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Towards Multi-Policy Hierarchical Scheduling in Linux for Containerized Space Applications

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1. Introduction

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1. Introduction

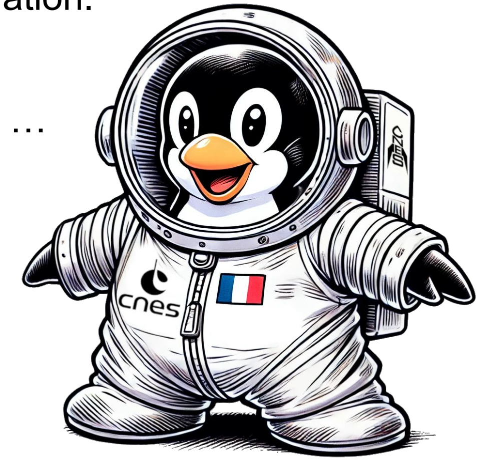
Why Using Linux for Space Applications ?

Current Solutions : RTOS and Hypervisors

- **Pros:** Deterministic, strong isolation, certifiable (DO-178C).
- **Cons:** Limited flexibility, restricted language/library support, static configuration.

Linux

- **Pros:** Open-source, rich ecosystem (languages, libraries, tools), scalable, …
- **Cons:** Limited isolation, unpredictable behavior for critical applications.



Need

- **Complement existing solutions** by **improving** Linux **guarantees**:
  - Enhanced isolation.
  - Performance for heterogeneous workloads.

2. Context

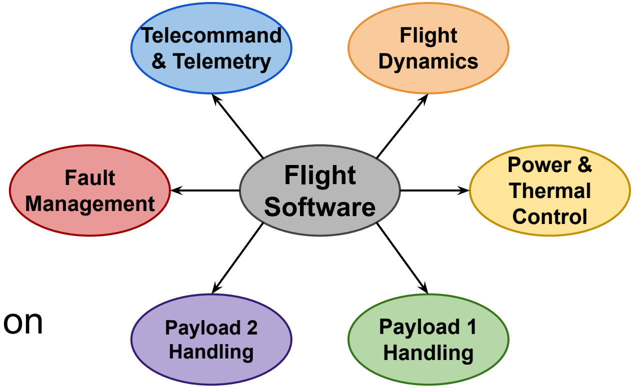
2.1. Spacecraft Flight Software

Diverse Functions

- Attitude and orbit control, power management, payload operations
- Monitoring, diagnostics, and fault management

Heterogeneous Requirements

- Varying **criticality** levels
- Mixed **timing constraints**



Needs

- **Isolation**
  - **Prevent fault propagation** by **separating** functions based on **criticality levels**.
  - **Simplify development**, validation, and integration by **reducing interdependencies**.
- **Optimized Scheduling**
  - Handle **heterogeneous workloads** with **mixed timing** constraints

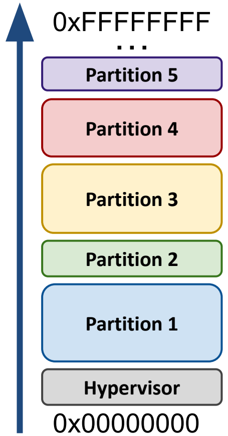
2.2. Isolation Concepts

Spatial Isolation

Ensures that each component can **access only** its **explicitly assigned memory** and **hardware** resources, and **cannot read** or **modify** the **state** of **other components**.

Examples :

- Memory partitioning (static or dynamic)
- Access control & permissions



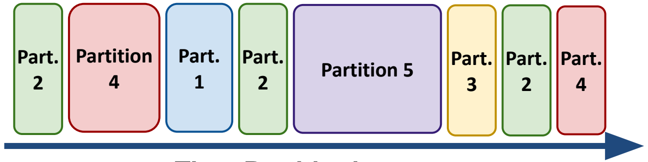
Memory Partitioning

Temporal Isolation

Ensures that the **timing behavior** of a component (e.g., execution time, response time, deadline satisfaction) **is independent** of the execution behavior **of other components**, within defined resource budgets.

Examples :

- Temporal partitioning
- Budget enforcement



Time Partitioning

⚠ *For our work, we adopt a **relaxed view** of **temporal isolation**, focusing on maintaining **bounded response-time guarantees** for tasks to **ensure predictable timing** behavior.*

2.3. Isolating Linux Applications

Hypervisor-Based Isolation

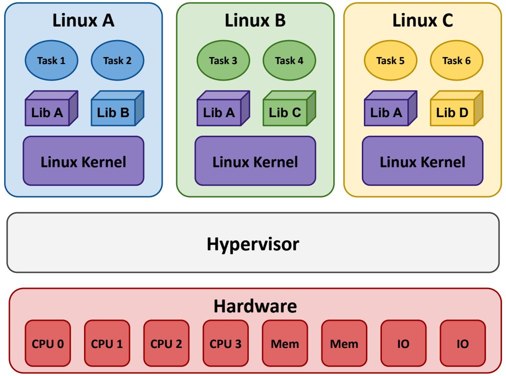
(Linux runs as a Guest OS in a virtualized partition)

Pros

- **Strong** spatial and temporal **isolation**

Cons

- **Limited flexibility**
- **High** memory **footprint**
- Hypervisor **overhead**



Hypervisor + Linux Partitions

Native Linux Isolation

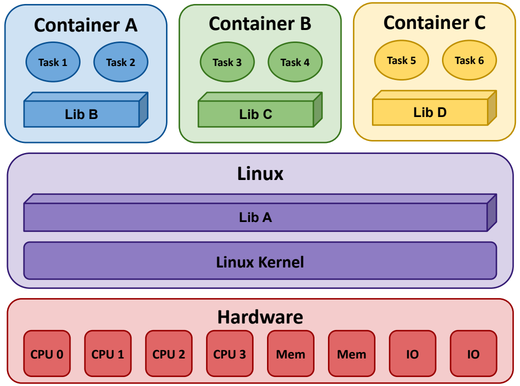
(Linux is the Host OS; isolation via processes, containers, etc.)

Pros

- **Low** memory **footprint**
- **Less overhead**

Cons

- Mostly **software-based** isolation
- **Limited guarantees**
- **Weak temporal** isolation



Linux + Containers

2.4. Linux Scheduling

POSIX Scheduling Policies

- **SCHED_FIFO**, **SCHED_RR**, **SCHED_OTHER** defined by **POSIX**
- **Linux** extension: **SCHED_DEADLINE**

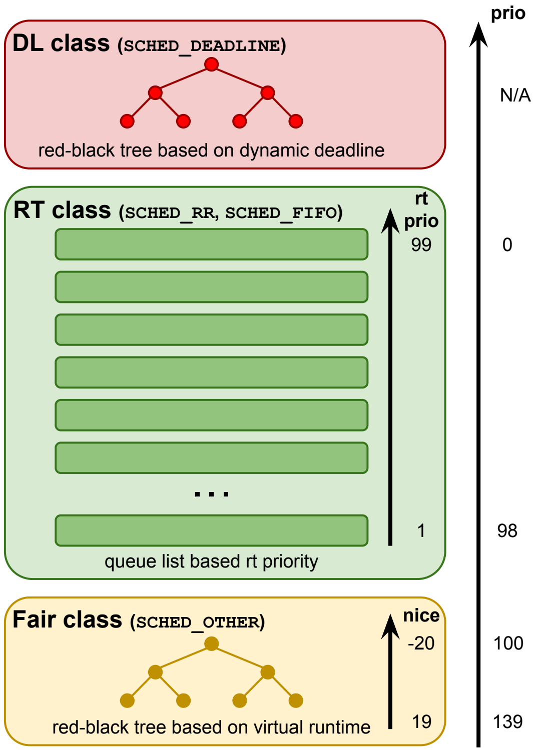
Linux Scheduling Classes vs Policies

- **DL class** ⇔ SCHED_DEADLINE : EDF + Constant Bandwidth Server (CBS) for bandwidth enforcement
- **RT class** ⇔ SCHED_FIFO, SCHED_RR : fixed-priority preemptive scheduling (FIFO vs RR when same priority)
- **FAIR class** ⇔ SCHED_OTHER : fair CPU sharing

For convenience, policies will be grouped by this 3 classes

Design

- Linux is a **multi-policy** OS : FAIR, RT, DEADLINE **coexist** at runtime
- Strict **class priority**: DEADLINE > RT > FAIR



2.5. Multi-Policy Scheduling

Limits of Single-Policy Scheduling

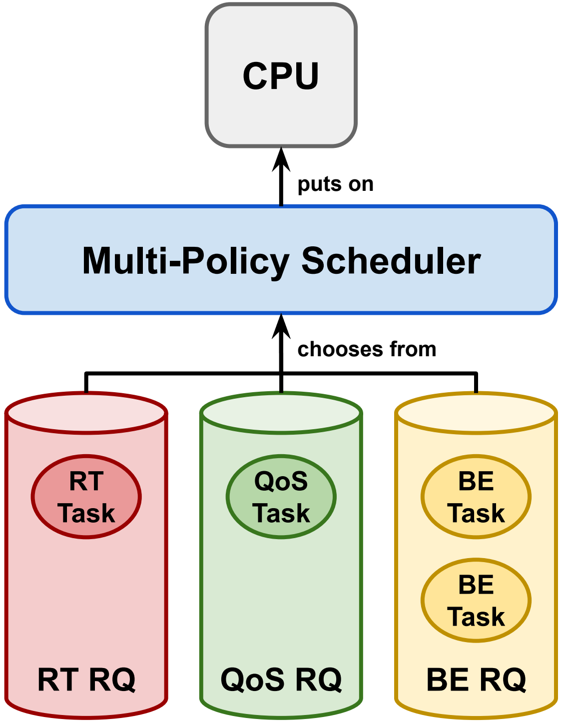
- **Optimized** for a **single objective** (e.g., reactivity, fairness, etc.)
- **Inefficient** for **heterogeneous software** needs

Origins of Multi-Policy Scheduling

- Emerged in **general-purpose operating systems**
- Designed to meet **diverse user requirements**

Key Benefits

- Provides **all** scheduling **policies at runtime**
- Enables **better fit** for **heterogeneous** workload **requirements**



2.6. Temporal isolation within Linux : HCBS patch

Overview

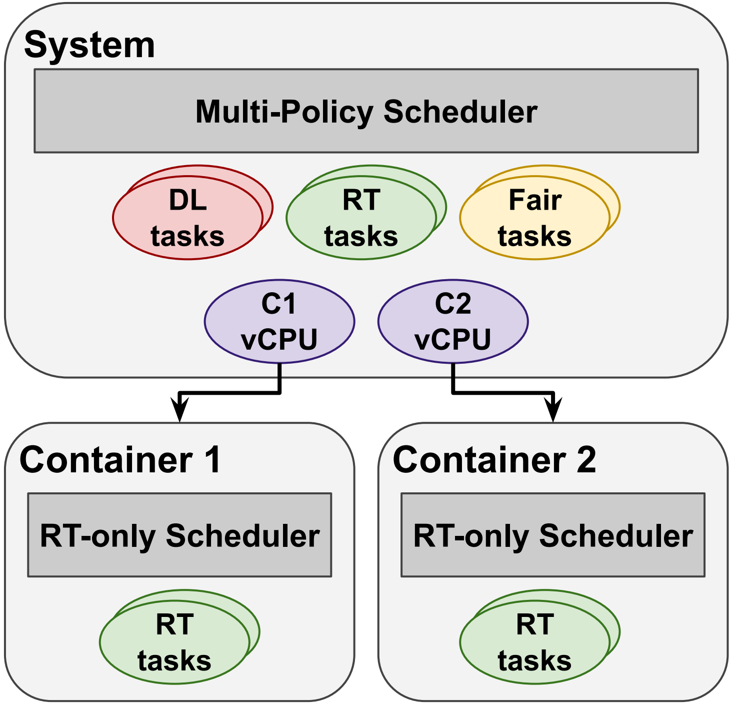
- **Hierarchical Constant Bandwidth Server** (HCBS) enables hierarchical scheduling for the RT class
- Developed by **Abeni et al**. in 2019 [1] and improved by **Andriaccio et al**. in 2025 [2]

Key Features

- Based on **deadline-servers** (CBS) to enable a **guaranteed bandwidth enforcement** between containers
- Associated **RT runqueues** with **deadline servers**, making it only suitable for RT tasks

Limitation

- **Mono-policy**, relies solely on RT class
- **Not suited** for task sets with **heterogeneous objectives**



➡ ***HCBS creates a hierarchical scheduling in Linux***

HCBS (original): https://github.com/lucabe72/LinuxPatches/tree/HCBS
HCBS (updated): https://github.com/Yurand2000/HCBS-patch/tree/rt-cgroups

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3. Problem Statement

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3.1. Current Capabilities and Limitations with Linux

Linux-based Flight Software Needs

- **Spatial isolation**
  Strict resource separation (memory, CPU, devices))
- **Temporal isolation**
  Guaranteed CPU bandwidth and bounded latency
- **Scheduler for heterogeneous workloads**
  Ability to handle tasks with varying constraints

Native Linux Current Capabilities

✓ **Spatial isolation**
Achieved via processes, cgroups, and namespaces

✗ **Temporal isolation**
No guaranteed temporal isolation

✓ **Scheduler for heterogeneous workloads**
Supports multiple scheduling policies

HCBS

✓ **Spatial isolation**
Achieved via processes, cgroups, and namespaces

✓ **Temporal isolation**
Hierarchical Scheduling including BW enforcement

✗ **Scheduler for heterogeneous workloads**
Supports only RT tasks in containers

3.2. Objective: Hierarchical Multi-Policy Scheduling

Problem Summary

Native Linux supports **multi-policy** scheduling but **lacks temporal isolation** guarantees. **HCBS** provides **hierarchical scheduling** with **bandwidth enforcement** but restricts scheduling to **real-time** tasks **only**.

Objective

Extend hierarchical scheduling to support all Linux scheduling class (RT, DEADLINE, FAIR) within containers while **preserving**:

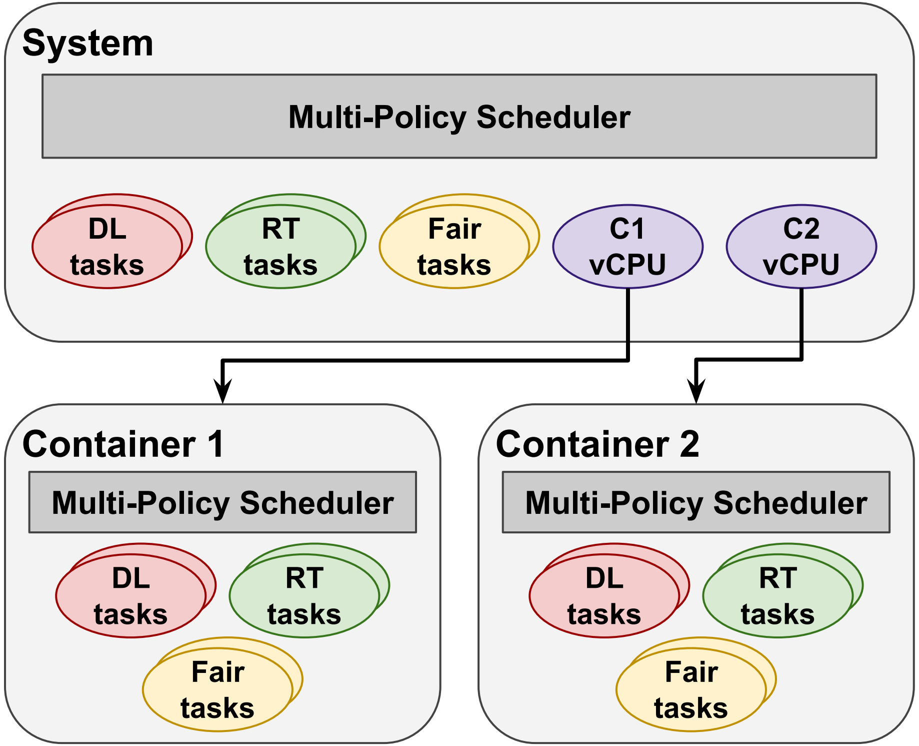
- **Temporal isolation** via bandwidth enforcement
- **Multi-policy flexibility** for heterogeneous workloads

4. Contribution

4.1. TGBS: Task Group Bandwidth Server

Overview

- TGBS **enforces** container-level **temporal isolation** while **preserving multiple** scheduling **policy** within each container
- The core idea behind TGBS is to:
  - **Recreate scheduling** at the container level by **virtualizing CPUs**.
  - **Guarantee temporal isolation** between virtual CPUs.



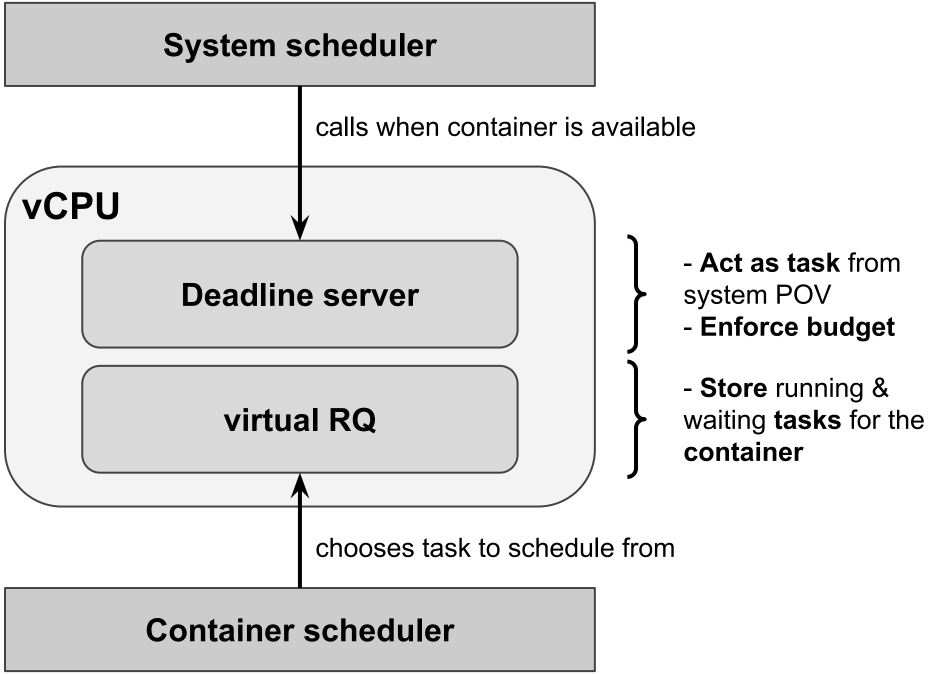
Limitation

This work assumes a **SINGLE-CORE** environment. Multi-core scheduling is not yet supported and remains a direction for future research.

TGBS : https://github.com/mkooshmanian/TGBS

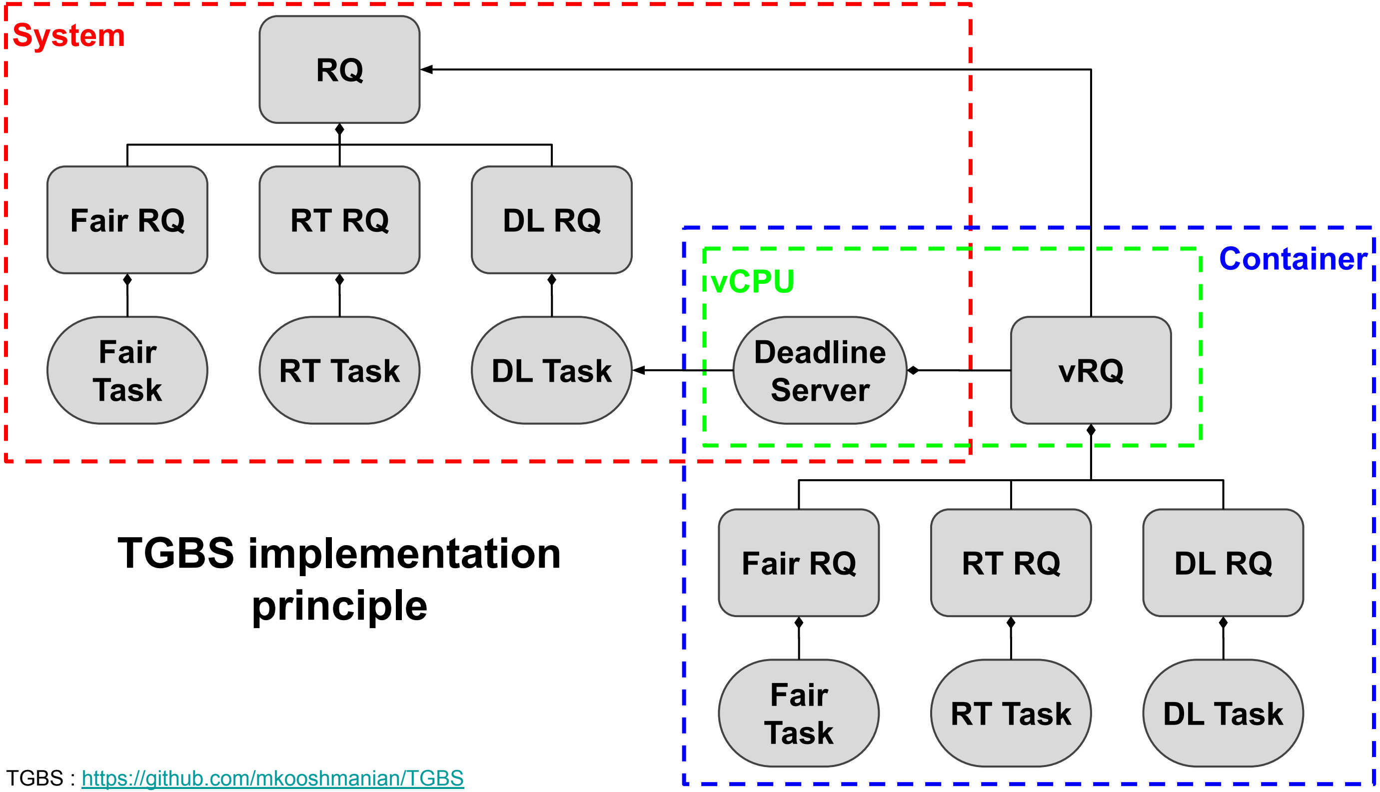
4.2. TGBS: CPU Virtualisation

- Rely on **deadline server** and **virtual runqueue**
- ***deadline server***
  - is a system **scheduling entity**
  - **schedule** by the **Constant Bandwidth Server** (CBS) : BW enforcement
  - designed to **serve** other **tasks**
- ***virtual runqueue***
  - **lightweight** version of a real **runqueue**



TGBS : https://github.com/mkooshmanian/TGBS

4.3. TGBS: Implementation Details

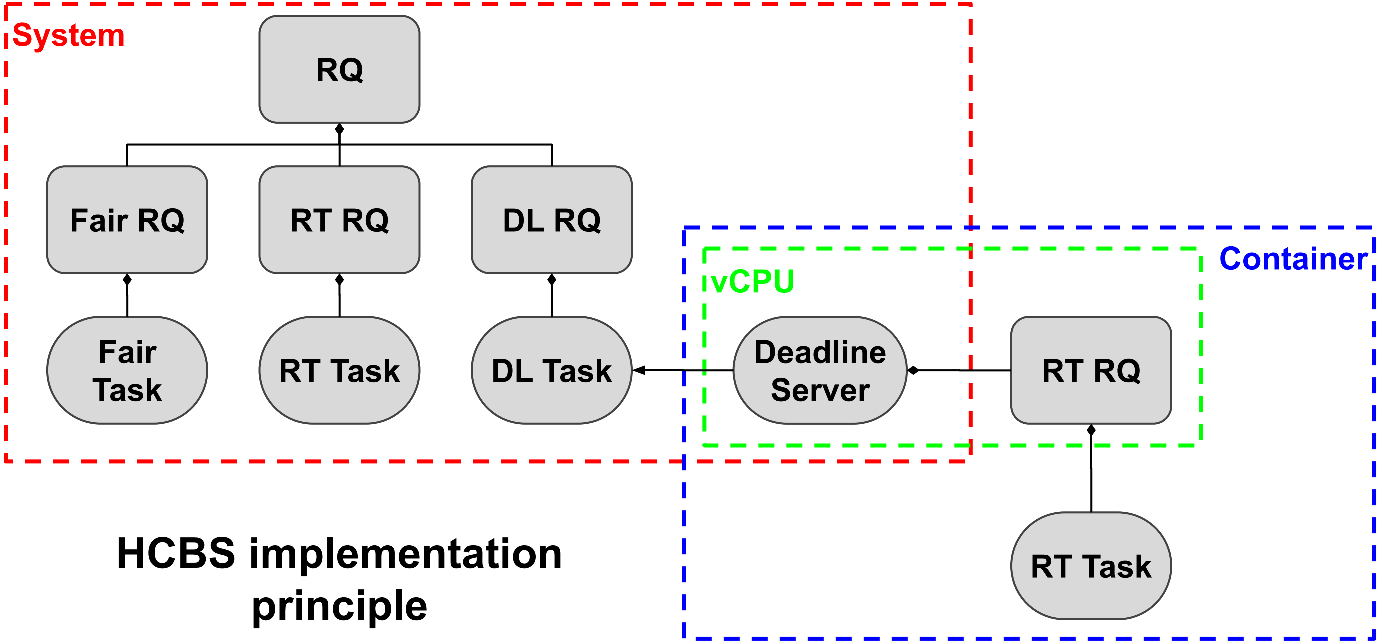


TGBS implementation principle

- TGBS **mirrors** Linux's **native scheduling structure** within containers.
- **Virtual runqueues replicate class-specific queuing** methods for all scheduling policies.

TGBS : https://github.com/mkooshmanian/TGBS

4.4. HCBS: Implementation Details (comparison)



HCBS implementation principle

- HCBS attaches **only** an **RT runqueue**, restricting it to real-time tasks.
- This **limits** HCBS to **mono-policy** scheduling.

HCBS (updated): https://github.com/Yurand2000/HCBS-patch/tree/rt-cgroups

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5. Experimental Evaluation

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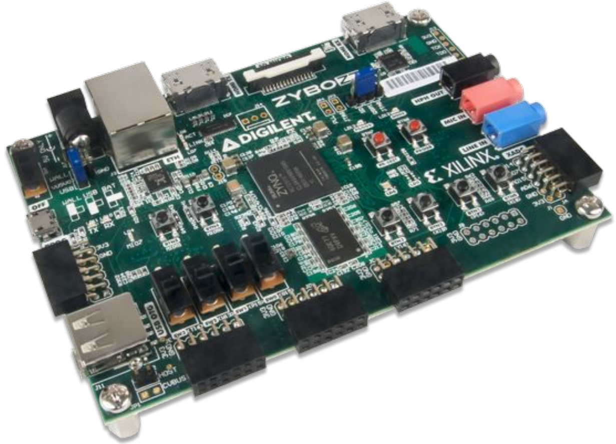
5.1. Objective and Setup

Objective

- **Evaluate TGBS** patch
  - Assess functional correctness and real-time performance
  - Compare with Vanilla Linux and HCBS

Setup

- **Zybo Z7** development board
  - Dual-core ARM Cortex-A9 (666 MHz) → **disabled 1 CPU**
  - 1 GB DDR3 memory
- Linux kernel **v6.17** configured with **PREEMPT-RT** extension
- **TGBS** patch applied for hierarchical and multi-policy scheduling



Zybo Z7 development board (Source: Digilent)

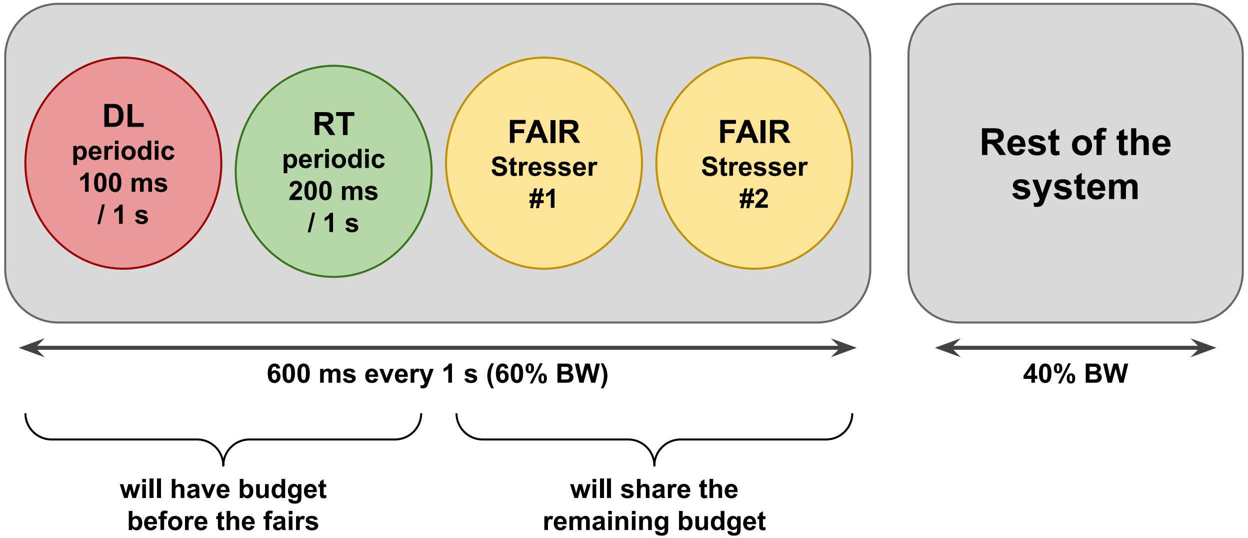
5.2. Functional Validation - Objectives

Objective

- Verify **correct prioritization** between **policies**
- **Ensure budget** enforcement is working properly

Setup

- 1 container with 4 threads
- 1 thread / policy → check multi-policy
- Stresser → check budget enforcement



Expected results

- **Prioritization**
  DL > RT > Fair
- **Budget enforcement**
  $U_{tot} \approx 60\%$
- **Fairness**
  U(stress#1)≈ U(stress#2)

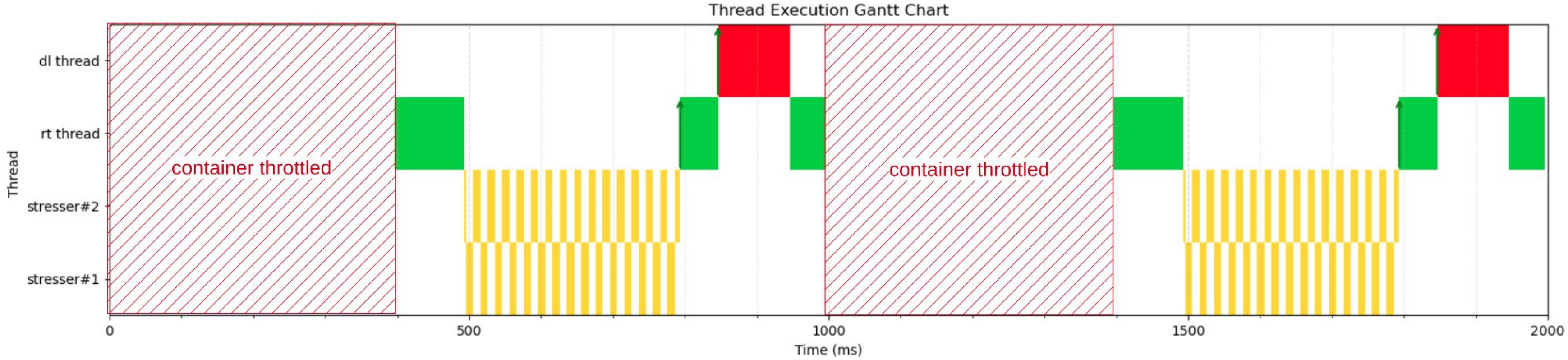
5.3. Functional Validation - Results

Results

- Measured **CPU shares** match **expected proportions**
- **Correct** enforcement of **container reservation**
- **Preemption** between different **policies** is **respected**

CPU usage under a 600 ms / 1 s container reservation.

Task	Policy	CPU share
DL task (100ms / 1s)	DEADLINE	≈ 10%
RT task (200ms / 1s)	FIFO	≈ 20%
FAIR task (stresser #1)	OTHER	≈ 15%
FAIR task (stresser #2)	OTHER	≈ 15%



5.4. Overhead Evaluation - Objectives

Objective

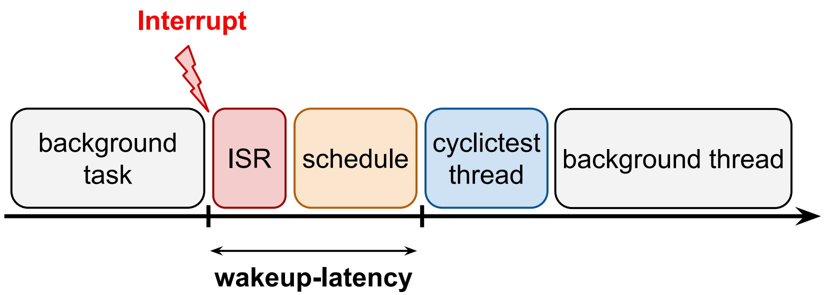
- Measure TGBS **scheduling overhead**
- **Compare** TGBS with **Vanilla** Linux and **HCBS**

Methodology

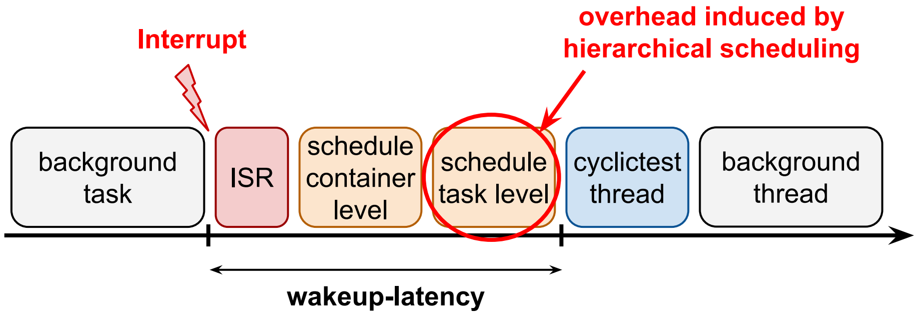
- Use **cyclictest** (rt-tests library) : evaluate **wake-up latency** (IRQ trigger to CPU execution)
- Run inside container for HCBS and TGBS

Expectations

Vanilla Linux



TGBS or HCBS Linux



5.5. Overhead Evaluation - Results

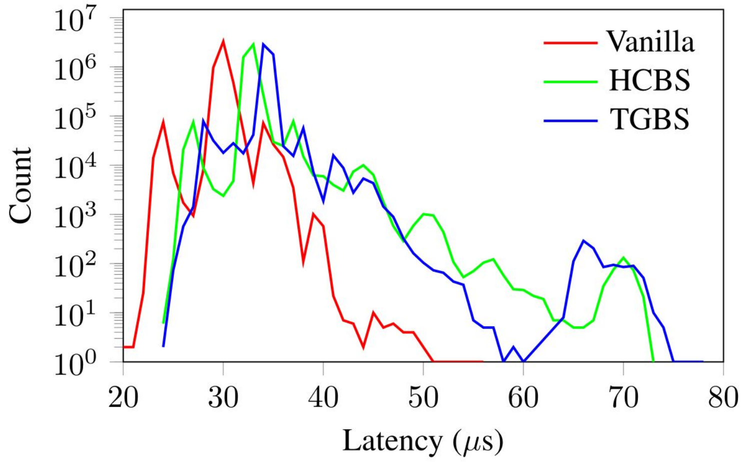
Results

- Avg latency: 30 µs (Vanilla) → 34 µs (TGBS) ≈ +15%
- Max latency: 56 µs (Vanilla) → 78 µs (TGBS) ≈ +40%
- **TGBS** overhead **comparable** to **HCBS**
- **No pathological behavior** observed

Cyclictest Latency Statistics (µs)

System	Min	Avg	Max	Std Dev
Vanilla	20	30	56	1.3
HCBS	24	33	73	1.7
TGBS	24	34	78	1.5

Cyclictest Latency Distribution



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6. Conclusion

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6. Conclusion and Future Work

Summary

- Demonstrated the **necessity** for **multi-policy** and **hierarchical scheduling** in future spacecraft flight software
- **Developed** and **tested** a Linux **kernel patch** (**TGBS**) to provide **temporal isolation** for **heterogeneous workloads**

Future Work

- **Address** the **current gap** in literature regarding multi-policy and hierarchical models
- Develop a **formal model** of **TGBS** to prove its **correctness** and **timing guarantees**
- **Extend** TGBS to support **multicore** architectures

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Thanks for listening !
Any questions ?

TGBS patch GitHub link

contact : merlin.kooshmanian@onera.fr

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Appendix

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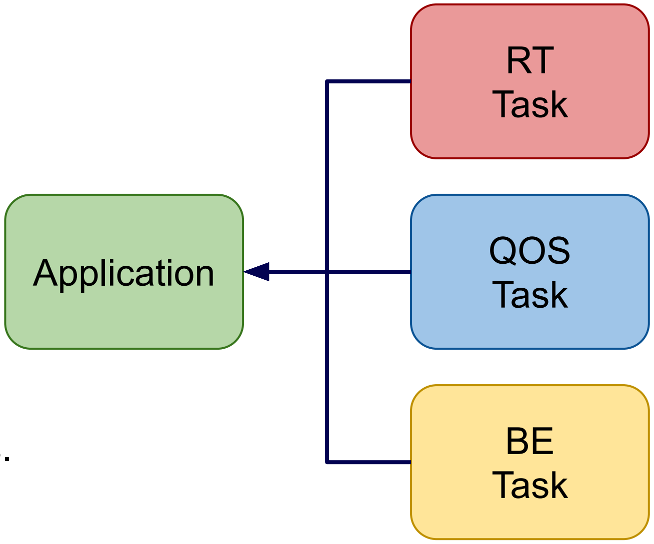
A. Task Classes

Diverse Operational Requirements

- **Heterogeneous** timing, reliability, and **operational demands** across space system functions
  - Predictability (critical control tasks)
  - Responsiveness (event driven tasks)
  - Fair sharing (variable workloads tasks)
  - Opportunistic execution (background tasks)

Task Types

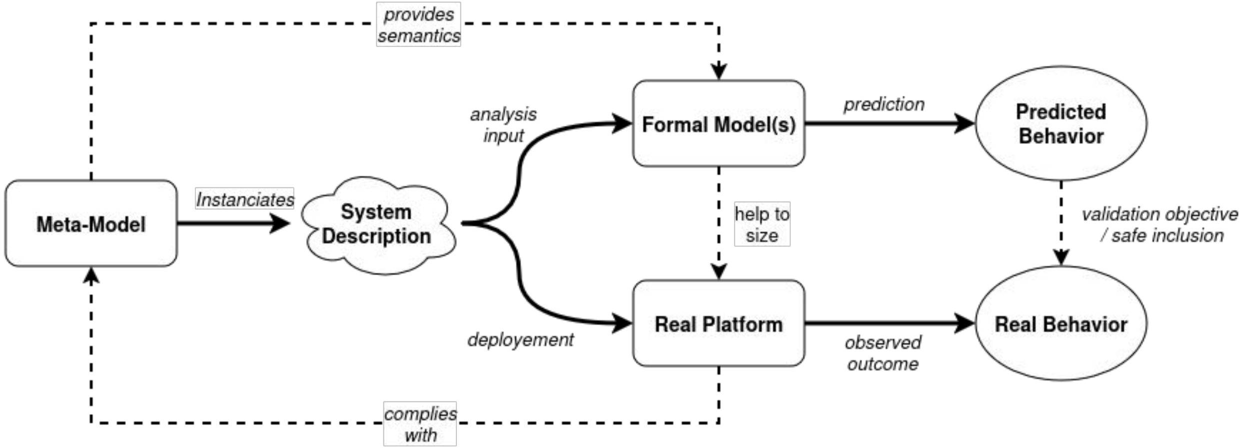
- **Real-Time (RT):** Hard deadlines, zero tolerance for delays.
- **Best-Effort (BE):** no needs, runs when possible
- **Quality-of-Service (QoS):** Predictable progress, flexible timing.



B. Methodology Overview

Structured Process

- **Links** conceptual **scheduling** systems to real platform **execution**
- **Ensures coherence** from **concept** definition to **implementation**



Core Elements

- **Meta-model / System Description**
  Defines and instantiates concepts
- **Real Platform**
  Executes the system description, yielding observed behavior

- **Formal Models :**
  - Provide conservative predictions for schedulability analysis
  - Provide real platform sizing methods

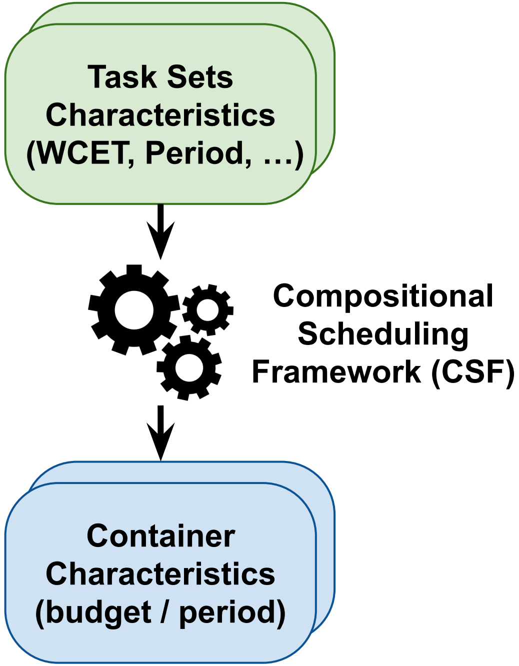
C. Container Sizing – CSF

Problem

- Need to **ensure** hard (RT) and soft (QoS) task **timing constraints** within container
- Guarantee **container schedulability** in **all situations** (migration, appearance, disappearance)

Solution - Compositional Scheduling Framework

- Designed for hierarchical systems; **compositional**, ensuring container **schedulability independently**
- Based on **demand /supply mechanism**
- But **pessimistic** and assumes **mono-political scheduling** (each component has a mono-policy scheduler)



D. Validation of the Container Sizing

Objective

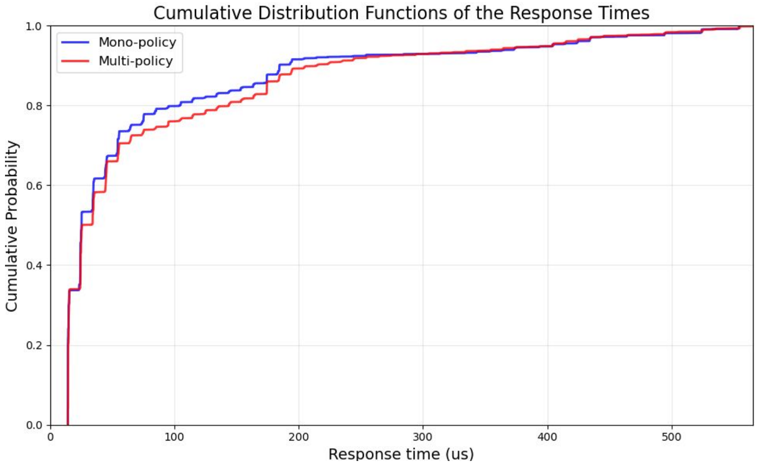
- **Validate** end-to-end **methodology**.
- Ensure **correct execution** under **TGBS**

Methodology

- **Synthetic workload** of **10 periodic tasks**, total utilization 50% ± 5%
- Tasks distributed across **two containers** (A and B) sized with **CSF** assuming mono-policy.
- **Mix** of **RT** tasks (SCHED_FIFO, RM priorities) and **QoS** tasks (SCHED_OTHER)

Results

- **No** deadline **misses** observed
- Analytically sized **reservations sufficient**
- **Correct execution** under both mono-policy and multi-policy configurations



Note : Mono-policy demonstrates slightly better response times than multi-policy, as expected since mono-policy prioritizes only system responsiveness, whereas multi-policy focuses also on fairness.