Design and Evaluation of Future Ethernet-based ECU Networks

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Outline

• Motivation

• Ethernet and IP in automotive networks

• Ethernet AVB
  • Timing analysis
  • Timing simulation

• Use Case and Conclusions
Motivation

- Novel applications in the infotainment and driver assistance domain
  - Bird’s eye view
  - Car-to-X
  - Rear seat entertainment
- Result: Heavily increasing bandwidth requirements
- Problem: Common field busses (FlexRay, CAN, ...) overstrained
List of Wishes for a Novel Field Bus

• Technical requirements
  • High bandwidth
  • Simplify current heterogeneous bus systems
  • Real-time capabilities

• Economical requirements
  • Low cost for communication controllers, wiring, ...
  • Open standard
Candidate: IP over Ethernet

• Technical advantages
  • 10MBit/s up to 10GBit/s bandwidth
  • IP as common addressing scheme
  • Extensions for hard (PROFINET, EtherCAT, ...) and soft (Ethernet AVB) real-time capabilities

• Economical advantages
  • Ethernet physical and MAC layer are a common standard in various areas
  • Unshielded twisted pair wires for 100MBit/s possible
Motivation
SEIS – Security in IP based embedded Systems
Our Focus in SEIS: Design Automation

(Graph-based) Model of applications and E/E architecture

- Explore design space
- Evaluate candidate implementations
- Performance estimation

Automatic design space exploration

Virtual prototyping
Automotive Design Automation

• Modeling: Tool coupling with industrial CASE tool PREEvision (supports model-based design)

mycodesign.com/research/scd

• Automatic Design Space Exploration
  • See talk of M. Lukasiewycz: *Model-based Design of Distributed Automotive Systems*

• This talk: Performance estimation
  • Timing evaluation of an IP/Ethernet-based E/E architecture
Ethernet/AVB (Audio/Video Bridging)

- Ethernet defines physical and MAC-Layer
- AVB enhances MAC layer by:
  - Clock Synchronization (IEEE802.1AS)
  - Bandwidth Reservation (IEEE802.1Qat)
  - Traffic Shaping (IEEE802.1Qav)
- IEEE1722 is the transport protocol of AVB
- TCP/IP can be used in parallel to AVB/1722
Credit Based Shaping of Ethernet AVB

- Traffic shaping at each output port
- CBS delays messages to avoid bursts
- Otherwise, bursts could lead to buffer overflows at switches and, thus, to message loss
CBS – Example 1

- Two consecutive frames of same traffic class

Frame 1 ready
Frame 2 ready

credit

delaying Frame 2
sendSlope
idleSlope
CBS – Example 2

- 3 queues; queue A and B with CBS
Delays in Ethernet-based Networks

1. Input Queuing Delay
   - Typically negligible

2. Store-and-forward Delay
   - Crossbar operates at high bandwidth
   - Non-blocking switches typically used: bandwidth of crossbar >> bandwidth of input links

3. Interference Delay
   - Interference with traffic from other input ports
   - Best effort, priority-based, and CBS

4. Frame Transmission Delay
   - Depends on link bandwidth
   - 10 MBit/s, 100MBit/s, 1GBit/s, 10GBit/s

5. LAN Propagation Delay
   - Signal propagation on medium at light speed
Real-time analysis of Ethernet AVB

• Real-time calculus to evaluate end-to-end best and worst case delays
• All message streams are known at design time (in contrast to common Ethernet-based systems)
  • Dynamic bandwidth reservation IEEE802.1Qat unnecessary
  • Routing, priorities, and traffic queues fixed during runtime
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Credit-based Shaping and RTC

• Typical use case: Video stream
  • One image each 33ms
  • HD resolution -> about 1400 Ethernet frames
  • Significant burst

• Simplified use case for this talk: 6kByte every 33ms
  • Burst of 4 frames with 1500 Byte each
  • No interfering traffic
Credit-based Shaping and RTC

- Available service depends on reserved bandwidth of the queue
- Models CBS by providing service in small chunks
Credit-based Shaping and RTC

- Resulting arrival curve shows equally shaped messages
- Bigger delay but much less jitter as with standard Ethernet
Credit-based Shaping and RTC

• Analysis has to consider additionally:
  • Interfering traffic of higher traffic classes
  • Traffic in same traffic class
    • Either already shaped or
    • New, unshaped input
  • Head of line blocking of best effort traffic from lower priority queues
Simulation-based evaluation

functional network

component network
Simulation-based evaluation

- Function performs an action instantaneous and calls `compute()` for timing simulation
- Component determines additional delays due to
  - Scheduling
  - Resource contention
- Delay of an action is assumed to be specified for each mapping edge
Simulation-based evaluation

Each message is routed statically
Each resource adds corresponding transfer delay
Ethernet and Ethernet AVB with credit-based traffic shaping are integrated as dedicated scheduler
Simulation-based evaluation

functional network

component network

- Acceleration of simulation speed:
  - Extract all static delays in IP/Ethernet stack (most are indep. on message size)
  - Only compute dynamic delays (dep. on message size) during simulation:
    - CRC calculation in UDP
    - delay on physical medium

ECU1

Communication Controller

![Graph showing network latency vs payload](image)
Use Case AVB: Streaming and Control

**Application**
- 40 tasks to map
- 39 messages to route

**Architecture**
- 15 ECUs
- 4 CANs
- 3 Switches
- 123 others
Use Case AVB Preliminary Results

<table>
<thead>
<tr>
<th>Source to Sink delay</th>
<th>Best case [ms]</th>
<th>Worst case [ms]</th>
<th>Relative difference</th>
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</thead>
<tbody>
<tr>
<td>Actuator 1</td>
<td>3,51</td>
<td>4,98</td>
<td>42%</td>
</tr>
<tr>
<td>Actuator 2</td>
<td>3,46</td>
<td>4,78</td>
<td>38%</td>
</tr>
<tr>
<td>Actuator 3</td>
<td>3,76</td>
<td>4,65</td>
<td>24%</td>
</tr>
<tr>
<td>Actuator 4</td>
<td>3,1</td>
<td>4,39</td>
<td>42%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average case [ms]</th>
<th>Sim. Vs RTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,82</td>
<td>TBD</td>
</tr>
<tr>
<td>3,79</td>
<td>TBD</td>
</tr>
<tr>
<td>4,13</td>
<td>TBD</td>
</tr>
<tr>
<td>3,55</td>
<td>TBD</td>
</tr>
</tbody>
</table>

Delay Jitter

Waiting for data
Lessons learnt from timing analysis

• Most important: Interference delay at output ports
• Traffic shaping reduces jitter
  • But: Best case delay higher as with best effort
• Jitter depends mainly on output port, i.e., messages with same direction
Conclusion

• Ethernet will be part of future cars!

• Successful integration of IP/Ethernet requires a holistic design flow
  • Consider specific features during modeling, optimization, and analysis

• This talk: Analytical and simulative timing evaluation for functional validation of Ethernet AVB-based E/E architectures
Thank you for your attention.

Questions?