Performance Bounds in In-Car and Aeronautic Networks

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Outline

Introduction
• Motivation of Ethernet-based In-Car Networks
• Motivation of Ethernet-based Aeronautic Networks

Scope of the work and Techniques
• Discrete Event Simulation
• Network Calculus

Performance Bounds and Evaluation
• Avionic Network
• In-Car Network with
  - IEEE 802.1Q – Prioritization mechanism
  - IEEE 802.1 Ethernet AVB

Summary, Conclusion
Motivation of Ethernet-based In-Car Networks

Internet Protocol (IP)-based Network
Replacement of current specific In-Car/Aeronautic protocols by standard IP

- Suitable technology to transport IP for the industrial use
  → Future applications have higher bandwidth demand

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

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Legacy Ethernet

<table>
<thead>
<tr>
<th>Layer</th>
<th>Applications</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>7: Application</td>
<td>?</td>
<td>(+) Mature Technology</td>
<td>(-) Real-time data transmission is not supported</td>
</tr>
<tr>
<td>6: Presentation</td>
<td>?</td>
<td>(+) Fast, easy to use</td>
<td>(-) Packets can be delayed or lost (Switch)</td>
</tr>
<tr>
<td>5: Session</td>
<td>?</td>
<td>(+) Two-wire unshielded available for automotive use</td>
<td>(-) Efficiency problems with small packets</td>
</tr>
<tr>
<td>4: Transport</td>
<td>TCP / UDP</td>
<td>(+) No single source</td>
<td></td>
</tr>
<tr>
<td>3: Network</td>
<td>IP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2: Data Link</td>
<td>Ethernet MAC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1: Physical</td>
<td>Ethernet Phy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ethernet is currently used only for two areas in a vehicle:
- Diagnosis and flashing (OBD)
- Remote disc access

Currently: Ethernet is only used as a direct link without prioritization mechanism
Future: More than 2 ECUs are connected to the Ethernet network
Ethernet in Aeronautic Networks

State of the art:
Avionics Full DupleX (AFDX):
• 100 ++ Endsystems; 10 ++ Switches

Additionally used technologies:
• LVDS, CAN, ARINC 429, RS232, 10Base2 Ethernet, FlexRay

Vision: Build up Cabin System by COTS Components; homogeneous end-to-end networks

Vision 2025: Integrate In-Flight Entertainment in same network => Validation of high level requirements
Delays in Switched Ethernet

Distinguish the following sources of network-induced delay

- **Propagation Delay**
  - Speed Light and Length of Cable
- **Processing Delay**
  - Processing of the packet by the network hardware and end devices
- **Transmission Delay**
  - Time between first and last bit of a packet on the link medium
- **Queuing Delay**
  - Time a packet remains in queue due to ports in service

<table>
<thead>
<tr>
<th>Delay Source</th>
<th>64 byte frame</th>
<th>1518 byte frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation Delay</td>
<td>&lt; 2μs / 300m</td>
<td>&lt; 2μs / 300m</td>
</tr>
<tr>
<td>Processing Delay</td>
<td>hardware dependent</td>
<td>hardware dependent</td>
</tr>
<tr>
<td>Transmission Delay</td>
<td>5.8 μs</td>
<td>122.7 μs</td>
</tr>
<tr>
<td>Queuing Delay</td>
<td>depends on load / # ports</td>
<td>depends on load / # ports</td>
</tr>
</tbody>
</table>
Scope of the work and Methodology

- Analysis of an In-Car/Aeronautic Network with typical applications
  - Influence of the
    1. Topology
    2. QoS mechanisms:
      - Prioritization as specified in IEEE 802.1Q
      - IEEE 802.1 AVB mechanisms
  - Verifying the provided application constraints in terms of maximum end-to-end delays

Worst Case Analysis
- Deterministic Network Calculus (DNC)

Simulation-based Analysis
- Network Simulation with INET-framework and some modifications to support:
  1. Loading external trace files (e.g. CAN, FlexRay traces)
  2. Prioritization mechanisms
  3. IEEE 802.1 Ethernet AVB
Deterministic Network Calculus – Short Introduction

- Arrival Curve $\alpha$ (1.6 MBit/s, burst 200 bytes)
- Service Curve $\beta$ (3.2 MBit/s, delay 200 ms)
- Horizontal Deviation gives worst case Delay
- Vertical Deviation gives Backlogs

- Simple Example with one flow and one service curve
- For tight bounds it will be crucial to find a tight service curve

Algorithms
- Total Flow Analysis (TFA)
- Separated Flow Analysis (SFA)
Cabin Scenario

Functionalities in Aircraft Cabin
- Passenger Call (PAX Call)
- Integrated Pre-recorded Announcement & Boarding Music
- Cabin Interphone
- Passenger Address (PA)
- Cabin Illumination
- Cabin Video Monitoring System

Topology
- Star
- Up to 16 lines (more are welcome)
- Up to 12 BACs per line (more are welcome)

Prioritization
- IEEE 802.1Q
- high prio traffic, safety relevant
- low prio traffic, IFE as games, multimedia, etc.
Worst Case Simulation vs. Network Calculus, Cabin

Validation of high level requirements

- Low Delay
  ⇒ 10 ms maximum delay
- Low Multicast Delay Difference
  ⇒ 100 ms maximum signaling delay
- Low Frame Loss
  ⇒ 1 ms maximum multicast delay diff
  ⇒ Worst Case Backlog

⇒ Deterministic Network Calculus
⇒ Network Simulation

Traffic Description

<table>
<thead>
<tr>
<th>Device</th>
<th>Traffic</th>
<th>Burst [bytes]</th>
<th>Rate [bytes/ms]</th>
<th>Peak [bytes/ms]</th>
<th>Sustain [bytes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Server</td>
<td>TokenBucket</td>
<td>108</td>
<td>3456</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSU</td>
<td>TokenBucket</td>
<td>108</td>
<td>25.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Handset</td>
<td>Dual TokenBucket</td>
<td>64</td>
<td>204</td>
<td>816</td>
<td>1000</td>
</tr>
<tr>
<td>Disturb (optional)</td>
<td>TokenBucket</td>
<td>1518</td>
<td>6250</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Worst Case Simulation vs. Network Calculus, Cabin

- Worst Case Delay of each flow, staircase shows number of hops
- NC bound (blue/black) is worst case as identified by total flow analysis
- Worst case in light traffic scenario as identified by simulation (o)
- Worst case in overload scenario as identified by simulation (+)

⇒10ms max delay and 100ms signalling delay are fulfilled
⇒1ms multicast delay difference could only be fulfilled with smaller MTU for high prio traffic

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Simulation CDF, Device to Server

Validation of high level requirements

• Signaling is lower than 10ms
  Requirement 100ms
• Audio Delay from handset to server is lower than 2ms
  Requirement 10ms
Switched Ethernet based In-Car Network [*]

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 Network: Traffic Characteristics

<table>
<thead>
<tr>
<th>Traffic Type</th>
<th>UDP Packet Length [Byte]</th>
<th>Sending Rate [ms]</th>
<th>Bandwidth [Mbit/s]</th>
<th>Prio</th>
<th>Max. End-to-End Delay [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>18</td>
<td>33</td>
<td>&lt; 1</td>
<td>3</td>
<td>10 [4,5]</td>
</tr>
<tr>
<td>Driver Assistance CAM</td>
<td>1400</td>
<td>0.481</td>
<td>24</td>
<td>2</td>
<td>45 [5]</td>
</tr>
<tr>
<td>Navigation</td>
<td>1000</td>
<td>100</td>
<td>16</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>MM Video</td>
<td>1400</td>
<td>0.28</td>
<td>41</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>MM Audio</td>
<td>1400</td>
<td>1.4</td>
<td>8.3</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>TV Video</td>
<td>1400</td>
<td>0.577</td>
<td>20</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>TV Audio</td>
<td>1400</td>
<td>2.33</td>
<td>4.9</td>
<td>0</td>
<td>150</td>
</tr>
</tbody>
</table>
Intermediate Result-1

(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. 69%

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

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Intermediate Result-2: Worst-Case Analysis

- Performance Comparison:

- worst case calculation gives the hard limit for the end-to-end delay
In-Car Network with IEEE 802.1 AVB

Following IEEE 802.1 AVB protocols are used for the performance evaluation:

- **IEEE 802.1AS**: Time Synchronization protocol
- **IEEE 802.1Qat**: Resource Reservation protocol for AVB streaming data
- **IEEE 802.1Qav**: Queuing and Forwarding rules for AVB streaming data
- **IEEE 1722**: Transport protocol at Layer-2

Traffic Characteristics for AVB data:

<table>
<thead>
<tr>
<th>Traffic Type</th>
<th>AVB Class</th>
<th>Frame Size [byte]</th>
<th>Rate [ms]</th>
<th>BW [Mbit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DA Stream (1)</td>
<td>A</td>
<td>390</td>
<td>0.125</td>
<td>≈ 27.6</td>
</tr>
<tr>
<td>TV Stream (2)</td>
<td>B</td>
<td>800</td>
<td>0.250</td>
<td>≈ 26.9</td>
</tr>
<tr>
<td>MM Stream (3)</td>
<td>B</td>
<td>800</td>
<td>0.125</td>
<td>≈ 53.8</td>
</tr>
</tbody>
</table>
In-Car Network with IEEE 802.1 AVB

**Assumption:**
- fixed and static clock drift
  (in reality: depending on the environment, e.g. temperature, pressure etc.)

<table>
<thead>
<tr>
<th>Time Aware System</th>
<th>HU</th>
<th>Switch1</th>
<th>DA_CAM</th>
<th>Control</th>
<th>Multimedia Disc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock drift [ppm]</td>
<td>0</td>
<td>30</td>
<td>-35</td>
<td>-50</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time Aware System</th>
<th>Switch2</th>
<th>RSE</th>
<th>Switch3</th>
<th>TV</th>
<th>AMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock drift [ppm]</td>
<td>-15</td>
<td>-15</td>
<td>20</td>
<td>-5</td>
<td>-50</td>
</tr>
</tbody>
</table>

Daisy chain-based Topology
Simulation Result

1. End-to-End delay

The end-to-end delays of MM-Streaming Data (AVB-Class B) are less than the maximum allowed latency.

2. Synchronization accuracy

After the listeners are synchronized ($t>t_{set}$), the presentation time of the listeners are the same; no quite differences.

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Summary and Conclusion

- A switched Ethernet based In-Car/Aeronautic network was analyzed by determining the influence of:
  1. Topology
  2. Prioritization mechanism as specified in IEEE 802.1Q

- A switched Ethernet based In-Car network with IEEE 802.1 AVB was analyzed to determine
  1. the latency of AVB streaming data
  2. the synchronization process

- Analysis was performed by
  1. Simulation
  2. Worst case estimation with determinitic network calculus

- Prioritization mechanisms can considerably improve the performance in terms of end-to-end delays and packet loss

- Ethernet AVB enables to synchronize different nodes with low latency after a certain time

- Worst case calculation with DNC gives information about the hard limit of end-to-end delays
  \[\Rightarrow\] DNC model has to be optimized to increase the accuracy
References

[1] Airbus, Internal Documents