Schedulability Analysis for Fixed Priority Real-Time Systems with Energy- Harvesting

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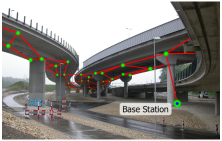
RTNS'14, 10 October 2014

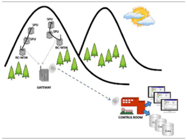
Outline

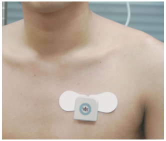
Energy Harvesting Systems

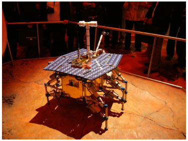
Energy-Harvesting

The process by which energy is captured from a system's environment and converted into usable electric power.









Energy Harvesting Systems

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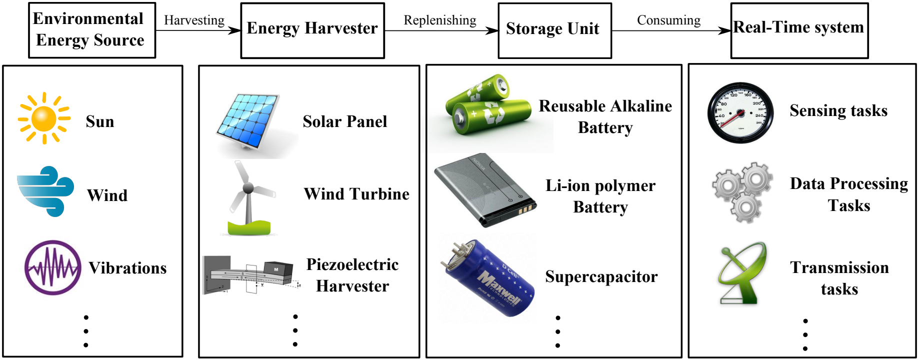
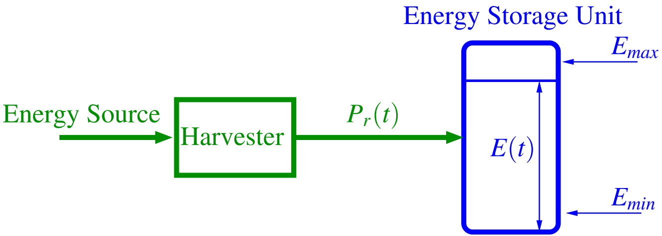


Energy Model



- Energy Source Model
  - Energy Sources: solar, thermal, mechanical, vibration, . . .
  - Harvester: transform the environmental energy into electrical power.
- Energy Storage Unit Model
  - Energy Unit: battery, super-capacitor, . . .
  - Store the harvested energy: $P_r(t)$ is the energy replenishment function.

    Constant rate of replenishment: $P_r(t) = P_r$
  - The energy stored may vary between two levels E_{min} and E_{max}.

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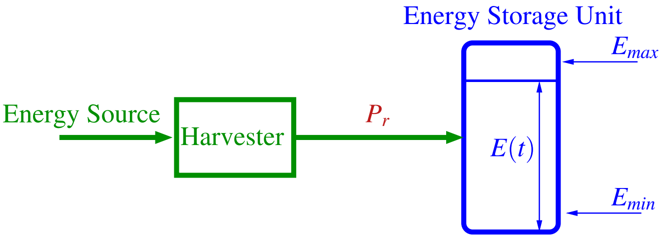

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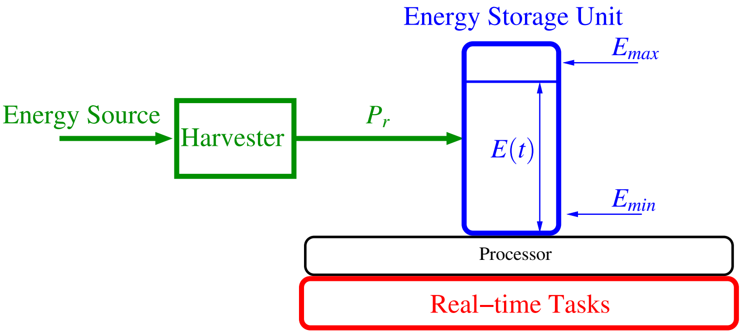
Task Model



A set of sporadic tasks $\tau_i(C_i, P_i, E_i, T_i, D_i)$

C_i: worst-case execution time,

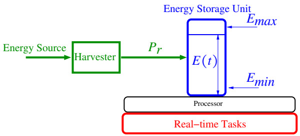
P_i: worst-case power consumption,

$E_i = P_i \times C_i$: worst-case energy consumption,

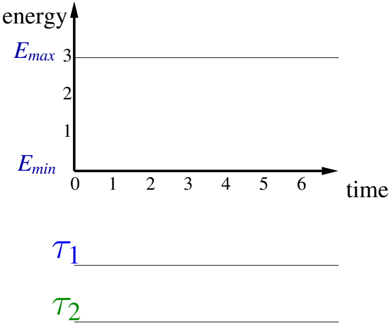
T_i: minimal inter arrival time,

D_i: relative deadline ($D_i \leq T_i$).

The Model



$$
\begin{array}{llll}
P_r = 3 & E_{max} = 3 & E_{min} = 0 & \\
\tau_1 : C_1 = 2 & P_1 = 6 & E_1 = 12 & T_1 = D_1 = 4 \\
\tau_2 : C_2 = 1 & P_2 = 1 & E_2 = 1 & T_2 = D_2 = 5
\end{array}
$$



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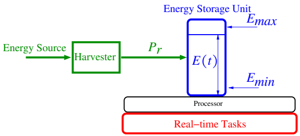

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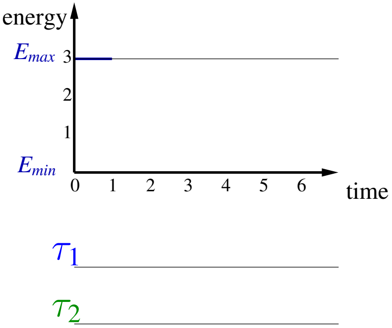

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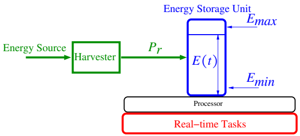

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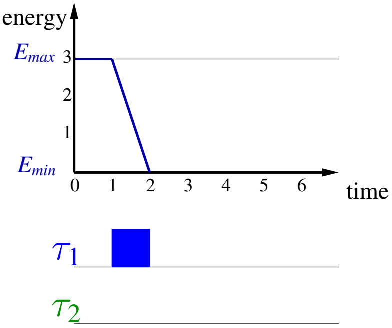
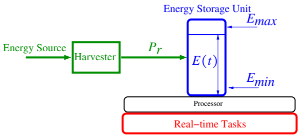


Consuming Task: $P_1 > P_r$

The Model



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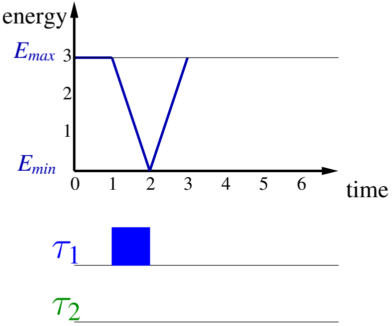

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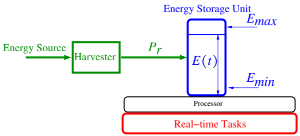

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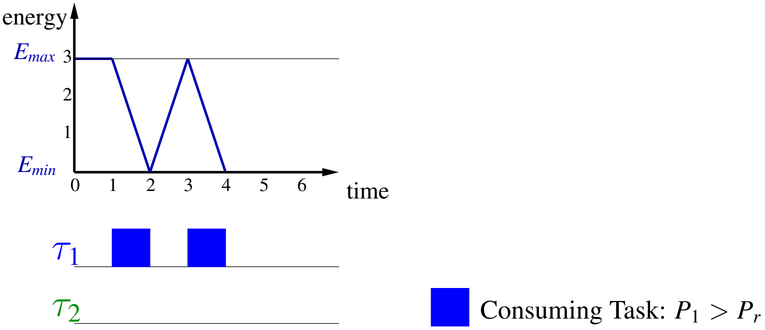

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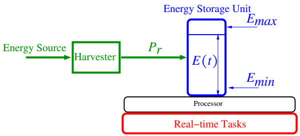

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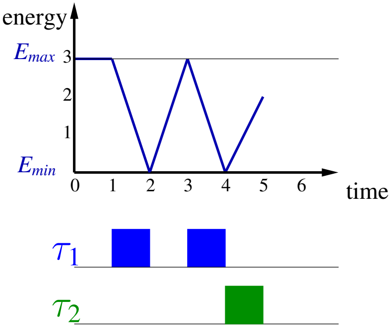

Consuming Task: $P_1 > P_r$

Gaining Task: $P_2 \leq P_r$

The Scheduling Problem

The Model

- Storage Unit: Constant rate replenishment P_r and E_{max}, E_{min} the maximal and minimal level of energy.
- A set $\Gamma = \Gamma_c \cup \Gamma_g$ of sporadic tasks $\tau_i = (C_i, P_i, E_i, T_i, D_i)$ in priority order with $D_i \leq T_i$:
  - Consuming Tasks: $\Gamma_c = \{\tau_i \in \Gamma, P_i > P_r\}$
  - Gaining Tasks: $\Gamma_g = \{\tau_i \in \Gamma, 0 \leq P_i \leq P_r\}$

Feasibility

A task set is feasible if all the tasks meet their deadlines: *timing constraints* and $\forall t \geq 0$ the energy level is between E_{min} and E_{max}: *energy constraints*.

Related Work

- An algorithm for Frame-Based Model,

  A. Allavena and D. Mossé,
  "Scheduling of Frame-based Embedded Systems with Rechargeable Batteries",
  Workshop in conjunction with RTAS, 2001.

  LSA Algorithm assumes variable execution time,

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- PFP_{ASAP} Algorithm

  Y. Abdeddaïm, Y. Chandarli and D. Masson,
  "The Optimality of PFP_{ASAP} Algorithm for Fixed-Priority Energy-Harvesting Real-Time Systems",
  ECRTS, 2013.

The PFP_{ASAP} Algorithm

- Execute tasks whenever there is enough energy available in the battery.
- Replenish as long as needed to execute one time unit of the highest priority active task.

PFP_{ASAP} is an Energy Work-Conserving FPPS Algorithm

The processor is idle only if there is insufficient energy to schedule at least one time unit of the highest priority active task.

Optimality

PFP_{ASAP} is optimal in the class of energy work conserving fixed priority pre-emptive scheduling algorithms in the case where all the task consume energy $(\Gamma = \Gamma_c)$.

Our Goal

Provide a schedulability test for PFP_{ASAP} when the set of tasks is composed of both consuming and gaining tasks.

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Classical Response Time Analysis

Method

1. Find the wost-case scenario: scenario where τ_i is subject to the maximum possible delay,
2. Compute R_i the longest response time of task τ_i: is the response time of τ_i in the worst-case scenario,
3. Exact schedulability test: If $\forall \tau_i, R_i \leq D_i$ the task set is schedulable.

Work-Conserving FPPS with $D_i \leq T_i$

1. Worst-case scenario for task τ_i: Synchronous release of all the tasks,
2. R_i is given by the smallest $t > 0$ that satisfies $t = F(i,t)$ with:
   $F(i,t) = C_i +$ Maximum interference from higher priority tasks in $[0,t)$

$$F(i,t) = \sum_{h \leq i} \left\lceil \frac{t}{T_h} \right\rceil \times C_h$$

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Response Time Analysis for PFP_{ASAP}

Response Time of a task τ_i

C_i + Replenishment time + Interference from higher priority tasks.

$P_r = 3$	$E_{max} = 10$	$E_{min} = 0$		
$\tau_1 : C_1 = 2$	$P_1 = 1$	$E_1 = 12$	$T_1 = 8$	$D_1 = 3$
$\tau_2 : C_2 = 3$	$P_2 = 5$	$E_2 = 15$	$T_2 = 10$	$D_2 = 9$

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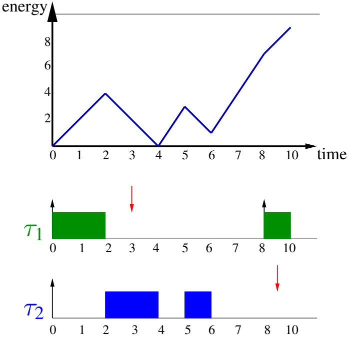
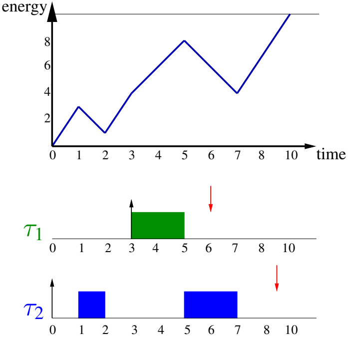


Response Time $\tau_2 = 6$



Response Time $\tau_2 = 7$

Response Time Analysis for PFP_{ASAP}

Worst-Case Scenario

The synchronous release of all the tasks is no longer the worst-case scenario.

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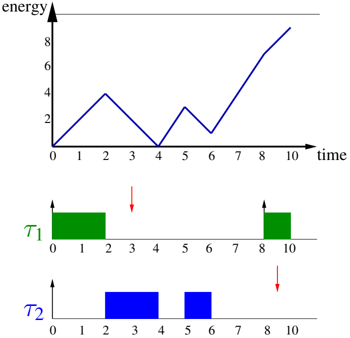

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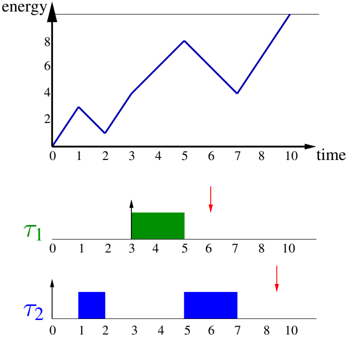

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Response Time Analysis for PFP_{ASAP}

- worst-case scenario is unknown,
- cannot compute exactly R_i, the worst-case response time of task τ_i,
- cannot provide an exact schedulability test.

Upper bound R_i to build a sufficient schedulability test.

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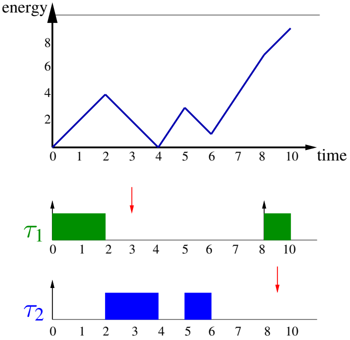

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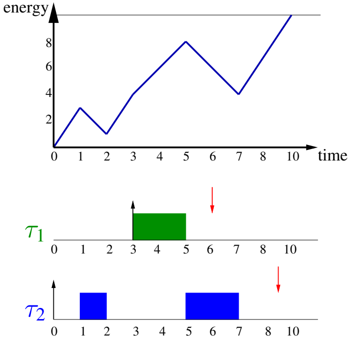

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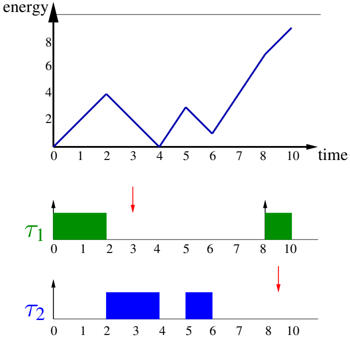

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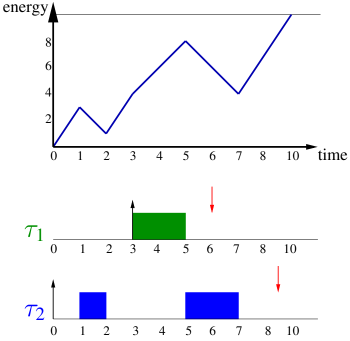

Response Time $\tau_2 = 7$

Bounding Response Time

- We require a monotonically non-decreasing function $F(i, w)$ that upper bounds the length of the worst-case response time of task τ_i within an interval of length w,
- The upper bound R_i^{UB} of the worst-case response time R_i corresponds to the smallest $w > 0$ that satisfies $F(i, w) = w$.
- We define for every task τ_i a virtual scenario that:
  1. Maximizes the amount of interference from higher priority tasks,
  2. Maximizes the amount of replenishment time needed.

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  1. Maximizes the amount of interference from higher priority tasks,
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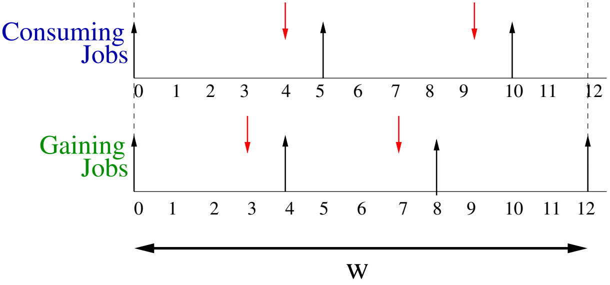
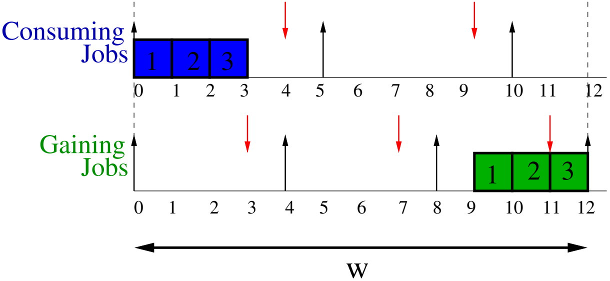
Maximal Interferences

For every task τ_i released in a window of length w, the maximal number of higher priority jobs that are active in this window is

$$\sum_{h<i} \left\lceil \frac{w}{T_h} \right\rceil = \sum_{h<i, \tau_h \in \Gamma_c} \left\lceil \frac{w}{T_h} \right\rceil + \sum_{h<i, \tau_h \in \Gamma_g} \left\lceil \frac{w}{T_h} \right\rceil$$



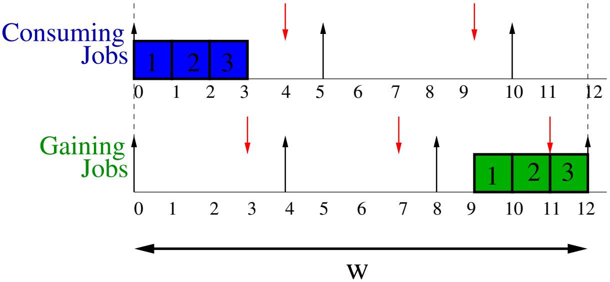
Maximal Replenishment



To upper bound the replenishment in a window of length w we consider a virtual sequence where:

1. The battery is empty at the beginning of the window,
   - to minimize the energy budget of interval w
2. All the consuming jobs are before all the gaining jobs.
   - to maximize replenishment periods

Upper Bound R_i^{UB1}



$$F^{UB1}(i,w) = \underbrace{\left[\sum_{h \le i, \tau_h \in \Gamma_c} \left\lceil \frac{w}{T_h} \right\rceil \times ((P_h - P_r) \times C_h / P_r) \right]}_{\text{maximum replenishment needed}} + \underbrace{\sum_{h \le i, \tau_h \in \Gamma_c} \left\lceil \frac{w}{T_h} \right\rceil \times C_h}_{\text{consuming jobs}}$$

$$+ \underbrace{\sum_{h \le i, \tau_h \in \Gamma_g} \left\lceil \frac{w}{T_h} \right\rceil \times C_h}_{\text{gaining jobs}}$$

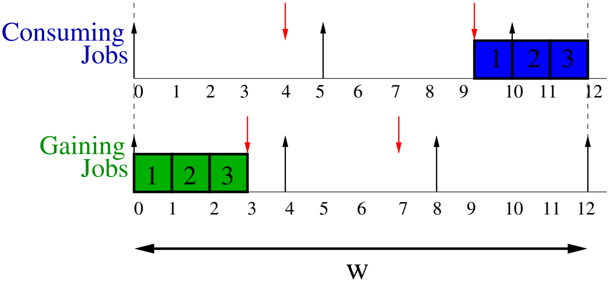
Sufficient Schedulability test $UB1$

- $F^{UB1}(i,w)$ is a monotonically non-decreasing function of w and $F^{UB1}(i,w) > C_i$
- R_i^{UB1} the upper bound of the longest response time of task τ_i is given by the smallest $t > 0$ that satisfies $w = F^{UB1}(i,w)$ with:

$$F^{UB1}(i,w) = \left\lceil \frac{\sum_{h \le i, \tau_h \in \Gamma_c} \left\lceil \frac{w}{T_h} \right\rceil \times E_h}{P_r} \right\rceil + \sum_{h \le i, \tau_h \in \Gamma_g} \left\lceil \frac{w}{T_h} \right\rceil \times C_h$$

- Sufficient Schedulability test $UB1$: $\forall \tau_i, R_i^{UB1} \le D_i$

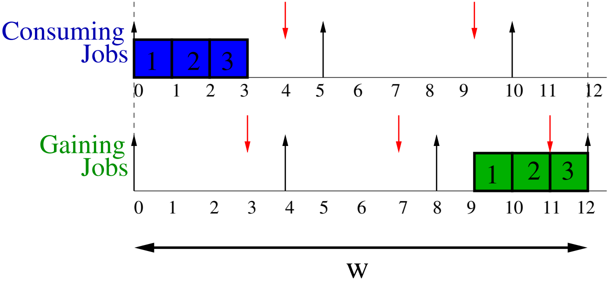
Necessary Schedulability Test $LB1$



To lower bound the worst-case response time of a task τ_i released in a window of length w we consider a virtual sequence where:

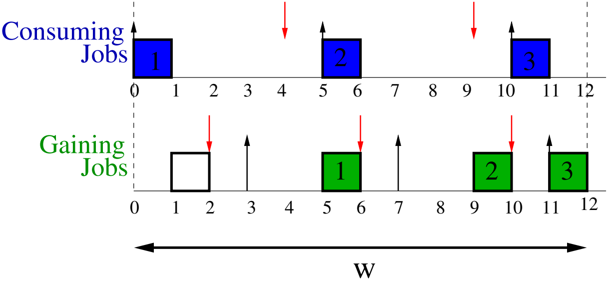
1. The battery is empty at the beginning of the window,
2. All the gaining jobs are before all the consuming jobs.

A Tighter Upper Bound R_i^{UB2}



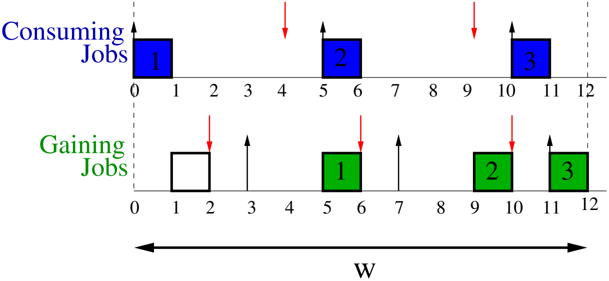
- Consuming jobs as soon as possible,
- Gaining jobs as late as possible

A Tighter Upper Bound R_i^{UB2}



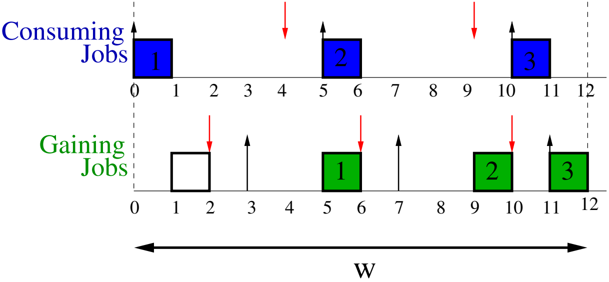
- Consuming jobs as soon as possible,
- Gaining jobs as late as possible

Sufficient Schedulability Test $UB2$



- To compute $F^{UB2}(i,w)$, we compute the response time of the virtual sequence:

Sufficient Schedulability Test $UB2$



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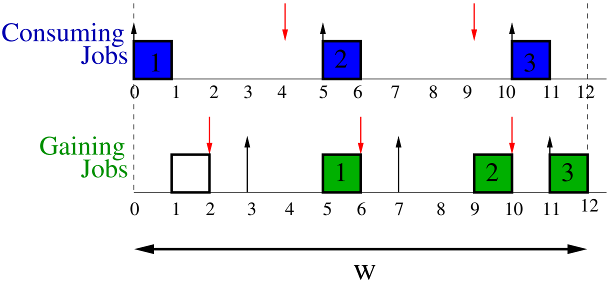

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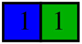

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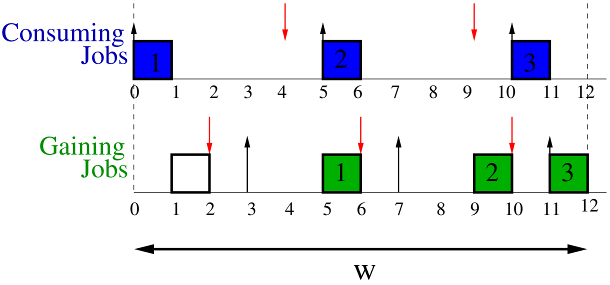

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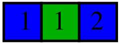

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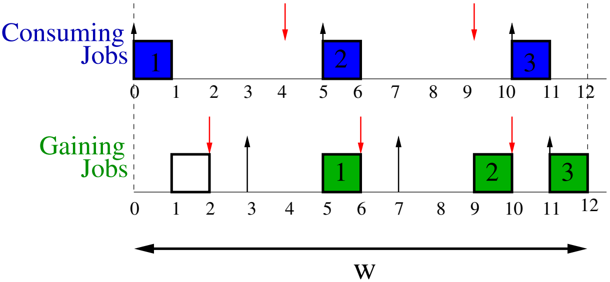

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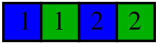

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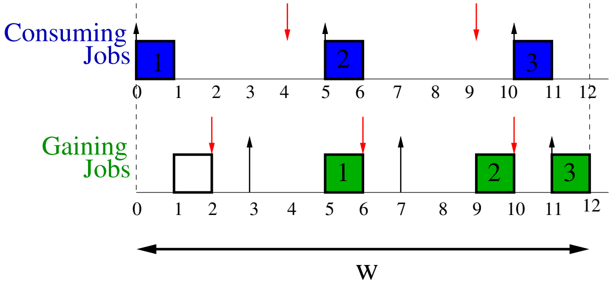

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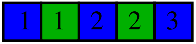

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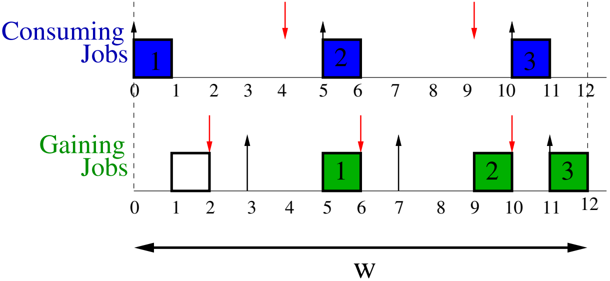

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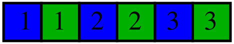
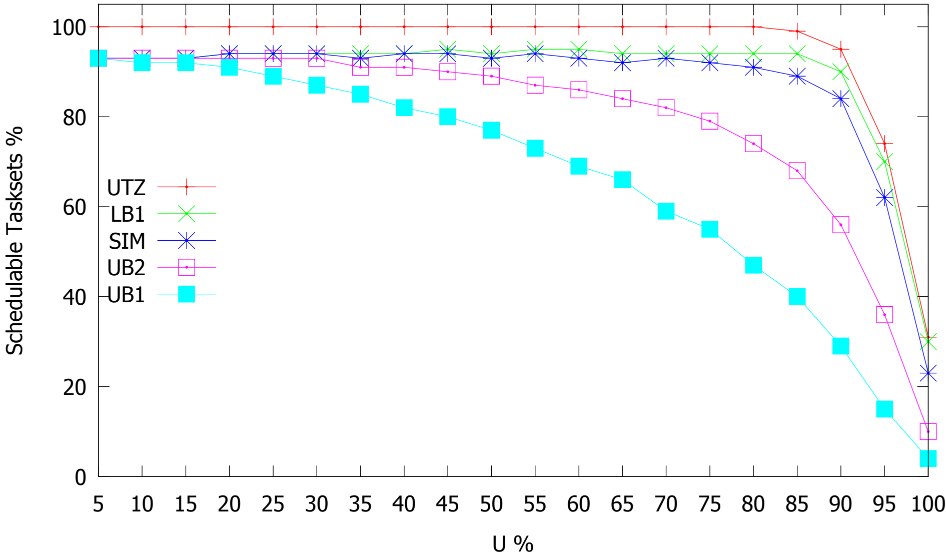


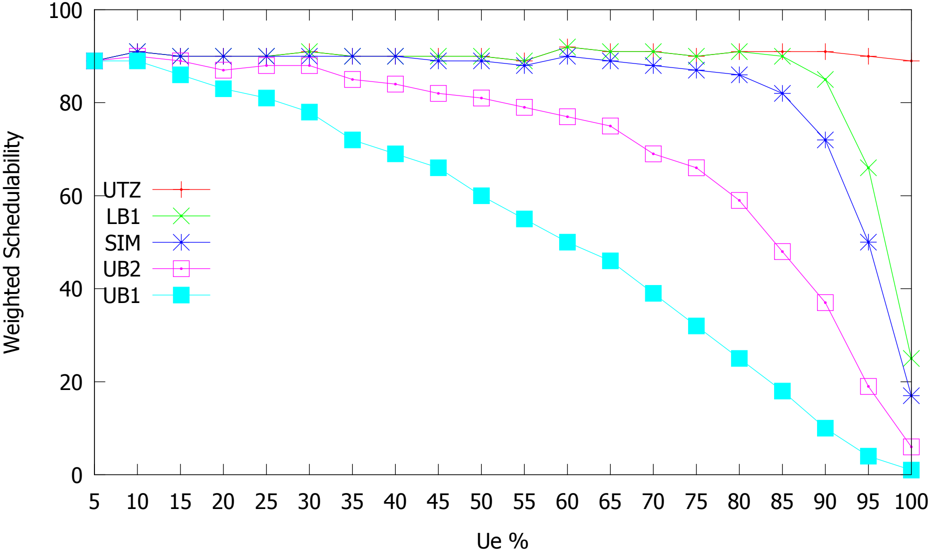
Performance Comparison

- Competitors
  - UTZ: the exact test for $FPPS$ ignoring energy constraints,
  - SIM: an empirical necessary test based on simulating the schedule of PFP_{ASAP} over more than twice the hyper-period,
  - $UB1$: sufficient schedulability test based on the upper bound R^{UB1},
  - $UB2$: sufficient schedulability test based on the upper bound R^{UB2},
  - $LB1$: necessary schedulability test based on the lower bound R^{LB1}.
- Input Data:
  - 40000 task sets randomly generated using UUniFast-Discard algorithm coupled with a technique of hyper-period limitation,
  - Processor utilization varied from 0.05 to 1,
  - Energy utilization varied from 0.05 to 1,
  - Percentage of gaining tasks varied from 0$\%$ to 100$\%$.
- Simulation tool: YARTISS Real-time systems simulator

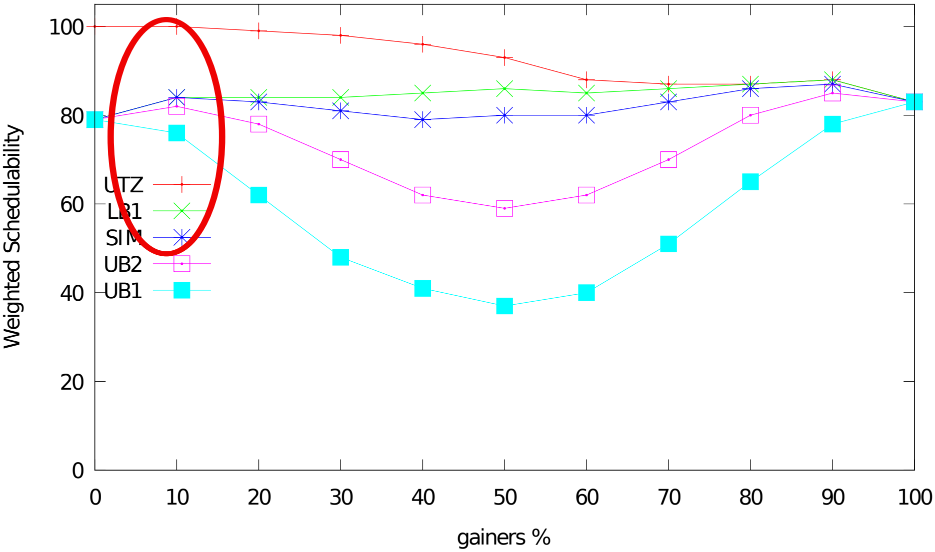
Varying the Processor Utilization



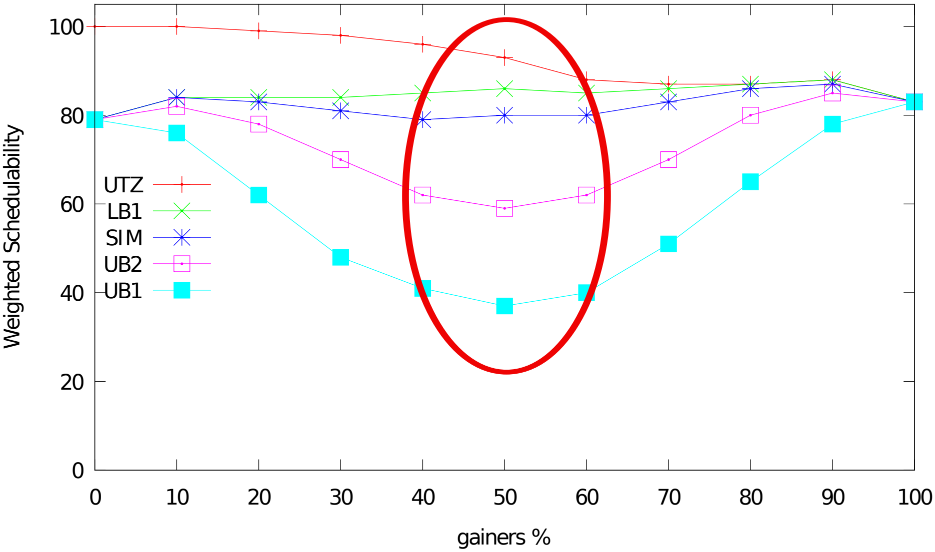
Varying the Energy Utilization



Varying the Gaining Tasks Ratio



Varying the Gaining Tasks Ratio



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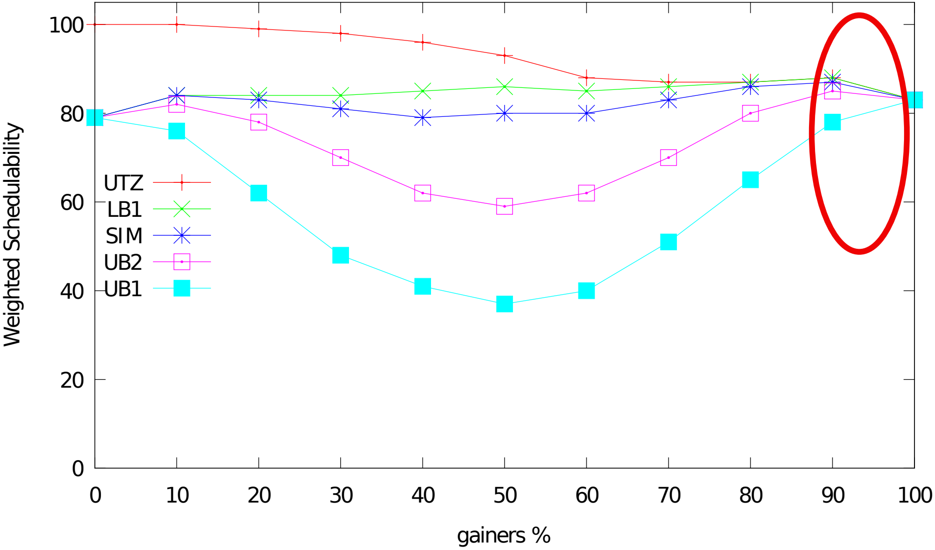

Conclusion and Future Work

1. In this paper we
   - Showed that under PFP_{ASAP}, the worst-case scenario for task sets with both consuming and gaining tasks is not necessarily synchronous release with all other tasks,
   - Derived two sufficient schedulability tests based on two upper bounds on task response times,
   - Derived a necessary schedulability test based on a lower bound on task response time,
   - Evaluated the performance of the sufficient tests in comparison with a number of necessary tests.
2. As future work we plan to:
   - Investigate the problem of optimal priority assignment,
   - Investigate analysis for more complex replenishment functions and additional costs of entering and exiting low power modes needed for energy replenishment.

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Questions ?

Battery Capacity

For the upper bounds to be valid, the battery capacity must be sufficient to store the maximum amount of energy needed in the virtual sequences.

1. For $UB1$: E_{max} must be sufficient to store the energy needed to execute one time unit of the most consuming task:

$$E_{max}^{UB1} \geq \max(\max_{\forall i}(E_i/C_i) - P_r, P_r)$$

2. For $UB2$: E_{max} must be sufficient to store the energy needed to execute consuming jobs in any possible energy busy period:

$$E_{max}^{UB2} \geq \max\left(\sum_{\forall i} \left\lceil \frac{\max_{\forall j}(D_j)}{T_i} \right\rceil \times \max\left(E_i - C_i \times P_r, 0\right), P_r\right)$$