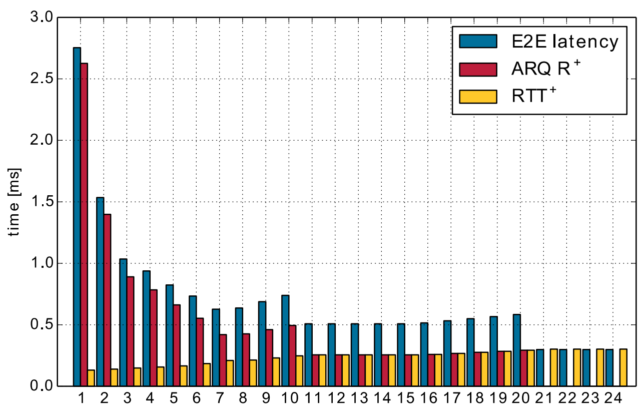
- **challenge: return channel timing (ACK)**
  - **efficient worst case analysis for ARQ meanwhile available [Axer 2014]**

Results [Axer 2014]

- **line topology w. 5 switches**
- **20 frames à 1024 bytes payload**
- **congestion: 5 additional terminals send to RX 1024 bytes every 0.5ms**

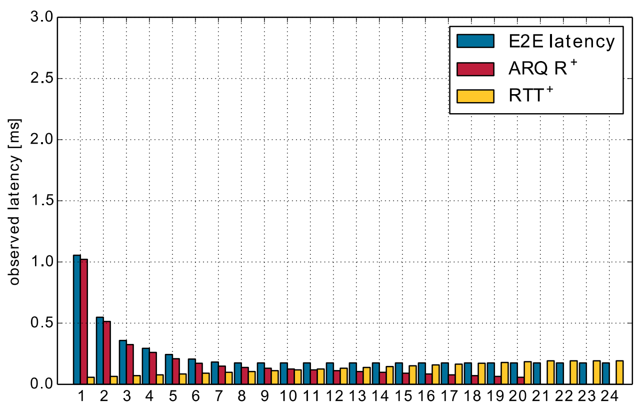


worst case analysis [ms]



send window

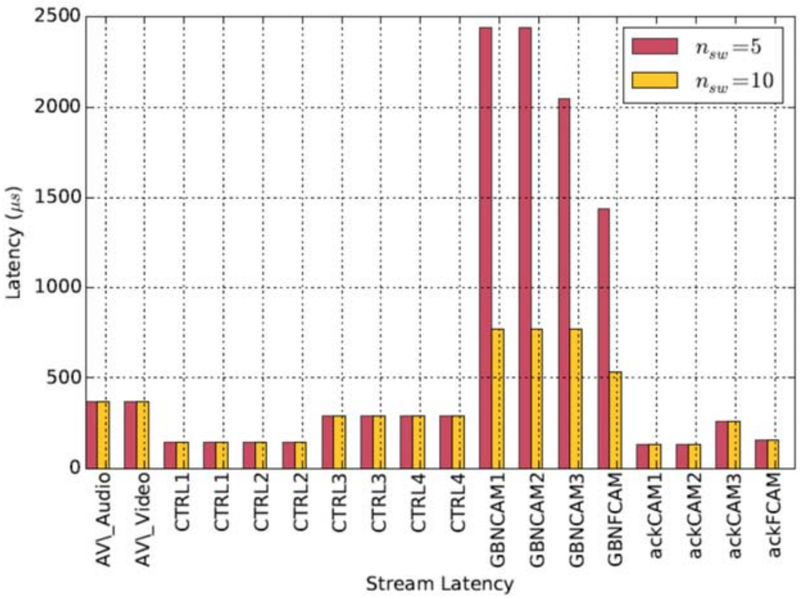
observed timing in simulation [ms]

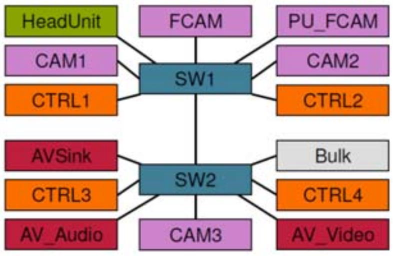


send window

ARQ in an automotive use case [Axer14]

- Go-Back-N end-to-end latency guarantees for N=5 and 10

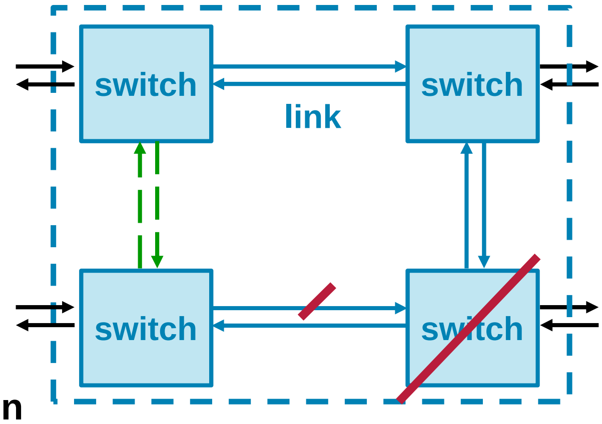




[Lim 2011]

Handling permanent component failures

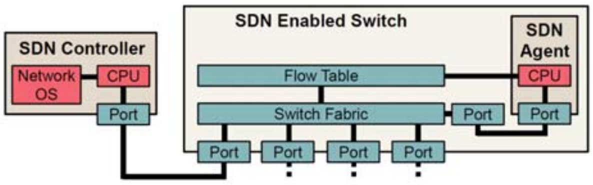
- introduction and control of component redundancy
  - multipath routing – TSN
    - zero extra delay
    - permanent overhead
  - automated path detection and routing
    - standard approach
    - large and unpredictable delay



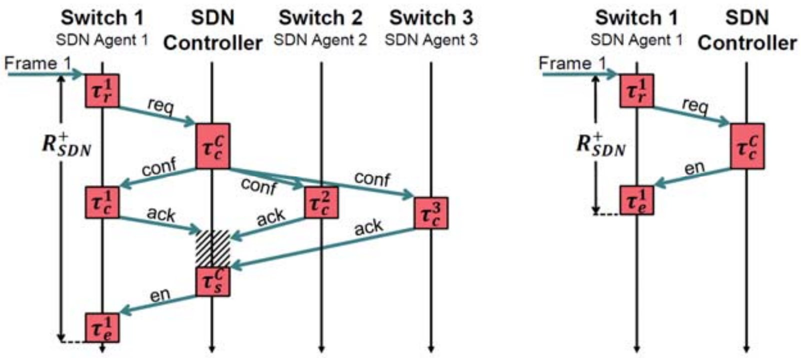
- alternative: centralized configuration
  - possible solution: Software Defined Networking (SDN)
  - introduces control plane
  - widely used: OpenFlow protocol
  - *fast enough?*

Software Defined Networking - Principle

- uses network to communicate switch configuration
  - access control, reconfiguration, ...
  - explicit control or preconfigured
  - control redundancy *must be added*

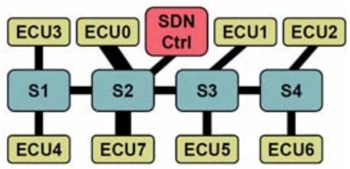


SDN architecture



explicit flow configuration preconfiguration

protocols (proposed)

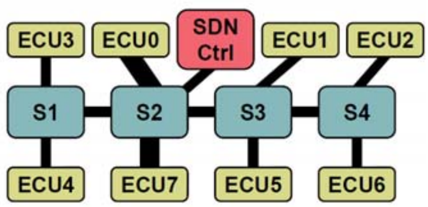


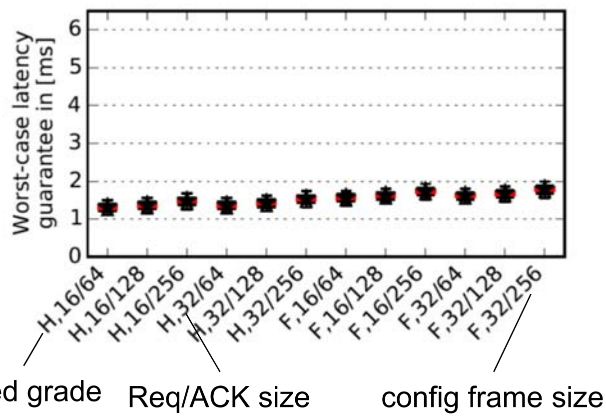
example topology

Feasibility study for SDN [Thiele 2016]

- protocol timing for access control
  - depends on load, number conf. requests
  - explicit configuration: 1ms ...6ms
  - preconf: < 1.3ms
  - feasible approach for automotive
- more research needed
  - *H2020 project, www.safure.eu*

SAFURE





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- **conclusion**

Ethernet standard development – Some comments

- **many new features introduced in TSN**
  - **addressing interests from many industries: industrial, automotive, media**
  - **some additions seem to be redundant compared to 802.1Qav (AVB)**
    - **peristaltic and burst limited shapers (worst WCRT - cp. Thiele)**
  - **for automotive applications**
    - **min. end-to-end latency typically > 1..2 ms**
      - **feasible with AVB - or w. additional preemption**
    - **clock synchronization already in AVB (802.1AS)**
- **additions increase protocol and circuit complexity**
  - **increases switch, terminal and network assurance effort**
  - **increases switch cost**

be selective with new standard features!

Design complexity and cost revisited
- The cost-of-ownership trap

- **many more parameters and variants than in current networks**
  - **MAC address management, switch management, protocol selection, packaging, ...**
  - ***new standards in TSN even increase feature set***
- **current software standardarization does not limit variety**
  - ***nor does TSN***
- **unified automotive solutions needed**
  - **different solutions and incompatibilities increase design process costs, tool costs, ...**
- ***cost of variety management at all levels generates new costs-of-ownership for automotive industry***

Conclusion

- **Ethernet is a viable basis for automatic driving**
  - **adaptable bandwidth and latency, supports integration**
  - **predictability for hard real-time systems**
  - **flexible end-to-end control for transient errors**
  - **extensions for resilient and secure networks w. fast reconfiguration**
- **many traps require highly systematic approach for risk mitigation**
  - **high-level standards needed for integration**
  - **solutions to individual problems, such as scheduling, are not sufficient**
- **research should address effective and efficient mechanisms for**
  - **mitigating and bounding interference on all levels (not only time)**
  - **providing analysis for end-to-end timing (worst case)**
  - **predictable dynamic network control, such as SDN**

References

- **Literature**

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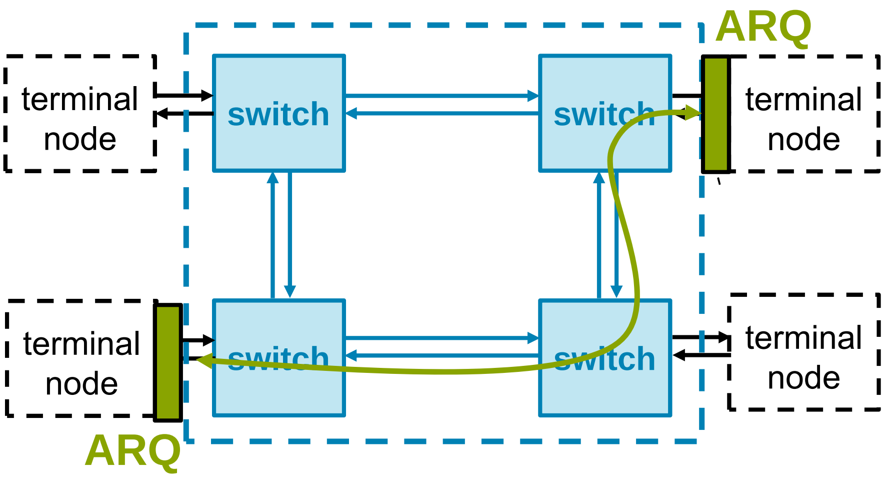
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