Exploring Partitioned and Semi-partitioned Callback Scheduling on ROS 2 Multi-threaded Executors

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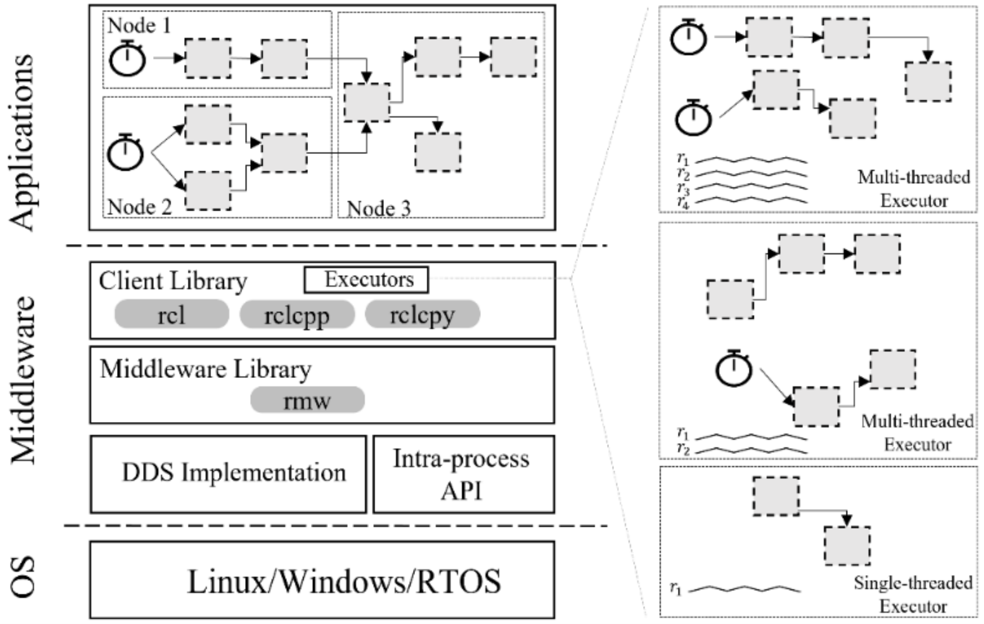
What is ROS 2

ROS 2: An important open-source middleware framework for the development of robotic applications

- Provides modular integration of software components for complex robotic applications



[8] H. Sobhani, H. Choi, and H. Kim, “Timing Analysis and Priority-driven Enhancements of ROS 2 Multi-threaded Executors,” in 2023 IEEE 29th Real-Time and Embedded Technology and Applications Symposium (RTAS). IEEE, 2023, pp. 106–118

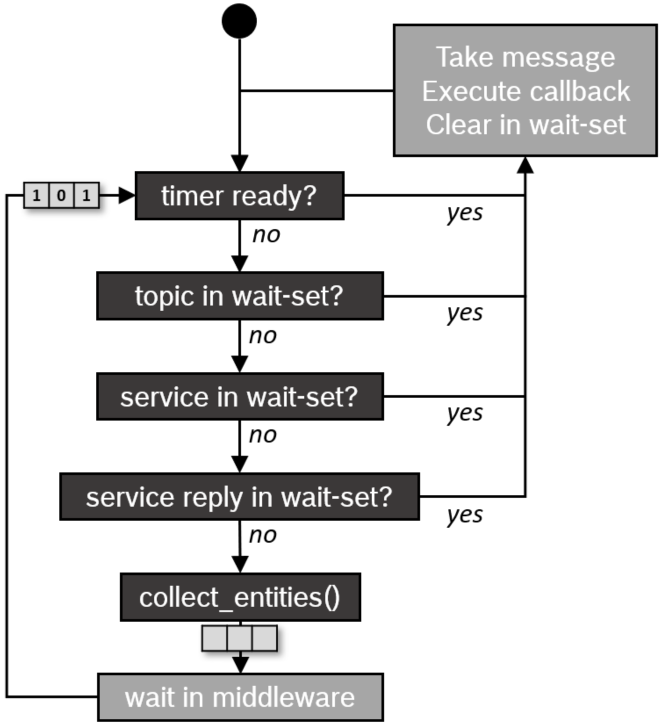
ROS 2 Architecture

Executors: processes with one or more threads scheduled by **OS scheduler**

- Can be single-threaded processes or multi-threaded processes
- Maintains a local wait-set of callbacks to be assigned to a thread for execution

Callbacks: smallest schedulable entity in ROS 2

- **Scheduled by executors** running on the CPU
- Five types of callbacks:
  - Timer, subscription, service, client, and waitable
- When callbacks are released, they are added to their executor's wait-set

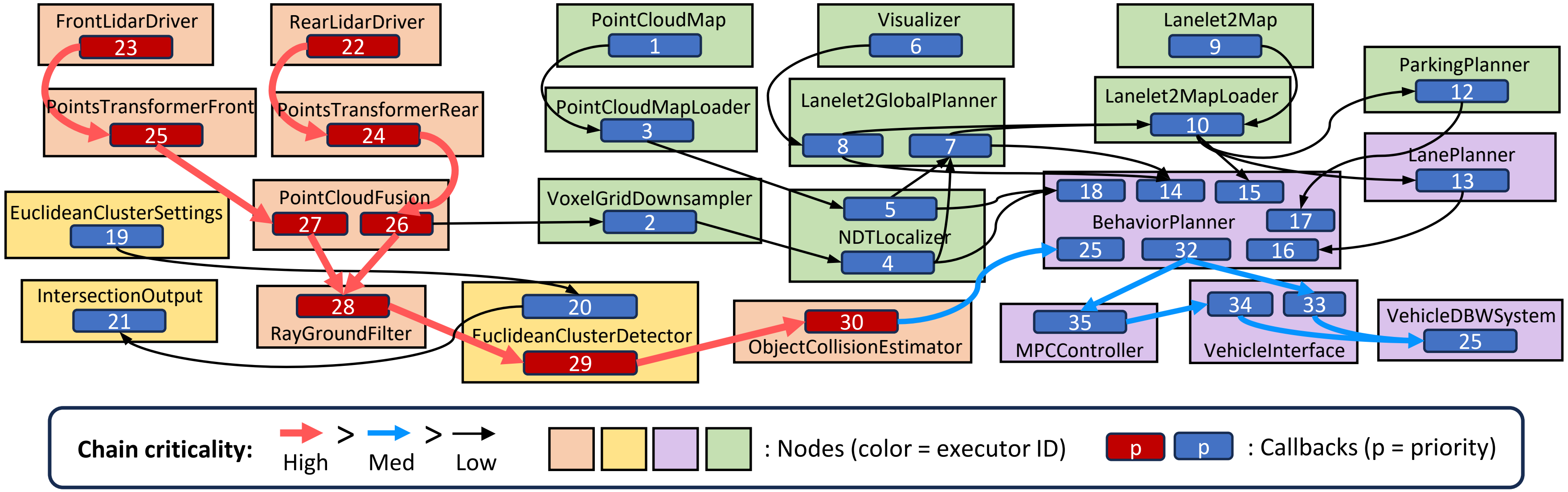


Nodes: syntactical organization of callbacks

- Used to assign callbacks to executors

Processing Chains in ROS 2

- Semantic abstraction of a sequence of **data-dependent** callbacks
  - Example: Apex.AI's Autoware Reference System*



* ROS 2 Real-time Working Group> Reference System. https://github.com/ros-realtime/reference-system/

Scheduling Callbacks on Multi-CPU Systems

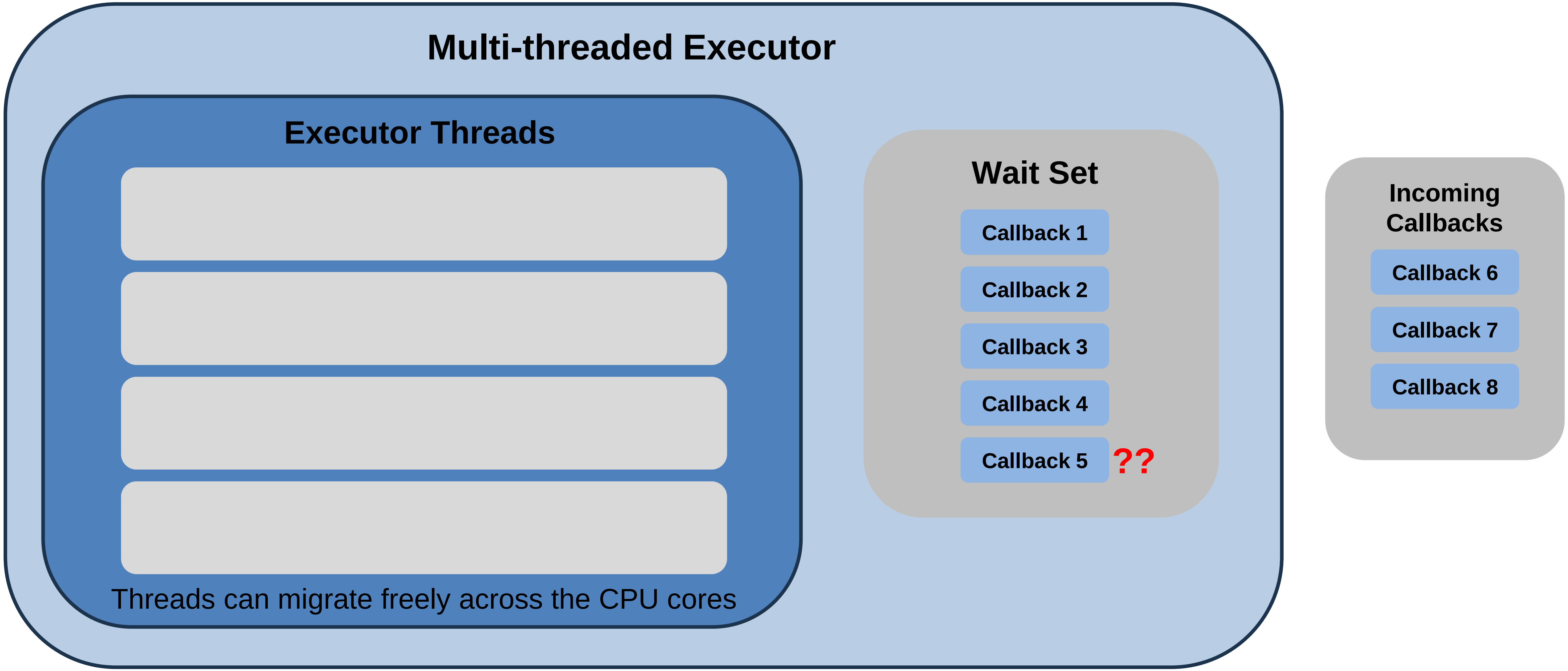
ROS Executor Types:

- Single-threaded executor:
  - One thread that pulls ready callbacks from the wait set to execute on the CPU
  - User can create *n* single-threaded executors for an *n-CPU* system
- Multi-threaded executor:
  - Multiple threads that pull ready callbacks from the wait-set to execute on one or more CPUs
  - By default, ROS creates *n-threads* for an *n-CPU* system

Callback Scheduling within ROS 2 Executors

1. Callbacks are executed on the CPU cores non-preemptively
2. Each executor maintains a single wait-set for ready callbacks
3. Callbacks in the wait-set are prioritized to execute in the following order:
    - Timer, subscription, service, client, and waitable
4. Wait-set is only updated when it is empty

Example: Callback Scheduling with MT Executor



Literature Review

- Multiple single-threaded executors vs. Single multi-threaded executor

Multiple single-threaded executors → Partitioned Scheduling	Single multi-threaded executor → Global Scheduling
• Per-thread wait-set: less contention • Better for isolation between workloads • No migration (potentially less overhead) • Difficult to determine callback-to-executor assignment • One node cannot be split into two executors • Potential resource underutilization	• Allows a single process memory space, allowing more efficient inter-callback data transfers (via intra-process API) • Better to reclaim unused CPU time • No isolation: potentially longer blocking time low-priority callbacks and more interference among different chains
Related Work	
- Daniel Casini et al. "Response-time analysis of ROS 2 processing chains under reservation-based scheduling." in ECRTS. 2019. - H. Choi, et. al, "PiCAS: New design of priority-driven chain-aware scheduling for ROS2," in RTAS, 2021.	- X. Jiang, et. al., "Real-time scheduling and analysis of processing chains on multi-threaded executor in ROS 2," in RTSS, 2022. - H. Sobhani, et. al., "Timing Analysis and Priority-driven Enhancements of ROS 2 Multi-threaded Executors," in RTAS, 2023

Proposed Idea

Implement partitioned and semi-partitioned scheduling within the default ROS 2 multi-threaded executor

- New thread affinity API introduced to the *rclcpp* library
- Allows developers to bind callbacks to specific threads within the multi-threaded executor
- Facilitates the reservation of execution bandwidth for high priority callbacks*

* When executor threads are applied the SCHED_DEADLINE policy and cgroups are used to set their CPU masks

Thread Affinity API Implementation Details

// Set thread (CPU) affinity

```
void Executor::set_thread_affinity(rclcpp::TimerBase::SharedPtr ptr, int* affinity_threads, int size);
void Executor::set_thread_affinity(rclcpp::SubscriptionBase::SharedPtr ptr, int* affinity_threads, int size);
void Executor::set_thread_affinity(rclcpp::ServiceBase::SharedPtr ptr, int* affinity_threads, int size);
void Executor::set_thread_affinity(rclcpp::ClientBase::SharedPtr ptr, int* affinity_threads, int size);
```

// Calculate final thread affinity based on threads assigned (Called by each of the above API methods)

```
size_t Executor::get_final_affinity_value(int* affinity_threads, int size);
```

// Default Parameters

```
#ifdef PICAS
        int callback_priority = 0;
#endif
        size_t thread_affinity = 0;
```

Thread Affinity API Implementation Details

// Check thread affinity for current thread

```
if((callback->thread_affinity >= 0 ) && !((callback->thread_affinity & (1 << thread_affinity_id)))) {
        ++callback_iterator;
        continue;
}
```

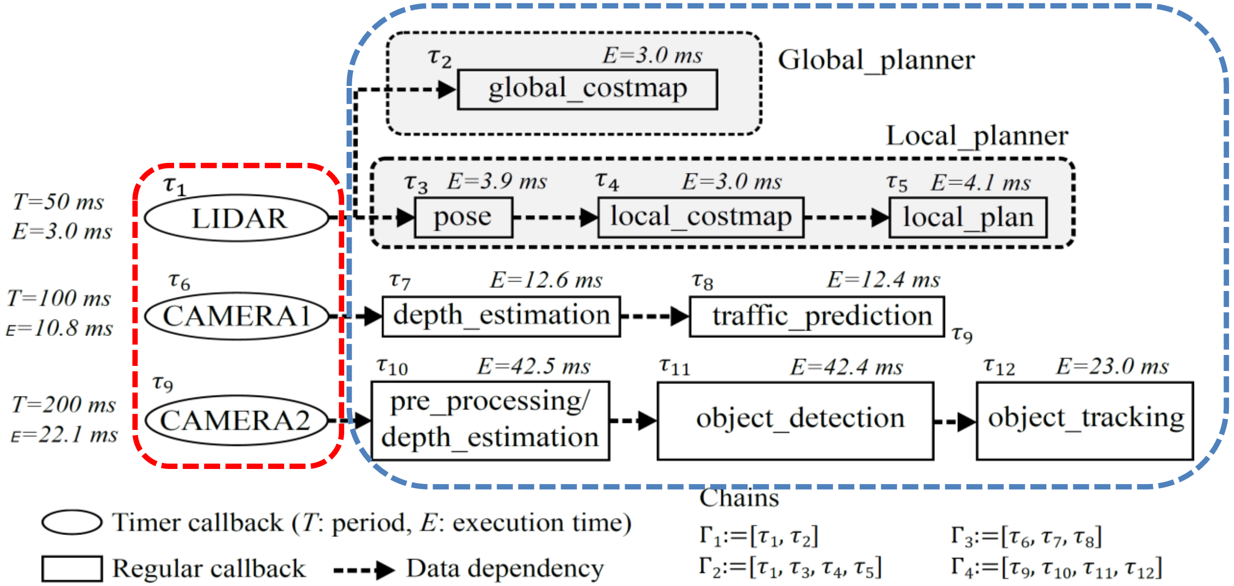
Skip this callback; check next ready callback

Runs inside:
get_next_timer(),
get_next_subscription(),
get_next_service(),
get_next_client(),
get_next_waitable()

Experiment: Platform and Taskset

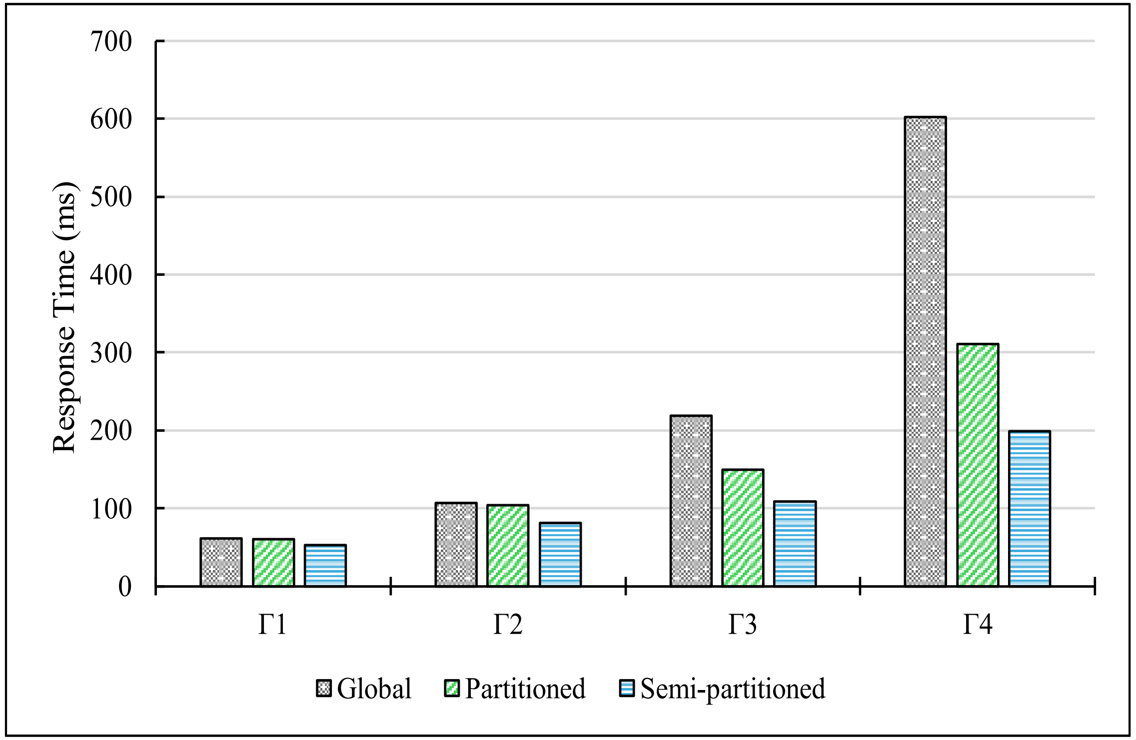
Implemented on ROS 2 Galactic

- Performed on an Intel Core i7-10875H (4 cores, pinned to maximum frequency)
- Using our modified *rclcpp* library incorporating the thread affinity API
- Followed default ROS 2 callback priority ordering



Experiment: Allocation and Results

- Partitioned scheduling: each thread is assigned a group of callbacks as follows
  - $\{\tau_{12}, \tau_1, \tau_2\}, \{\tau_3, \tau_4, \tau_5\}, \{\tau_6, \tau_7, \tau_8\}, \{\tau_9, \tau_{10}, \tau_{11}\}$
- Semi-partitioned scheduling: callbacks τ_1, τ_6, and τ_9 are statically assigned to separate threads. Other callbacks can migrate between threads 1-4.



Conclusion

- What would be the best way to utilize multiple CPUs in ROS 2?

Prior Work		This Work
Partitioned Scheduling (via multiple single-thread executors)	Global Scheduling (via multi-threaded executor)	Semi-Partitioned Scheduling (within multi-threaded executor)
- Daniel Casini et al. "Response-time analysis of ROS 2 processing chains under reservation-based scheduling." in ECRTS. 2019. - H. Choi, et. al, "PiCAS: New design of priority-driven chain-aware scheduling for ROS2," in RTAS, 2021.	- X. Jiang, et. al., "Real-time scheduling and analysis of processing chains on multi-threaded executor in ROS 2," in RTSS, 2022. - H. Sobhani, et. al., "Timing Analysis and Priority-driven Enhancements of ROS 2 Multi-threaded Executors," in RTAS, 2023	Pros: • Better isolation and predictability compared to global scheduling • Better resource utilization compared to partitioned scheduling Cons: • Complexity in maintaining predictability and managing task migration between cores

*Source code: https://github.com/rtenlab/ros2-picas (branch: multi_threaded_partitioned_scheduling)

Questions