RTAS 2021

PiCAS: New Design of Priority-Driven Chain-Aware Scheduling for ROS2

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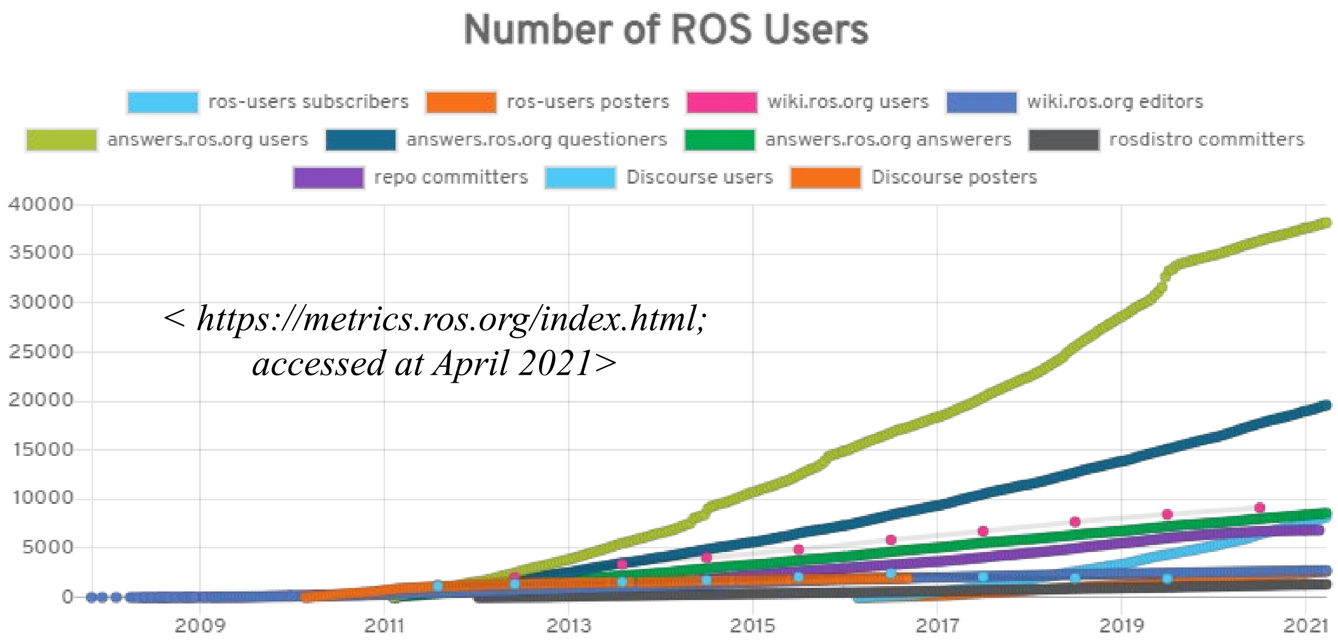
I. Introduction

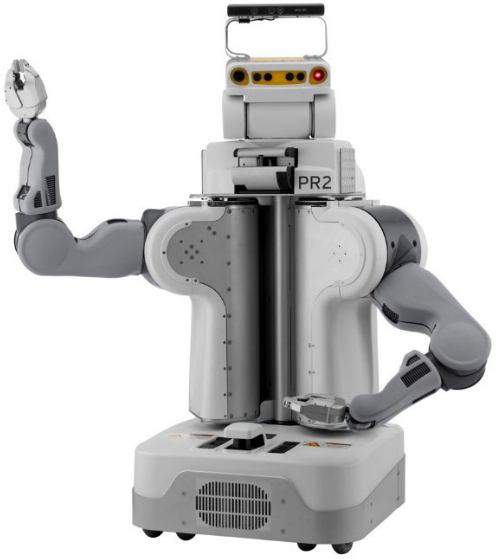
Robot Operating System (ROS)

- ROS (since 2007)
  - Popular open-source middleware in academia and industry
  - Provides software tools, robot systems, and best-practices

➡ Over the decades, it has revealed shortcomings in real-time support for timing- and safety-critical applications



ROS 1.0
http://ros.org/



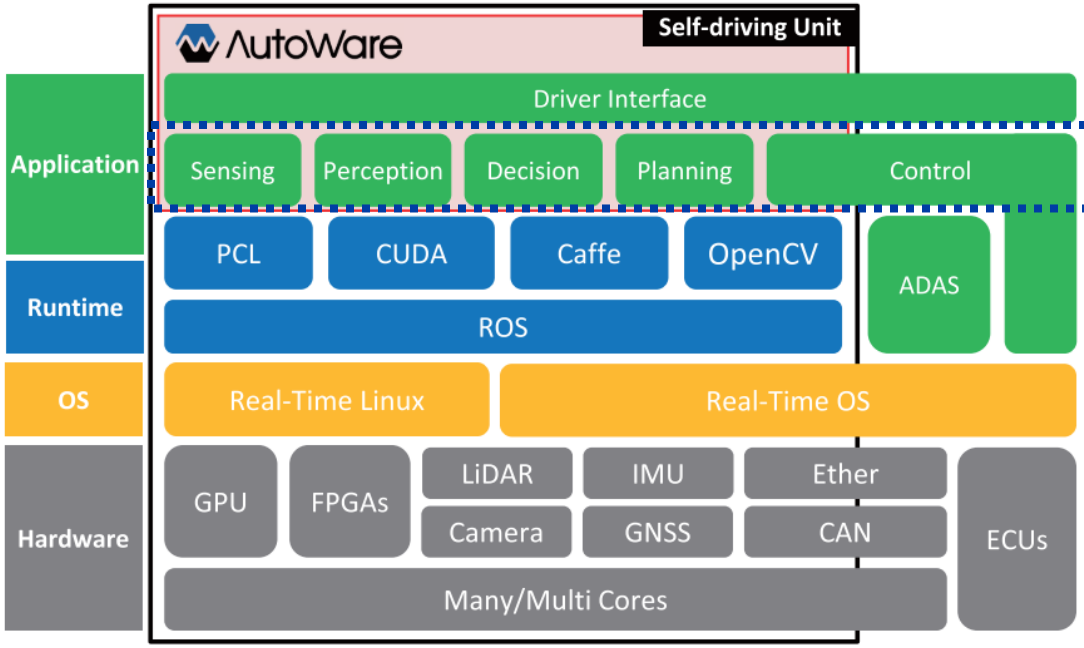
Willow Garage PR2
(original ROS robot)

http://willowgarage.com

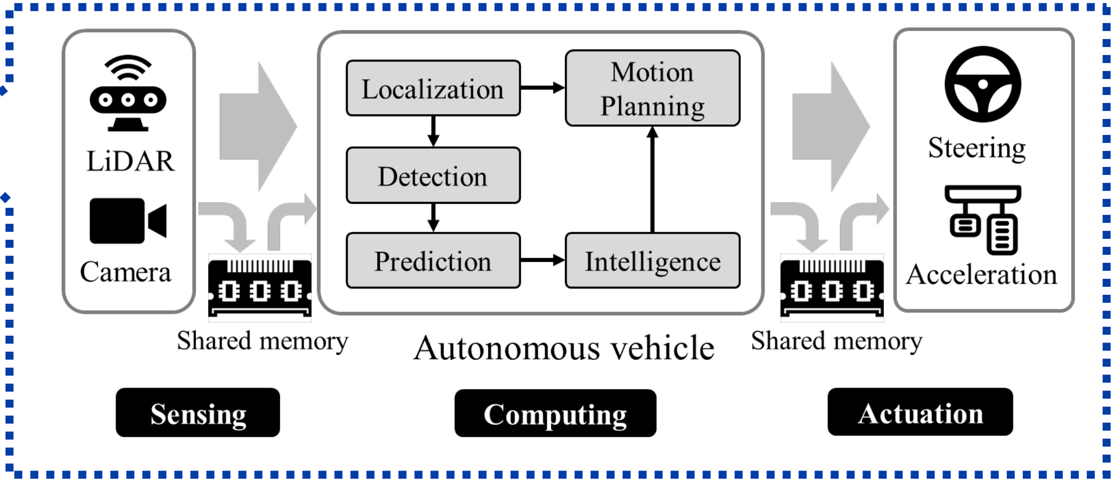
I. Introduction

Why real-time in ROS ?

- To develop safety-critical application with ROS
  - Autonomous driving software (e.g., autoware.ai)



< Autoware.ai > †



< Chain in self-driving application >

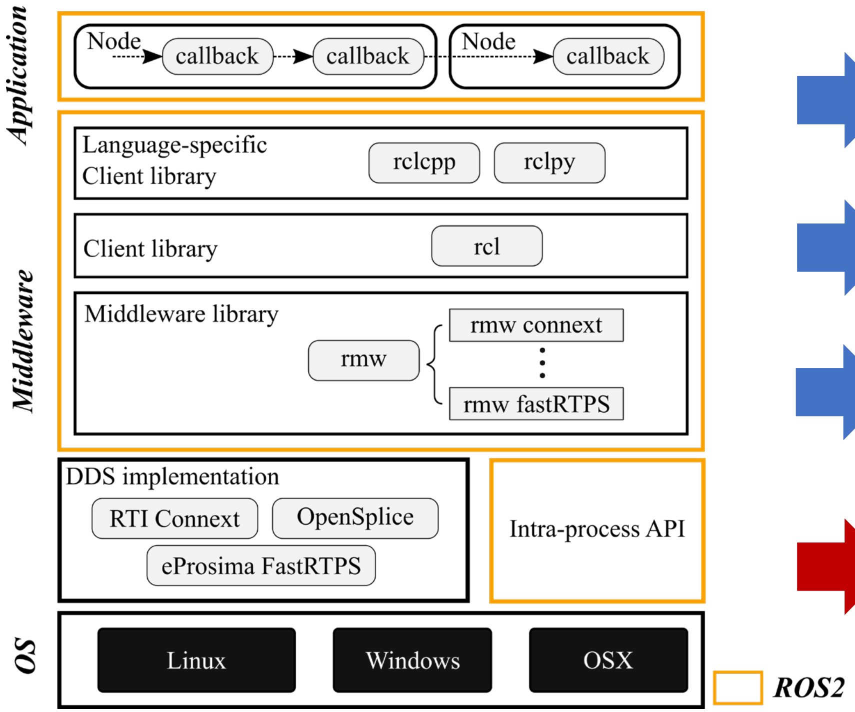
➡ **Timing constraint violations (e.g., end-to-end latency) can cause catastrophic accidents**

†S. Kato et al. "Autoware on Board: Enabling Autonomous Vehicles with Embedded Systems", ICCPS, 2018

I. Introduction

ROS 2 (since 2017)

- Most concepts are inherited from the original ROS design (e.g., pub-sub)
- Aims to improve **real-time capability, QoS, and security**
- Supports Data Distribution Service (DDS)



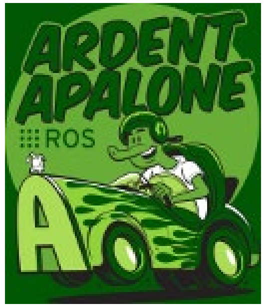
< ROS2 architecture >

Suffers from priority inversion

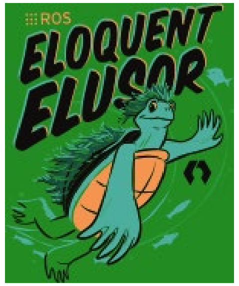
Too complex and pessimistic to analyze

No systematic resource allocation policy

Needs a new RT scheduler for ROS2 !



Ardent Apalone, released Dec 2017



Eloquent Elusor, released Nov 2019

Contributions

- We propose **a new priority-driven chain-aware scheduler** for ROS2 in a multi-core environment (PiCAS)
- We develop **analysis to upper-bound the end-to-end latency of chains** under the proposed PiCAS framework
- We **implement PiCAS** in the Eloquent Elusor version of ROS2 on an **embedded platform** (NVIDIA Xavier NX)
- PiCAS outperforms the default ROS2 scheduler and the latest analysis work in terms of **end-to-end latency**

II. ROS2 Background & System Model

Scheduling-related abstractions in ROS2

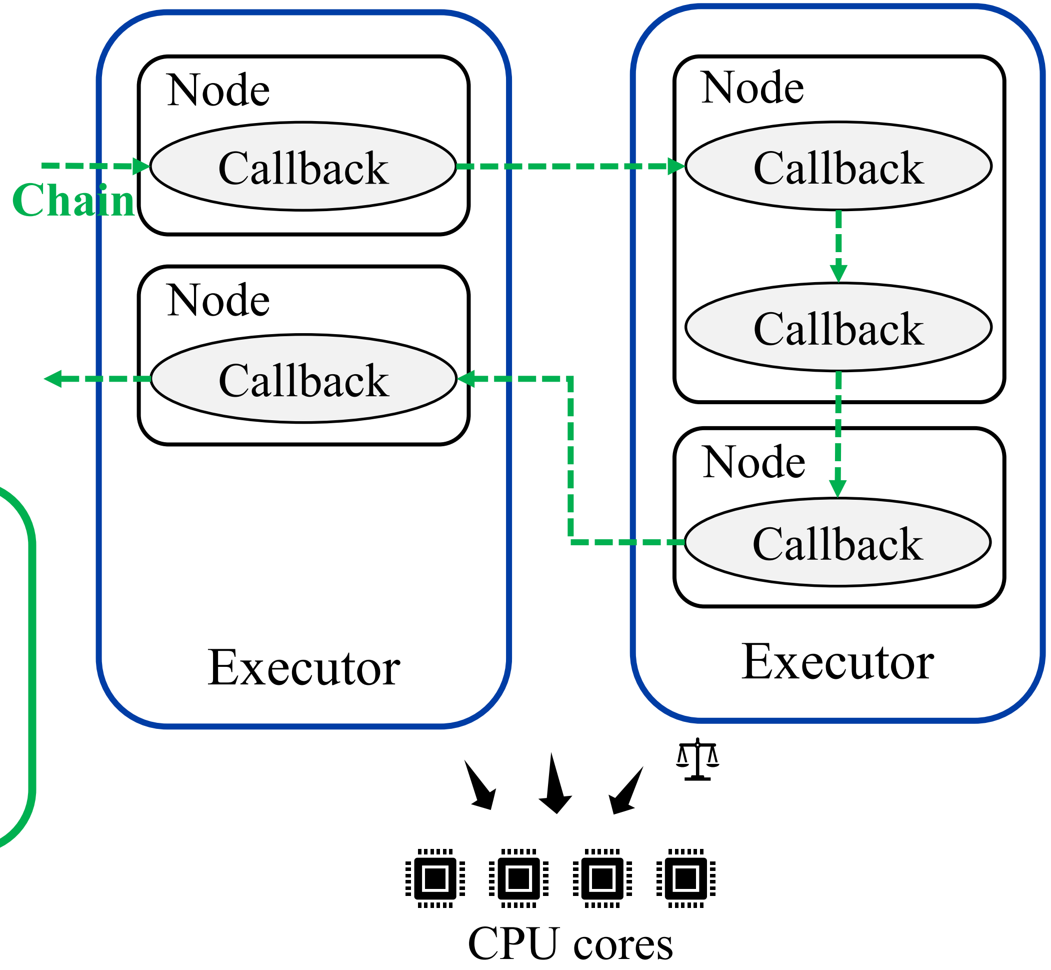
- *Callbacks*, *nodes*, and *executors*

Callback model

- ✓ Timer / regular callbacks
- ✓ Non-preemptive
- ✓ $\tau_i := (C_i, D_i, T_i, \pi_i)$

Chain model

- ✓ $\Gamma^c := [\tau_s, \tau_{m1}, \dots, \tau_e]$
- ✓ τ_s : the start callback of Γ^c
- ✓ τ_{m*} : the intermediate callback of Γ^c
- ✓ τ_e : the end callback of Γ^c



Node model

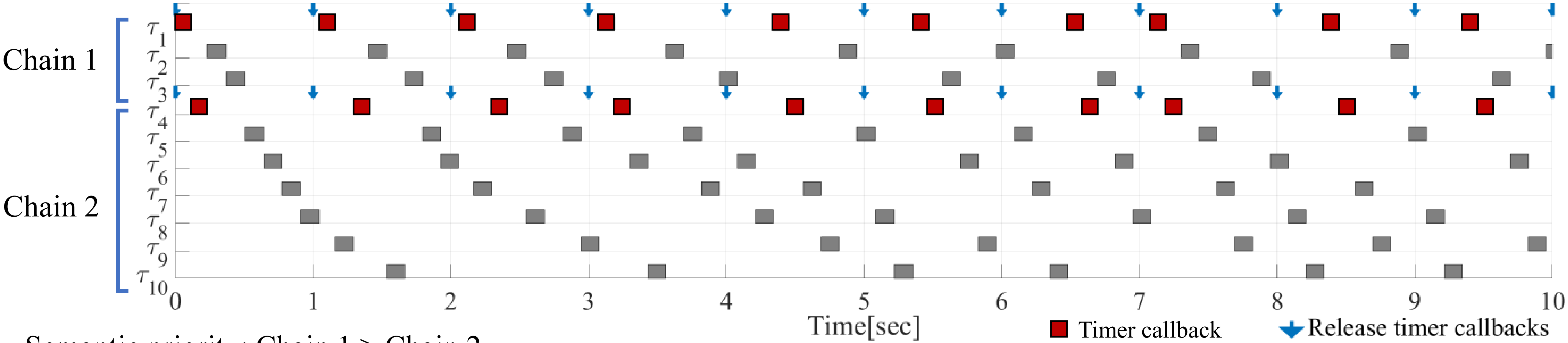
- ✓ $\mathcal{N} =: \{n_1, \dots, n_j, \dots, n_N\}$
- ✓ Not schedulable entities

Executor model

- ✓ $\mathcal{E}_i =: \{e_1,, \dots, e_j, \dots, e_E\}$
- ✓ Preemptive
- ✓ Schedule with `SCHED_FIFO`

Challenges (1/2)

- Challenge I: Fairness-based scheduling ***within executors***



Semantic priority: Chain 1 > Chain 2

Single executor	Mean	Max	Min	STD
Chain 1	36.865	72.752	0.505	21.223
Chain 2	36.730	73.149	0.773	21.154

< End-to-end latency results [sec] >

O1. Prioritizes timer callbacks regardless of chain priority [†]
O2. Does not distinguish callbacks by their origin chains

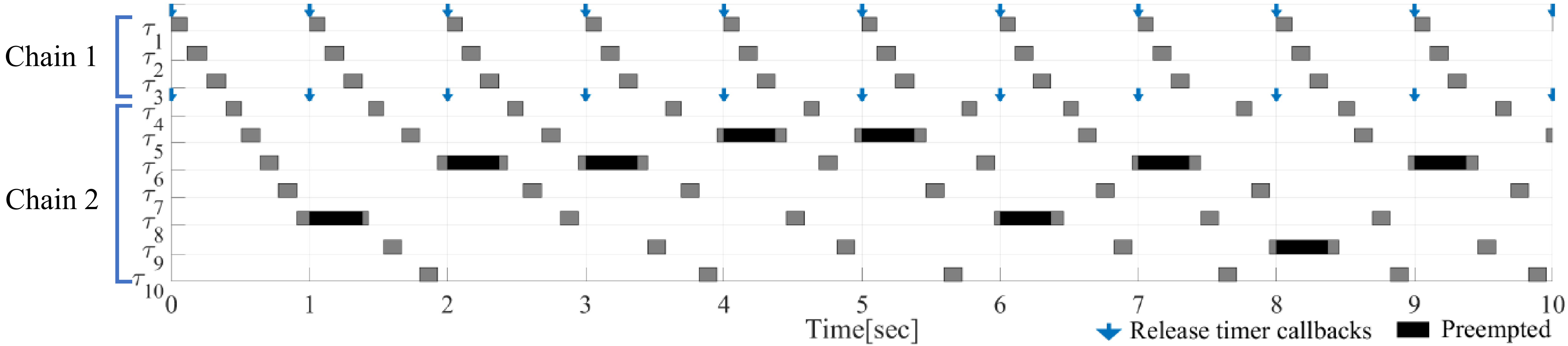
➡ **Jeopardizes the timeliness of safety-critical chains**

[†] D. Casini et al. “Response-time analysis of ROS 2 processing chains under reservation-based scheduling”, ECRTS, 2019

Challenges (2/2)

- Challenge II : Priority assignment for executors

(Chain 1 in a higher-priority executor)



Semantic priority: Chain 1 > Chain 2

Single executor	Mean	Max	Min	STD
Chain 1	0.370	0.392	0.366	0.004
Chain 2	48.795	97.783	0.772	28.304

< End-to-end latency results [sec] >

O3. High penalty due to self-interference
O4. No guidelines on executor priority assignment

Default ROS2 causes unacceptably high latency for chain 2

Priority-driven chain-aware scheduling

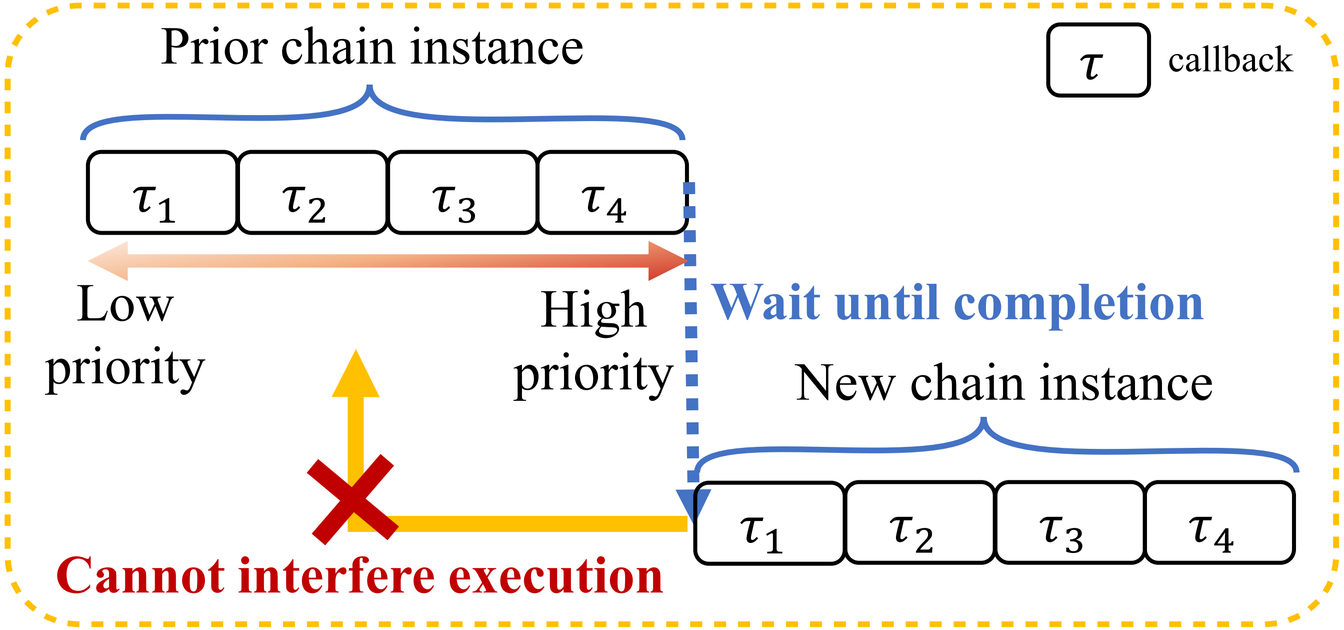
- Re-design ROS2 default scheduling architecture
  - (1) Higher-semantic priority chain executes first (from challenge I)
  - (2) For each chain, its instances on the same CPU execute in arrival order to prevent self-interference (from challenge II)

Lemma 1

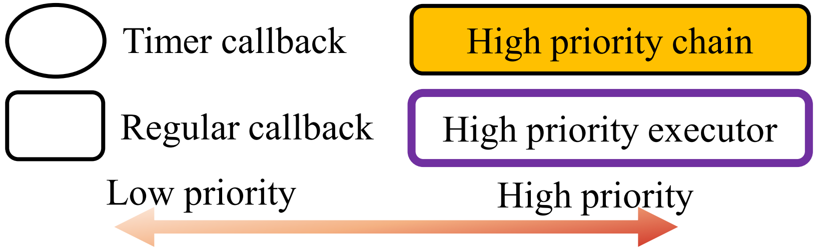
For $\Gamma^c := [\tau_1, .., \tau_i, \dots, \tau_j, \dots, \tau_N]$ whose callbacks are on the same CPU, ***a prior chain instance is guaranteed to complete***, if the following conditions are met:

① $\boldsymbol{\tau_j}$ **has a higher callback priority** than τ_i,

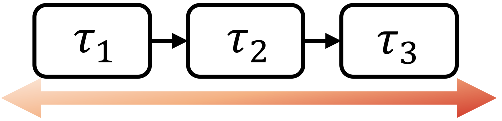
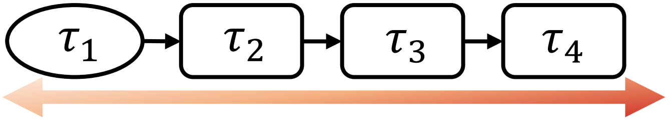
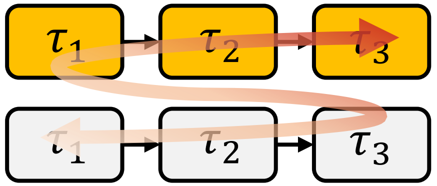
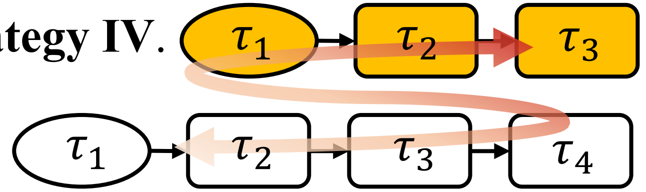
② $\boldsymbol{\tau_j}$ **runs on an executor with the same or higher priority** than τ_i's executor.



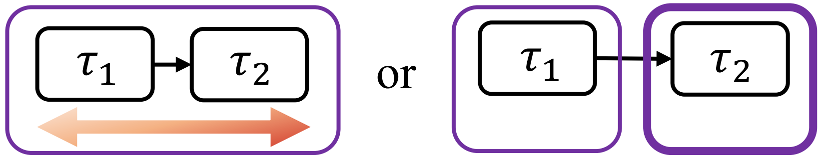
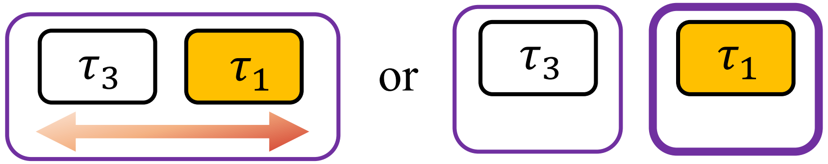
Scheduling strategies



- Strategies for chains running within an executor

	Regular callbacks only	Timer and regular callbacks
Single chain	**Strategy I.** (To satisfy ① of Lemma 1) 	**Strategy II.** (To satisfy ① of Lemma 1) 
Multiple chains	**Strategy III.** 	**Strategy IV.** 

- Strategies for chains running across executors

Single chain on one CPU	Multiple chains on one CPU
Strategy V. (To satisfy ② of Lemma 1) 	**Strategy VI.** 

Priority assignment

- ***Realization*** **of scheduling strategies** in two aspects
  - **Callback priority assignment**
  - **Chain-aware node allocation algorithm**

Algorithm 1 Callback priority assignment

Input: Γ: chains

```
Γ ← sort in ascending order of semantic priority π_Γ
p ← 1                                  ▷ Initialize current priority
for all Γ^c ∈ Γ do
    for all τ_i ∈ Γ^c do
        τ_i ← p
        p ← p + 1
    end for
end for
```

Chain-aware node allocation

- Purpose: **minimize interference between chains**

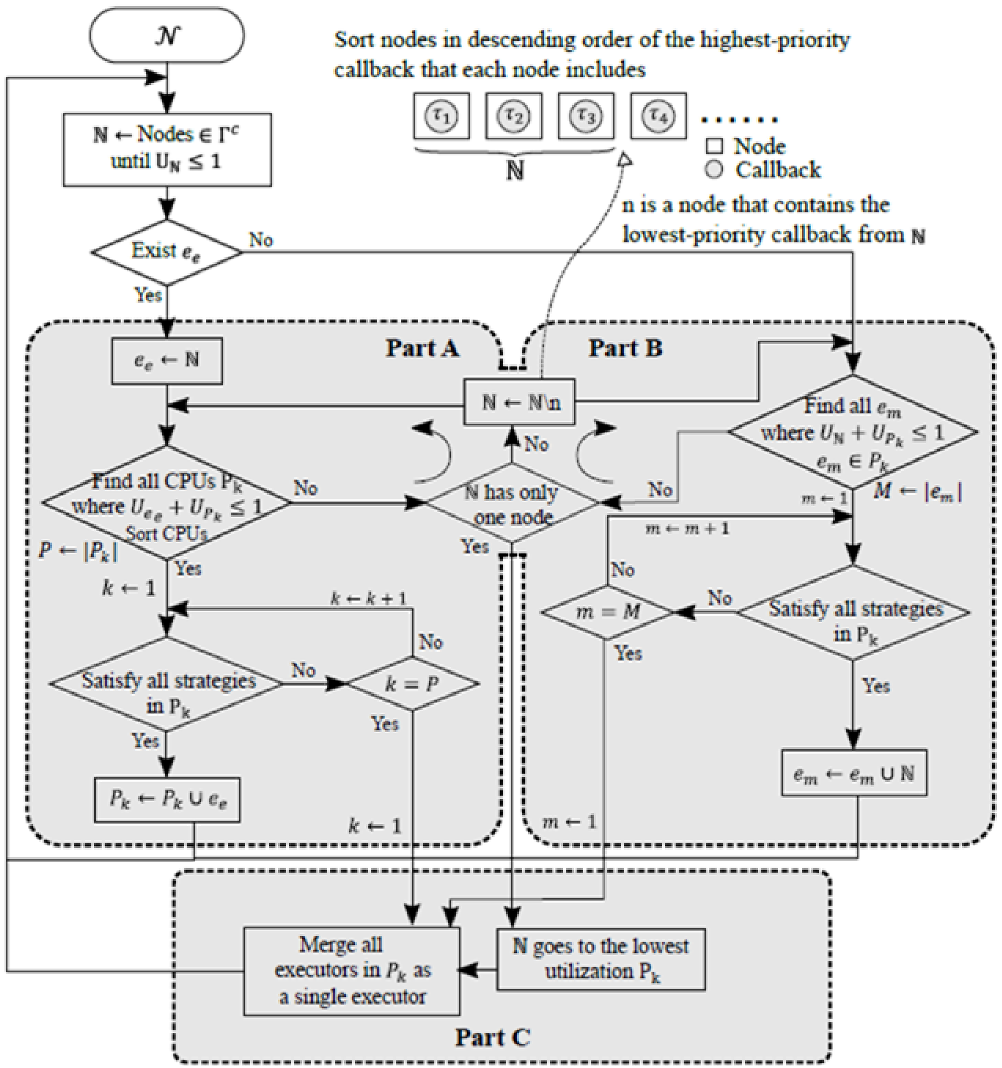
(1) allocate given ***nodes to executors***, and then
(2) maps ***executors to available CPU cores***

Part A. Allocate sorted nodes ℕ to e_e and e_e to a feasible CPU

Part B. Allocate sorted nodes ℕ to feasible e_m when e_e does not exist

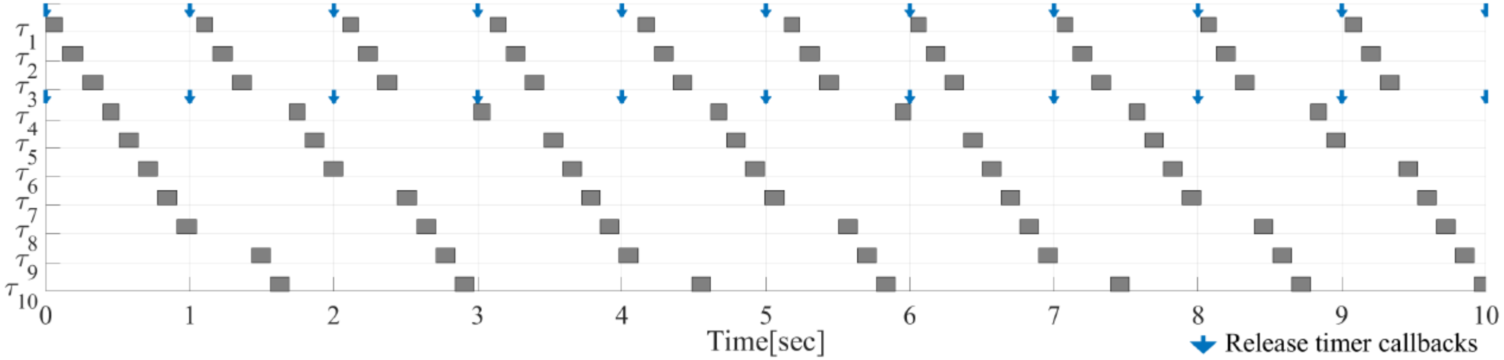
Part C. Handle all leftover nodes that were not allocated to executors by Part A & B

	Parameters		
$\mathcal{N}$	Nodes	e_m	Non-empty executors
ℕ	A node set consists of callbacks of a chain Γ^c ($U_{\mathbb{N}} \leq 1$)	M	The number of e_m
e_e	Empty executor	P	The number of P_k
U_{P_k}	Utilization of CPU core P_k		
n	A node that has the lowest priority callback of Γ^c in ℕ		



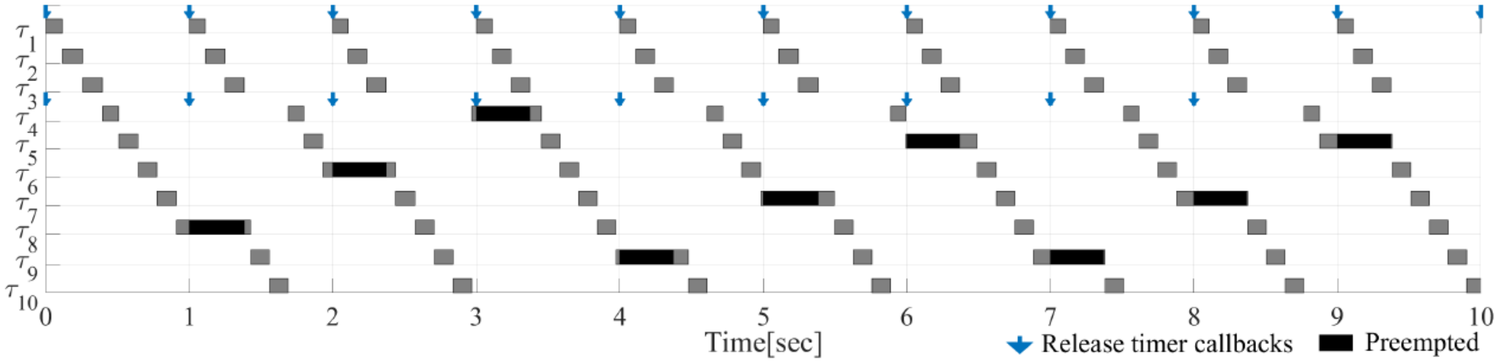
Examples of chain-aware scheduling

- With the same workload at page 7.



< All callbacks in a single executor >

Single executor	Mean	Max	Min	STD
Chain 1	0.436	0.506	0.368	0.038
Chain 2	1.196	1.738	0.741	0.348



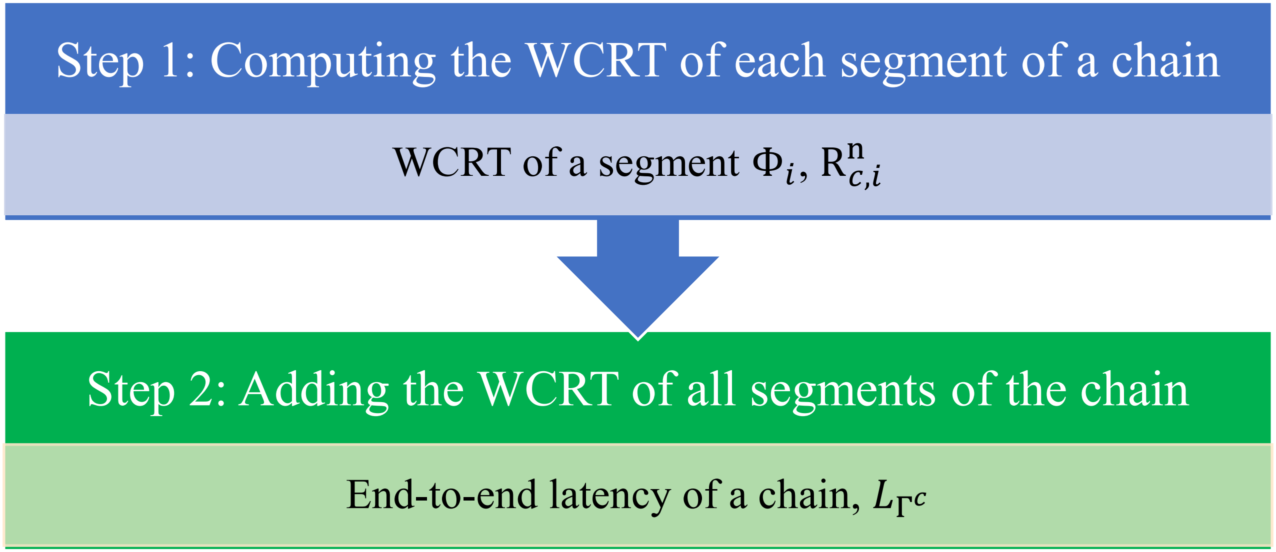
< One executor per chain >

Executor per chain	Mean	Max	Min	STD
Chain 1	0.369	0.394	0.366	0.004
Chain 2	1.255	1.731	0.737	0.352

Significantly improved end-to-end latency under PiCAS

Analysis of end-to-end latency

- Latency analysis in a multi-core system
  - Segment Φ_i: a subset of a chain on one CPU core
  - Multiple segments if a chain executes over multiple CPU cores



< Latency analysis of a chain in a multi-core system >

Execution time of callbacks for the segment

$$R_{c,i}^{n+1} \leftarrow B_i + \sum_{\forall j:\tau_j\in\Phi_i} C_j + \sum_{\substack{\forall k:\tau_k\in e(\Phi_i)\vee\\ \tau_k\in e_{HP}}} \eta_i\left(R_{c,i}^{n},\tau_k\right)\times C_k$$

Blocking time from lower priority callback

Interference from higher semantic priority chains

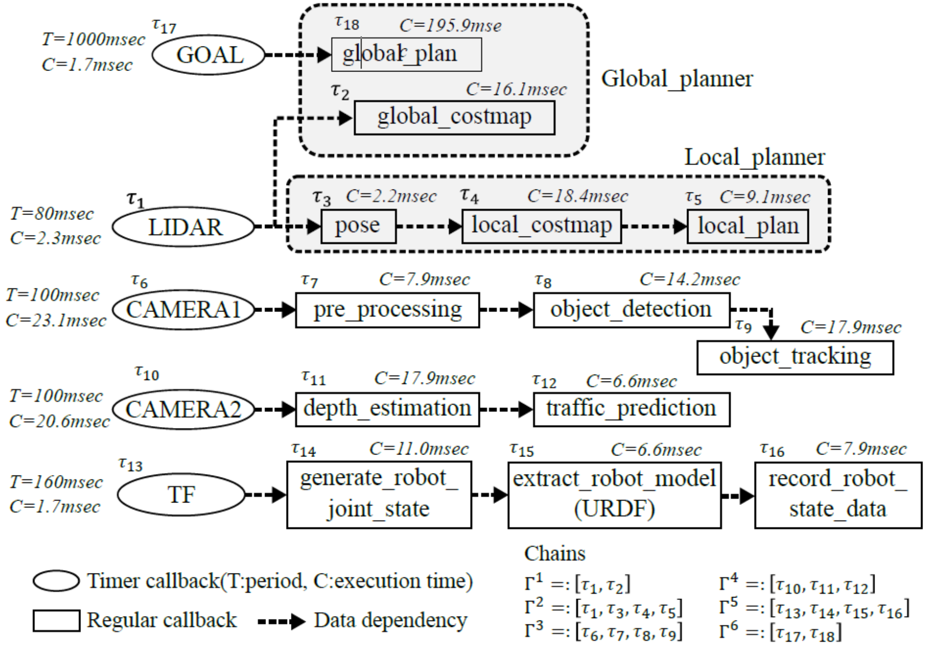
$$L_{\Gamma^c} = \sum_{\Phi_i\subset\Gamma^c} R_{c,i}^{n} + S(\Gamma^c)$$

Blocking delay by prior instance

V. Evaluation

Evaluation

- **Case studies**, **schedulability analysis**, and **analysis running time**
- Experimental setup for case study
  - Implemented in the Eloquent Elusor of ROS2 on Ubuntu18.04 on NVIDIA Xavier NX
  - Comparison of approaches
    - ✓ **ROS2** : **ROS2 default scheduler** with no analysis
    - ✓ **ROS2-SD** † : **ROS2 default scheduler** with resource reservation and **WCRT analysis**
    - ✓ **ROS2-PiCAS** : proposed scheduler with end-to-end latency analysis
  - Case study in a multi-core system
    - ✓ Inspired by the indoor self-driving stack of F1/10 vehicle
    - ✓ 6 real-time chains (18 callbacks) and 6 best-efforts chains in a 4-core system
    - ✓ Low-indexed chains are more critical chains

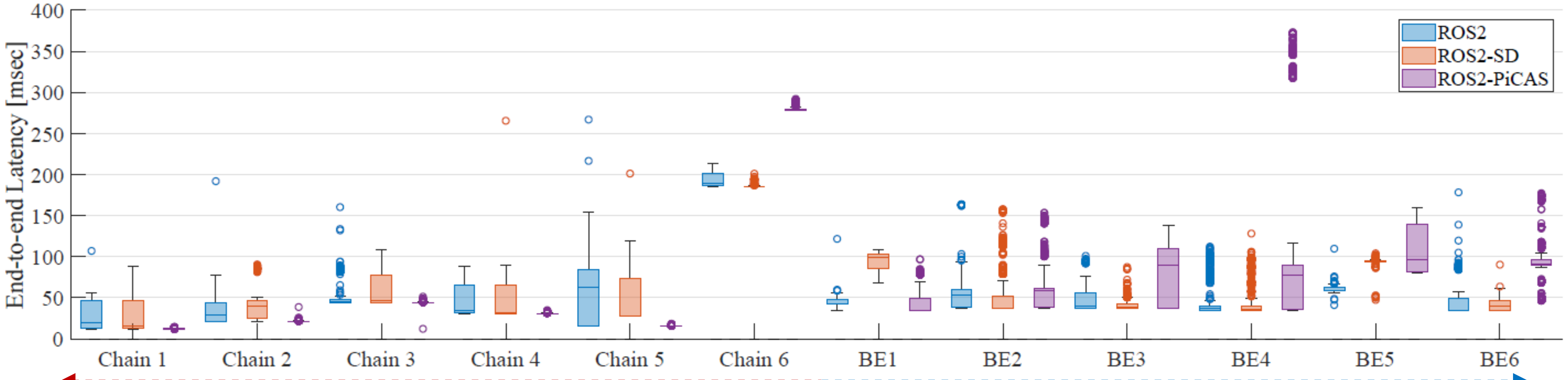


< Case study >

† D. Casini et al. "Response-time analysis of ROS 2 processing chains under reservation-based scheduling", ECRTS, 2019

V. Evaluation

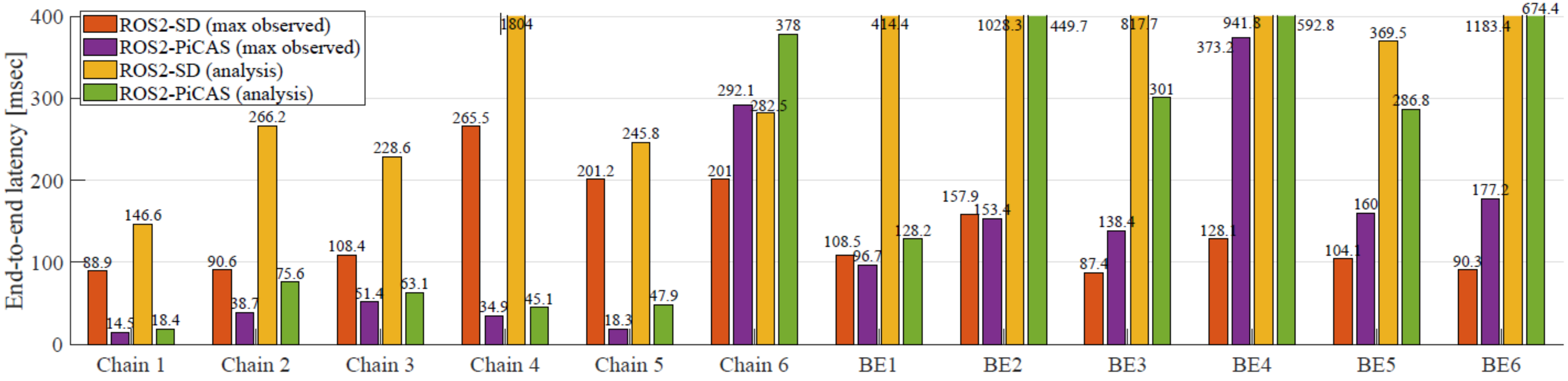
Case study



Real-time chains

Best-effort chains

< End-to-end latency of chains >



< Maximum observed latency vs. analyzed latency >

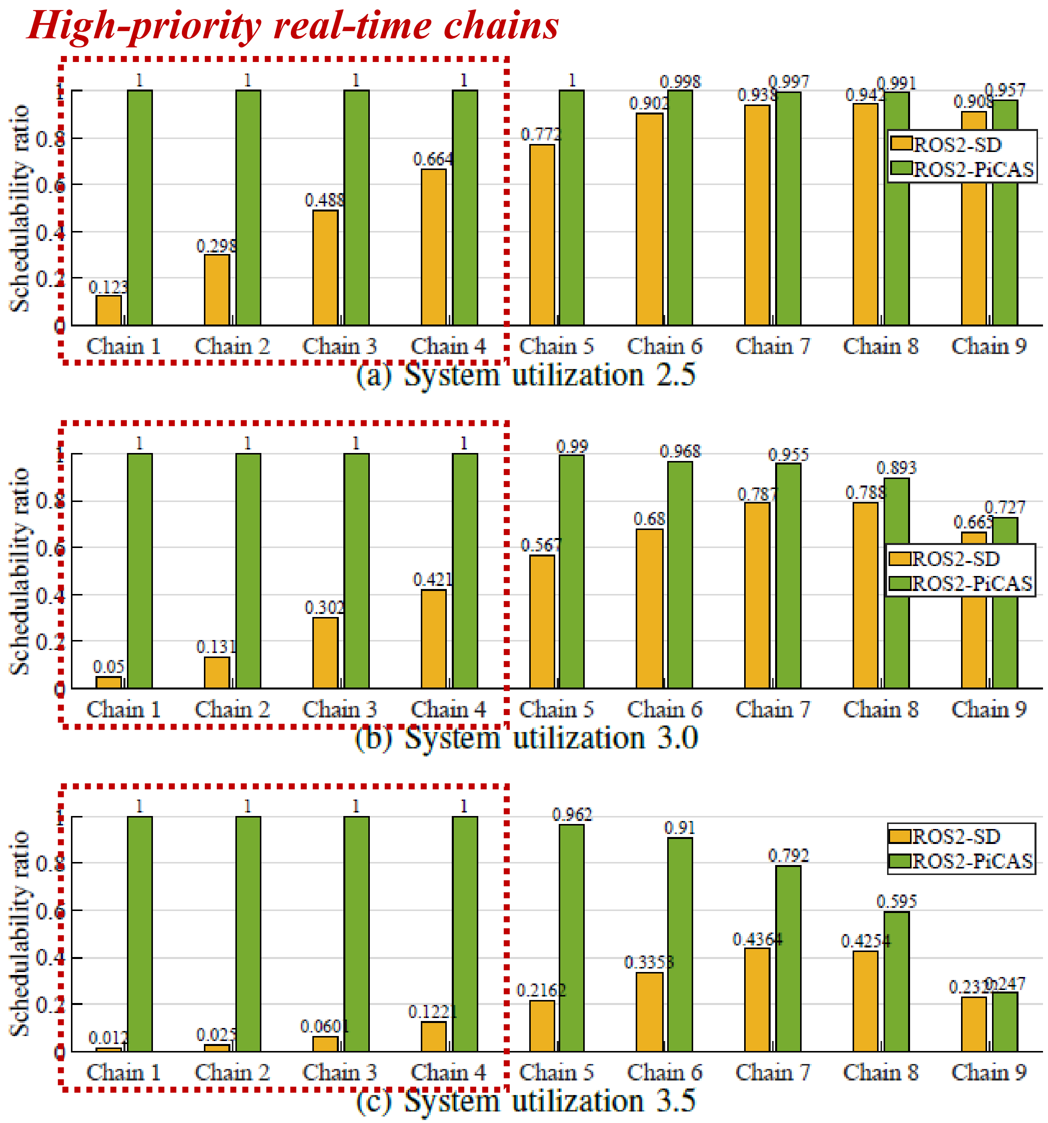
PiCAS outperforms on most real-time chains (e.g., 14ms vs 88ms for chain 1)

Schedules chains while respecting their semantic priority

Our latency analysis provides tighter upper-bounds for real-time chains

Schedulability experiments

- Workload generation
  - 1,000 randomly-generated workload sets of callbacks
  - Utilization from {2.5, 3.0, 3.5} for 4-core environment
  - 45 callbacks that forms 9 chains (i.e., 5 callbacks per chain)
  - Chain's period (deadline) is chosen in the range [50, 1000] msec



(a) System utilization 2.5

(b) System utilization 3.0

(c) System utilization 3.5

Schedulability ratio decreases as the utilization increase

ROS2-PiCAS outperforms ROS2-SD for all utilization setups.

ROS2-PiCAS prioritizes chains based on their semantic priority

Conclusion & Future work

- Conclusion
  - Proposed **a priority-driven chain-aware scheduling** and its **end-to-end latency analysis** framework
  - New design of ROS2 scheduling includes **scheduling strategies**, **priority assignment of callbacks**, and **chain-aware node allocation**
  - ROS2-PiCAS **outperforms** the existing ROS2 scheduling w.r.t. the end-to-end latency **under practical scenarios**
- Future work
  - Deploy PiCAS to more complex scenario, e.g., autoware.auto (built on ROS2)

Thank you

PiCAS: New Design of Priority-Driven Chain-Aware Scheduling for ROS2

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Q & A