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Applying and optimizing Trajectory approach for performance evaluation of AFDX networks

Real-Time and (Networked) Embedded Systems - 14th ETFA
Presentation outline

• Context
• The AFDX network
• End-to-end delay analysis
• The Trajectory approach
  ‣ Applied to AFDX networks
  ‣ Illustration on a sample example
  ‣ Analysis of the pessimism introduced by the Trajectory approach
• Introducing the grouping technique
• Evaluation on an industrial configuration
• Conclusion
Context

• MCUs host avionics functions throughout the aircraft
• Traditional mono-emitter ARINC 429:
  ‣ Limited bandwidth
  ‣ High number of wires (significant weight)
  ‣ Architectures lack flexibility and can hardly evolve
  ‣ Not scalable for complex modern Aircrafts
Context

• A modern Aircraft with numerous functions and MCUs
• Avionics Full Duplex Switched Ethernet:
  ‣ Communication multiplexing
  ‣ A backbone network for the avionics platform
Context

• How to guarantee communication determinism in a multiplexed environment?

- Find a modeling and apply a formal approach in order to find a guaranteed upper bound for end-to-end transmission delay
- Optimize the upper bound, in order to minimize the pessimism between the modeling and the real network
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The AFDX network

• Avionics Full Duplex Switched Ethernet:
  ‣ Relies on recognized standards
  ‣ Wide range of existing development and monitoring tools
  ‣ High 100Mb/s bandwidth, compared to:
    ‐ ARINC 429: 12.5kb/s to 100kb/s
    ‐ CAN: 20kb/s to 1Mb/s
    ‐ Flexray: 10Mb/s per channel

• Differences compared to conventional switched Ethernet:
  ‣ Deterministic data flows
  ‣ No collision on links
  ‣ No packet loss (nominal)
  ‣ Avionics flows are statically defined
• The AFDX network:
  ‣ Interconnected switches
  ‣ FIFO output ports
  ‣ End-Systems

![Diagram of AFDX network showing interconnected switches, FIFO output ports, and end-systems.](image)
The AFDX network

- Avionics flows are characterized as **Virtual Links**:
  - Statically defined
  - Deterministic routing
  - Unidirectional
  - Multicast routing
  - Guaranteed traffic envelope contract at network ingress:
    - Maximum frame length: $S_{\text{max}}$
    - Minimum delay between two consecutive frames: $\text{BAG}$ (Bandwith Allocation Gap)

⇒ Leaky bucket model:

- Bucket capacity: $S_{\text{max}}$
- Bucket leaking rate: $S_{\text{max}}/\text{BAG}$
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End-to-end delay analysis

- Network Calculus
  - Provides upper bounds on end-to-end delay and jitter
  - Used for avionics network certification purposes
  - Pessimism: working with traffic envelopes

- Simulation
  - Provides a per flow end-to-end delay distribution
  - Rare events can be missed: no deterministic bounds

- Model Checking
  - Provides exact worst-case end-to-end delays
  - Not (yet) scalable to an industrial configuration

- Trajectory approach
  - Provides worst case upper bounds
  - Bounds can be compared with Network Calculus results
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The Trajectory approach

- The Trajectory approach considers distributed systems:
  - Set of processing nodes
  - Links between the nodes
  - Trajectory $\tau_i$ follows path $P_i=\{1, 5, 6, 10\}$
  - A flow of $P_j$ never visits a flow of $P_i$ after having left $P_i$
The Trajectory approach

- Moving backwards through the sequence of nodes
- Identify all the preceding packets and busy periods

![Diagram of Trajectory approach]

1. Moving backwards through the sequence of nodes:
   - Identify all the preceding packets and busy periods.
The Trajectory approach

- Construction of the worst case scenario
- End-to-end delay = processing time of resulting packets + transmission time on links

1. $f(1)$  
2. $f(2)$  
3. $f(3)$  
4. $f(h)$  
5. $f(h+1)$  
6. $f(q-1)$  
7. $f(q)$  
8. $m$
The Trajectory approach applied to AFDX networks

• Trajectory/AFDX mapping:
  ‣ System node ↔ Switch output port
  ‣ System link ↔ Switching fabric
  ‣ Flow ↔ VL path

• Trajectory assumptions are verified:
  ‣ FIFO service discipline in switch output port
  ‣ Switching fabric delay is bounded
  ‣ No collisions on the AFDX network → no packet loss
  ‣ A VL path never crosses another VL path twice
  ‣ Statically defined VL routing
Illustration on a sample example

- **Sample configuration:**
  - \( \text{BAG} = 4000 \ \mu s \)
  - \( \text{Smax} = 4000 \ \text{bits} \)
  - \( \text{R} = 100 \ \text{Mb/s} \)
  - \( L = 16 \ \mu s \)

- **Worst-case configuration for packet 3 from e3**
  - \( 40 + 16 + 2 \times 40 + 16 + 3 \times 40 = 272 \ \mu s \)
Analysis of the pessimism introduced by the Trajectory approach

- Same configuration:
  - Packet 5 from e5
  - Serialization is not taken into account
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Introducing the grouping technique

- A refinement of the network modeling
- Serialization of flows having shared a common link
- Worst case incoming traffic in an output port
- Divided and grouped by source (i.e. transmission link)
- Each group is shaped by a leaky bucket:
  - Burst: largest frame size in the group
  - Rate: rate of the source

\[
\max_{\tau \in S1} \left( s_{\text{max}} \right)
\]

\[
R_{S1-S3}
\]
Introducing the grouping technique

- Worst case end-to-end delay $R_i$ depends on the latest starting time of the packet in its last node $W_{i,t}^{last}$

$$R_i = \max_{t \geq -J_i} (W_{i,t}^{last} + C_i - t)$$

- The latest starting time is calculated recursively
  - Delay due to other flows

$$W_{i,t}^{last} = \sum_{\substack{j \in [1,n] \setminus i \setminus \emptyset \setminus P_j \cap P_i \neq \emptyset}} \left( 1 + \left[ \frac{t + A_{i,j}}{T_j} \right] \right)^+ \cdot C_j + \left( 1 + \left[ \frac{t + J_i}{T_j} \right] \right)^+ \cdot C_i + \sum_{h \in P_i \setminus \emptyset \setminus last_i} \left( 1 + \left[ \frac{t + A_{i,j}}{T_j} \right] \right)^+ \cdot C_j - C_i + (|P_i| - 1) \cdot L_{max}$$

$$\sum_{\text{other flows}} \left( 1 + \left[ \frac{t + \text{Jitter}}{\text{Period}} \right] \right)^+ \cdot C \rightarrow \sum_{\text{source}} \left( \min \left[ \lambda(t), \sum_{\text{flows} \in \text{src}} \left( 1 + \left[ \frac{t + \text{Jitter}}{\text{Period}} \right] \right)^+ \cdot C \right] \right)$$

Sum of staircase functions  Leaky bucket

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Introducing the grouping technique

- Graphically: search for the maximum vertical deviation
- Grouping ⇒ step corner shaping

Staircase function

\[ W_{i,t}^{\text{last}} + C_i \]

\[ R_i = \max_{t \geq J_i} \left( W_{i,t}^{\text{last}} + C_i - t \right) \]
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## Evaluation on an industrial configuration

<table>
<thead>
<tr>
<th>Approach</th>
<th>Versus</th>
<th>Average</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC WITH GROUPING</td>
<td>NC</td>
<td>24.21%</td>
<td>51.07%</td>
<td>8.59%</td>
</tr>
<tr>
<td>TRAJ WITH GROUPING</td>
<td>TRAJ</td>
<td>18.36%</td>
<td>56.66%</td>
<td>4.87%</td>
</tr>
<tr>
<td>TRAJ</td>
<td>NC</td>
<td>16.69%</td>
<td>37.83%</td>
<td>-6.02%</td>
</tr>
<tr>
<td>TRAJ WITH GROUPING</td>
<td>NC WITH GROUPING</td>
<td>10.46%</td>
<td>34.02%</td>
<td>-18.39%</td>
</tr>
<tr>
<td>BEST</td>
<td>NC WITH GROUPING</td>
<td>10.71%</td>
<td>34.02%</td>
<td>0%</td>
</tr>
</tbody>
</table>
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Conclusion

• Trajectory approach applicable to AFDX networks:
  ‣ Bounds can be compared to Network Calculus ones
  ‣ The method can be improved thanks to the grouping technique
  ‣ Impact of the grouping technique is significant

• Performance evaluation on an industrial configuration:
  ‣ Trajectory approach: 10% average upper-bounds improvement compared to Network Calculus
  ‣ It is always possible to keep the tightest of both bounds

• Perspectives:
  ‣ Study more precisely the parameters that impact the performance of both methods
  ‣ Trajectory approach is promising for handling heterogeneous flows (i.e. with QoS needs)
Questions

Thank you for your attention

Any questions?