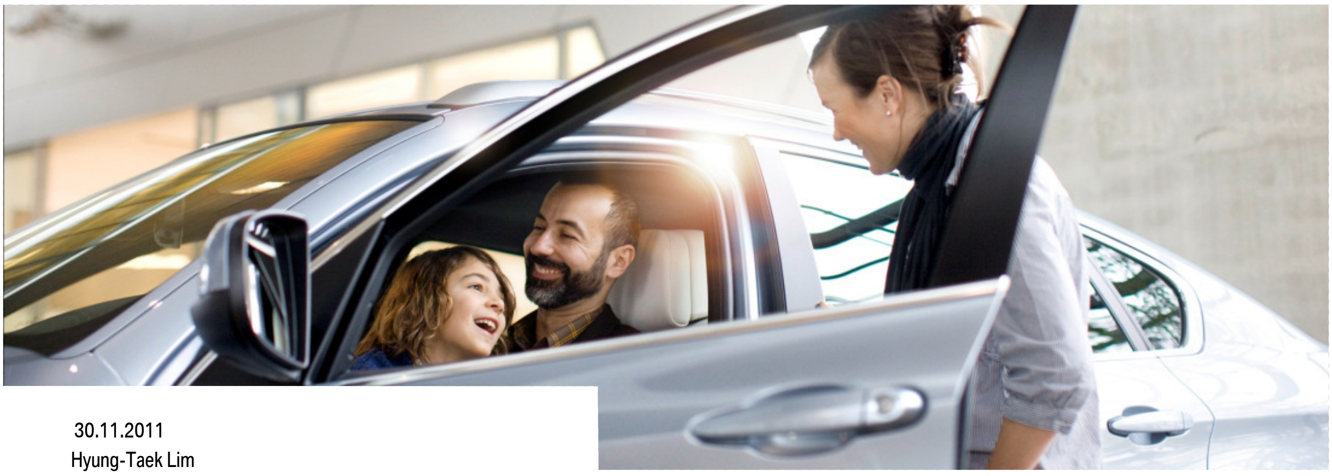


30.11.2011
Hyung-Taek Lim

REAL-TIME COMMUNICATION IN AN IP/ETHERNET-BASED IN-CAR NETWORK

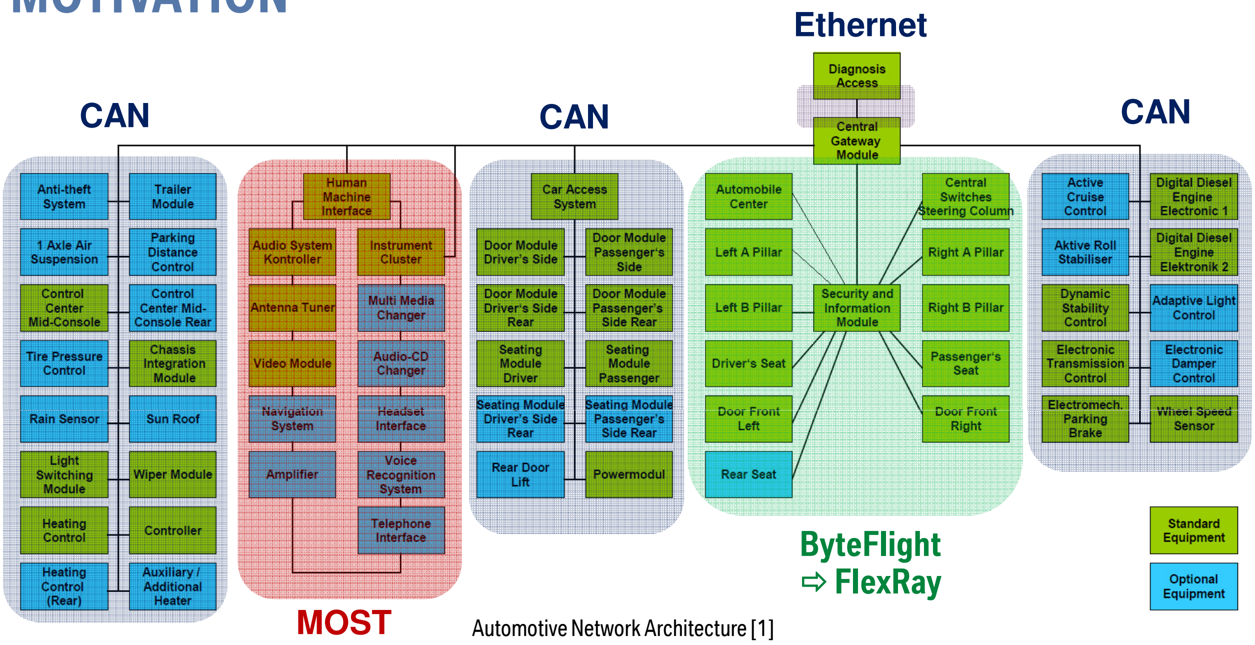
Forschung und Technik.

BMW GROUP

OUTLINE

1. **Introduction and Scope**
   - Motivation
   - Vision and Challenges for the future In-Car network
   - Ethernet in a Vehicle
   - Reverse Engineering of current bus systems: CAN and FlexRay
   - Methodology
2. **Solutions 1/2: Standard Switched Ethernet**
   - Influence of the Topologies
   - Non Prioritized (1) vs. Prioritized Network (2)
3. **Solution 3: IEEE 802.1 Ethernet AVB**
   - Background Information
   - Evaluation of an Ethernet AVB based In-Car Network
   - Summary
4. **Future Work**
   Publications

MOTIVATION



Automotive Network Architecture [1]

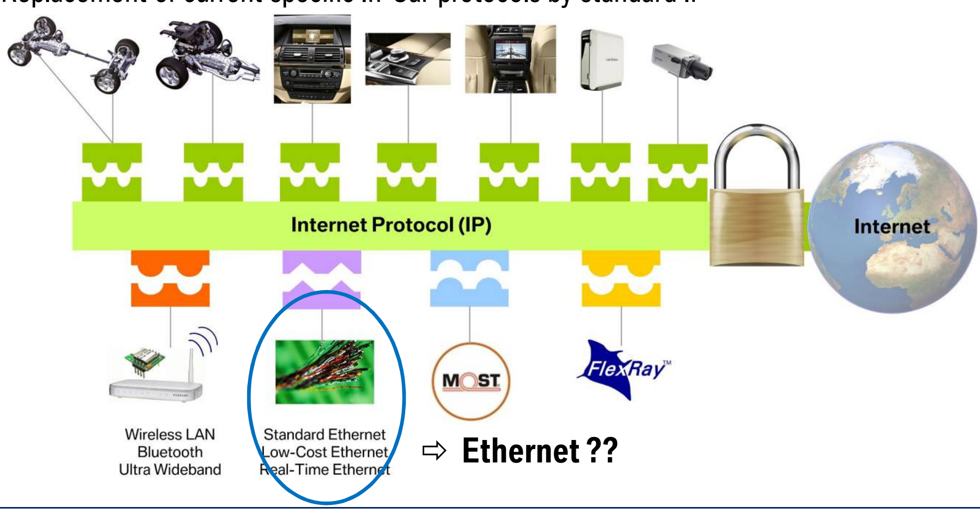
(-) heterogenous network
- different protocols, used complex centralized application gateway
- complex cable harness
  ⇒ Costs
- slow down innovations

[1] Freymann, R.: Anforderungen an das Automobil der Zukunft. The 2nd Mobility Forum, Munich, Germany

VISION AND CHALLENGES

Internet Protocol (IP)-based In-Car Network

- Replacement of current specific In-Car protocols by standard IP



- Suitable technology to transport IP for the automotive use
  → Future applications have higher bandwith demand due to the increasing number of advanced driver assistance (ADADS) systems and ECUs

- Which of the existent In-Car technologies are capable to transport IP and can fulfill the high bandwidth demand of future applications ?

LEGACY ETHERNET

	Applications
7: Application	?
6: Presentation	?
5: Session	?
4: Transport	TCP / UDP
3: Network	IP
2: Data Link	Ethernet MAC
1: Physical	Ethernet Phy

(+) Mature Technology
(+) Fast, easy to use
(+) Two-wire unshielded available for automotive use
(+) No single source

(-) Real-time data transmission is not supported
(-) Frames can be delayed or lost (Switch)
(-) Efficiency problems with small packets

Ethernet is currently used only for two areas:

- Diagnosis and flashing (OBD)
- Remote disc access (CIC⇔RSE)

Currently: no real-time applications; Ethernet without any QoS mechanisms

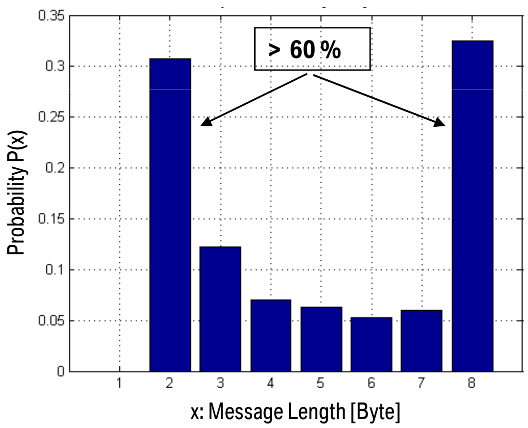
Research Questions ⇨ Can Ethernet also be used for Real-Time in the car ??

REVERSE ENGINEERING OF CAN, FLEXRAY [*]

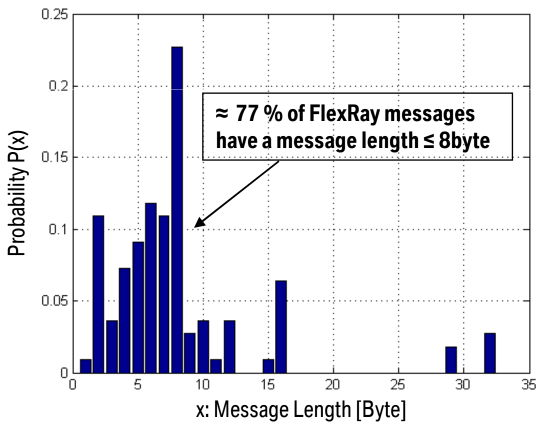
- Trace Analysis:
  Analysis of control messages based on real In-Car CAN and FlexRay data derived from a BMW vehicle

  (1) Message length and their distribution
  (2) Cycle Times – Time between two consecutive messages for cycle based messages

CDF: Probability of used message length (CAN)



CDF: Probability of used message length (FlexRay)



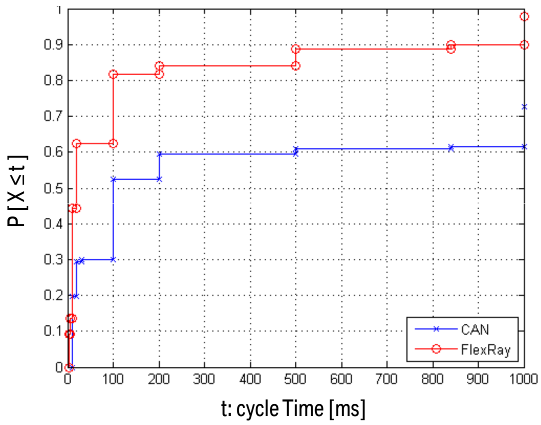
Most of the in-car control messages have a message length less than 8 Byte. A single UDP packet with a minimum payload size of 20 bytes will cover 95% of the in-car control message length.

[*] Work was presented at the Nets4Cars 2011 Conference, Oberpfaffenhofen, Germany

REVERSE ENGINEERING OF CAN, FLEXRAY -2- [*]

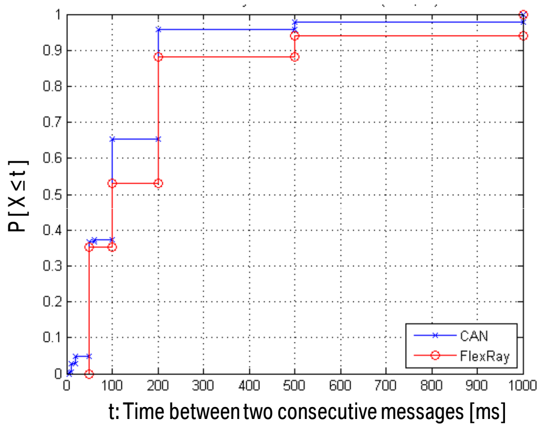
(2) Cycle Times – Time between two consecutive messages for cycle based messages

CDF: Probability of having cycle time (CDF)



<cycle based messages>

CDF: Probability of having inter-arrival time (CDF)



<event based messages>

ECUs using **cycle messages** with low cycle times are preferred by FlexRay, while high cycle times are mainly used by the CAN bus.

In case of **event based messages**, CAN bus system are preferred to use.

[*] Work was presented at the Nets4Cars 2011 Conference, Oberpfaffenhofen, Germany

RESEARCH WORK AND METHODOLOGY

Three essential aspects are considered in our work:

No.	Ethernet Types	Methodology	
		Simulation based Evaluation	Prototyping Evaluation
1	Switched Ethernet without Prio. (‚Legacy')	Finished	Finished
2	Switched Ethernet with Prio	Finished	Finished
3	IEEE 802.1 Audio Video-Bridging (AVB)	Ongoing	Ongoing

Do the different Ethernet types support real-time communications and fulfill QoS-requirements in terms of **bandwidth** and **end-to-end delay** by a given topology and applications ?

RESEARCH WORK AND METHODOLOGY

Three essential aspects are considered in our work:

No.	Ethernet Types	Methodology	
		Simulation based Evaluation	Prototyping Evaluation
1	Switched Ethernet without Prio. (‚Legacy‘)	**Finished**	**Finished**
2	Switched Ethernet with Prio	**Finished**	**Finished**
3	IEEE 802.1 Audio Video-Bridging (AVB)	**Ongoing**	**Ongoing**

INTRODUCTION: OMNET++

- Network Simulation Tool
- component-based, modular and open-architecture discrete event network simulator.
- Specific application areas are implemented by various simulation models and frameworks, most of them open source.

OMNeT++ with the INET-Framework

- Framework for wired and wireless TCP/IP based simulations (contains most of the standard protocols from OSI-Layer L1 – L7)
- some limitations for my purposes

Framework modified [*]

1. No Prioritization mechanism:
   - data traffic is not classified by different priorities.
   - all applications are considered as best effort
   - the switches use only a single output queue and a First-In-First-Out (FIFO) scheduler

   → Prioritization as defined in IEEE 802.1Q (MAC-Layer Prio.)

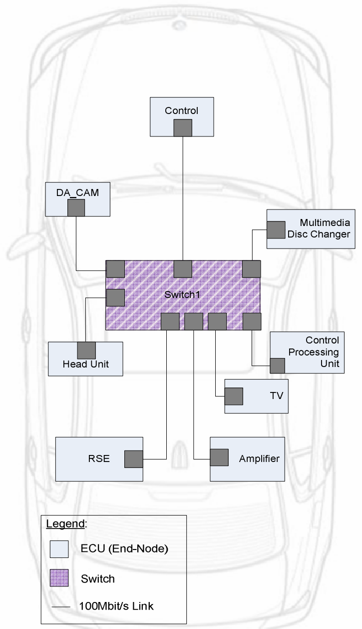
2. Data Traffic based on statistical models:
   - packet size and sending rate are set by statistical distribution functions

   → Loading external Trace data

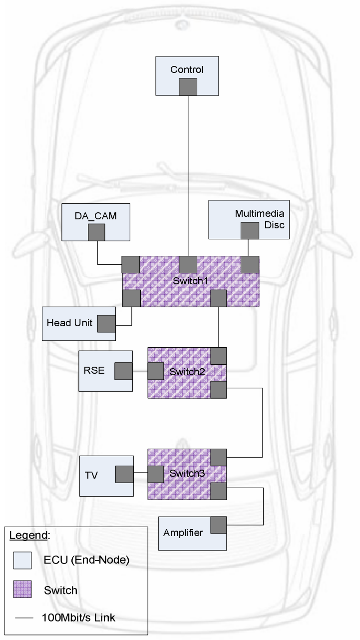
[*] Work was realized in cooperation with the BMW development part

SWITCHED ETHERNET-BASED IN-CAR NETWORK [*]

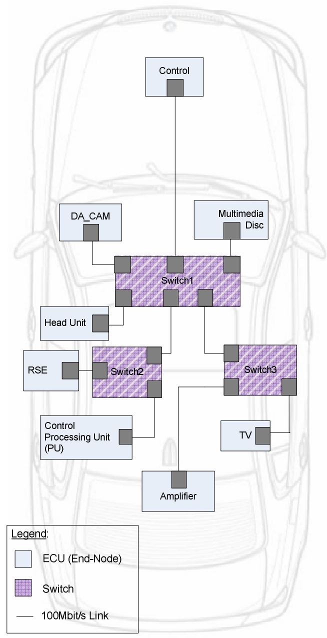
Goal of the analysis:
Influence of the **(1) Topology** **(2) Prioritization mechanisms** **(3) Linkload**



Star-based (Topology-1)



Daisy chain-based (Topology-2)



Tree-based (Topology-3)

[*] Work was presented at the 48th Design Automation Conference (DAC 2011) Conference, San Diego

IN-CAR APPLICATIONS: TRAFFIC CHARACTERISTICS

Traffic Type	UDP Packet Length [Byte]	Sending Rate[ms]	Bandwidth [Mbit/s]	Prio	Max. End-to-End Delay [ms]
Control	18	uniform (10,100)	< 1	3	**10** [1,2]
Driver Assistance CAM	1472	0.5	24	2	**45** [2]
Navigation	1400	0.7	16	1	**100**
MM Video	1400	0.28	40	0	**150**
MM Audio	1400	1.4	8	0	**150**
TV Video	1400	uniform (0.56,1.12)	10 – 20	0	**150**
TV Audio	1400	2.33	4.8	0	**150**

[1] R. Steffen, R. Bogenberger, M. Rahmani, J. Hillebrand, W. Hintermaier, and A. Winckler, Design and Realization of an IP-based In-Car Network Architecture, The First Annual International Symposium on Vehicular Computing Systems, Dublin, July 2008.
[2] M. Rahmani, R. Steen, K. Tappayuthpijarn, G. Giordano, R. Bogenberger, and E. Steinbach, Performance Analysis of Different Network Topologies for In-Vehicle Audio and Video Communication, The 4th International Telecommunication Networking WorkShop on QoS in Multiservice IP Networks(QoS-IP 2008), Venice, Italy, Feb 2008.

PERFORMANCE EVALUATION [*]

System Model

- **Assumptions**

  1) Ethernet Link Bandwidth: 100Mbit/s
     - Ethernet is based on the 100Base-TX standard

  2) Quality-of-Service (QoS) with Prioritization mechanism as specified in IEEE 802.1Q (VLAN-tag)

     - 4 Queues per output Port:
       ⇨ Prio3 (highest Priority): Strict Priority Scheduler
       ⇨ Prio2 .. Prio1: Weighted Fair Queuing (WFQ)

  3) MAC Transmission Queue Size: 100 Frames
  4) Switch Processing Time: 3µs [1]

- **Metrics**

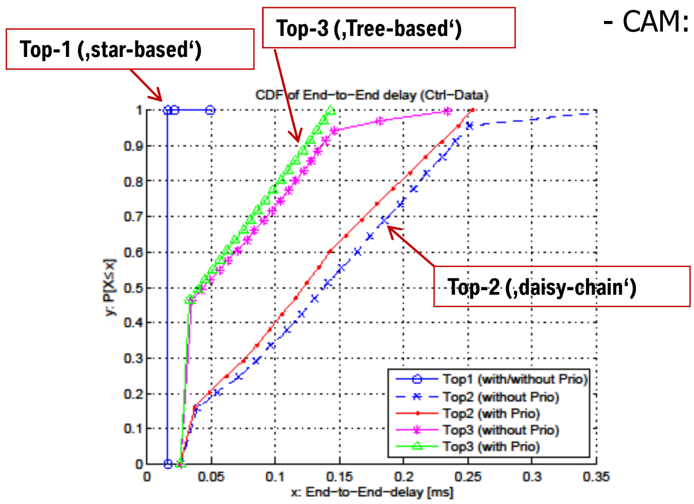
  -End-to-End delay

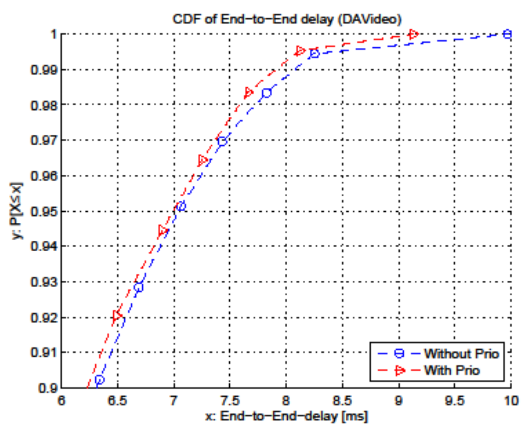
[1] M. Rahmani, R. Steen, K. Tappayuthpijarn, G. Giordano, R. Bogenberger, and E. Steinbach, *Performance Analysis of Different Network Topologies for In-Vehicle Audio and Video Communication*, The 4th International Telecommunication Networking WorkShop on QoS in Multiservice IP Networks(QoS-IP 2008), Venice, Italy, Feb 2008.

RESULT: PERFORMANCE ANALYSIS

(1) CDF: End-to-End delay

Service constraints:
- CTRL: Delay ≤ 10 ms
- CAM: Delay ≤ 45 ms





Prioritization reduces the end-to-end delay of the highest data class to approx. 40%

Independent of the used Topology, Prioritization reduces the end-to-end delay of driver assistance camera data to approx. less than 10%

SUMMARY: PERFORMANCE ANALYSIS

- Prioritization mechanism at a MAC-Layer as defined in the IEEE 802.1p/q standard can considerably improve the performance in terms of the end-to-end delay
  - ⇨ Application constraints of the in-car applications are fulfilled

- The star-based topology has the best performance in terms of the minimum end-to-end delay.

- Are there any mechanisms at Layer-2 to support a deterministic behavior of applications in a switched Ethernet network ?
  - frames should arrived at the destination within a certain time
  - high synchronization accuracy
  - low jitter

⇨ **IEEE 802.1 Audio/Video Bridging (AVB) standard**

IEEE 802.1 ETHERNET AUDIO/VIDEO BRIDGING (AVB)

- **IEEE 802.1 AVB**:

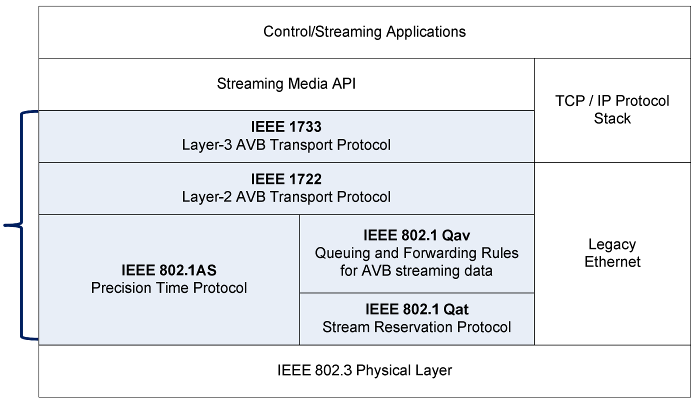
- Specifications that will allow time-synchronized low latency streaming services and QoS through 802 networks (Switched Ethernet, WLAN)

- Mechanisms on Layer2 (MAC-Layer)

- The Standard guarantees
  - Maximum latency of 2ms over 7 Hops (Class A) or 50ms (Class B)
  - Synchronization accuracy of less than 1us over 7 Hops

- consists of several sub-standards which are currently ratified and published

➡ **AVB Protocols**



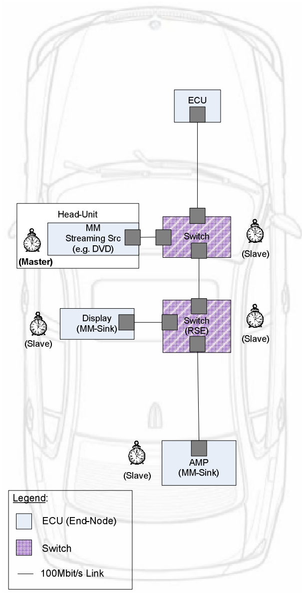
- Max. 75% of Bandwidth for AVB
- Min. 25% of Bandwidth for legacy

BACKGROUND INFORMATION: ETHERNET AVB -1-

IEEE 802.1AS – Time Synchronization Protocol

- Synchronization of distributed nodes in a switched Ethernet network to achieve two goals:

1. <u>Common Time Basis/Reference Clock</u>
   - Synchronization of distributed, networked ECUs (Audio/Video: Lip Sync)
   - Coordination multiple ECUs
2. <u>Meets jitter requirements</u>
   - Guarantees timely execution
   - Administration free protocol



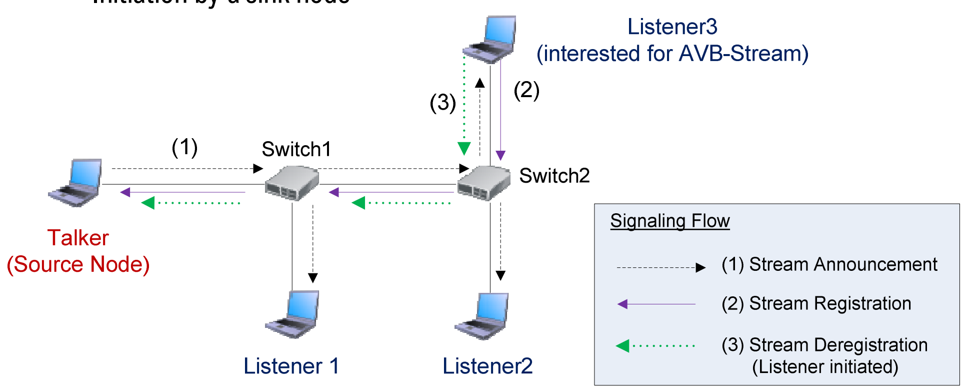
- Sync Process is executed by two steps:
  (1) Selection of the best master clock (BMC) in a network
  (2) Start of the synchronization by the BMC (grandmaster)
    - Measurement only between two adjacent systems
    - Clock drifts between AVB systems and the grandmaster are determined

BACKGROUND INFORMATION: ETHERNET AVB -2-

IEEE 802.1Qat – Stream Reservation Protocol

- Signaling protocol to reserve the required bandwidth for a specific stream (AVB-Stream) over the network

- Signaling process is executed by three steps:
  1. Stream Announcement by a source node ('Talker')
  2. Stream Registration by a sink node ('Listener')
  3. Stream Deregistration
     - Initiation by a source node
     - Initiation by a sink node



BACKGROUND INFORMATION: ETHERNET AVB -3-

IEEE 802.1Qav – Queuing and Forwarding Rules

- Mechanisms for switches to guarantee time-sensitive data transmission in terms of delay, jitter and frame loss requirements

- Based on the IEEE 802.1Q standard which allows a seperation of the network traffic into different classes by proritization mechanisms

  - Following two mechanisms are specifed:

    1) <u>Mapping of the IEEE 802.1Q priority values to AVB</u>

       - AVB frames have always the highest priority value

		Number of Available Traffic Classes						
		2	3	4	5	6	7	8
Priority	0 (Default)	0	0	0	0	0	0	1
	1	0	0	0	0	0	0	0
	2	1	1	2	3	4	5	6
	3	1	2	3	4	5	6	7
	4	0	0	1	1	1	1	2
	5	0	0	1	1	1	2	3
	6	0	0	1	2	2	3	4
	7	0	0	1	2	3	4	5

AVB Frames (Class-A; Class-B) (rows 2 and 3)

BACKGROUND INFORMATION: ETHERNET AVB -4-

IEEE 802.1Qav – Queuing and Forwarding Rules

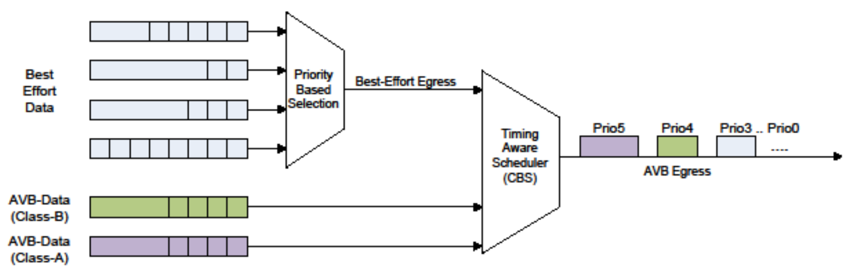
2) <u>Queuing Algorithms for AVB- and non AVB-frame</u>

   - Two different scheduling algorithms to transmit AVB and non AVB (legacy Ethernet) frames in a network

     a) <u>Strict Priority Algorithm</u> for Legacy Ethernet

     b) <u>Credit Based Shaper Algorithm</u> for AVB
        - Each AVB-Class (A or B) has certain credits
        - A Transmission is only allowed when a credit is >=0
        - For each transmission the credit is decreased at a rate of sendSlope

        <u>Otherwise</u>: - credit is increased at a rate of idleSlope
        ⇨ Transmission of legacy Ethernet frames



RESEARCH WORK

Three essential aspects are considered in our work:

No.	Ethernet Types	Methodology	
		Simulation based Evaluation	Prototyping Evaluation
1	Switched Ethernet without Prio. ('Legacy')	Finished	Finished
2	Switched Ethernet with Prio.	Finished	Finished
3	IEEE 802.1 Audio Video-Bridging (AVB)	**Ongoing**	**Ongoing**

EVALUATION OF ETHERNET AVB [*]

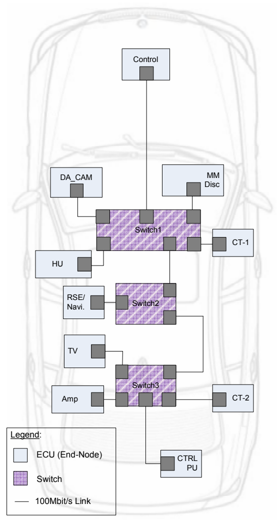
Research Questions:

1. Is the IEEE 802.1 Ethernet AVB standard able to guarantee the latency, jitter and synchronization requirement of streaming data even in high load situations ?

2. Do control data transmitted with legacy Ethernet frames meet the application constraints in terms of the maximum latency and frame loss rate ?

System Model

- Topology: daisy-chain with 3 switches in a network
- Applications
  1) Driver Assistance Camera Data (AVB: Class A)
  2) TV Streaming Data (AVB: Class B)
  3) MM Streaming Data (AVB: Class B)
  4) Control Data
  5) Navigation Data
  6) Bulk Data
- Metrics:
  - Maximum Latency
  - Jitter
  - Frame Loss Rate



[*] Work is submitted at the 75th IEEE VTC2012-Spring Conference, Yokohama, Japan

EVALUATION OF ETHERNET AVB – SYSTEM MODEL

Assumptions

- Ethernet Link: 100Mbit/s
- Static clock drifts of the ECUs without BMCA
  - Grandmaster (node with best clock): HeadUnit
  - Each nodes have static clock drifts
- Six Different Traffic Classes
  - Six Queues per output port (2 AVB + 4 Legacy Ethernet)

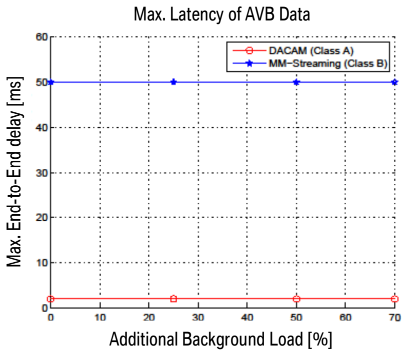
Traffic Characteristics

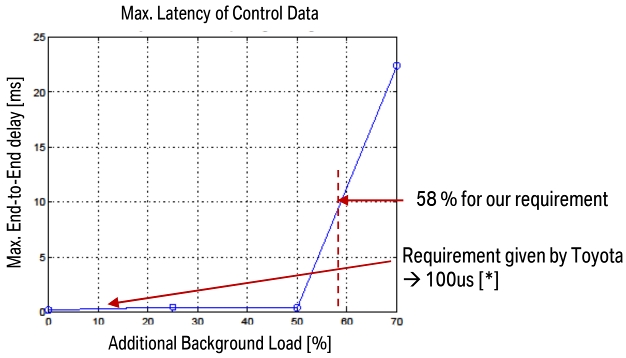
Traffic Type	Ethernet Payload [Byte]	Sending Rate [ms]	Bandwidth [Mbit/s]	Prio
Driver Assistance CAM	390	0.125	27.6	Class A (Prio5)
TV Streaming	700	0.250	23.7	Class B (Prio4)
MM Streaming	700	0.125	47.5	
Control	46	uniform (10,100)	70 e-3 .. 700e-3	3
Bulk	1428	0 .. 0.168	[0,25,50,70]	1
Navigation	1000	5	1.667	2

EVALUATION OF ETHERNET AVB – RESULT

Control and AVB data depending on the background Load

Metric	Control Data (Control → CTRL_PU)				AVB Class-A (DA_CAM→HU)			
Add. Load	0%	25%	50%	70%	0%	25%	50%	70%
Max Latency [ms]	0.095	0.434	0.391	22.40	2.0003	2.0004	2.0003	2.0003
Max Jitter [ms]	0.059	0.372	0.285	12.39	0.0003	0.0004	0.0003	0.0004
Frame Loss Rate	0	0	0	0.584	0	0	0	0





[*] Requirements for Automotive AVB System Profiles, White Paper, Toyota, 2011

EVALUATION OF ETHERNET AVB – SUMMARY

The simulation based performance Evaluation of the AVB protocols shows:

(1) The latency and frame loss of AVB streaming data are independent of the network load.

- All applications modeled as AVB Class-A/B frames have the latency less or equal than specified values (2ms for Class-A; 50ms for Class-B)

(2) The performance of control data in an AVB-network depends strongly on the network load.

- In order to guarantee the hard latency requirement of 100us, the additional background load should be less or equal than 15%.

- The IEEE 802.1 Ethernet AVB standard improves definitely the performances of multimedia and applications for driver assistance purposes.
  A deterministic behavior of these applications are achieved.
- In order to fulfill the hard real-time requirements of control data additional scheduling and prioritization mechanisms are required.

PUBLICATIONS – 2011 -

Published

– **Hyung-Taek Lim**, Kay Weckemann, Daniel Herrscher:
Performance Study of an In-Car Switched Ethernet Network Without Prioritization.
Springer Lecture Notes on Computer Science, Proc. of the 3rd International Workshop on Communication Technologies for Vehicles, March 2011, Oberpfaffenhofen, Germany.

– **Hyung-Taek Lim**, Lars Völker, Daniel Herrscher:
Challenges in a Future IP/Ethernet-based In-Car Network for Real-Time Applications. Proc. of DAC 2011,
The 48th Design Automation Conference (DAC) 2011, June 2011, San Diego, USA.

– Kay Weckemann; **Hyung-Taek Lim**, Daniel Herrscher:
Practical Experiences on a Communication Middleware for IP-based In-Car Networks.
Proc. of the Fifth International Conference on COMmunication System softWAre and middlewaRE (COMSWARE), July 2011, Verona, Italy.

– **Hyung-Taek Lim**, Benjamin Krebs, Lars Völker, Peter Zahrer:
Inter-Domain Communication in an IP/Ethernet-based In-Car Network,
Proc. of the 36th IEEE Conference on Local Computer Networks (LCN), October 2011 , Bonn, Germany.

– **Hyung-Taek Lim**, Daniel Herrscher, Lars Völker, Martin Johannes Waltl:
IEEE 802.1AS Time Synchronization in a switched Ethernet based In-Car Network,
Proc. of the 3rd IEEE Vehicular Networking Conference (VNC) 2011 , November 2011, Amsterdam, The Netherlands.

Submitted

– **Hyung-Taek Lim**, Daniel Herrscher, Firas Chaari
IEEE 802.1 Ethernet Audio/Video Bridging in an In-Car Network,
Proc. of the 75th IEEE Vehicular Technology Conference: VTC2012-Spring, Yokohama, Japan.

- **Hyung-Taek Lim**, Daniel Herrscher, Martin Johannes Waltl, Firas Chaari
Performance Analysis of the IEEE 802.1 Ethernet Audio/Video Bridging Standard,
SimuTools 2012, The 5th International ICST Conference on Simulation Tools and Techniques, Sirmione-Desenzano, Italy

Questions ?
Any Comments ?

thank you.

Research and Technology.

INNOVATIONEN GESTALTEN - STEIGEN SIE EIN

- Möglichkeiten zur Mitarbeit bei BMW Forschung und Technik
  - Praktikum (nach Bedarf)
  - Diplom-/Masterarbeit (6 Monate)
  - Dissertation (3 Jahre)
- Arbeit vor Ort bei BMW, wissenschaftliche Betreuung durch Uni
- Bevorzugt Informatiker, Elektrotechniker oder verwandte Studiengänge

E-Mail: hyung-taek.lim@bmw.de

Thank You

Research and Technology.

BMW GROUP