Performance Enhancement of Extended AFDX via Bandwidth Reservation for TSN/BLS Shapers

Anaïs Finzi, Ahlem Mifdaoui et al.

July 3, 2018, RTN’18
Context and Objectives

- Up to 500 km of cables
- Heterogeneous network
- AFDX
- ARINC 429
- CAN
- MIL-STD-1553
Context and Objectives

Up to 500 km of cables
Up to 500 km of cables

Heterogeneous network
Context and Objectives

- Up to 500 km of cables
- Heterogeneous network
- AFDX
Context and Objectives

- Up to 500 km of cables
- Heterogeneous network
- ARINC 429
- AFDX
Context and Objectives

- Up to 500 km of cables
- Heterogeneous network
- ARINC 429
- AFDX
- CAN
Context and Objectives

Up to 500 km of cables

Heterogeneous network

ARINC 429

AFDX

CAN

MIL-STD-1553
Context and Objectives

Current Avionics Communication Architecture limitations

- **Heterogeneity**: high complexity, delays and costs
- **One criticality level**: backbone supports only essential traffic
- **Unfair service policy**: strong impact of high priorities
### Context and Objectives

<table>
<thead>
<tr>
<th>Current Avionics Communication Architecture limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>- <strong>Heterogeneity</strong>: high complexity, delays and costs</td>
</tr>
<tr>
<td>- <strong>One criticality level</strong>: backbone supports only essential traffic</td>
</tr>
<tr>
<td>- <strong>Unfair service policy</strong>: strong impact of high priorities</td>
</tr>
</tbody>
</table>

### Main Objective

**Homogenize avionics communication architecture**

→ *Extend the backbone network to support* **Safety-Critical** and **Best-Effort** Traffic
Avionics Requirements and Challenges

Requirements

- **Predictability**: guaranteeing schedulability constraints, i.e. bounded delays respecting deadlines
- **Modularity**: minimizing the (re)configuration effort
Avionics Requirements and Challenges

Requirements

- **Predictability**: guaranteeing schedulability constraints, i.e. bounded delays respecting deadlines
- **Modularity**: minimizing the (re)configuration effort

Challenges

- **Complexity**: Reduce the implementation and configuration effort
- **Fairness**: Limit the impact of high priorities on lower ones
## Promising Solution

<table>
<thead>
<tr>
<th>Solutions</th>
<th>TTE&lt;sup&gt;1&lt;/sup&gt;</th>
<th>TAS&lt;sup&gt;2&lt;/sup&gt;</th>
<th>PS&lt;sup&gt;3&lt;/sup&gt;</th>
<th>UBS&lt;sup&gt;4&lt;/sup&gt;</th>
<th>BLS&lt;sup&gt;5&lt;/sup&gt;</th>
<th>CBS&lt;sup&gt;6&lt;/sup&gt;</th>
<th>NP-SP&lt;sup&gt;7&lt;/sup&gt;</th>
<th>DRR&lt;sup&gt;8&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
</tr>
<tr>
<td>Predictability</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
</tr>
<tr>
<td>Fairness</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>X</td>
<td>✓✓</td>
</tr>
<tr>
<td>Complexity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Existing solutions vs avionics requirements and challenges

✓✓: 😊
✓: 😐
X: 😞

1. Time Triggered Ethernet
2. Time Aware Shaper
3. Peristaltic Shaper
4. Urgency Based Scheduler
5. Burst Limiting Shaper
6. Credit-based Shaper
7. Non-preemptive Static Priority
8. Deficit Round Robin
### Promising Solution

<table>
<thead>
<tr>
<th>Solutions</th>
<th>TTE&lt;sup&gt;1&lt;/sup&gt;</th>
<th>TAS&lt;sup&gt;2&lt;/sup&gt;</th>
<th>PS&lt;sup&gt;3&lt;/sup&gt;</th>
<th>UBS&lt;sup&gt;4&lt;/sup&gt;</th>
<th>BLS&lt;sup&gt;5&lt;/sup&gt;</th>
<th>CBS&lt;sup&gt;6&lt;/sup&gt;</th>
<th>NP-SP&lt;sup&gt;7&lt;/sup&gt;</th>
<th>DRR&lt;sup&gt;8&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
</tr>
<tr>
<td>Predictability</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
</tr>
<tr>
<td>Fairness</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✗</td>
<td>✓✓</td>
</tr>
<tr>
<td>Complexity</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

### Existing solutions vs avionics requirements and challenges

- ✓✓: 😊
- ✓: 😐
- ✗: 😞

<sup>1</sup> Time Triggered Ethernet  
<sup>2</sup> Time Aware Shaper  
<sup>3</sup> Peristaltic Shaper  
<sup>4</sup> Urgency Based Scheduler  
<sup>5</sup> Burst Limiting Shaper  
<sup>6</sup> Credit-based Shaper  
<sup>7</sup> Non-preemptive Static Priority  
<sup>8</sup> Deficit Round Robin
## Promising Solution

### Existing solutions vs avionics requirements and challenges

<table>
<thead>
<tr>
<th>Solutions</th>
<th>TTE&lt;sup&gt;1&lt;/sup&gt;</th>
<th>TAS&lt;sup&gt;2&lt;/sup&gt;</th>
<th>PS&lt;sup&gt;3&lt;/sup&gt;</th>
<th>UBS&lt;sup&gt;4&lt;/sup&gt;</th>
<th>BLS&lt;sup&gt;5&lt;/sup&gt;</th>
<th>CBS&lt;sup&gt;6&lt;/sup&gt;</th>
<th>NP-SP&lt;sup&gt;7&lt;/sup&gt;</th>
<th>DRR&lt;sup&gt;8&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>Predictability</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>Fairness</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>X</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>Complexity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

<sup>1</sup> Time Triggered Ethernet  
<sup>2</sup> Time Aware Shaper  
<sup>3</sup> Peristaltic Shaper  
<sup>4</sup> Urgency Based Scheduler  
<sup>5</sup> Burst Limiting Shaper  
<sup>6</sup> Credit-based Shaper  
<sup>7</sup> Non-preemptive Static Priority  
<sup>8</sup> Deficit Round Robin
## Promising Solution

<table>
<thead>
<tr>
<th>Solutions</th>
<th>TTTEch</th>
<th>TAS²</th>
<th>PS³</th>
<th>UBS⁴</th>
<th>BLS⁵</th>
<th>CBS⁶</th>
<th>NP-SP⁷</th>
<th>DRR⁸</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
</tr>
<tr>
<td>Predictability</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓</td>
<td>✓✓</td>
<td>✓✓</td>
</tr>
<tr>
<td>Fairness</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>X</td>
<td>✓✓</td>
</tr>
<tr>
<td>Complexity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Existing solutions vs avionics requirements and challenges

- ✓✓: 😊
- ✓: 😞
- X: 😞

---

1. Time Triggered Ethernet
2. Time Aware Shaper
3. Peristaltic Shaper
4. Urgency Based Scheduler
5. Burst Limiting Shaper
6. Credit-based Shaper
7. Non-preemptive Static Priority
8. Deficit Round Robin
Promising Solution

<table>
<thead>
<tr>
<th>Solutions</th>
<th>TTE(^1)</th>
<th>TAS(^2)</th>
<th>PS(^3)</th>
<th>UBS(^4)</th>
<th>BLS(^5)</th>
<th>CBS(^6)</th>
<th>NP-SP(^7)</th>
<th>DRR(^8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Predictability</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fairness</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>Complexity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Existing solutions vs avionics requirements and challenges

✓✓: 😊 ✓: 😐 X: 😞

---

1 Time Triggered Ethernet
2 Time Aware Shaper
3 Peristaltic Shaper
4 Urgency Based Scheduler
5 Burst Limiting Shaper
6 Credit-based Shaper
7 Non-preemptive Static Priority
8 Deficit Round Robin
## Promising Solution

### Table: Existing solutions vs avionics requirements and challenges

<table>
<thead>
<tr>
<th>Solutions</th>
<th>TTE 1</th>
<th>TAS 2</th>
<th>PS 3</th>
<th>UBS 4</th>
<th>BLS 5</th>
<th>CBS 6</th>
<th>NP-SP 7</th>
<th>DRR 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
</tr>
<tr>
<td>Predictability</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓</td>
<td>✓✓</td>
<td>✓✓</td>
</tr>
<tr>
<td>Fairness</td>
<td>X</td>
<td>X</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>X</td>
<td>✓✓</td>
</tr>
<tr>
<td>Complexity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

### Existing solutions vs avionics requirements and challenges

- ✓✓: 😊
- ✓: 😞
- X: 😞

---

1. Time Triggered Ethernet
2. Time Aware Shaper
3. Peristaltic Shaper
4. Urgency Based Scheduler
5. Burst Limiting Shaper
6. Credit-based Shaper
7. Non-preemptive Static Priority
8. Deficit Round Robin
## Promising Solution

<table>
<thead>
<tr>
<th>Solutions</th>
<th>TTE(^1)</th>
<th>TAS(^2)</th>
<th>PS(^3)</th>
<th>UBS(^4)</th>
<th>BLS(^5)</th>
<th>CBS(^6)</th>
<th>NP-SP(^7)</th>
<th>DRR(^8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Predictability</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fairness</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>Complexity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Existing solutions vs avionics requirements and challenges

- ✓✓: 😊
- ✓: 😐
- X: 😞

→ the **Burst Limiting Shaper** is the most promising solution

---

1. Time Triggered Ethernet
2. Time Aware Shaper
3. Peristaltic Shaper
4. Urgency Based Scheduler
5. Burst Limiting Shaper
6. Credit-based Shaper
7. Non-preemptive Static Priority
8. Deficit Round Robin
Followed Methodology

**Specification of an Extended AFDX**

→ **Low complexity** and few hardware/software modifications\(^a\)

Followed Methodology

**Specification of an Extended AFDX**
→ **Low complexity** and few hardware/software modifications\(^a\)

\(^a\)\[ERTS2-18\] Finzi, A., Mifdaoui et al., "Mixed-Criticality on the AFDX Network: Challenges and Potential Solutions”, ERTS 2018

**Formal timing analysis**
→ **New Network Calculus model with good tightness** \(^a\)

\(^a\)\[WFCS-18\] Finzi, A., Mifdaoui et al., ”Incorporating TSN/BLS in AFDX for Mixed- Criticality Applications: Model and Timing Analysis”, WFCS 2018
Followed Methodology

**Specification of an Extended AFDX**

→ **Low complexity** and few hardware/software modifications$^a$


**Formal timing analysis**

→ New Network Calculus model with **good tightness**$^a$

$^a$[WFCS-18] Finzi, A., Mifdaoui et al., ”Incorporating TSN/BLS in AFDX for Mixed- Criticality Applications: Model and Timing Analysis”, WFCS 2018

**Performance Enhancement**

→ **Bandwidth Reservation** methods for TSN/BLS to enhance system schedulability
Outline

1. System Model
2. Bandwidth Reservation Methods
3. Performance Evaluation
4. Conclusion and perspectives
Outline

1. System Model
2. Bandwidth Reservation Methods
3. Performance Evaluation
4. Conclusion and perspectives
We consider 3 types of traffics: Safety Critical Traffic (SCT), Rate Constrained (RC), and Best-Effort (BE).
We consider 3 types of traffics: Safety Critical Traffic (SCT), Rate Constrained (RC), and Best-Effort (BE).
Extended AFDX output port

3-classes example: high BLS priority

- SCT class
- RC class
- BE class

BLS

- #0
- #1
- #3

SP

sets queue priority between \{0,2\}
Extended AFDX output port

3-classes example: low BLS priority

- RC class
- SCT class
- BE class

sets queue priority between \{0,2\}
Each BLS credit has 3 parameters:

- Maximum Level ($L_M$)
- Resume Level ($L_R$)
- Reserved Bandwidth (BW)

BW is used with the output link capacity $C$ to compute the credit slopes as follows:

- the sending slope, $I_{send} = (1 - BW) \cdot C$
- the idle slope, $I_{idle} = BW \cdot C$
Burst Limiting Shaper credit evolution

Bursty traffic

\[ L_M \]

\[ L_R \]

Transmitted traffic
Burst Limiting Shaper credit evolution

Bursty traffic

Transmitted traffic

\[ L_M \]

\[ I_{send} \]

\[ L_R \]
Burst Limiting Shaper credit evolution

Bursty traffic

Transmitted traffic

non-preemption

$L_M$

$L_R$

$I_{\text{send}}$

$t$

$t$
Burst Limiting Shaper credit evolution

Bursty traffic
Burst Limiting Shaper credit evolution

Bursty traffic

\[ L_M \]
\[ L_R \]
\[ I_{\text{send}} \]
\[ I_{\text{idle}} \]

Transmitted traffic

non-preemption
Burst Limiting Shaper credit evolution

Bursty traffic

\[ L_M \]

\[ L_R \]

Transmitted traffic

\[ I_{\text{send}} \]

\[ I_{\text{idle}} \]

non-preemption

non-preemption

\( t \)

\( t \)
Network calculus
Characteristics of an aggregate traffic of class $k$ crossing the node $n$

Input arrival curve
$\alpha_k^n(t)$

class $k$ →

node $n$

maximum service curve
$\gamma_k^n(t)$

minimum service curve
$\beta_k^n(t)$

Output arrival curve
$\alpha^{*,n}_k(t) = \alpha_k^n(t) \otimes \beta_k^n(t)$

$f \otimes g(t) = \sup_{s \geq 0} \{f(t + s) - g(s)\}$
$f \otimes g(t) = \inf_{0 \leq s \leq t} \{f(t - s) + g(s)\}$
Network calculus
Characteristics of an aggregate traffic of class $k$ crossing the node $n$

Input arrival curve $\alpha^k_n(t)$

| node n |
| maximum service curve $\gamma^k_n(t)$ |
| minimum service curve $\beta^k_n(t)$ |

Output arrival curve $\alpha^{*,n}_k(t) = \alpha^k_n(t) \odot \beta^k_n(t)$

$f \odot g(t) = \sup_{s \geq 0} \{f(t + s) - g(s)\}$
$f \otimes g(t) = \inf_{0 \leq s \leq t} \{f(t - s) + g(s)\}$
Network calculus
Characteristics of an aggregate traffic of class $k$ crossing the node $n$

Input arrival curve $\alpha^k_n(t)$

Class $k$ $\rightarrow$ Output arrival curve $\alpha^*_n(t) = \alpha^k_n(t) \odot \beta^k_n(t)$

node $n$

| maximum service curve $\gamma^k_n(t)$ |
| minimum service curve $\beta^k_n(t)$ |

$\beta^S_k(t) = \beta^m_k(t) \otimes ... \otimes \beta^i_k(t) \otimes .. \otimes \beta^m_k(t)$

$f \otimes g(t) = \inf_{0 \leq s \leq t}\{f(t - s) + g(s)\}$

$f \odot g(t) = \sup_{s \geq 0}\{f(t + s) - g(s)\}$
Traffic and Network Model

Traffic modelisation: **leaky buckets**

\[ \alpha(t) \]

The Network Calculus model has been proved in previous work\(^a\)

Traffic and Network Model

Traffic modelisation: **leaky buckets**
Node modelisation: **rate-latency**

\[
\alpha(t) \\
\beta(t)
\]

\[\forall i \in \text{BLS}, j \in \text{NBLS}, \beta_{\text{mux}}i, \beta_{\text{mux}}j, \beta_{\text{bls}}i, \gamma_{\text{bls}}i\]

The Network Calculus model has been proved in previous work\(^a\)

\(^a\)[WFCS-18] Finzi, A., Mifdaoui et al., ”Incorporating TSN/BLS in AFDX for Mixed-Criticality Applications: Model and Timing Analysis”, WFCS 2018
Traffic and Network Model

Traffic modelisation: **leaky buckets**
Node modelisation: **rate-latency**

The Network Calculus model has been proved in previous work\textsuperscript{a}

\textsuperscript{a}[WFCS-18] Finzi, A., Mifdaoui et al., ”Incorporating TSN/BLS in AFDX for Mixed-Criticality Applications: Model and Timing Analysis”, WFCS 2018
Traffic and Network Model

Traffic modelisation: **leaky buckets**
Node modelisation: **rate-latency**

The Network Calculus model has been proved in previous work\(^a\)

\(^a\)[WFCS-18] Finzi, A., Mifdaoui et al., ”Incorporating TSN/BLS in AFDX for Mixed-Criticality Applications: Model and Timing Analysis”, WFCS 2018
Traffic and Network Model

Traffic modelisation: **leaky buckets**
Node modelisation: **rate-latency**

The Network Calculus model has been proved in previous work\(^a\)

\(^a\)[WFCS-18] Finzi, A., Mifdaoui et al., ”Incorporating TSN/BLS in AFDX for Mixed-Criticality Applications: Model and Timing Analysis”, WFCS 2018
Traffic and Network Model

Traffic modelisation: **leaky buckets**
Node modelisation: **rate-latency**

The Network Calculus model has been proved in previous work[WFCS-18] Finzi, A., Mifdaoui et al., "Incorporating TSN/BLS in AFDX for Mixed-Criticality Applications: Model and Timing Analysis", WFCS 2018
Traffic and Network Model

Traffic modelisation: **leaky buckets**

Node modelisation: **rate-latency**

The Network Calculus model has been proved in previous work\(^a\)

\(^a\)[WFCS-18] Finzi, A., Mifdaoui et al., ”Incorporating TSN/BLS in AFDX for Mixed-Criticality Applications: Model and Timing Analysis”, WFCS 2018
Outline

1. System Model
2. Bandwidth Reservation Methods
3. Performance Evaluation
4. Conclusion and perspectives
Problem Overview

Objective

Find the reserved BLS bandwidth minimizing RC delay bounds for each flow along its path.
Problem Overview

Objective
Find the reserved BLS bandwidth minimizing RC delay bounds for each flow along its path

Constraints
- **Class rate constraint**: in each output port, the class rate is lower than the guaranteed service rate
- **Aggregate rate constraint**: the total load of an output port is lower than the total capacity $C$
- **Deadline constraints**: the delay bound of each traffic class is lower than its deadline
∀ \( f \in RC \), ∀ \( \text{mux} \in \text{path}_f \),

\[
\min_{L_M^\text{mux}, L_R^\text{mux}, BW^\text{mux}} \quad EED_{RC,f}(L_M^\text{mux}, L_R^\text{mux}, BW^\text{mux})
\]

s.t. ∀ \( f \) in \( j \in \{SCT, RC\} \), ∀ \( \text{mux} \in \text{path}_f \):

\[
R_j^\text{mux} \geq \sum_{f \in F_j^\text{mux}} r_f
\]

\[
\sum_{g \in F_{SCT}^\text{mux}} r_g + \sum_{f \in F_{RC}^\text{mux}} r_f \leq C
\]

\[
DL_f \geq EED_{j,f}(L_M^\text{mux}, L_R^\text{mux}, BW^\text{mux})
\]
∀f ∈ RC, ∀mux ∈ path_f,  
\[
\min_{L_M^{mux}, L_R^{mux}, BW_{mux}} EED_{RC,f}(L_M^{mux}, L_R^{mux}, BW_{mux})
\]

s.t. ∀f in j ∈ \{SCT, RC\}, ∀mux ∈ path_f :

\[
R_j^{mux} \geq \sum_{f \in F_j^{mux}} r_f
\]

\[
\sum_{g \in F_{SCT}^{mux}} r_g + \sum_{f \in F_{RC}^{mux}} r_f \leq C
\]

\[
DL_f \geq EED_{j,f}(L_M^{mux}, L_R^{mux}, BW_{mux})
\]

A complexity of $O(l^m \cdot N^{3 \cdot m})$ for $m$ ports and $l$ flows.
Relaxed Objective

Find the reserved BLS bandwidth minimizing RC delay bounds for each class within each output port

→ Reducing the complexity down to $O(m \cdot N^3)$

→ Need to define a local Deadline within each output port
Problem Solving

### Relaxed Objective

Find the reserved BLS bandwidth **minimizing RC delay bounds** for each **class** within each **output** port

→ Reducing the complexity down to $O(m \cdot N^3)$

→ Need to define a **local Deadline** within each output port

### Solving the problem based on Heuristics

- The optimisation problem is a **non-linear** problem
- Take advantage of conducted **sensitivity analysis** of the analytical model to deduce **heuristics**
Problem Solving

Relaxed Objective

Find the reserved BLS bandwidth minimizing RC delay bounds for each class within each output port

→ Reducing the complexity down to $O(m \cdot N^3)$

→ Need to define a local Deadline within each output port

Solving the problem based on Heuristics

- The optimisation problem is a non-linear problem
- Take advantage of conducted sensitivity analysis of the analytical model to deduce heuristics

Two proposed methods to compute the local deadlines

- Heuristic Deadline: defined proportionally to the port load
- Dichotomous Deadline: defined accurately in each port
1-Gigabit Avionics Case study

Figure: Multi-hop network and traffic communication pattern
1-Gigabit Avionics Case study

Figure: Multi-hop network and traffic communication pattern

<table>
<thead>
<tr>
<th>Priority</th>
<th>Traffic type</th>
<th>MFS (Bytes)</th>
<th>BAG (ms)</th>
<th>deadline (ms)</th>
<th>jitter (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/2</td>
<td>SCT</td>
<td>64</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>RC</td>
<td>320</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>BE</td>
<td>1024</td>
<td>8</td>
<td>none</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Numerical results

Intuitive parameters: \( BW = UR_{SCT}^{bn} \), \( LR = MFS_{RC} \cdot BW \) and
\( LM = 80 \cdot (1 - BW) \cdot MFS_{SCT} \)

\( UR_{k}^{bn} \): bottleneck utilisation rate of class \( k \)
Numerical results

Intuitive parameters: $BW = UR_{sct}^{bn}$, $ LR = MFS_{RC} \cdot BW$ and $LM = 80 \cdot (1 - BW) \cdot MFS_{SCT}$

$Scenario_{SCT} = (UR_{sct}^{bn} \in [0.4 : 80], UR_{RC}^{bn} = 20)$

$UR_{k}^{bn}$: bottleneck utilisation rate of class $k$
Numerical results

Intuitive parameters: $BW = UR_{SCT}^{bn}$, $L_R = MFS_{RC} \cdot BW$ and $L_M = 80 \cdot (1 - BW) \cdot MFS_{SCT}$

$Scenario_{SCT} = (UR_{SCT}^{bn} \in [0.4 : 80], UR_{RC}^{bn} = 20)$
Numerical results

Intuitive parameters: $BW = UR_{SCT}^{bn}$, $L_R = MFS_{RC} \cdot BW$ and $L_M = 80 \cdot (1 - BW) \cdot MFS_{SCT}$

$Scenario_{SCT} = (UR_{SCT}^{bn} \in [0.4 : 80], UR_{RC}^{bn} = 20)$

→ **SCT schedulability is increased by up to 31% under Dichotomous Deadline method**

$UR_k^{bn}$: bottleneck utilisation rate of class k
Numerical Results

Intuitive parameters: $BW = UR_{SCT}^{bn}$, $L_R = MFS_{RC} \cdot BW$ and $L_M = 80 \cdot (1 - BW) \cdot MFS_{SCT}$
Numerical Results

Intuitive parameters: \( BW = UR_{\text{sct}}^{bn}, \ L_R = MFS_{RC} \cdot BW \) and \( L_M = 80 \cdot (1 - BW) \cdot MFS_{\text{sct}} \)

Scenario\(_{RC} = (UR_{\text{sct}}^{bn} = 20, UR_{\text{RC}}^{bn} \in [0.4 : 80]) \)
Intuitive parameters: $BW = UR_{SCT}^{bn}$, $L_R = MFS_{RC} \cdot BW$ and $L_M = 80 \cdot (1 - BW) \cdot MFS_{SCT}$

$Scenario_{RC} = (UR_{SCT}^{bn} = 20, UR_{RC}^{bn} \in [0.4 : 80])$
Numerical Results

Intuitive parameters: $BW = UR_{SCT}^{bn}$, $L_R = MFS_{RC} \cdot BW$ and $L_M = 80 \cdot (1 - BW) \cdot MFS_{SCT}$

$Scenario_{RC} = (UR_{SCT}^{bn} = 20, UR_{RC}^{bn} \in [0.4 : 80])$

→ RC delay bounds decreased by up to 50% under Dichotomous Deadline method
## Numerical Results

<table>
<thead>
<tr>
<th></th>
<th>Improvement compared to SP(%)</th>
<th>Maximum RC delay at maximum</th>
<th>Computation times (s) of Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$UR^n_{SCT} = 33%$</td>
<td>$UR^n_{RC} = 28%$</td>
</tr>
<tr>
<td>HD</td>
<td>BLS</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>DD</td>
<td>BLS</td>
<td>77</td>
<td>55</td>
</tr>
</tbody>
</table>
Numerical Results

<table>
<thead>
<tr>
<th></th>
<th>improvement compared to SP(%)</th>
<th>maximum RC delay at</th>
<th>maximum</th>
<th>computation times (s) of Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$UR^b_{SCT} = 33%$</td>
<td>$UR^b_{RC} = 28%$</td>
<td>$UR^b_{SCT}$</td>
<td>$UR^b_{RC}$</td>
</tr>
<tr>
<td>HD</td>
<td>BLS</td>
<td>18</td>
<td>22</td>
<td>33</td>
</tr>
<tr>
<td>DD</td>
<td>BLS</td>
<td>77</td>
<td>55</td>
<td>52</td>
</tr>
</tbody>
</table>

→ Higher Complexity for Dichotomous Deadline method
Outline

1. System Model
2. Bandwidth Reservation Methods
3. Performance Evaluation
4. Conclusion and perspectives
Conclusion and perspectives

Two optimized bandwidth reservation methods for TSN/BLS

→ **Heuristic Deadline**: simple but average performances
→ **Dichotomous Deadline**: complex but good performances

Conducted Performance evaluation on a realistic avionics case study

→ **Enhanced SCT schedulability** (up to 31%) under DD
→ **Enhanced RC delay bounds** (up to 50%) under DD
**Conclusion and perspectives**

<table>
<thead>
<tr>
<th>Two optimized bandwidth reservation methods for TSN/BLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ <strong>Heuristic Deadline</strong>: simple but average performances</td>
</tr>
<tr>
<td>→ <strong>Dichotomous Deadline</strong>: complex but good performances</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conducted Performance evaluation on a realistic avionics case study</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ Enhanced SCT <strong>schedulability</strong> (up to 31%) under DD</td>
</tr>
<tr>
<td>→ Enhanced RC <strong>delay</strong> bounds (up to 50%) under DD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Approach Generalization to multiple TSN/BLS classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ Offer higher configuration flexibility</td>
</tr>
</tbody>
</table>
Thank you for your attention