Response Time Analysis for Dynamic Priority Scheduling in ROS2

Abdullah Al Arafat
Sudharsan Vaidhun
Kurt M. Wilson
University of Central Florida, USA

Jinghao Sun
Dalian University of Technology
China

Zhishan Guo
University of Central Florida
USA

ABSTRACT

Robot Operating System (ROS) is the most popular framework for developing robotics software. Typically, robotics software is safety-critical and employed in real-time systems requiring timing guarantees. Since the first generation of ROS provides no timing guarantee, the recent release of its second generation, ROS2, is necessary and timely, and has since received immense attention from practitioners and researchers. Unfortunately, the existing analysis of ROS2 showed the peculiar scheduling strategy of ROS2 *executor*, which severely affects the response time of ROS2 applications. This paper proposes a deadline-based scheduling strategy for the ROS2 *executor*. It further presents an analysis for an end-to-end response time of ROS2 workload (processing chain) and an evaluation of the proposed scheduling strategy for real workloads.

ACM Reference Format:
Abdullah Al Arafat, Sudharsan Vaidhun, Kurt M. Wilson, Jinghao Sun, and Zhishan Guo. 2022. Response Time Analysis for Dynamic Priority Scheduling in ROS2. In *Proceedings of the 59th ACM/IEEE Design Automation Conference (DAC) (DAC '22), July 10–14, 2022, San Francisco, CA, USA.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3489517.3530447

1 INTRODUCTION

Over a decade, Robot Operating System (ROS) has been the standard and most popular framework for developing robotics software, mainly for its modularity and composability. However, the first version of ROS was fundamentally limited in terms of real-time capabilities, which eventually necessitated the emergence of ROS2 in 2017. ROS2 got immediate attention from both the autonomous systems industry and academia, due to its capability of providing real-time guarantees through enabling the Distributed Data Service (DDS) communication interface.

As a foundational cornerstone for autonomous and robotic systems, it is essential that the response time of ROS2 workload can be bounded. However, there was no such formal analytical model for ROS2 before the pioneering work of Casini et al. [3]. It presented a model for the default ROS2 scheduler to enumerate the response-time of workloads, the architectural hierarchy of the ROS2 framework, and working principle of the default ROS2 scheduler.

We thank Nan Guan from City University of Hong Kong for fruitful discussions on the paper. This work is supported by NSF grants CNS 1850851, and PPoSS 2028481.

DAC '22, July 10–14, 2022, San Francisco, CA, USA
© 2022 Association for Computing Machinery.
ACM ISBN 978-1-4503-9142-9/22/07…$15.00
https://doi.org/10.1145/3489517.3530447

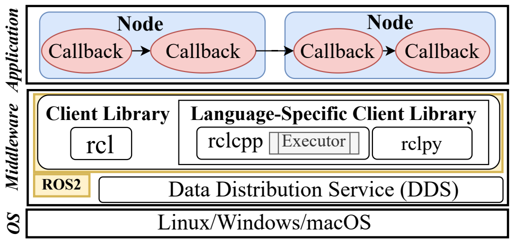


Figure 1: ROS2 Architecture [3]

Overview of ROS2. Fig. 1 presents the architecture of ROS2. ROS2 applications are typically composed of series of individual *nodes* distributed in the application layer. Nodes preserve the molecularity of application programs, and communicate with each other through a publish/subscribe mechanism: nodes first publish *messages* on a *topic*, and then the topic broadcasts messages to nodes subscribed to the topic. When receiving a messages, nodes invoke *callbacks* (fundamental programming blocks) to process the message. To implement the publish/subscribe system, ROS2 leverages the underlying data distribution service (DDS), which is an anonymous and asynchronous message passing framework. To deploy a ROS2 application, individual nodes are mapped onto operating system processes. ROS2 uses *executors* (in the client library) to coordinate the execution of the callbacks of the nodes assigned in a process.

An *executor* maintains a *readySet* that stores the ready callbacks assigned to the *executor*. At each time, the *executor* selects one callback from the *readySet* to be executed non-preemptively on the process. The updating strategies of *readySet* as follows — it is only updated when it becomes empty, and it cannot contain two same callbacks from different instances of a chain simultaneously. In contrast, a timer callback (first callback of a processing chain) can enter the *readySet* instantly, and it starts execution either immediately or after the completion of a non-preemptively executing callback.

Limitations of default ROS2. Following the properties of *readySet*, there are two critical issues raised that affect the response time of processing chains. (i) There is no notion of priority among different processing chains in an *executor*, as any processing chain can enter the *readySet* directly through activating the timer callback. Therefore, in default ROS2 *executor*, it is not possible to provide higher priority to any critical chain for better response time. (ii) Any processing chain instance can receive interference from both **past** and **future** instances of the same processing chain (self-interference) due to the updating strategy of *readySet* and the privilege entrance of the timer callback to the *readySet*.

The limitations of the *readySet*-based scheduling policy of ROS2 *executor* lead to longer response time of workloads in ROS2. To eliminate such limitations of *readySet*-based scheduling, we aim to design a new priority-based scheduling scheme for ROS2 *executor*. Intuitively, priority-driven scheduling policies (e.g., fixed- and dynamic-priority-based scheduling) dominate over default *readySet*-based scheduling, as the former schedulers can mitigate the self-interference of processing chains by simply providing a unique priority-order to each instance.

Related Works. Casini et al. [3] presented the first formal analysis and modeling of ROS2 for bounding the end-to-end latency of ROS2 application. This paper pointed out the peculiar scheduling strategy of the default ROS2 executor. It developed the response time-bound of any ROS2 processing chain that may span multiple executors leveraging the compositional performance analysis tool. Later, Tang et al. [9] published a follow-up paper improving response time bound for default ROS2. The critical observations of Tang et al. are the pipeline-style execution pattern of the callbacks of a chain in the processing windows of executor, and only the priority of the last callback in a chain has an impact on response time. These observations enable them to reduce interference from interfering chain instances, and providing the highest priority to the last callback of the chain further improves the response time-bound. A concurrent work from Blaß et al. [2] developed a better response time response analysis for ROS2 exploiting the starvation freedom and execution-time variance of callbacks.

A recent work by Choi et al. [4] partially addressed the limitations of the default ROS2 executor scheduler and proposed a chain level (fixed) priority-based scheduling scheme. The proposed method performed well for prioritized chains over default scheduler, specifically for high-priority chains. However, low-priority chains may suffer very high latency in an overloaded (in fact, in general cases also) system due to frequent preemptions (see Fig. 2 and Table 2 in Section III). Therefore, instead of the fixed priority of each chain, we propose chain instance-level deadline-based dynamic priority scheduling for ROS2 *executor*.

Contributions. In this paper, we first propose a deadline-driven dynamic-priority-based scheduling scheme for ROS2 *executor*. Our proposed scheduling scheme addresses the limitations of the default ROS2 scheduler and dominates both the default ROS2 and existing fixed-priority-based scheduler in terms of end-to-end latency. Specifically, we make the following contributions in this paper:

(1) We propose the first dynamic priority (deadline-based) scheduling scheme for the ROS2 *executor*. As a result, the proposed scheduler has a fine granularity to assign priorities at the chain instance-level as opposed to fixed chain-level priorities.

(2) We analyze the proposed deadline-based scheduling scheme for end-to-end latency of a ROS2 processing chain that could span over multiple executors.

(3) We perform a detailed evaluation of the proposed scheduling scheme through case studies using real-world workloads.

2 SYSTEM MODEL

Workload Model. We model the ROS2 workload following the hierarchy of ROS2 architecture — Callbacks, *Executor*, and Chain model of the workload.

Callback. The system consists of a set of N_c callbacks $\tau = \{\tau_i | 1 \le i \le N_c\}$. Each callback $\tau_i \in \tau$ is represented by the following 2-tuple,

$$\tau_i = (C_i, \chi_i) \tag{1}$$

where, C_i is the worst-case execution time of the callback. The parameter $\chi_i \in \{\chi_T, \chi_R\}$ represents the callback type – timer callback χ_T or regular callback χ_R. The regular callback is triggered by messages published on the topic. The timer callback do not subscribe to topics and therefore cannot be triggered by messages. Instead, timer callbacks are activated by system timers.

Executor. We consider a set of N_κ *executors*, $E = \{E_k \mid 1 \le k \le N_\kappa\}$. Each callback is assigned to an *executor* and the mapping is fixed throughout the runtime of the system. An *executor* can be either single-threaded or multi-threaded. The same as in [3, 4, 9], this paper considers the **single-threaded** *executor*.

Chain Model. We represent the workload generated by all the activations of the callbacks as a set of N_Γ *processing chains*, $\Gamma = \{\Gamma_i \mid 1 \le i \le N_\Gamma\}$. Each chain $\Gamma_i \in \Gamma$ consists of a sequence of callbacks,

$$\Gamma_j = < \tau_{j_1}, \tau_{j_2}, \ldots, \tau_{j_{|\Gamma_j|}} > \tag{2}$$

where, $\tau_{j_i} \in \tau$ and $|\Gamma_j|$ is the length of the chain. The starting callback, τ_{j_1}, of the chain is usually a timer callback, and remaining callbacks, $\{\tau_{j_i} | i \in \{2, \ldots, |\Gamma_j|\}\}$ are the regular callbacks.

Each chain Γ_j is represented by the following 3-tuple:

$$\Gamma_j = (C_{\Gamma_j}, D_j, T_j) \tag{3}$$

where C_{Γ_j} is WCET of the chain, derived from the sum of the WCET of all callbacks in the chain,

$$C_{\Gamma_j} = \sum_{\forall i:\tau_i \in \Gamma_j} C_i$$

D_j and T_j are the relative deadline and the minimum inter-arrival time of the chain, Γ_j, respectively. Note that, all callbacks $\tau_i \in \Gamma_j$ have same absolute deadline instant as the associated chain Γ_j.

Now, we define the workload of an *executor* E_k as a set of processing (sub)chains[1] in the *executor*,

$$E_k(\Gamma) = \{\Gamma_j^k | \Gamma_j^k \in E_k\}$$

Here, Γ_j^k is either the chain Γ_j or a segment of Γ_j that belongs to the *executor* E_k and $\Gamma_j = \bigcup_{\forall k} \Gamma_j^k$. We further denote the relative deadline of Γ_j^k as D_j^K which either equal to D_j or derived from D_j using the fact that all callbacks in a chain have same absolute deadline.

Resource Model. The threads utilized by the *executors* are scheduled using the Linux scheduler. Linux scheduler works by scheduling the thread with the highest priority, and if there are multiple threads with the same priority, then a specific scheduling policy is followed to determine the thread to schedule. In our model, all ROS2 threads will be preemptively scheduled with the same (highest) static priority and follow the SCHED_FIFO policy. The budget guarantees are provided to the threads by implementing them as constant bandwidth server.

Communication Overhead. The communication among the callbacks adds delay (overhead) in addition to the execution time of callbacks. However, we neglect the communication overhead if the callbacks in a communication link are in the same *executor*. In case

[1](sub)chain can be either a chain or a segment of a chain

two communicating nodes are in two *executor*s, we add a fixed communication delay between $k^{th}(\tau_k \in E_k)$ and $\ell^{th}(\tau_\ell \in E_\ell)$ callbacks as follows:

$$d(\tau_k, \tau_\ell) = \begin{cases} 0, \text{ if } E_k = E_\ell \\ \gamma, \ \forall k, \ell : E_k \neq E_\ell \end{cases}$$

Overload Handling Mechanism. ROS2 contains an overload handling mechanism to drop a timer callback (and so the associated chain) in case the timer callback missed one or more of its period to start execution. The overload handling mechanism is activated by running `rcl_timer_call` function at the release instant of timer callback. First, the `next_call_time` variable is incremented by the timer's period. Then `next_call_time` is compared with current time instant to see whether `next_call_time` is in the past. If so, `next_call_time` is incremented to the number of periods timer already behind, ensuring that the timer skips missed periods.

3 PROBLEM AND METHOD

3.1 Problem Statement

As mentioned earlier, the default scheduler of the ROS2 *executor* introduces two critical issues that adversely affect the response time of processing chains. The existing chain-level fixed priority-based scheduling scheme of ROS *executor* [4] addressed those critical problems. However, the *chain-level priority* proposed by PiCAS [4] disproportionately affects lower priority chains, which is further worsened in an overloaded scenario where the lowest priority chains may receive no service. In this paper, we particularly attempt to resolve two *issues*:

(1) We address the limitations of default *readySet*-based scheduling scheme of ROS2 executor replacing the default scheduler with a dynamic-priority based scheduler.

(2) We address the limitations of *chain-level priority*-based scheduling when the workload has chains with equal (semantic) priority.

3.2 Proposed Scheduler

To replace the default scheduler of ROS2 *executor*, we proposed a deadline-based (Earliest Deadline First (EDF)) scheduling policy redesigning the *readySet* as a *readyQueue*.

Definition 1. ***readyQueue*** Ω *is maintained in executor similar to readySet in default ROS2. Unlike readySet, readyQueue is updated after the completion of each non-preemptively executing callback. The priority of the readyQueue is set based on the deadline of each callback, where the earliest deadline callback has higher priority than the later one.*

As the *readyQueue* prioritizes any callback only based on the deadline parameter, there is no privilege priority of timer callback in the *readyQueue*. This property of the *readyQueue* mitigates both of the limitations of the default scheduler, as any released chain has to wait to execute until the completion of high priority chains.

Scheduling Strategy. Our deadline-based scheduling policies for (sub)chain scheduling in the *executor* are as follows:

(1) Whenever any chain instance releases, it enters to the waitset. The *readyQueue* Ω of the *executor* is updated after the completion of the execution of the current active callback due to the non-preemptive execution of the callbacks.

Chains	Specifications [sec]
(1) $< \tau_1, \tau_2, \tau_3 >$	$C_1 = 0.109; C_{\{2,3\}} = 0.131; T_1 = 1$
(2) $< \tau_{\{4,\cdots,10\}} >$	$C_4 = 0.109; C_{\{5,\cdots,10\}} = 0.131; T_2 = 1$

Table 1: Chain set for illustrative experiments.

	Chain ID	Mean	Max	Min	STD
Default	1	1.478	1.879	0.632	0.355
	2	4.108	4.913	2.415	0.445
PiCAS	1	0.442	**1.373**	0.373	0.565
	2	2.055	2.654	1.655	0.314
OURs	1	0.849	**1.372**	0.376	**0.305**
	2	**1.424**	**1.922**	**0.903**	**0.310**

Table 2: End-to-end latency results[sec] of two chains (Table 1) running in default ROS2 scheduler, PiCAS [4], and our deadline-based scheduler of ROS2 *executor*.

(2) The *readyQueue* Ω is prioritized based on the absolute deadline of each callback, and the callback with the earliest absolute deadline is scheduled to execute non-preemptively. The higher priority chain's callback can only preempt any active chain (executing) after the completion of the currently executing callback.

(3) Suppose a chain instant is released, but the previous instant of the chain has not started executing yet. In that case, the previous instant of the chain is dropped by enabling the (original) overload handing mechanism of ROS2.

Remark. Tardiness is allowed as ROS2 is unaware of deadlines. Meeting deadlines can only be guaranteed by verifying that the worst-case latency of the chains does not exceed the deadlines. In this work, we use the deadlines *only* to prioritize chains (and callbacks) during runtime dynamically, but *not* to drop workloads. This is acceptable since ROS2 inherently provides its own overload handling mechanism to prevent unbounded latencies.

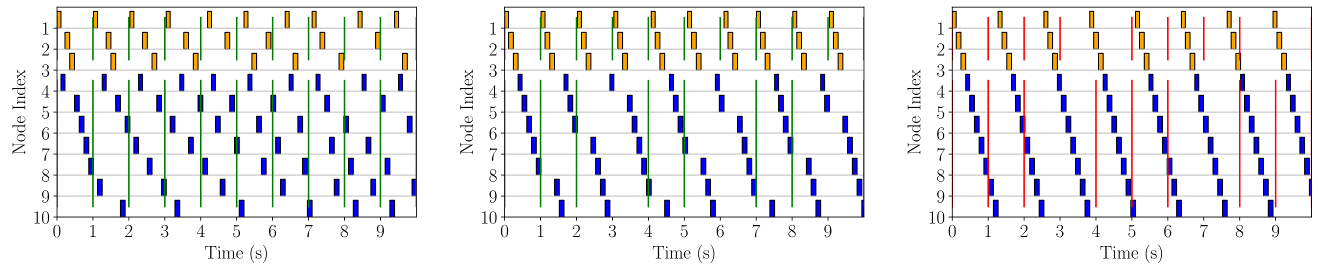
3.3 Illustrative Experiment

We present an experimental study on a simple workload (Table 1) consisting of two processing chains. The experimental setup on the ROS2 environment is presented in the evaluation section. We perform the experiments for default ROS2 scheduler, PiCAS [4], and our deadline-based scheduler of ROS2 *executor*. The execution patterns for these three algorithms are illustrated in the Gantt charts in Fig. 2. From the Gantt charts, Fig. 2 (b, c), in priority-based scheduling, all chain instances complete the execution before starting later instances, and only the chains with higher priorities are active, reducing the interference in an active window. The end-to-end latency of the chains for all three schedulers is shown in Table 2. Our schedulers outperform the default scheduler for both of the chains. Compared with PiCAS, our scheduler performs better than PiCAS on average, and specifically, low-priority chains consistently outperformed PiCAS.

4 RESPONSE TIME ANALYSIS

4.1 Overview

We first analyze the worst-case response time (WCRT) of a (sub)chain (analyzed chain) in an *executor*, then extend the analysis for end-to-end latency of the chain span over the multiple *executors* using CPA tool [6]. Fig. 3 illustrates a possible scenarios of ROS2 processing



(a) Default ROS2 Scheduler [3, 9] **(b) PiCAS Scheduler [4]** **(c) EDF Scheduler (this paper)**

Figure 2: Gantt-charts of ROS2 scheduling example for the workload of Table 1. The first three lines, in orange, represent the executions of Chain 1. The remaining lines, in blue, represent the executions of Chain 2. In PiCAS scheduler (Fig. 2(b)), no chain instances from chain 1 (orange) is dropped, but three instances (at 3, 6, and 9) from second chain (blue) is dropped. In contrast, our scheduler dropped chain instances from both chain 1 (at 4 and 9) and chain 2 (at 3 and 7).

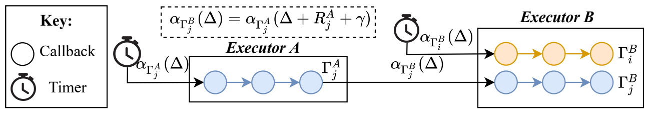

Key:
Callback
Timer
$\alpha_{\Gamma_j^B}(\Delta) = \alpha_{\Gamma_j^A}(\Delta + R_j^A + \gamma)$
Executor A
$\alpha_{\Gamma_j^A}(\Delta)$
Γ_j^A
$\alpha_{\Gamma_i^B}(\Delta)$
$\alpha_{\Gamma_j^B}(\Delta)$
Executor B
Γ_i^B
Γ_j^B

Figure 3: ROS2 processing chains in *executors*

chains assigned in the *executors*. We are particularly interested in analyzing the response time of the sub-chain Γ_j^B in *executor B*, then extend the analysis to calculate the end-to-end response time of $\Gamma_j = \Gamma_j^A \cup \Gamma_j^B$ that span over *executors A & B*.

Arrival Curve. The release patterns of chains/sub-chains in an *executor* E_k are characterized by *arrival curve*, $\alpha(\Delta)$. Chains start with a timer callback have a staircase *arrival curve*, $\alpha_{\Gamma_i}(\Delta) = \lceil \frac{\Delta}{T_i} \rceil$ where at each period one instance of the chain is released. However, the *arrival curve* for a chain starts with regular callback (sub-chain) depends on the *arrival curve* of the starting sub-chain of the parent chain and the response time of all precedent sub-chains (see Fig. 3). The *request bound function* (rbf) of a chain Γ_j^k in a time range Δ is upper bounded by [3],

$$\mathrm{rbf}(\Gamma_j^k, \Delta) = \alpha_{\Gamma_j^k}(\Delta) \cdot C_{\Gamma_j^k}$$

therefore, the *demand bound function* (dbf) of the chain is upper-bounded by [5],

$$\mathrm{dbf}(\Gamma_j^k, \Delta) = \mathrm{rbf}(\Gamma_j^k, \Delta - D_j^k) \tag{4}$$

dbf(Γ, Δ) implies that the maximum resource demand generated by the chain instances of Γ that have both release and deadline instances in the range of Δ times.

Resource Model. We consider a general case where resource supply to each server is lower bounded by the supply-bound function sbf(Δ). sbf(Δ) implies the minimum guaranteed supply to the server in each Δ time interval [7, 8]. In our analysis, we assume sbf(Δ) is known (provided by the system designer). We define the pseudo-inverse of sbf(Δ) as follows,

$$\overline{\mathrm{sbf}}(x) = \min\{\Delta \mid \mathrm{sbf}(\Delta) = x\} \tag{5}$$

$\overline{\mathrm{sbf}}(x)$ provides the minimum time in which the server gets x unit of processing time.

Intuitively, to bound the WCRT, we first calculate the slack time[2], instead of directly calculating the WCRT, for analyzed (sub)chain instant similar to [5]. So, the WCRT, R_j of the analyzed chain, Γ_j is as follows:

$$R_j = D_j - S_j^* \tag{6}$$

The minimum slack time, S_j^*, for all (sub)chain instances of the analyzed (sub)chain Γ_j is estimated from the resource demand of all (sub)chains in the *executor* and the available resource supply to the *executor*.

Finally, we develop the end-to-end WCRT of the analyzed chain, adding the individual sub-chain WCRT and communication delays between the sub-chains of different *executors*.

4.2 Properties

To compute the WCRT of a (sub)chain, Γ_j^k inside an *executor* E_k, we consider a 'busy period' of the *executor*. Any busy interval, $(t_o, t_d]$, in the *executor* is an interval where at least one chain instance is ready to execute at any instant in the interval with a release time no earlier than the t_o and deadline no later than t_d. Here, t_o is the last idle instant of the busy interval. To develop the resource demand of all (sub)chain instances in such a busy period, let consider a minimal set $\sigma(\Gamma)$ that includes all (sub)chain instances with a release time no earlier than the t_o and deadline no later than the t_d. Following are the two facts of the minimal set $\sigma(\Gamma)$,

Fact 1. *All (sub)chain instances in $\sigma(\Gamma)$ must have an execution in $(t_o, t_d]$ but the one with a deadline equal to t_d.*

Proof. If any (sub)chain instance does not execute in the busy interval, the instance is removed from the minimal set $\sigma(\Gamma)$. So, if any instance in $\sigma(\Gamma)$ does not execute in $(t_o, t_d]$, it contradicts the minimality of set $\sigma(\Gamma)$. However, a chain instance in $\sigma(\Gamma)$ with deadline t_d cannot execute at all, implying that it will miss the deadline. □

Fact 2. *In any busy interval, $(t_o, t_d]$, at most one (sub)chain instance with deadline $> t_d$ can execute non-preemptively for one callback.*

[2]Slack time is the difference between the deadline and completion time of a chain instance. Note that slack time can be negative, which usually occurred for 'tardy' instance, and we allow tardiness in our model.

Proof. Following the deadline-based strategy, any chain instance can be preempted by a higher priority chain at the completion instants of callbacks of the executing chain. Therefore, the chain instance with deadline $> t_d$ can at most execute non-preemptively for one callback with an execution starting time instant $< t_o$. Further, once the chains in $\sigma(\Gamma)$ with deadline $\leq t_d$ starts executing, any chain instance with deadline $> t_d$ cannot execute in $(t_o, t_d]$ following the minimality constraint of $\sigma(\Gamma)$ and the fact 1. □

Following facts 1 and 2, we can bound the blocking term for a busy interval by low-priority chain instances.

Lemma 1. *The maximum blocking time of analyzed chain, Γ_j^k in a 'busy interval' of executor E_k is upper-bounded by:*

$$B_j^k = \max_{\forall \tau_i \in E_k(\Gamma)\setminus\Gamma_j^k} \left\{ C_i - \left\lfloor \frac{C_i}{T_j} \right\rfloor \cdot T_j \right\} \tag{7}$$

and T_j is the minimum inter-arrival time of the analyzed chain, Γ_j^k.

Proof. Following fact 2, the blocking time by a lower priority chain can be at most the execution time of 'one callback'. However, the blocking time for the analyzed chain, Γ_j^k cannot be from the lower-priority instances of Γ_j^k as the release time of lower-priority instances always later than the current instance. Therefore, lower-priority blocking (sub)chain instances are from $\forall \tau_i \in E_k(\Gamma) \setminus \Gamma_j^k$.

Now, from the overload handling mechanism, if any chain instant cannot start execution for one or more periods of the chain instance, then the chain instance is dropped. Therefore, $\left\lfloor \frac{C_i}{T_j} \right\rfloor \cdot T_j$ of C_i is not included in blocking time. □

So, the maximum possible blocking time in a 'busy interval' of the *executor* E_k is,

$$B_k = \max_{\forall j:\Gamma_j^k \in E_k(\Gamma)} \{B_j^k\} \tag{8}$$

Lemma 2. *The 'Resource Demand' in a busy interval $(t_o, t_d]$, $\mathsf{RD}(t_d - t_o)$ of the executor E_k is upper-bounded by:*

$$\mathsf{RD}(\ell) = B_k + \sum_{\forall j:\Gamma_j^k \in E_k(\Gamma)} \mathsf{dbf}(\Gamma_j^k, \ell) \tag{9}$$

here, $\ell = t_d - t_o$ and $\mathsf{dbf}(\Gamma_j^k, t_d - t_o)$ is the demand-bound function of the chain Γ_j^k in the time interval of $(t_o, t_d]$.

Proof. The demand-bound function of any chain in the *executor* can be estimated using Eqn. (4). Therefore, $\sum_{\forall j:\Gamma_j^k \in E_k(\Gamma)} \mathsf{dbf}(\Gamma_j^k, \ell)$ provides the maximum possible resource demand by the workload $E_k(\Gamma)$ in $(t_o, t_d]$ interval and B_k is the maximum blocking term (Eqn. 8) for the workload. Hence, the lemma follows. □

Without loss of generality, we consider the idle instant as $t_o = 0$, so the resource demand for any 'busy interval' ℓ:

$$\mathsf{RD}(\ell) = B_k + \sum_{\forall j:\Gamma_j^k \in E_k(\Gamma)} \mathsf{dbf}(\Gamma_j^k, \ell)$$

4.3 Response-Time inside an *Executor*

So far, we have both the maximum resource demand $\mathsf{RD}(\ell)$ and minimum resource supply by the supply-bound function, $\mathsf{sbf}(\ell)$. Now, we compute the minimum slack time for the analyzed chain instances Γ_j^k in the *executor* E_k using following *lemma*,

Lemma 3. *The slack time of the analyzed (sub)chain Γ_j^k in executor E_k is lower-bounded by:*

$$S_j^{*k} = \min_{\forall \delta: D_j^k \leq \delta \leq L_j^k} \left\{ \delta - \overline{\mathsf{sbf}}(\mathsf{RD}(\delta)) \right\} \tag{10}$$

where L_j^k [3] is an upper-bound of range [1].

Proof. The lemma directly follows Theorem III.2 of [5]. □

Lemma 3 provides the exact slack for the tardy chains but gives pessimistic slack time for hard sporadic chain scheduling [5]. However, we allow the tardiness of the processing chains. So, we do not develop an exact test for hard sporadic chains.

Theorem 1. *The response time of the analyzed chain (Γ_j^k) in the executor (E_k) is*

$$R_j^k = D_j^k - S_j^{*k} \tag{11}$$

Proof. It directly follows from response time defined in (6). □

The response time of the analyzed chain Γ_j^k can further be bound from above for the overloaded system using the overload handling mechanism of ROS2 as follows,

$$R_j^k = \begin{cases} R_j^k, & \text{if } R_j^k \leq T_j + C_{\Gamma_j} \\ T_j + C_{\Gamma_j}, & \text{otherwise} \end{cases} \tag{12}$$

this works following the fact that the overloading handling mechanism allows at max T_j idle time for any chain instance to start execution and the EDF makes the chain instance highest priority among all active instances.

4.4 End-to-end Response Time

Finally, we analyze the end-to-end response time of the analyzed chain, $\Gamma_j = \bigcup_{\forall k} \Gamma_j^k$, which can span over the multiple *executors* in the system.

Theorem 2. *The end-to-end response time of the analyzed chain Γ_j is:*

$$R_j = \sum_{\forall k} R_j^k + (K_j - 1) \cdot \gamma \tag{13}$$

where K_j is the number of executors that the chain Γ_j spanned.

Proof. It follows from the principle of the CPA tool: the end-to-end response of the chain is the sum of individual response time in each *executor* and the total communication delays. □

5 EVALUATION

In this section, we first explain our implementation of the proposed chain instance-level priority scheduler in ROS2. Next, we present experimental results comparing the different schedulers.

[3] $L_j^k = \frac{c}{1-c} \cdot \max\{T_j - D_j^k\}$ where, $\sum_{\forall \Gamma_j^k \in E_k(\Gamma)} (C_{\Gamma_j^k}/T_j) \leq c$ [1].

Chains	Specifications (msec)
$< \tau_1, \tau_2 >$	$C_1 = 2.3, C_2 = 16.1, T_1 = 80$
$< \tau_1, \tau_3, \tau_4, \tau_5 >$	$C_3 = 2.2, C_4 = 18.4, C_5 = 9.1, T_1 = 80$
$< \tau_{\{6,\cdots,9\}} >$	$\{C_{\{6,\cdots,9\}}\} = \{23.1, 7.9, 14.2, 17.9\}, T_6 = 100$
$< \tau_{10}, \tau_{11}, \tau_{12} >$	$C_{10} = 20.6, C_{11} = 17.9, C_{12} = 6.6, T_{10} = 100$
$< \tau_{\{13,\cdots,16\}} >$	$\{C_{\{13,\cdots,16\}}\} = \{1.7, 11, 6.6, 7.9\}, T_{13} = 160$
$< \tau_{17}, \tau_{18} >$	$C_{17} = 1.7, C_{18} = 195.5, T_{17} = 1000$
$(BE_{1,\ldots,6})$	$C_1 = 33.2, C_2 = 6.6, T = 120$

Table 3: Specifications for the case study tests, where first six chains are real-time chains and last row specifies the best-effort (six) chains with same parameters.

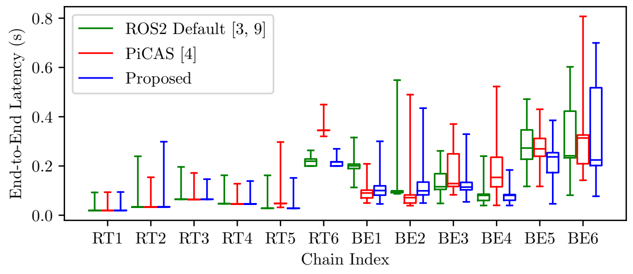


Figure 4: End-to-end latency - tested with the default ROS2, PiCAS [4], our modified *executor* scheduler for the case study workloads presented in Table 3.

5.1 Implementation

Our implementation features an alternate *executor* based on the default `SingleThreadedExecutor` provided by `rclcpp`. Our modified *executor* maintains a priority queue, named *readyQueue*, and populates it from the *wait_set* after every callback execution. We created a unified structure to represent any type of callback along with its chain membership, period, and deadline parameters, and replaced the default *executor's* unordered callback lists.

When a chain completes execution, the executor checks the `time_until_trigger` field of the chain's associated *timer* and sets the deadline field of the chain's callbacks to `time_until_trigger` + `period`. Before a chain completes execution, the timer callback may be triggered resulting in multiple chain instances ready for execution. To prevent multiple chains from running at once, each callback in a chain has a counter that keeps track of where in the chain execution is happening. The counter can used to ensure that the newly released chain instance is not scheduled until the counter reaches the end of the current chain. The callbacks in the queue is prioritized by chain instance first and then by callback deadlines.

5.2 Case Study

The ROS2 schedulers are implemented on an *Nvidia Jetson Xavier AGX* in the 30*W* mode, with the clock frequencies fixed at 1.2Ghz.

Workload. To evaluate the deadline executor implementation, we perform tests with a node layout inspired by case study II from [4]. The workload parameters are presented in Table 3.

Each test uses 4 CPU cores, and each thread is set to the SCHED_FIFO Linux scheduling class. When testing the default ROS *executor* and our modified *executor*, we use 8 *executors*. We distribute the real-time chains across the first four *executors* and the best-effort chains across the next four *executors*. Each *executor* runs in its own thread. Threads containing real-time (RT) chains have their priorities set to 99 (the maximum priority available in Linux), and the best-effort (BE) chains are assigned priority 98. We then distribute the *executors* across 4 CPU cores for load balancing. For testing the PiCAS *executor*, we added chain membership and priority fields and followed the allocation scheme presented in the paper.

Results. We compare our deadline-based *executor* against the default ROS `SingleThreadedExecutor` and the existing chain-aware priority-based execution strategy developed by Choi et al., PiCAS [4]. We observe that for any chain, our proposed scheduler has a lower or equal latency compared to PiCAS as well as the default scheduler. Within each category (RT, BE), we observes that our proposed scheduler has better average latency compared to others for higher chain indices (Fig. 4). As a general trend, the default scheduler has a lower average irrespective of the chain, but higher worst-case latencies. In contrast, our proposed approach maintains a lower average while having lower worst-case latencies as well. All algorithms appear to favor lower index over higher index chains and we believe this due to the tie-breaking behavior.

Note. Our latency times are not directly comparable to those found in [4], due to the difference in the definition of latency. In our work, we define latency as the time difference between release time of the chain and the completion time of the last callback in the chain. Whereas, [4] measure the latency starting from the point the timer callback begins execution. The presented latency is in line with the definition of latency in the real-time scheduling theory.

6 CONCLUSION AND FUTURE WORKS

In this paper, we proposed a deadline-based scheduling scheme for ROS2 *executor* to overcome the limitations of the default *readySet*-based scheduling technique. We used deadline as a tool to realize dynamic priority setting, and presented an end-to-end response time analysis for each processing chain spanning over multiple *executors*. We evaluated the proposed scheduler using a case study of the ROS2 application. Our future goal is to develop techniques to optimally assign dynamic priorities (deadlines) for the workload, such that the user-specified response time and latency requirements can be met. While no such results exists yet, this work serves as a first and important step, where the latency for a given workload can be upper bounded, while deadlines are used to set dynamic priorities.

REFERENCES

[1] S. K. Baruah *et al.* Algorithms and complexity concerning the preemptive scheduling of periodic, real-time tasks on one processor. *Real-time systems.*

[2] T. Blaß *et al.* A ros 2 response-time analysis exploiting starvation freedom and execution-time variance. In *2021 IEEE Real-Time Systems Symposium (RTSS).*

[3] D. Casini *et al.* Response-time analysis of ROS 2 processing chains under reservation-based scheduling. In *31st Euromicro Conference on Real-Time Systems (ECRTS 2019).* Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, 2019.

[4] H. Choi *et al.* PiCAS: New Design of Priority-Driven Chain-Aware Scheduling for ROS2. In *2021 IEEE 27th Real-Time and Embedded Technology and Applications Symposium (RTAS).*

[5] N. Guan and W. Yi. General and efficient response time analysis for edf scheduling. In *2014 Design, Automation & Test in Europe Conference & Exhibition (DATE).*

[6] R. Henia *et al.* System level performance analysis–the symta/s approach. *IEE Proceedings-Computers and Digital Techniques.*

[7] I. Shin and I. Lee. Periodic resource model for compositional real-time guarantees. In *24th IEEE Real-Time Systems Symposium (RTSS), 2003*, pages 2–13. IEEE, 2003.

[8] I. Shin *et al.* Hierarchical scheduling framework for virtual clustering of multiprocessors. In *2008 Euromicro Conference on Real-Time Systems.*

[9] Y. Tang *et al.* Response time analysis and priority assignment of processing chains on ROS2 executors. In *2020 IEEE Real-Time Systems Symposium (RTSS).*