Mixed-Criticality Scheduling of Processing Pipelines

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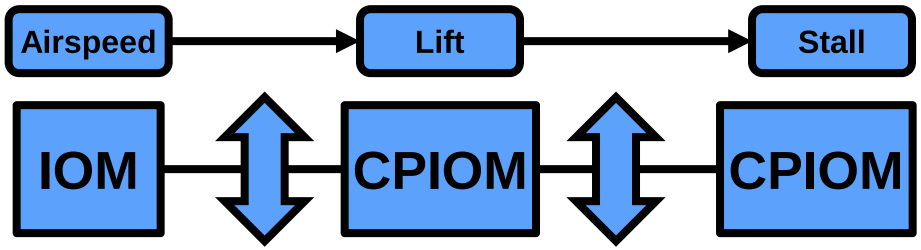
Motivation

Mixed-Criticality

- Certification standards (DO-178B/C)
  - Different assurance rigor depending on severity of failure (criticality)
  - If proven that low-criticality task cannot interfere with higher-criticality ones

Distributed Scheduling

- End-to-end threads running across multiple processors



Distributed Mixed-Criticality Scheduling

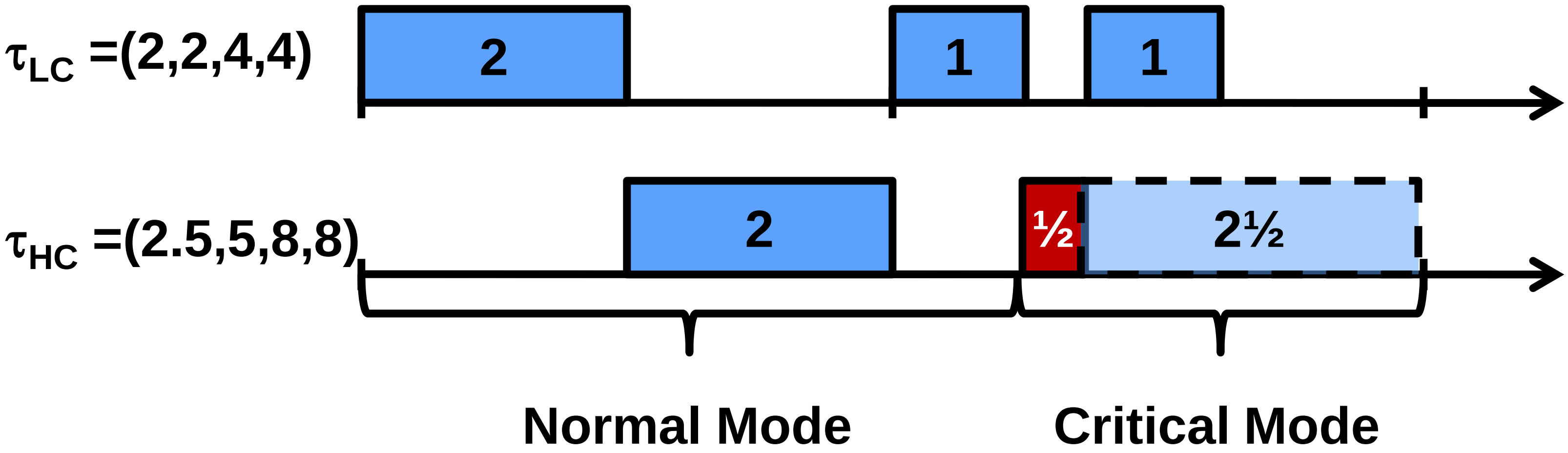
Zero-Slack Scheduling (1)

Tasks : $\tau_i = (C_i, C_i^o, T_i, D_i, \zeta_i)$

- C_i: nominal WCET, C_i^o: overloaded WCET, T_i: period, D_i: deadline, ζ_i:criticality

Start with DM

- Calculate last instant to stop lower-critical task Z_i: zero-slack instant
- Stop lower-criticality tasks

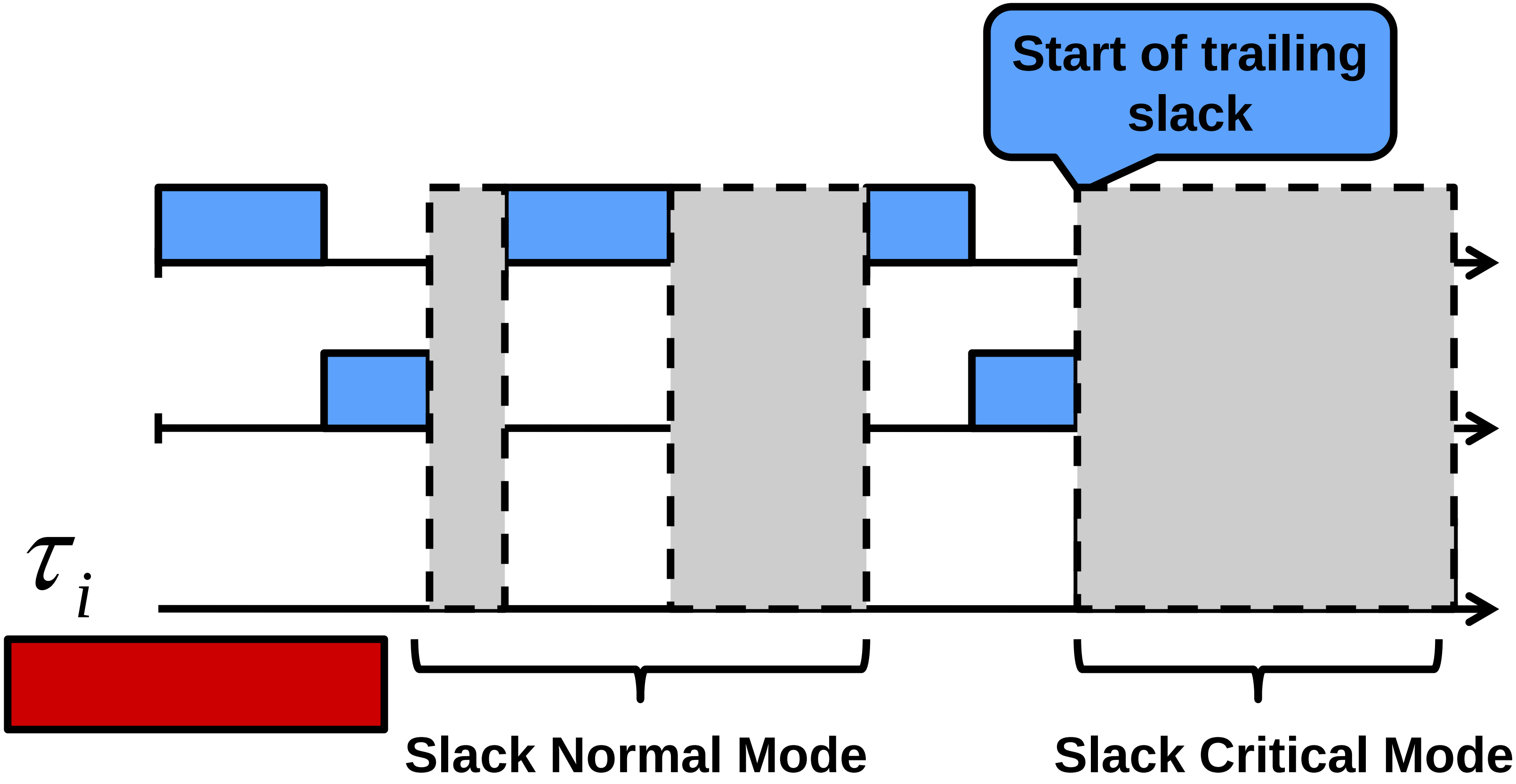


Zero-Slack Scheduling (2)

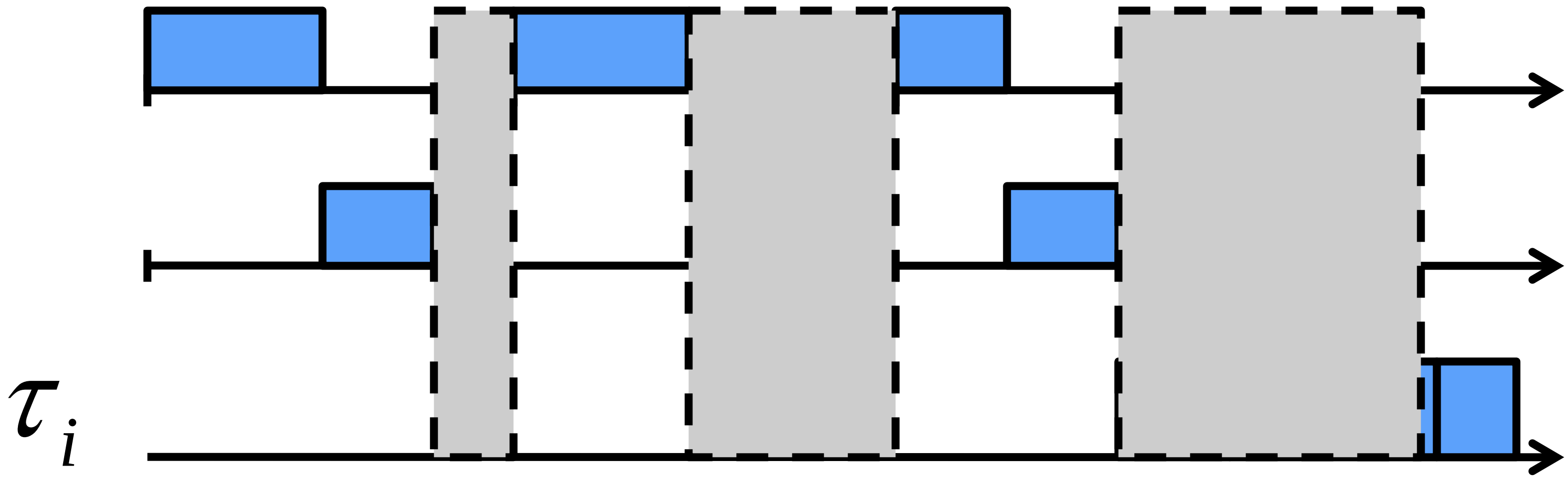
Guarantee

- τ_i guaranteed to execute for C_i^o before its deadline D_i
  - If no higher criticality task τ_j executes for more than C_j

Calculating The Zero-Slack Instant



Calculating The Zero-Slack Instant



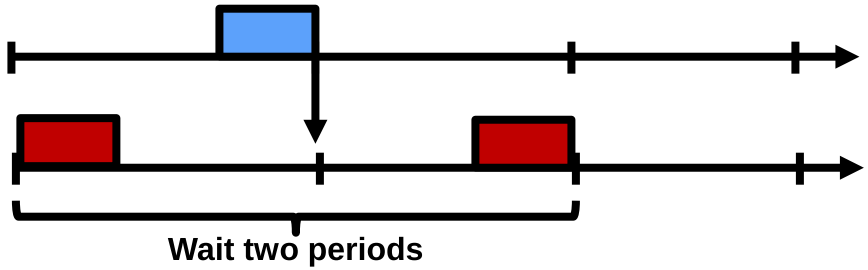
New slack can open after each iteration

Needs to repeat until no new slack opens

Distributed Scheduling

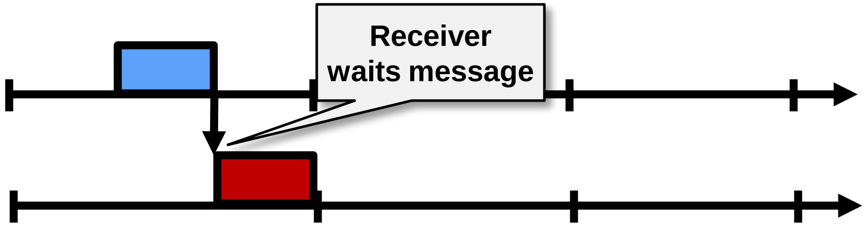
Multi-period end-to-end deadlines

- Start of receiver task not synchronized
- Message reception guaranteed after two periods

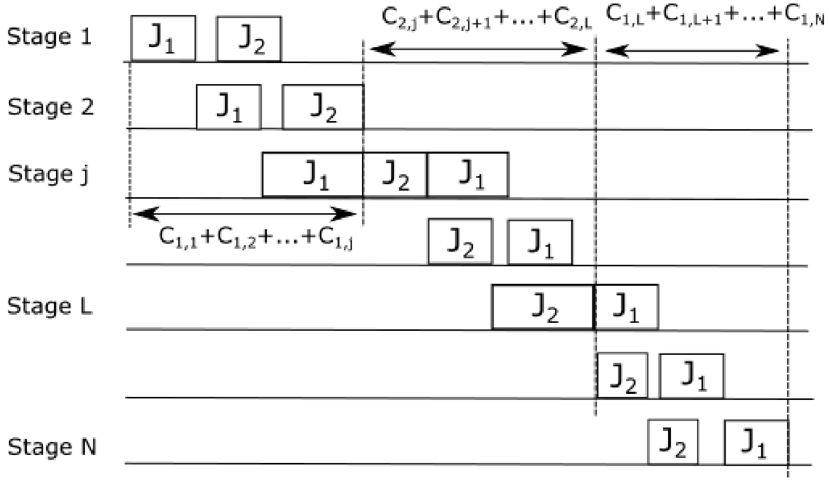


Pipelines to reduce wait

- Synchronize start of receiver task



Fixed-Priority Pipelines



$$Delay(J_i) \leq \sum_{j=i}^{n} C_{eq_j} + \sum_{s=1}^{N-1} \max_{j=i}^{n}(C_{j,s})$$

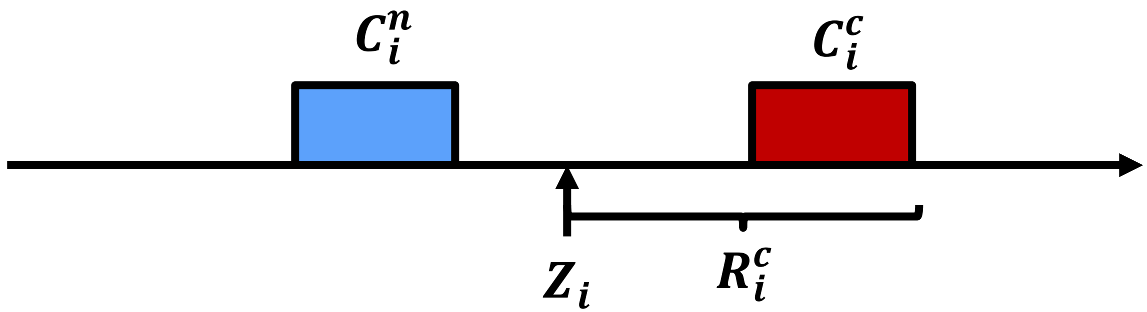
$$C_{eq_j} = \begin{cases} C_{j,max1} + C_{j,max2} \; if \; A_i < A_j \\ C_{j,max1} \; otherwise \end{cases}$$

Real-Time Pipelines Response Time

Synthetic Taskset

- τ_i execution:
  - $C_e^*(i) = \sum_{(j|\rho_j \geq \rho_i)} C_{j,max1} + \sum_{s=1}^{N-1} \max_{(j|\rho_j \geq \rho_i)} (C_{j,2})$
- Preemption on others
  - $C_j^* = C_{j,max1} + C_{j,max2}$
- Response time
  - $R_i^{(k)} = C_e^*(i) + \sum_{(j|\rho_j > \rho_i)} \left\lceil \frac{R_i^{k-1}}{T_j} \right\rceil C_j^*$

ZSRM Response Time Equations



$$C_i^c = C_i^o \;; C_i^n = 0$$

$$R_i^c = C_i^c + \sum_{j \in H_i^{hc}} \left\lceil \frac{R_i^c}{T_j} \right\rceil C_j + \sum_{j \in L_i^{hc}} \left\lceil \frac{R_i^c}{T_j} \right\rceil (C_j - C_j^n) + \sum_{j \in H_i^{sc}} \left\lceil \frac{R_i^c}{T_j} \right\rceil C_j^o$$

Interfering Tasksets

Set	Prio	Crit
H_i^{hc}	H	H
H_i^{lc}	H	L
H_i^{sc}	H	S
L_i^{lc}	L	L
L_i^{hc}	L	H

$$Z_i = D_i - R_i^c$$

$$I_i = \sum_{j \in H_i^{hc}} \left\lceil \frac{Z_i}{T_j} \right\rceil C_j + \sum_{j \in H_i^{lc} \cup H_i^{sc}} \left\lceil \frac{Z_i}{T_j} \right\rceil C_j^o$$

$$S_i^n = \max(0, Z_i - I - I \; - C_i^n)$$

$$C_i^c = \max(0, C_i^c - S_i^n) \;; C_i^n = \min(C_i^o, C_i^n + S_i^n)$$

ZSRM Pipeline Response Time (1)

Stages in normal and critical mode

- σ_i^Z : stage where Z_i occurs
- $\Pi_i^c = \{\pi_j \mid \sigma_i^Z \leq j \leq N\}$; $\Pi_i^n = \{\pi_j \mid 1 \leq j < \sigma_i^Z\}$

Critical mode synthetic task

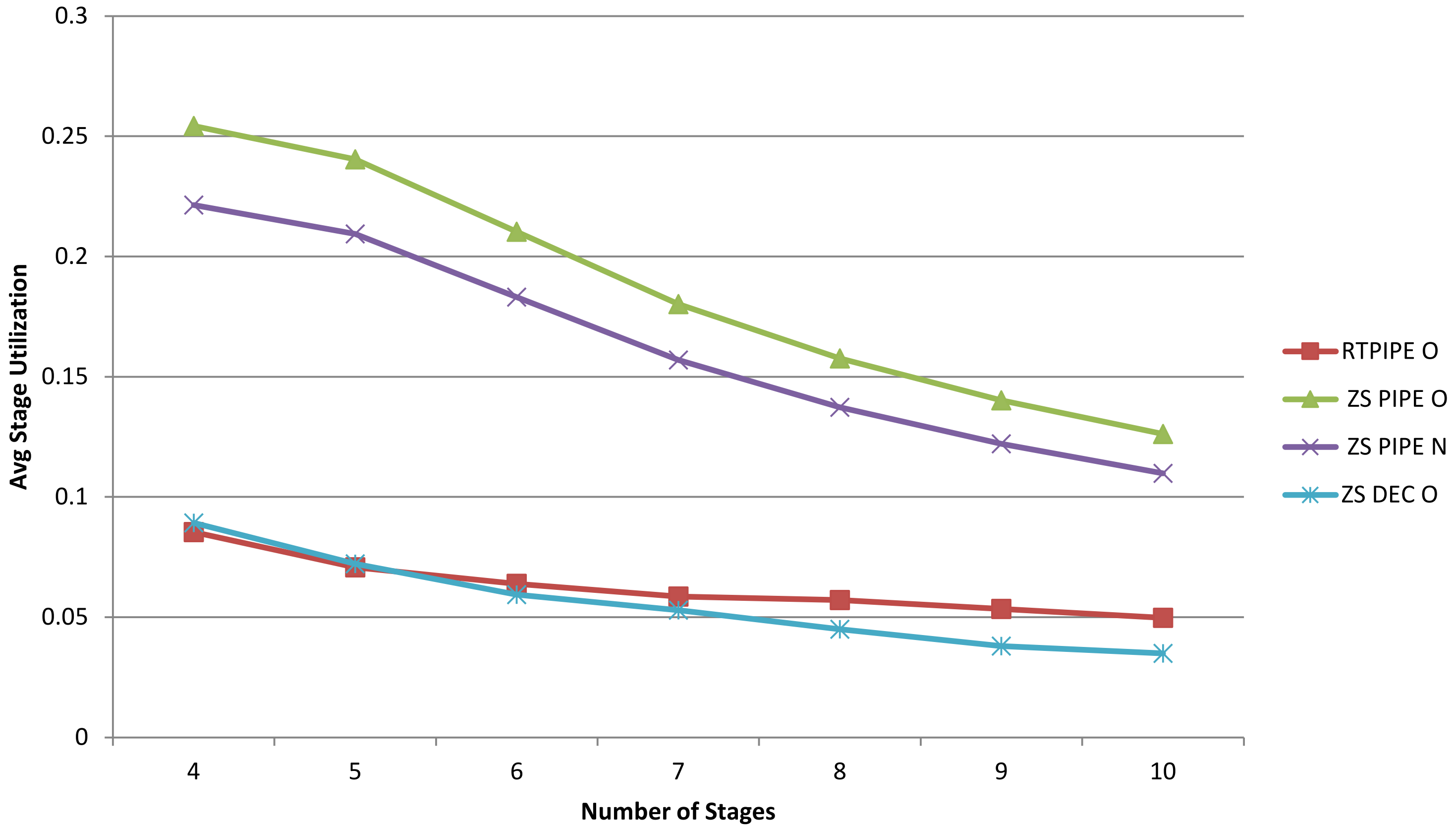
- $C_e^c(i) = C_e^K(i)$
- $C_e^K(i) - \sum_{\tau_i \in \Gamma_i^c \cup \tau_i} C_{j,max1}^{C_i} + \sum_{\pi_{i,s} \in \Pi_i^c \setminus \pi_N} \max_{\tau_j \in \Gamma^c \cup \tau_i} C_{j,s}^{e_i}$
- To calculate which stages overload $C_{j,s}^{e_i}$ is calculated solving optimization
  - Maximize $\sum_{s \in \Pi_i^c \setminus \pi_N} \max_{j \in \Gamma_i^c \cup \tau_i} x_{j,s}$
    - Subject to:
    - $\forall \langle j, s \rangle$ s.t. $(j \in \Gamma_i^c \cup \tau_i) \wedge (s \in \Pi_i^c), x_{j,s} \leq C_{j,s}^o$
    - $\forall j$ s.t. $(j \in \Gamma_i^c \cup \tau_i) \wedge (\zeta_j > \zeta_i), \sum_{s \in \Pi_i^c} x_{j,s} \leq \sum_{s \in \Pi_i^c} C_{j,s}$
- $C_j^{*C_i} = C_{j,max1}^{C_i} + C_{j,max2}^{C_i}$
- $R_i^c = C_e^c(i) + \sum_{j \in \Gamma_i^c} \left\lceil \frac{R_i^c}{T_j} \right\rceil C_j^{*C_i}$

ZSRM Pipeline Response Time (2)

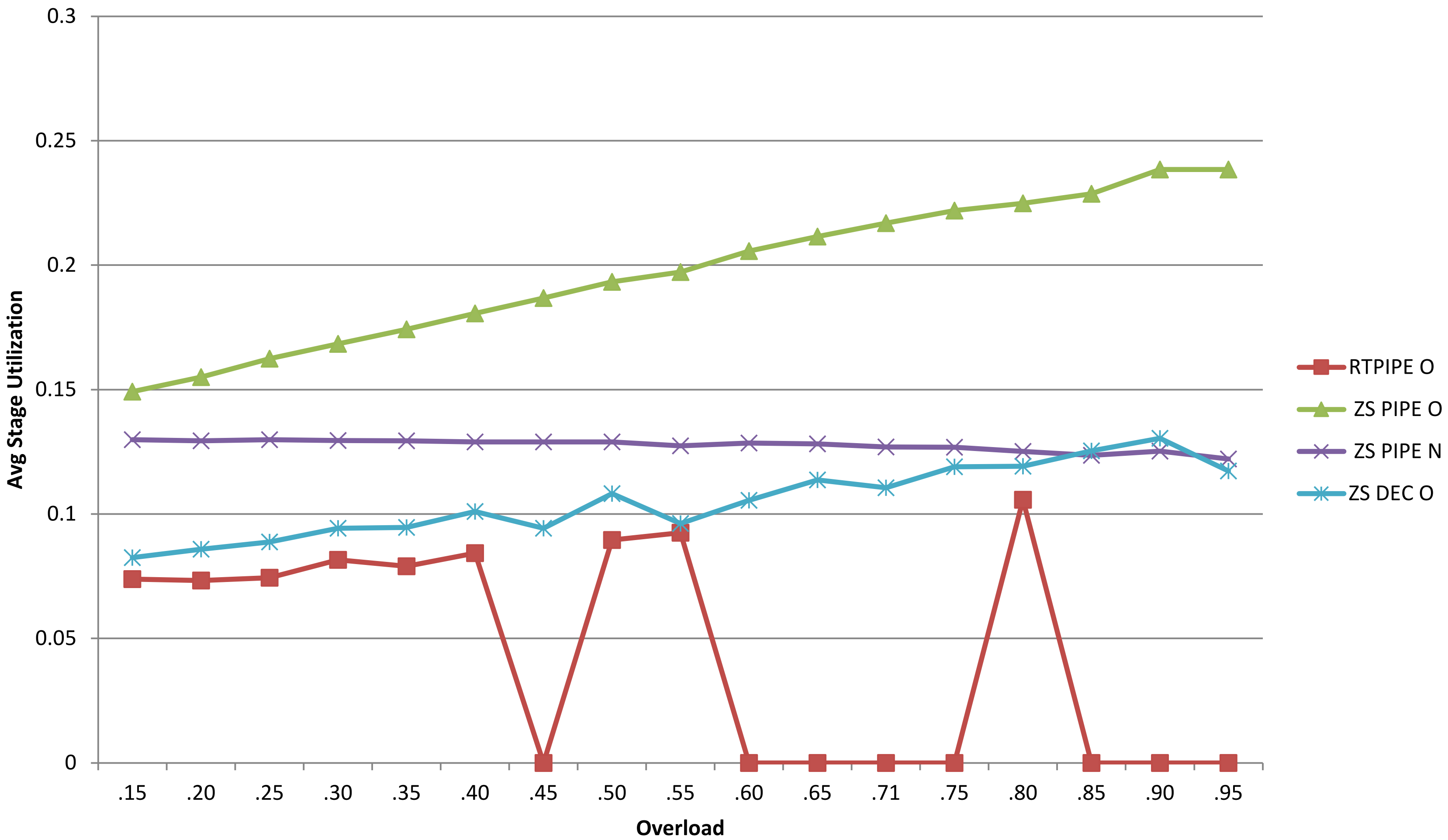
Normal mode

- $Z_i = D_i - R_i^c$
- $I_i = \sum_{j \in \Gamma_i^n} \left\lceil \frac{Z_i}{T_j} \right\rceil C_j^{*n_i}$
- $S_i^n = \max\left(0, Z_i - I_i - C_e^n(i)\right)$
- $C_e^C(i) = \max(0, C_e^c(i) - S_i^n)$
- $C_e^n(i) = \min(C_i^o, C_e^n(i) + S_i^n)$
- $\sigma_i^Z = \min_{1 \le j \le N} \{j \mid \sum_{s=1}^{j} C_{i,s}^o > C_e^n(i)\}$

Average Utilization With Increasing Stages



Increasing Overload



Implementation

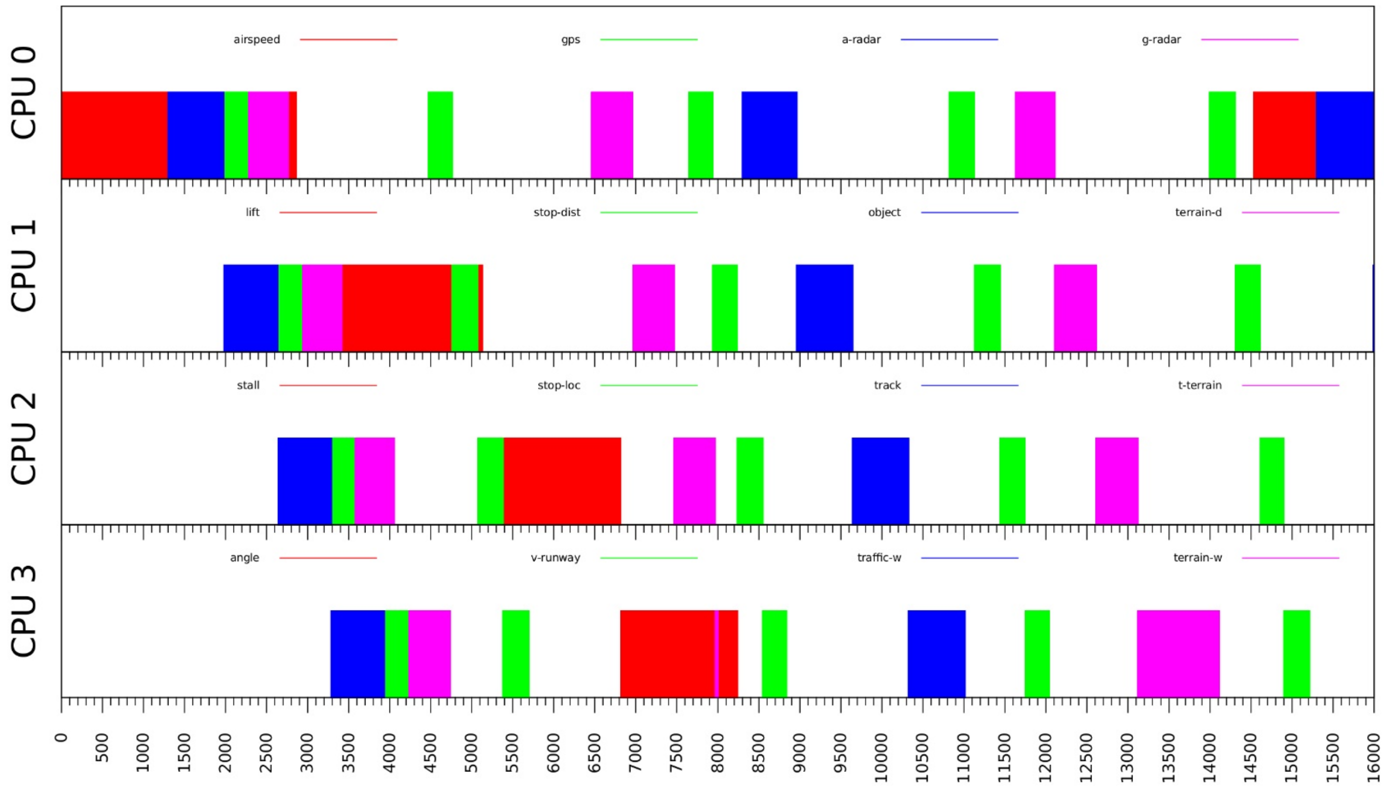
Linux Kernel Module

- Periodic Activation of Root Stage
  - wait_next_root_period()
  - Wait for periodic timer to activate
- Middle Stage Activation
  - wait_next_stage_arrival()
  - Wait for message and enforce minimum inter-arrival
  - Execute stage computation
  - Send message to next stage
- Leaf Stage Activation
  - wait_next_leaf_arrival()
  - Wait for minimum interarrival
  - Execute stage computation
- End-to-end overload monitoring
- Defer after overload enforcement

Synthetic Avionics Taskset

Stage\Task	Stall Warning $\zeta = 4, \rho = 1$	Runway Overrun $\zeta = 2, \rho = 3$	Traffic Aware $\zeta = 1, \rho = 4$	Terrain Aware $\zeta = 3, \rho = 2$
IOM	Airspeed	GPS Pos.	Air Radar	Ground Radar
CPIOM1	Lift	Stop Distance	Object Ident.	Terrain Distance
CPIOM2	Stall threshold	Stop location	Track build.	Time to terrain
CPIOM3	Angle attack	Virtual runway	Traffic warn.	Terrain warn.
T	14534(ms)	3174(ms)	7002(ms)	5164(ms)
C	1090(ms)	238(ms)	525(ms)	387(ms)
C^o	1362(ms)	297(ms)	656(ms)	484(ms)
Z	8000(ms)	3174(ms)	7002(ms)	5164(ms)

Avionics Taskset Execution Timeline



Conclusions

Pipeline Scheduling Improves Utilization

- In contrast to unsynchronized activation
- Response-Time Pipeline Model by Jayachandran and Abdelzaher

Created First Mixed-Criticality Scheduling

- ZSRM
  - – Reformulated Response Time Z Calculation
  - – End-to-end overload
  - – End-to-end enforcement

Improved Performance

- 4X average state utilization
- Increase overload tolerance