Segment-Fixed Priority Scheduling for Self-Suspending Real-Time Tasks

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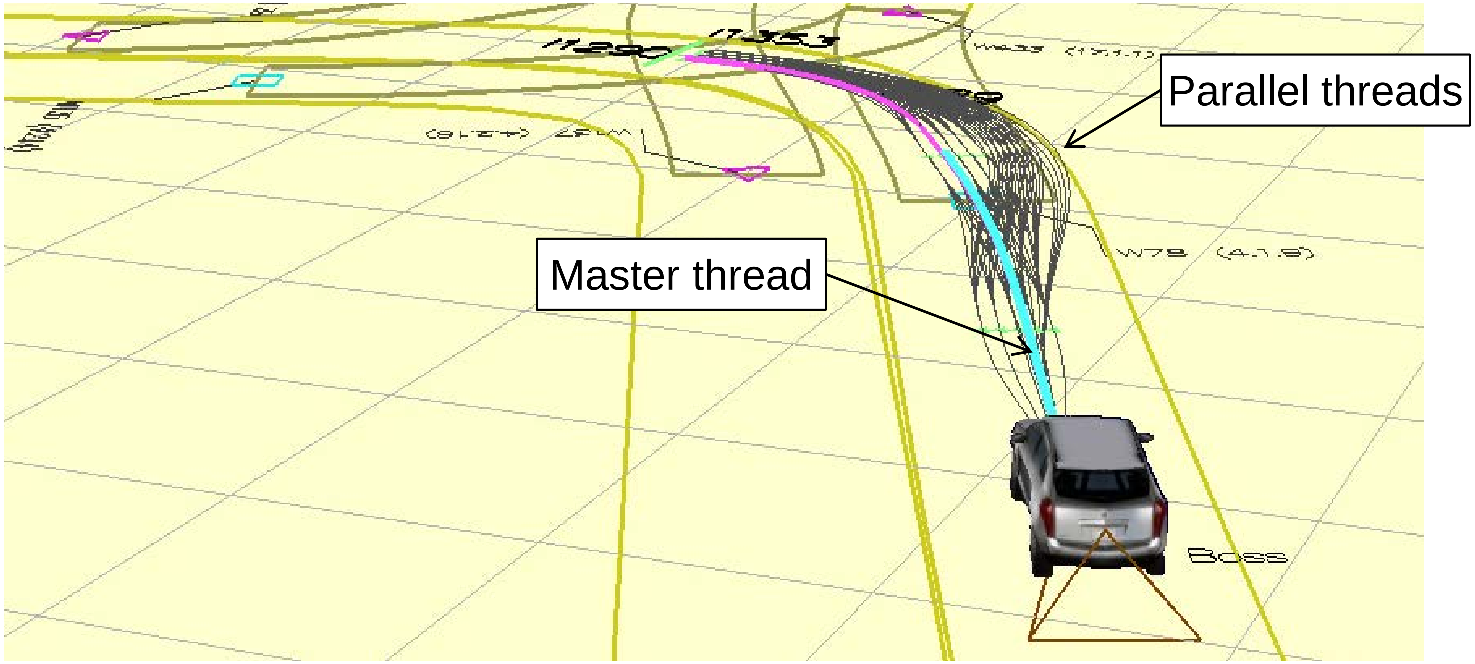
Motion Planning on Self-driving



- A motion planning algorithm outputs the best path using
  - *Parallel* threads that calculate the cost of each *possible* path
  - *Master* thread that picks up the *best* path
- *Parallelism* is essential for the motion-planning algorithm to meet its deadline

Motion Planning with Parallelism

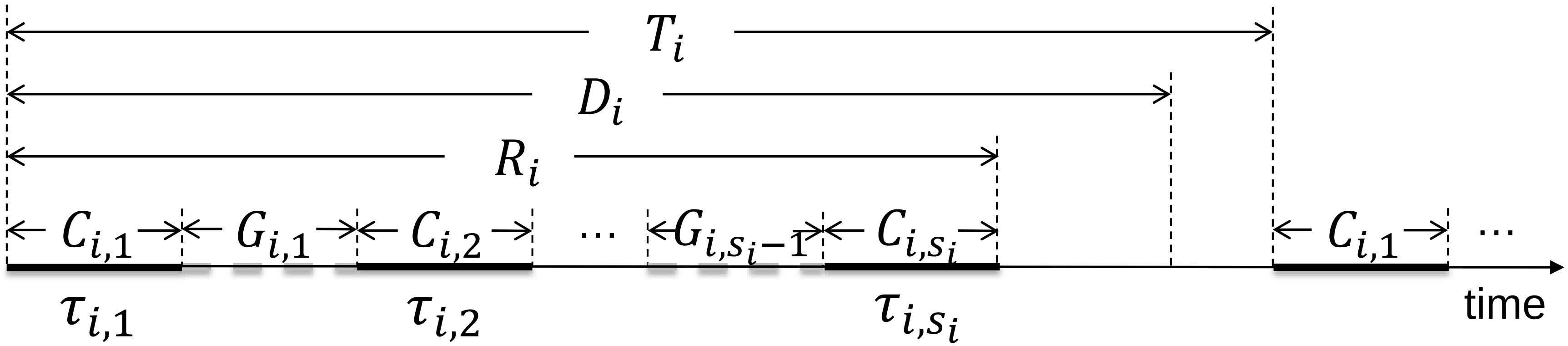
- **Multi-core Processor**
  - A quad-core Intel processor was used.
    - We proposed a scheduling algorithm for this at ICCPS 2013.
  - Some challenging cases are still present.
    - When a difficult maneuver is necessary (e.g. parking lot)
    - When there are just too many obstacles on our path
- **Many-core Processor**
  - Server-class processors are not an option due to space, heating and cost constraints.
  - Using a GP-GPU is a good option.
    - Task executes on CPU, suspends, executes on GPU, and then resumes execution on CPU → **self-suspension**

How to deal with tasks that self-suspend?

Our Goals

- **Dealing with tasks that self-suspend**
  → Does not satisfy the assumptions of RMS
  - Identify cases in which *RMS is still optimal*
  - Find a *utilization bound* if possible
  - Discover a way to schedule self-suspending tasks when RMS is sub-optimal
- **Glimpse of the solution**
  - Assign a priority to each segment of a job
    - Segment: a continuous portion of execution without self-suspension
  - Leverage phase enforcement for each segment

Task Model



- **Model of a self-suspending real-time task**

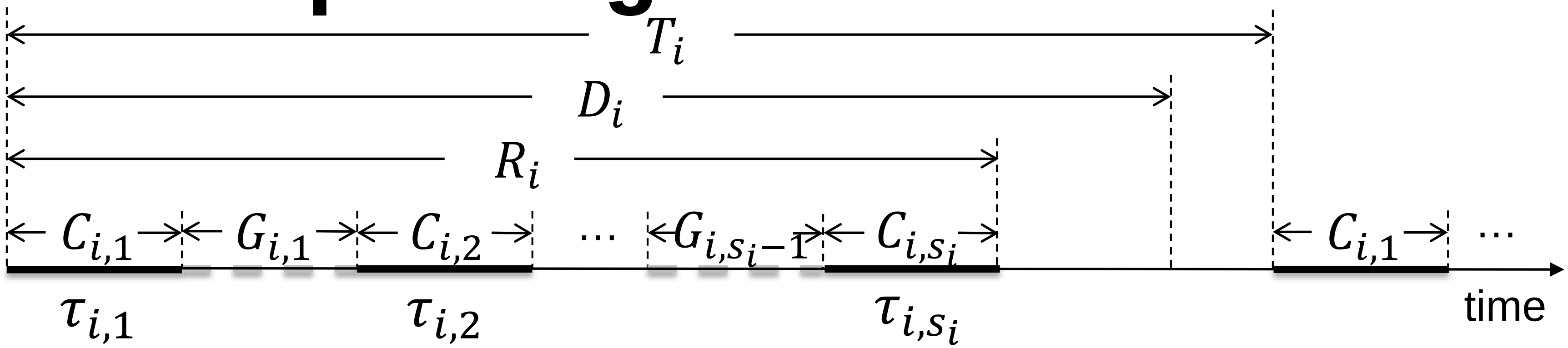
$$\tau_i: \left(\left(C_{i,1}, G_{i,1}, C_{i,2}, \ldots, G_{i,s_i-1}, C_{i,s_i}\right), T_i\right)$$

  - s_i is the **number of task segments** for τ_i.
  - $C_{i,j}$ is the **worst-case execution time for the *j*th execution segment**, and there are s_i execution segments.
  - $G_{i,j}$ is the **worst-case suspension time for the *j*th suspension segment**, and there are $s_i - 1$ suspension segments.
  - T_i is the **period** of τ_i, and an implicit deadline is assumed.

Outline

- Motivation, Goals, and Models
- Task-Fixed Priority Scheduling for Self-Suspending Tasks
- Segment-Fixed Priority Scheduling
- Evaluation
- Conclusion and Future Work

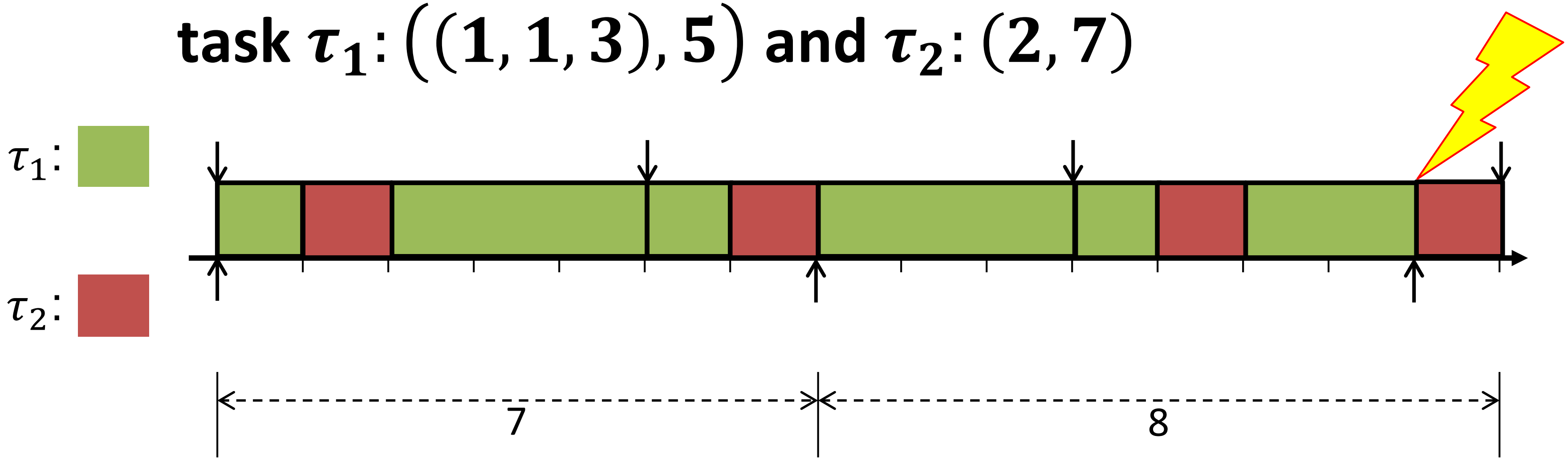
Task-Fixed Priority Scheduling for Self-Suspending Tasks



- **Assumptions**
  - $G_{i,j} = G_{i,j}^{MAX} = G_{i,j}^{MIN}$
  - $\tau_{i,j}$ always runs for $C_{i,j}$.
  - No phase enforcement is used.
- **Glimpse of the results**
  - The conventional critical instant does ***not*** always hold.
  - When it does hold, a utilization bound exists.

Failure of L&L Critical Instant

- **One self-suspending task and one non-suspending task τ_1: $\big((1, 1, 3), 5\big)$ and τ_2: $(2, 7)$**

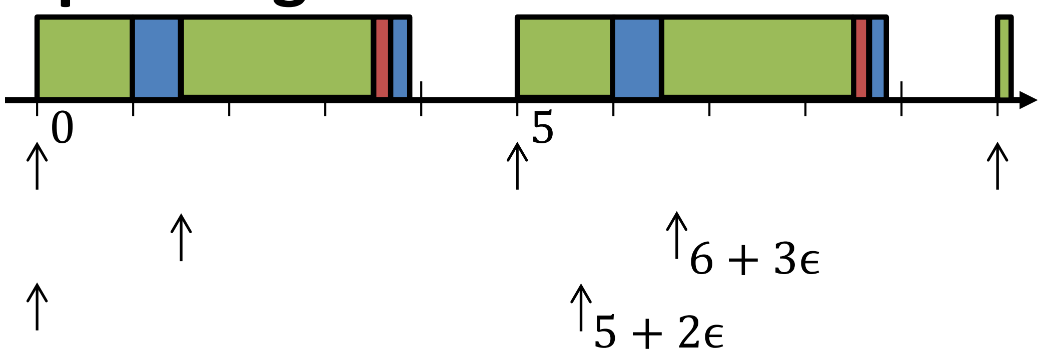


- τ_2 **misses** its deadline at the **second job** release.
- This violates the conventional definition of a critical instant.
- It actually depends on **which segment of τ_1** is released with τ_2.

Critical Instant Failure (cont'd)

- **For a taskset with one self-suspending task τ_1 and one non-suspending task τ_2:**
  - Critical instant candidates arise when τ_2 arrives at the same time as any of the segments of τ_1
    - Pick the worst (paper has the proof)
- **For a taskset with one self-suspending task τ_1 and many non-suspending tasks:**

τ_1: $((1, 2\epsilon, 2), 5)$
τ_2: $(\epsilon, 5+\epsilon)$
τ_3: $(3\epsilon, 5+2\epsilon)$



The critical instant for τ_2 may be different from that of τ_3.

* The paper provides an algorithm to find the critical instant of each task.

When Does RMS Hold Good?

- **For a taskset with one self-suspending task and $n - 1$ non-suspending tasks:**
  - When $R_1 = C_1 + G_1 < C_i \leq T_1 - R_1$, where $i \leq n$
    - Please refer to the paper for the proof.
  - Then, the utilization bound (UB) for this case is given by

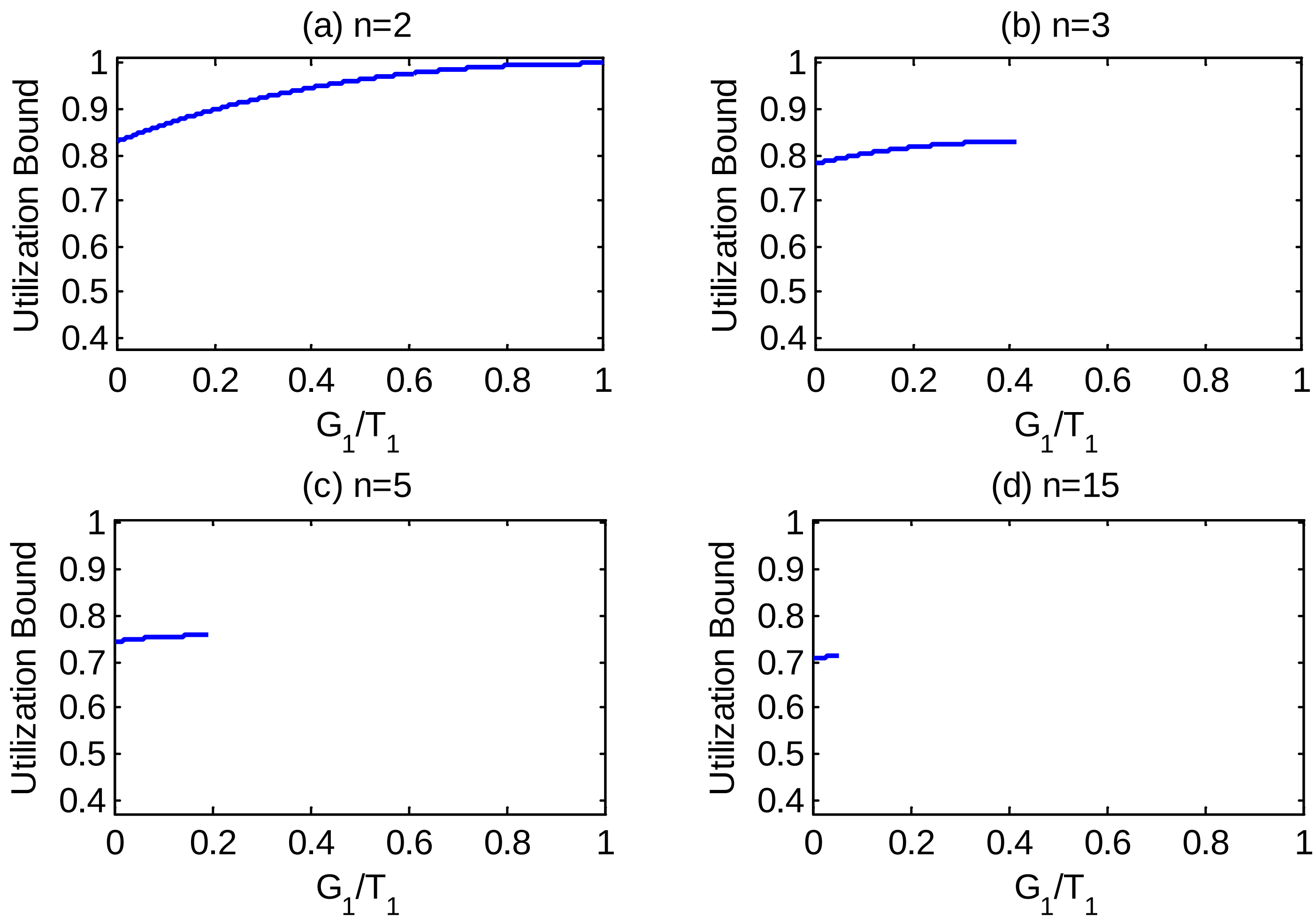
$$U_{RM-SS}(n,k) = n\left((2+2k)^{\frac{1}{n}} - 1\right) - k$$

where, $k = {}^{G_1}/_{T_1}$

- k lies in $\left[0, 2^{\frac{1}{n-1}} - 1\right]$
- When $k = 0$, it simply becomes the Liu and Layland bound.

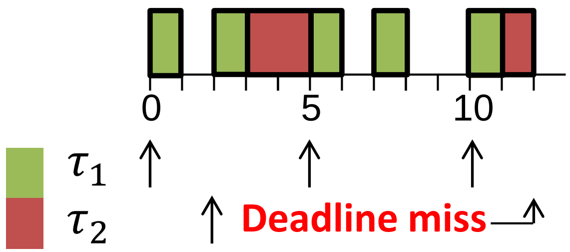
UB with One Self-Suspending Task

- $U_{RM-SS}(n) = n\left((2+2k)^{\frac{1}{n}} - 1\right) - k, 0 \le k \le 2^{\frac{1}{n-1}} - 1$

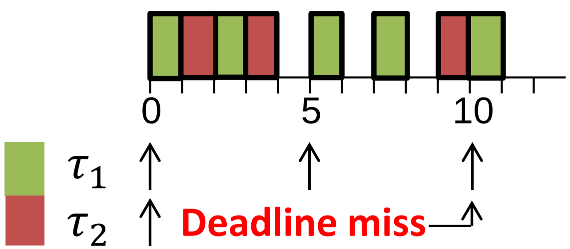


Case of Multiple Self-Suspending Tasks

- **Need to consider all possible release offsets**
- **Consider a set of two tasks scheduled with RMS:**
  - $\tau_1 : \left((1,1,1), 5\right)$
  - $\tau_2 : \left((2,5,2), 10\right)$
  - $\tau_{1,2}$ and $\tau_{2,1}$ arrive together



  - $\tau_{1,1}$ and $\tau_{2,1}$ arrive together



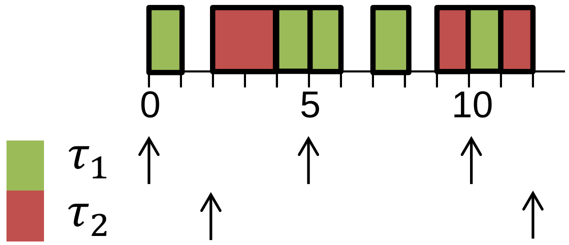
Observation:
There is enough slack, but it is not used well.

Key Idea:
Assign a different priority to each segment.

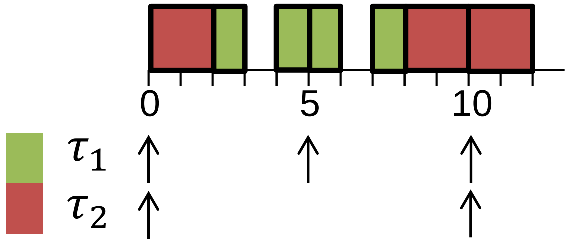
Multiple Self-Suspending Tasks (cont'd)

- **Idea: assign a higher priority to a segment that needs to complete sooner**
- **Consider a set of two tasks:**
  - $\tau_1 : \big((1,1,1), 5\big)$
  - $\tau_2 : \big((2,5,2), 10\big)$
  - New priority assignment: $\tau_{2,1} > \tau_{1,1} > \tau_{1,2} > \tau_{2,2}$

- $\tau_{1,2}$ and $\tau_{2,1}$ arrive together



- $\tau_{1,1}$ and $\tau_{2,1}$ arrive together



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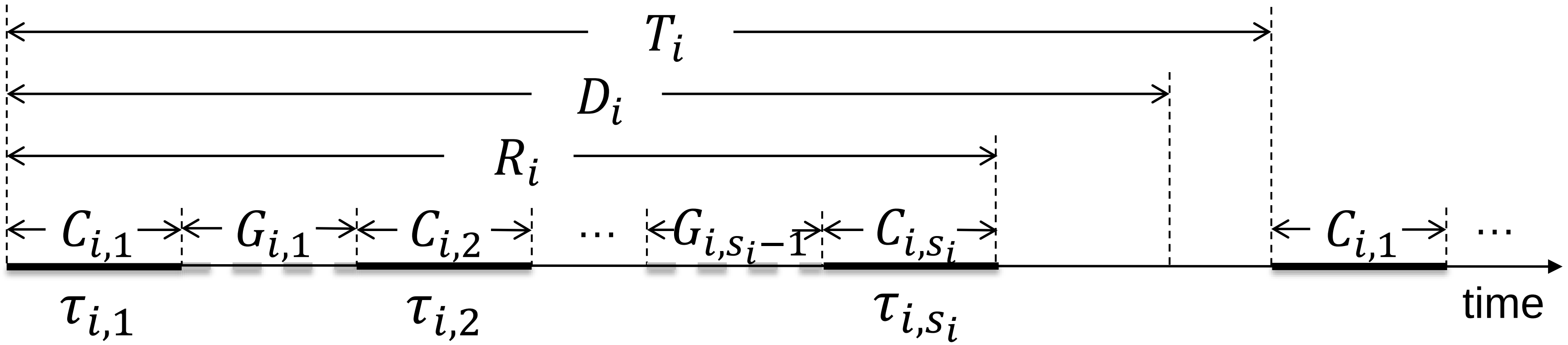
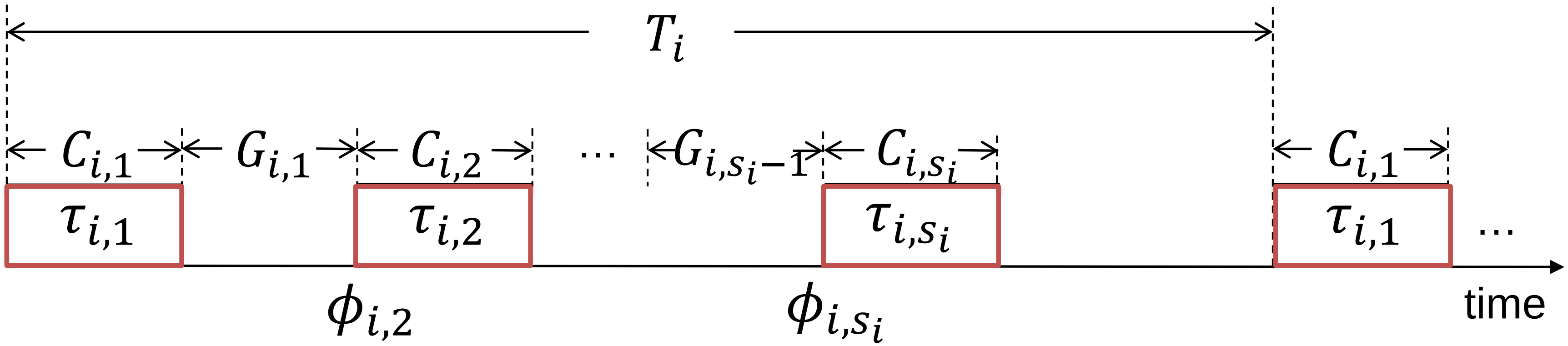
Segment-Fixed Priority Scheduling



- **Assumptions**
  - $G_{i,j}$ lies in $\left[G_{i,j}^{MIN}, G_{i,j}^{MAX}\right]$.
  - $\tau_{i,j}$ always runs for at most $C_{i,j}$.
  - This can be extended to sporadic tasks.
- **Glimpse of the results**
  - Segment-fixed priority scheduling
  - An exact schedulability analysis based on MILP
  - The optimal priority and phase assignment
  - Some heuristics

Segment-Fixed Priority Scheduling



- Each segment $\tau_{i,j}$ has its own priority.
- $\tau_{i,j}$ does not arrive before $\phi_{i,j}$.
  - The varying suspension time yields many different phase offsets.

Mixed-Integer Linear Programming

- **For an exact schedulability analysis of task-fixed priority scheduling:**
  - Find R_1, R_2, and R_3 such that

$$\left.\begin{aligned}
R_1 &= C_1 \\
R_2 &= C_2 + \left\lceil R_2/T_1 \right\rceil C_1 \\
R_3 &= C_3 + \left\lceil R_3/T_1 \right\rceil C_1 + \left\lceil R_3/T_2 \right\rceil C_2 \\
R_1 &\le D_1 \\
R_2 &\le D_2 \\
R_3 &\le D_3
\end{aligned}\right\} \text{A traditional response-time test}$$

The taskset is schedulable if a feasible solution exists.

Mixed-Integer Linear Programming

- **For an exact schedulability analysis of task-fixed priority scheduling:**
  - Find R_1, R_2, and R_3 such that

$$
\begin{aligned}
R_1 &= C_1 \\
R_2 &= C_2 + I_{2,1}C_1 \\
R_3 &= C_3 + I_{3,1}C_1 + I_{3,2}C_2 \\
I_{2,1} &= \left\lceil {R_2}/{T_1} \right\rceil \\
I_{3,1} &= \left\lceil {R_3}/{T_1} \right\rceil \\
I_{3,2} &= \left\lceil {R_3}/{T_2} \right\rceil \\
R_1 &\le D_1 \\
R_2 &\le D_2 \\
R_3 &\le D_3
\end{aligned}
$$

$I_{2,1}$, $I_{3,1}$, and $I_{3,2}$ are integers.

The taskset is schedulable if a feasible solution exists.

Mixed-Integer Linear Programming

- **For an exact schedulability analysis of task-fixed priority scheduling:**
  - Find R_1, R_2, and R_3 such that

$$
\begin{aligned}
&R_1 = C_1\\
&R_2 = C_2 + I_{2,1}C_1\\
&R_3 = C_3 + I_{3,1}C_1 + I_{3,2}C_2\\
&I_{2,1}T_1 - T_1 < R_2 \le I_{2,1}T_1\\
&I_{3,1}T_1 - T_1 < R_3 \le I_{3,1}T_1\\
&I_{3,2}T_2 - T_2 < R_3 \le I_{3,2}T_2\\
&R_1 \le D_1\\
&R_2 \le D_2\\
&R_3 \le D_3
\end{aligned}
$$

$I_{2,1}, I_{3,1}$, and $I_{3,2}$ are integers.

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Mixed-Integer Linear Programming

- **For an exact schedulability analysis of task-fixed priority scheduling:**
  - Find R_1, R_2, and R_3 such that

$$
\begin{aligned}
R_1 &= C_1 \\
R_2 &= C_2 + I_{2,1} C_1 \\
R_3 &= C_3 + I_{3,1} C_1 + I_{3,2} C_2 \\
I_{2,1} T_1 - T_1 &\le R_2 \le I_{2,1} T_1 \\
I_{3,1} T_1 - T_1 &\le R_3 \le I_{3,1} T_1 \\
I_{3,2} T_2 - T_2 &\le R_3 \le I_{3,2} T_2 \\
R_1 &\le D_1 \\
R_2 &\le D_2 \\
R_3 &\le D_3
\end{aligned}
$$

Changing $<$ to $\le$ does not affect the feasibility. (See the paper)

The taskset is schedulable if a feasible solution exists.

Mixed-Integer Linear Programming

- **For an exact schedulability analysis of task-fixed priority scheduling:**
  - Find R_1, R_2, and R_3 such that

$$
\left.\begin{aligned}
R_1 &= C_1 \\
R_2 &= C_2 + I_{2,1}C_1 \\
R_3 &= C_3 + I_{3,1}C_1 + I_{3,2}C_2 \\
I_{2,1}T_1 - T_1 &\le R_2 \le I_{2,1}T_1 \\
I_{3,1}T_1 - T_1 &\le R_3 \le I_{3,1}T_1 \\
I_{3,2}T_2 - T_2 &\le R_3 \le I_{3,2}T_2 \\
R_1 &\le D_1 \\
R_2 &\le D_2 \\
R_3 &\le D_3
\end{aligned}\right\}
$$

This is linear, and an MILP problem.

The taskset is schedulable if a feasible solution exists.

MILP for Priority Assignment

- **Introducing a few parameters for priority assignment**
  - Find $R_1, R_2, R_3, x_{1,2}, x_{1,3}, x_{2,1}, x_{2,3}, x_{3,1}$, and $x_{3,2}$ such that

$$R_1 = C_1 + \left\lceil {}^{R_1}/_{T_2} \right\rceil C_2 x_{1,2} + \left\lceil {}^{R_1}/_{T_3} \right\rceil C_3 x_{1,3}$$
$$R_2 = C_2 + \left\lceil {}^{R_2}/_{T_1} \right\rceil C_1 x_{2,1} + \left\lceil {}^{R_2}/_{T_3} \right\rceil C_3 x_{2,3}$$
$$R_3 = C_3 + \left\lceil {}^{R_3}/_{T_1} \right\rceil C_1 x_{3,1} + \left\lceil {}^{R_3}/_{T_2} \right\rceil C_2 x_{3,2}$$
$$R_1 \le D_1$$
$$R_2 \le D_2$$
$$R_3 \le D_3$$

  - $x_{i,j}$ is a binary variable, and it becomes 1 if τ_j has higher priority than the priority of τ_i.
    - When $x_{i,j}$ is given, this can be used to check the schedulability.
  - The phase assignment can be found using a similar approach.

Heuristics for Priority and Phase Assignment to Task Segments

- **Idea: assign a deadline to a task segment such that the Deadline-Monotonic policy can be used**
- **Four heuristics that assign a deadline to a segment:**
  - **ED** (Equal Density): Assign to $\tau_{i,j}$ a segment deadline so that all segment densities for τ_i are same.
  - **MTD** (Minimize Total Density): Assign to $\tau_{i,j}$ a segment deadline such that the total density for τ_i is minimized.
  - **ES** (Equal Slack): Assign to $\tau_{i,j}$ a segment deadline such that $D_{i,1} - C_{i,1} = D_{i,2} - C_{i,2} = \cdots = D_{i,s_i} - C_{i,s_i}$.
  - **PS** (Proportional Slack): Assign to $\tau_{i,j}$ a segment deadline such that $D_{i,j} - C_{i,j} : D_{i,j+1} - C_{i,j+1} :: U_{i,j} : U_{i,j+1}$.

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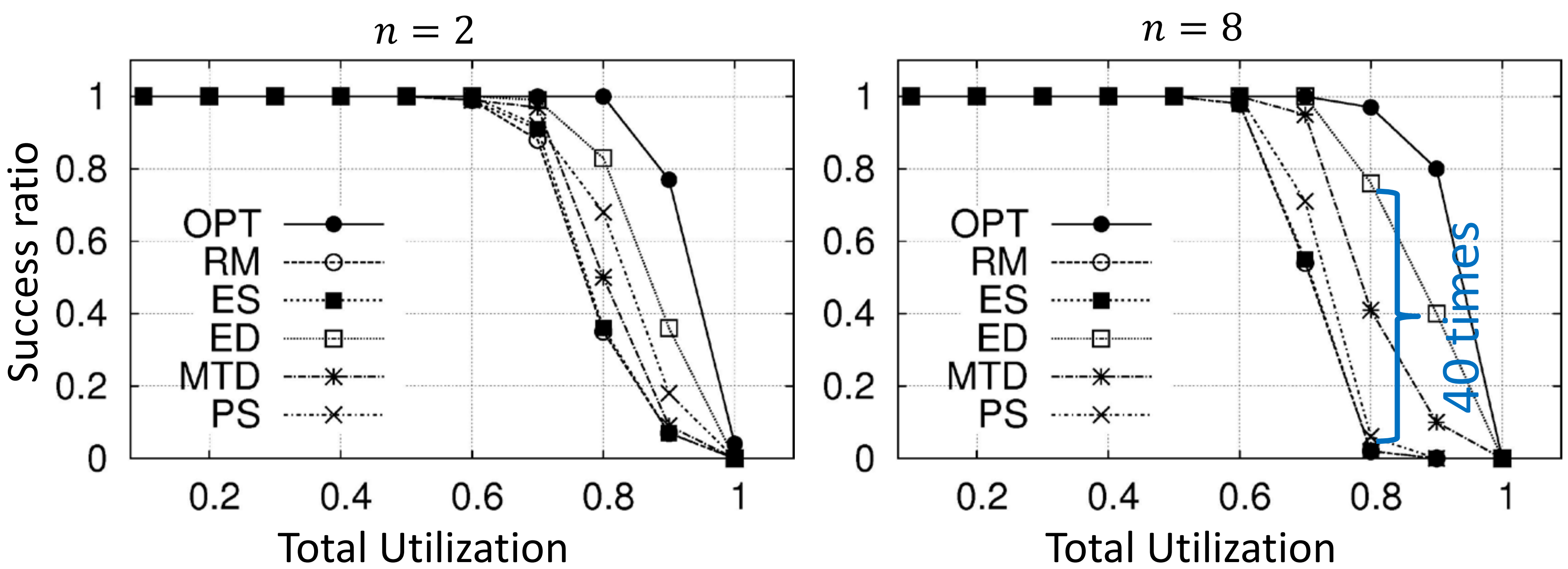
Evaluation Parameters

- **Generated 100 tasksets per datapoint such that**
  - The number of tasks varies from 2 to 16
  - The total utilization of each taskset varies from 0.1 to 1
  - The period of each task is uniformly distributed between 10 and 100
  - The maximum value of G_i/T_i is either 0.1 or 0.6
  - The number of segments is set to 2
  - We assume $D_i = T_i$

Evaluation Parameters (cont'd)

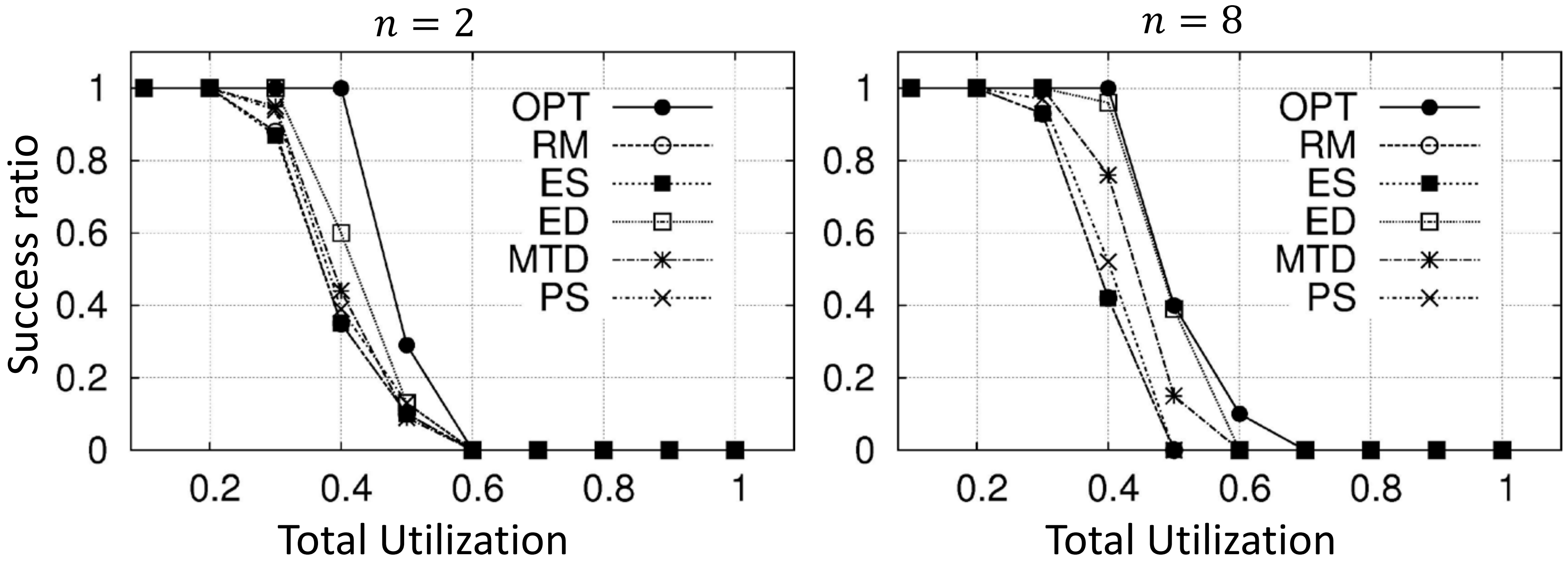
- **Techniques compared:**
  - **OPT**: Exact schedulability analysis based on MILP
  - **RM**: Rate-Monotonic
  - **ES**: Equal Slack
  - **ED**: Equal Density
  - **MTD**: Minimize Total Density
  - **PS**: Proportional Slack

When $\max_i {G_i}/{T_i} \leq 0.1$



- All heuristics perform better than **RM**.
- **ED** performs the best among all techniques.
- The performance difference between **OPT** and **ED** gets larger as the total taskset utilization becomes larger.

When $\max_i G_i/T_i \leq 0.6$



- As the suspension time becomes larger, it is **difficult** for tasks to meet their deadlines (due to tight constraints) regardless of the amount of CPU idle time.

Related Work

- Scheduling self-suspending tasks with task-fixed priority scheduling is **NP-hard** in the strong sense. [Ridouard 04]
- Other contributions

	Soft Real-time	Hard Real-time
Suspension-agnostic	[Elliott 12]	[Gai 03]
Suspension-aware	[Liu 09] [Liu 12]	[Rajkumar 91] [Gai 03] [Bletsas 05] [Lakshmanan 10]

Conclusions and Future Work

- **Dealing with tasks that self-suspend**
  - Determined a new *critical instant* when there is one self-suspending task and multiple non-suspending tasks.
  - Derived a *utilization bound* when RMS is still optimal.
  - Proposed *segment-fixed priority scheduling* (SFPS).
  - Performed *exact schedulability* analysis for SFPS.
  - Gave an *optimal configuration* for priority and phase offset.
  - Four practical *heuristics* were proposed and evaluated.
    - Deadlines that lead to equal density of segments do best.
- **Future work**
  - Multi-core processing

Thank you and Questions?

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