# Implementation and Evaluation of the Synchronization Protocol Immediate Priority Ceiling in PREEMPT-RT Linux

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# Introduction

- In real-time operating systems,
  task synchronization mechanisms:
  - Provide internal consistency of resources and data structures
  - Provide determinism of waiting time
  - Avoid unbounded priority inversions

- In mainline Linux priority inversions occur frequently

- Patch PREEMP-RT uses Priority Inheritance
  - for priority inversion control

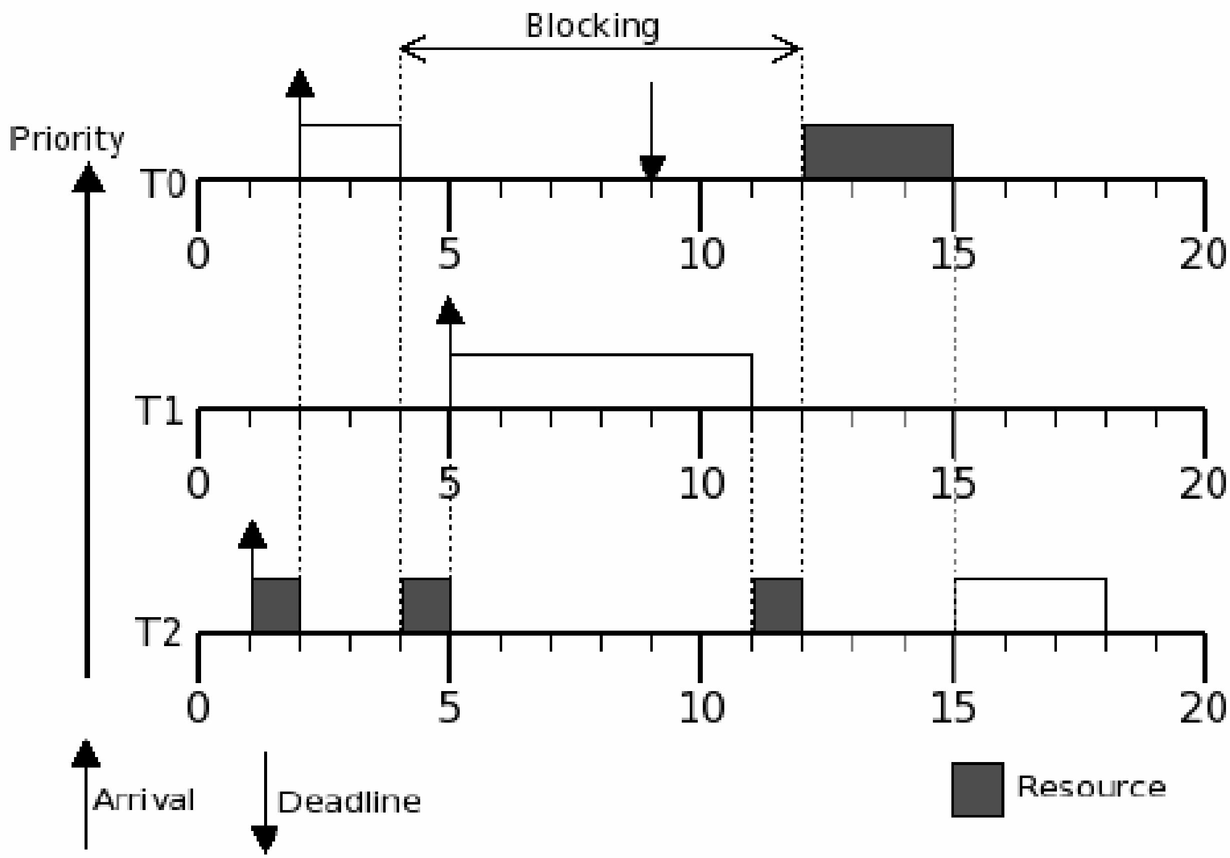
# Objective

- The objective of this paper is
  the implementation of an alternative protocol,
  the Immediate Priority Ceiling (IPC)

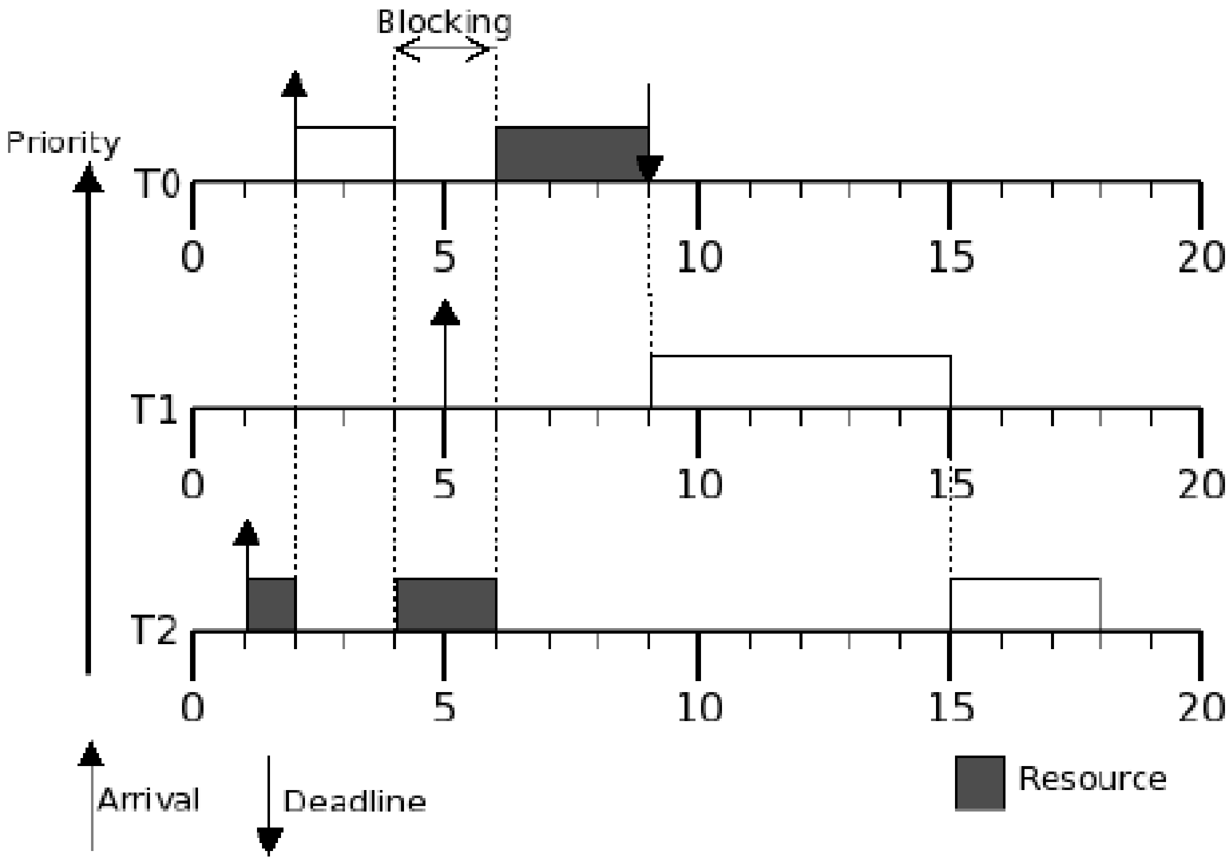
- We intend to use it in dedicated, real-time device-drivers
- For example:
  - an embedded Linux supports an specific known application
  - that does not change task priorities after its initialization

- It is not the objective of this paper
  to propose a complete replacement of the existing protocol
  - but an alternative for use in some situations
- This work considers only single processors

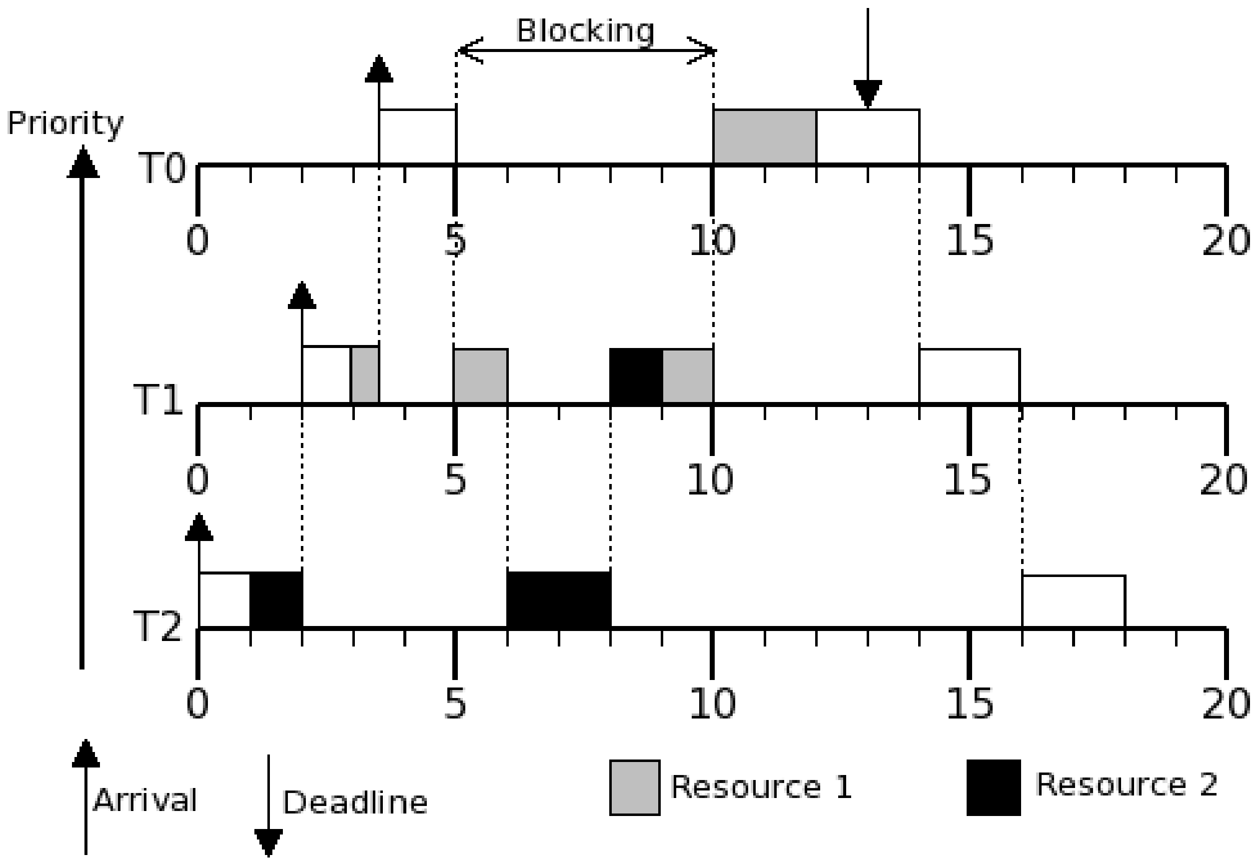
# --Unbounded Priority Inversion



# --Priority Inheritance Protocol 1/2



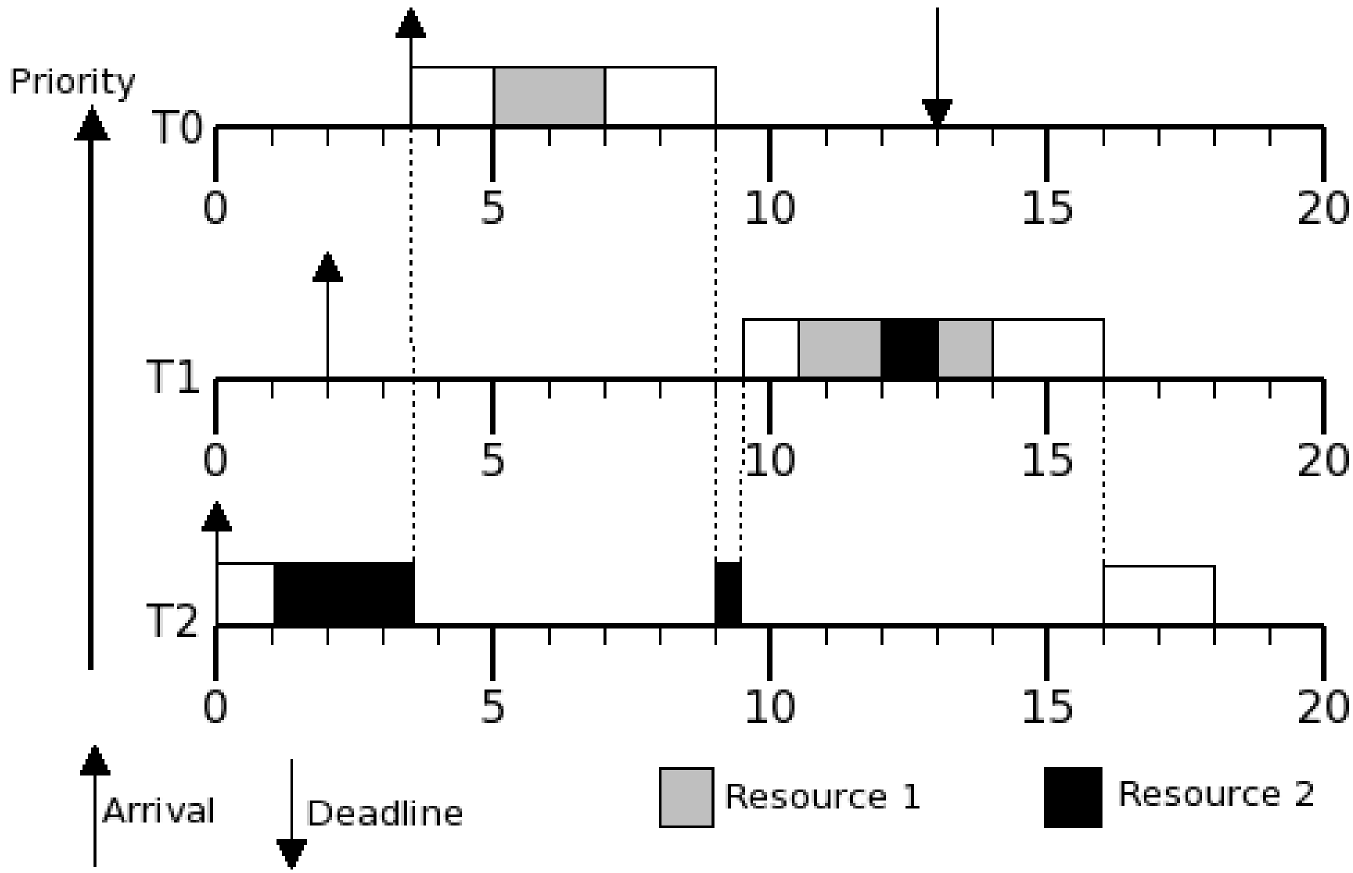
# Priority Inheritance Protocol 2/2



# Immediate Priority Ceiling

- It is a variation of Priority Ceiling Protocol
  - Highest Locker Priority
- Every resource has a priority ceiling
  - The highest priority of all task that access this resource
- The priority is adjusted immediately when occurs a resource acquisition
  - and not when the resource becomes necessary to a higher priority tasks
- Maximum blocking time of Ti under fixed priority:
  - The larger critical section of the system
    whose priority ceiling is higher than the priority of task Ti
    and is also used by a lower priority task

# Immediate Priority Ceiling




- Ceiling of R1 = T0 Ceiling of R2 = T1

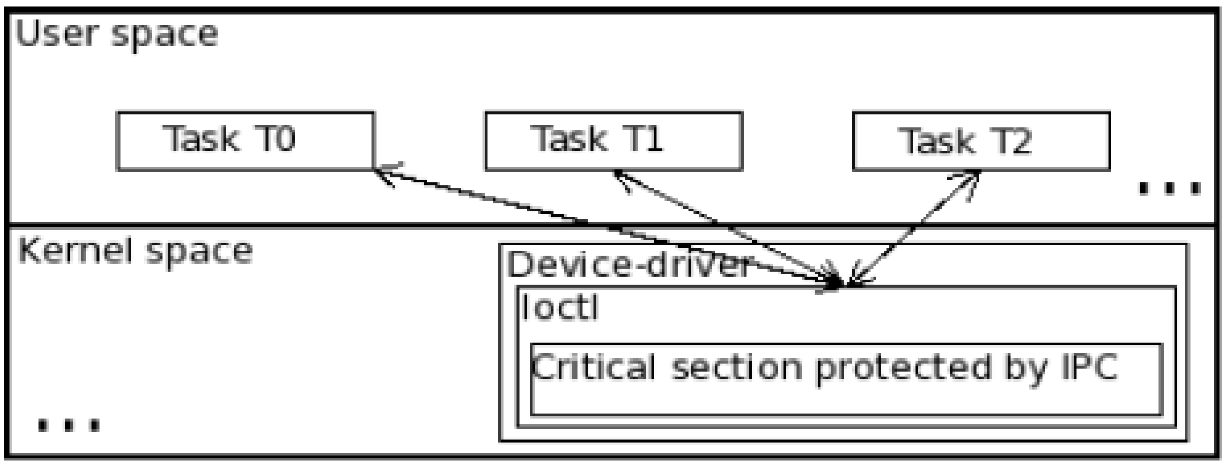
# Description of the Implementation

- The Immediate Priority Ceiling Protocol was implemented
- Based on the code of rt_mutexes already in the patch PREEMPT-RT
- The rt_mutexes implement the Priority Inheritance protocol
- Kernel version used was the 2.6.31.6 [10]
  with PREEMPT-RT patch rt19

- rt_mutexes are implemented in PREEMPT-RT also for multiprocessors
- Our implementation considers only single processors

## --Description of the Implementation

- Implementation was made for use in device-drivers (kernel space)
- For example, tasks share a critical section accessed through an ioctl() system call to a device-driver



# Description of the Implementation: Data Structure

- The type that implements the Immediate Priority Ceiling protocol is defined as struct ipc_mutex

```
struct ipc_mutex {
  atomic_spinlock_t wait_lock;
  struct plist_head wait_list;
  struct plist_node on_task_entry;
  struct task_struct *owner;
  int ceiling;
  ... // other rt_mutex fields
};
```

## Description of the Implementation: Data Structure

- The type that implements the Immediate Priority Ceiling protocol is defined as struct ipc_mutex

- `wait_lock` is the spin-lock that protects the access to the structure
- `wait_list` is an ordered (by priorities) list that stores pending lock requests
- `on_task_entry` serves to manage the locks acquired by a task
  - and, consequently, control its effective priority
- `owner` stores a pointer to the task owner of the mutex
  - or null pointer if the mutex is available
- `ceiling` stores the priority ceiling of the mutex

# Description of the Implementation: Operations

- **DEFINE_IPC_MUTEX( mutexname, priority)**

- Defines an Immediate Priority Ceiling mutex
- mutexname is the identifier of the mutex
- priority is the ceiling of the mutex

- The current version can only create mutexes with priorities set at compile time
- It is somewhat restrictive
- It is acceptable when an embedded Linux runs a known application that does not change task priorities after its initialization

# Description of the Implementation: Operations

- **void ipc_mutex_lock( struct ipc_mutex * lock)**

- Lock operation
- In single-processor computers this is a non-blocking function
- If a task requests a resource, it is because this resource is available

- It manages the priority of the calling task along with the resource blocking, taking into account all ipc_mutexes acquired so far

# Description of the Implementation: Operations

- **void ipc_mutex_unlock( struct ipc _mutex * lock)**

- Unlock operation
- Releases the resource and adjusts the priority of the calling task

# Test Scenario

- We developed a device-driver that provides critical sections to perform the tests
- This device-driver exports a single service: unlocked_ioctl
- It multiplexes the calls of three tasks in their correspondent critical sections
- This device-driver provides critical sections to run with both
  - Immediate Priority Ceiling
  - Priority Inheritance

# Test Scenario

- A set of sporadic tasks executes in user space
- All critical sections are executed within the device-driver
- Measurement of 1000 activations of T0
- Task set configuration:

| **Task** | **T0/High** | **T1/Med.** | **T2/Low** |
|---|---|---|---|
| **Priority** | 70 | 65 | 60 |
| **Activation interval** | rand in [400,800] ms | rand in [95,190] ms | rand in [85,170] ms |
| **Resource** | R1 | R1,R2 | R2 |
| **Critical section size** | aprox. 17 ms | aprox. 2x17 ms | aprox. 17 ms |

| **Task** | **T0/High** | **T1/Med.** | **T2/Low** |
|---|---|---|---|
| **Action 1** | Lock(R1) | Lock(R1) | Lock(R2) |
| **Action 2** | Critical Sec. | Critical Sec. | Critical Sec. |
| **Action 3** | Unlock(R1) | Lock(R2) | Unlock(R2) |
| **Action 4** | | Critical Sec. | |
| **Action 5** | | Unlock(R2) | |
| **Action 6** | | Unlock(R1) | |

# Test Scenario

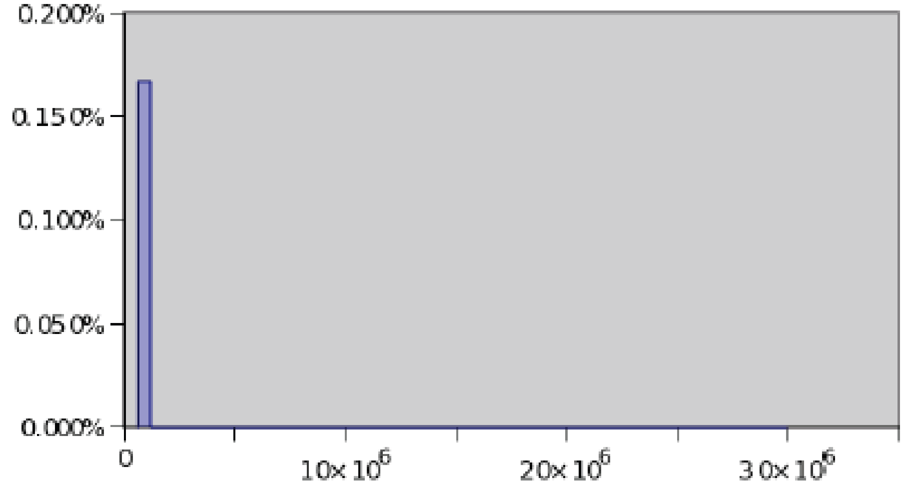
- All tasks were set at only one CPU
- Priority ceiling of mutex R1 is 70 (priority of task T0)
- Priority ceiling of mutex R2 is 65 (priority of task T1)

| **Task** | **T0/High** | **T1/Med.** | **T2/Low** |
|---|---|---|---|
| **Priority** | 70 | 65 | 60 |
| **Activation interval** | rand in [400,800] ms | rand in [95,190] ms | rand in [85,170] ms |
| **Resource** | R1 | R1,R2 | R2 |
| **Critical section size** | aprox. 17 ms | aprox. 2x17 ms | aprox. 17 ms |

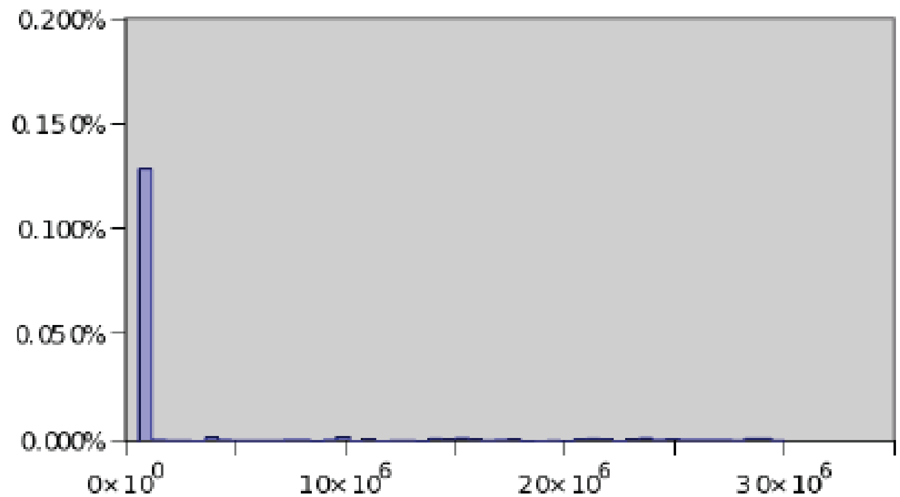
| **Task** | **T0/High** | **T1/Med.** | **T2/Low** |
|---|---|---|---|
| **Action 1** | Lock(R1) | Lock(R1) | Lock(R2) |
| **Action 2** | Critical Sec. | Critical Sec. | Critical Sec. |
| **Action 3** | Unlock(R1) | Lock(R2) | Unlock(R2) |
| **Action 4** | | Critical Sec. | |
| **Action 5** | | Unlock(R2) | |
| **Action 6** | | Unlock(R1) | |

# Test Results: Activation Latency Histogram of T0

- Time between entering the ready queue and actually running
- Priority Inheritance

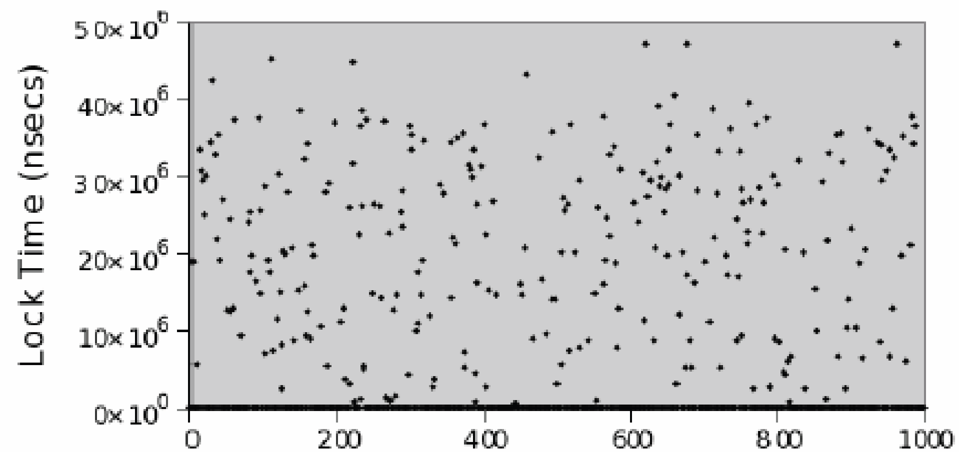



- Immediate Priority Ceiling
  - Task waits at the activation

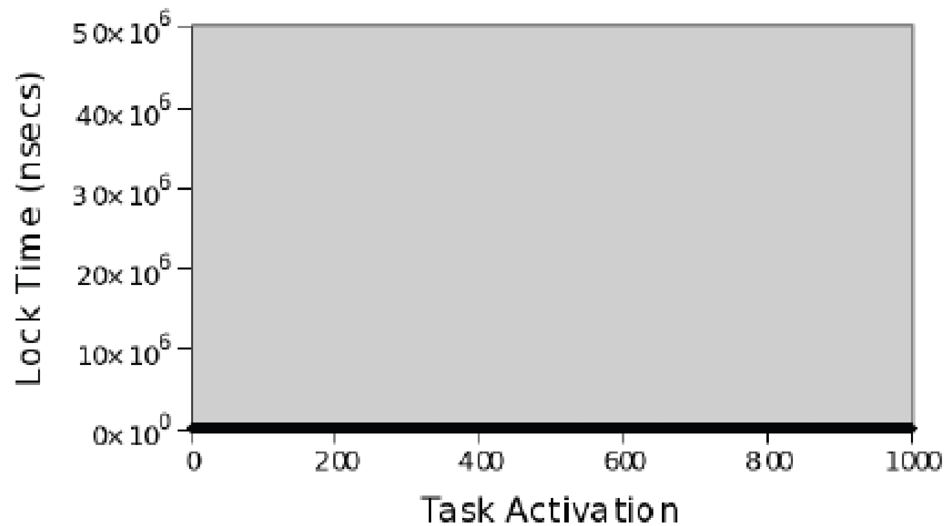


# Test Results: Locking Time of T0

- Time waiting at the lock operation
- Priority Inheritance
  - Task waits at the lock

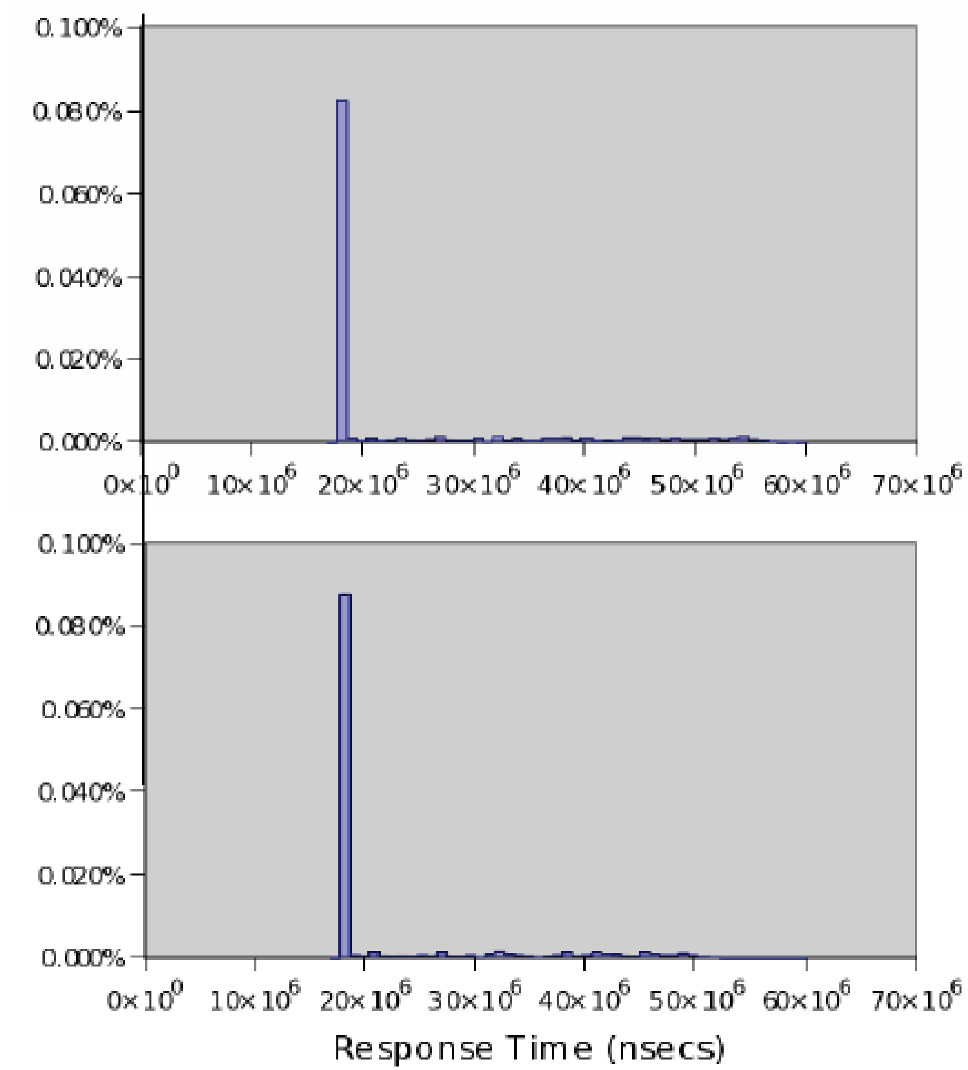



- Immediate Priority Ceiling



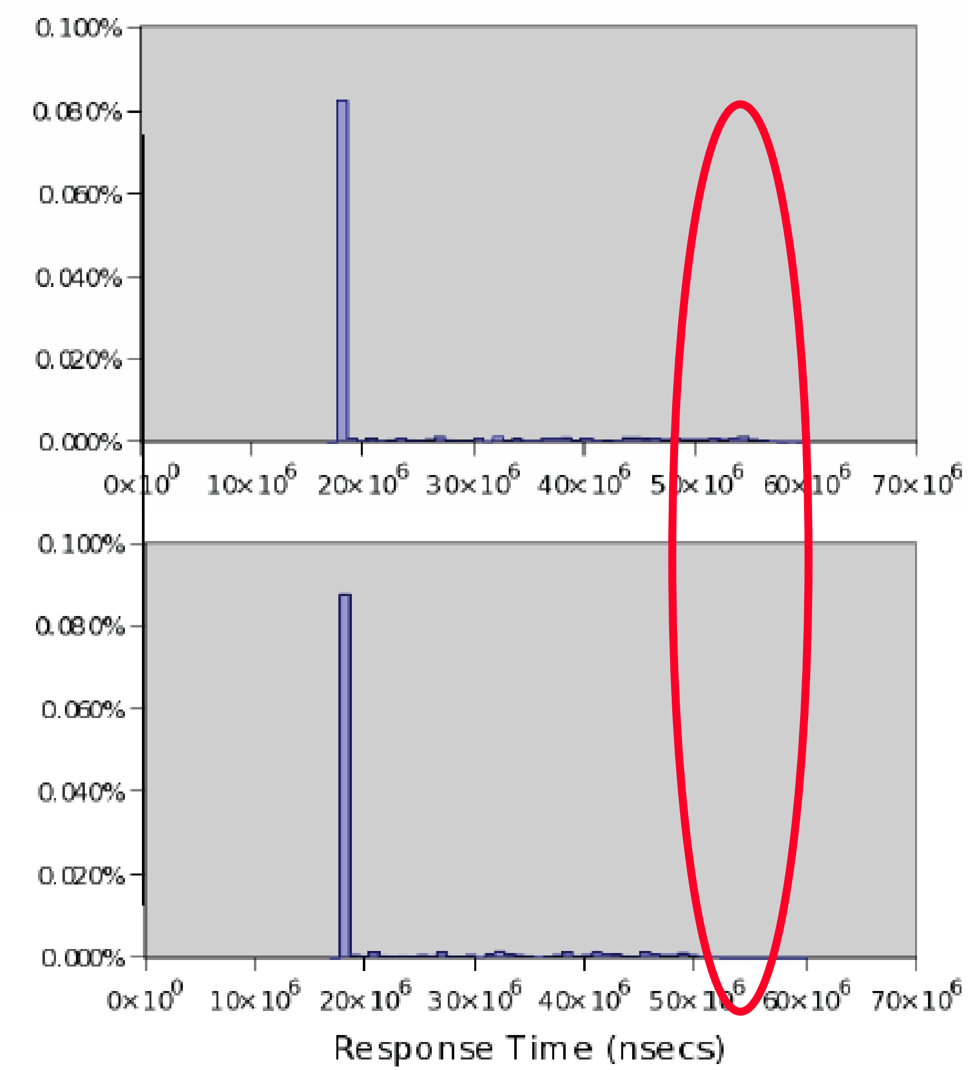
# Test Results: Response Time of T0

- Priority Inheritance
- Immediate Priority Ceiling



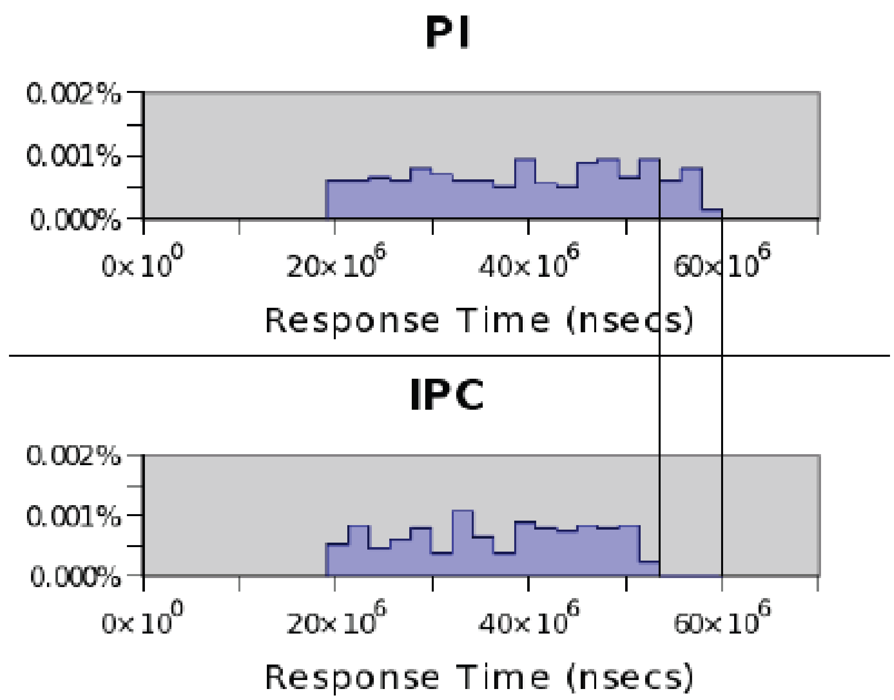
# Test Results: Response Time of T0

- Priority Inheritance
- Immediate Priority Ceiling



# Test Results: Response Time of T0

- Priority Inheritance
- Immediate Priority Ceiling



# Test Results: Comments

- Immediate Priority Ceiling is in general similar to Priority Inheritance

- Immediate Priority Ceiling
  - Better average response time for T0
  - Worst-case response time is almost one critical section smaller
  - The length of a critical section is 17 ms, the difference between then is 14 ms

| Protocol: | PI | IPC |
|---|---|---|
| Average response time: | 22,798,549 ns | 21,014,311 ns |
| Std dev: | 11,319,355 ns | 8,723,159 ns |
| Max: | 64,157,591 ns | 50,811,328 ns |

# Test Results: Overhead

- Overhead = Decreasing of CPU time available to the rest of the system, given the presence of a set of higher priority tasks sharing resources protected
- Test used a set of tasks that access the device-driver (mutexes)
- Measuring task has lowest priority (priority 51)
  - Lower priority than tasks that access the mutexes inside the device-driver
  - Higher priority than threaded irq handlers and softirqs
- All tasks fixed to a single CPU

# Test Results: Overhead

- Any CPU time that is not used by tasks accessing the device-driver
  - is assigned to the measurement task
- The measurement task implements a loop
  - that just increments a variable

- The overhead will be noticed by how much the measurement task could increment a count
  - When Pririty Inheritance is used
  - When Immediate Priority Ceiling is used

# Test Results: Overhead

- The collected data indicate that there is a difference between the counts when the other tasks use
  - Mutexes with Priority Inheritance
  - Mutexes with Immediate Priority Ceiling
- The counting task (lowest priority) receives more processor time when Priority Inheritance mutexes are used
- The implementation of Priority Inheritance mutexes is more efficient
- Likely due to the fast path used
  - Our implementation of Immediate Priority Ceiling does not use a fast path

| **Protocol** | **IPC** | **PI** |
|---|---|---|
| Average($\mu$) | 189,136,685.72 | 189,682,847.91 |
| Var.($S_x^2$) | 524,003,070,588.27 | 191,603,683,258.35 |
| Minimum | 187,882,717 | 188,776,389 |
| Maximum | 190,338,011 | 190,539,875 |

## Summary

- We implemented the Immediate Priority Ceiling protocol in Linux with patch PREEMPT-RT
- This protocol is suitable for dedicated applications on single processors
- Offers smaller maximum response time for high priority tasks
  - Maximum blocking time is always at most one critical section
- Requires manual determination of the priority ceiling of each mutex
  - Feasible for small/static control applications
  - Dedicated device-drivers accessed by some well known tasks
- Overhead is higher than traditional Priority Inheritance
  - Fast path implementation is on the way
- It is possible to implement a version with adaptive ceiling
  - Priority ceiling is detected automatically in run-time for each mutex

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