FusionClock: Energy-Optimal Clock-Tree Reconfigurations for Energy-Constrained Real-Time Systems

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Lehrstuhl für Verteilte Systeme und Betriebssysteme

Friedrich-Alexander-Universität
Technische Fakultät

Application Scenarios

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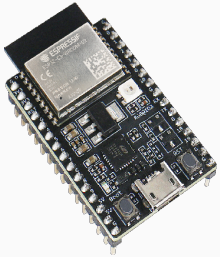
- devices massively influence timing and energy behaviour
  $\Rightarrow$ reduce energy consumption for longer battery life

Devices on Embedded Systems



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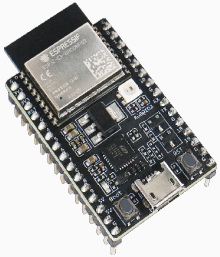

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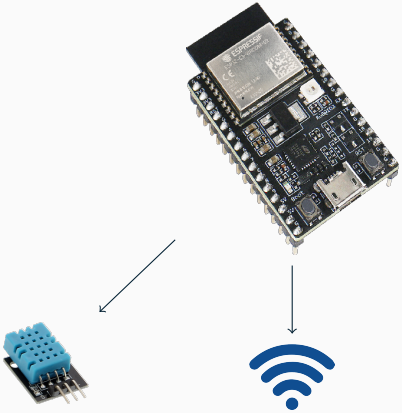

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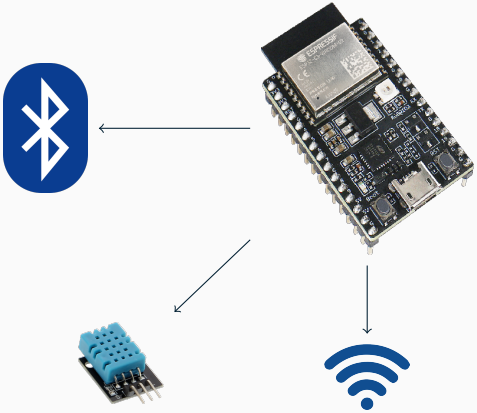

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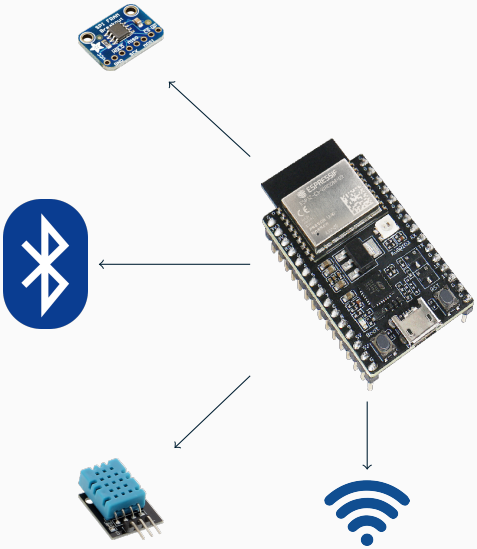

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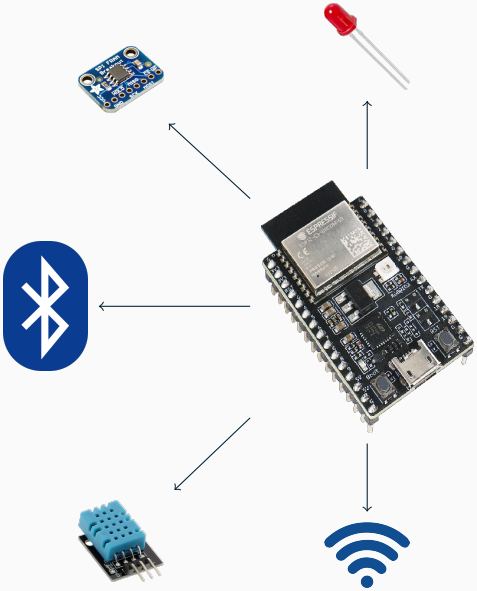

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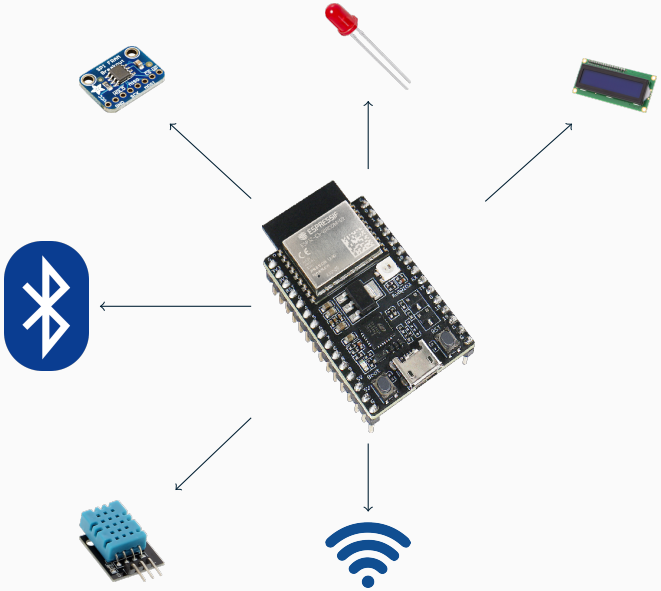

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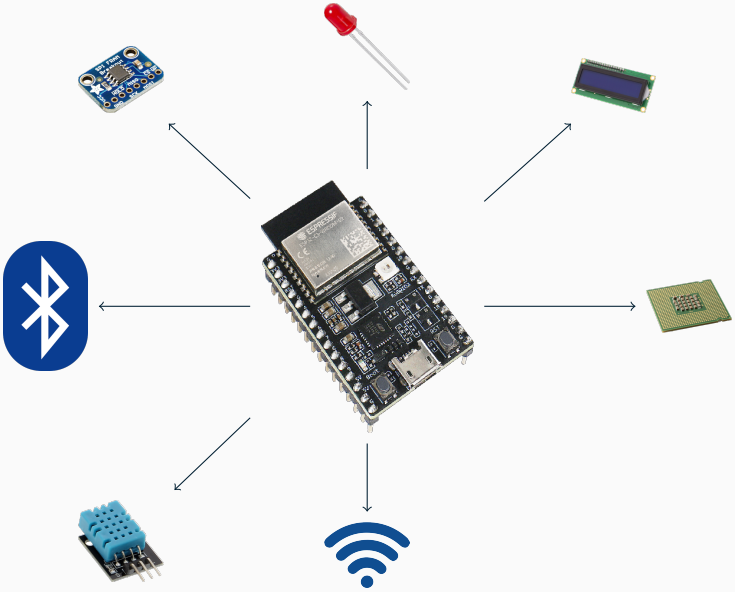

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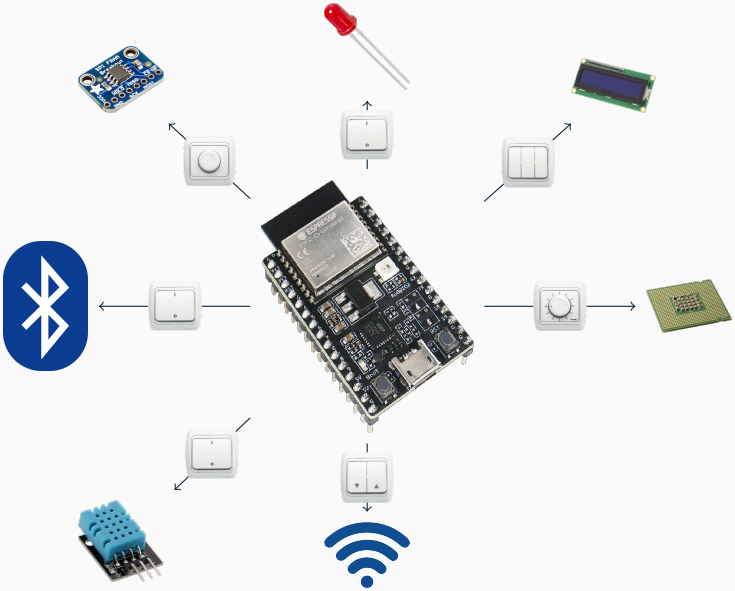

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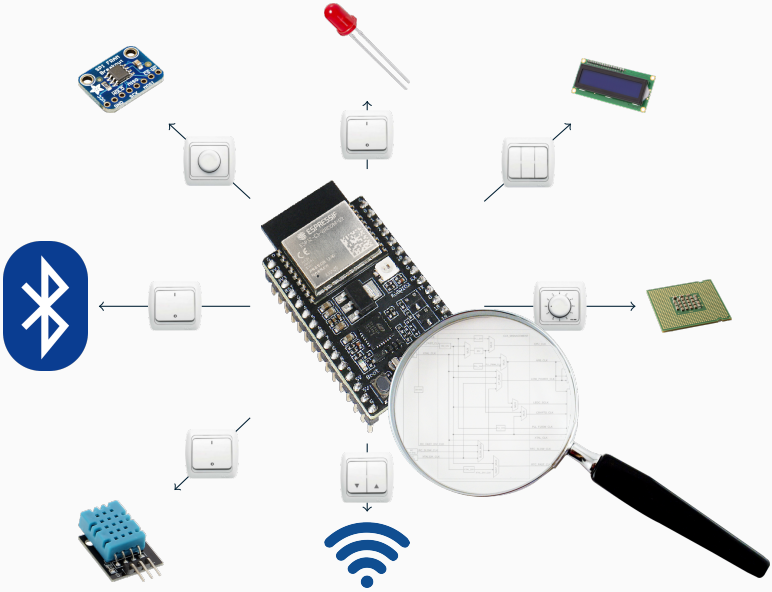
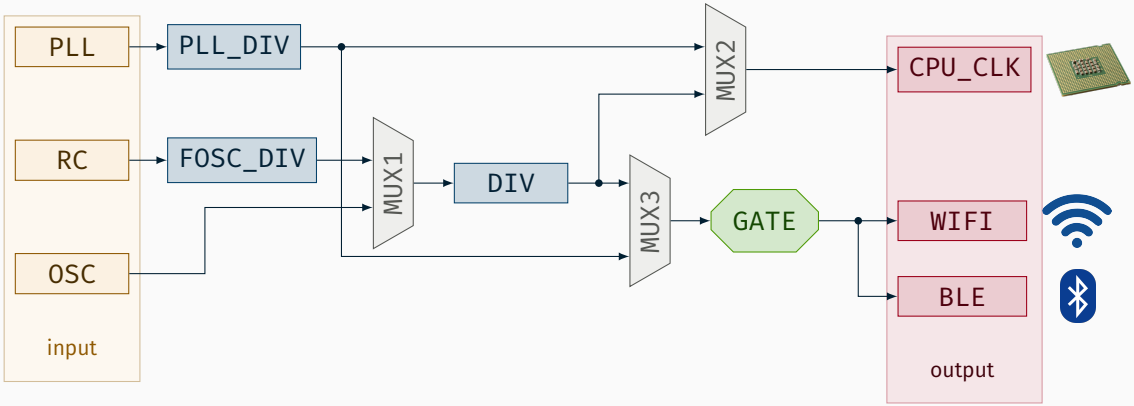


The Clock Tree



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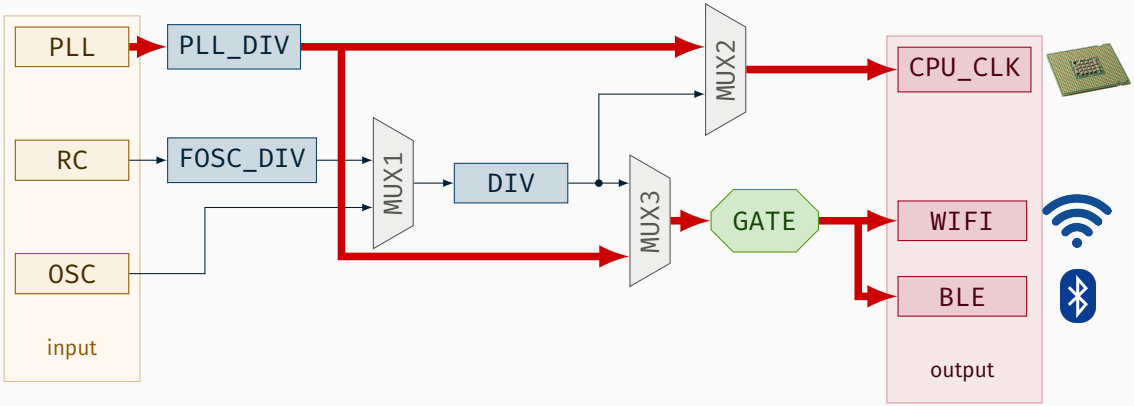

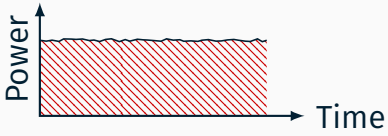

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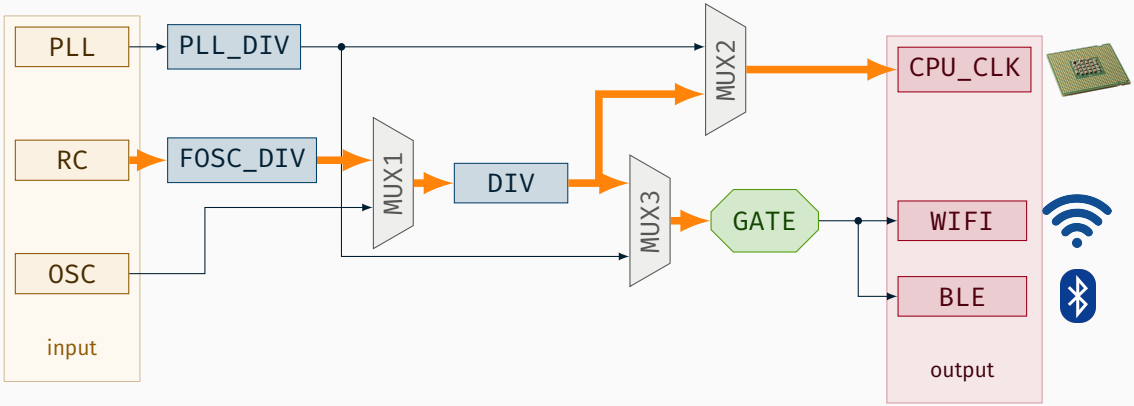

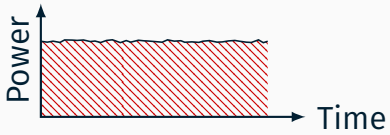

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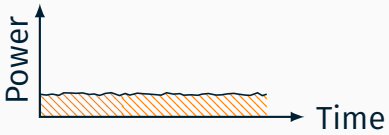

Problem Description

System Model / Requirements for FusionClock

- single-core platforms

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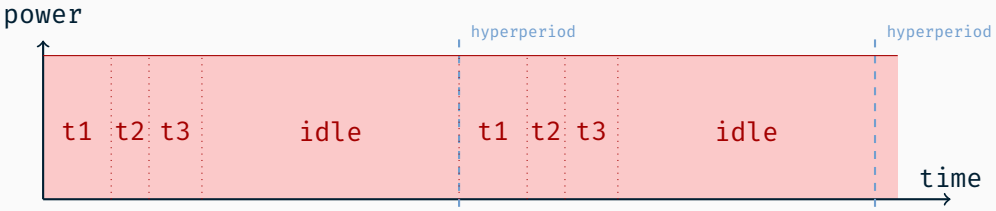
- single-core platforms
  - configurable via **clock tree**
- static and sound model of the system for WCET/WCEC analyses
  - including the **devices** of the system
- strictly periodic, cyclic task model
  - **time-triggered schedule**

Problem Analysis



all-always-on approach

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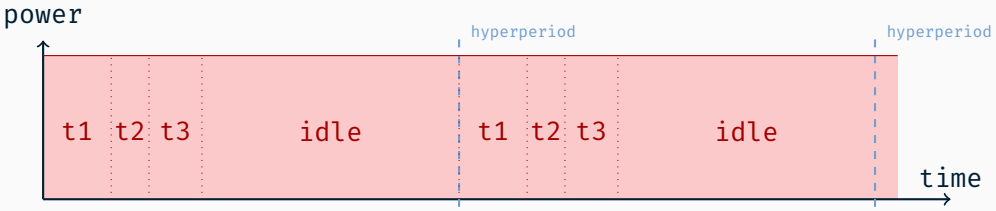

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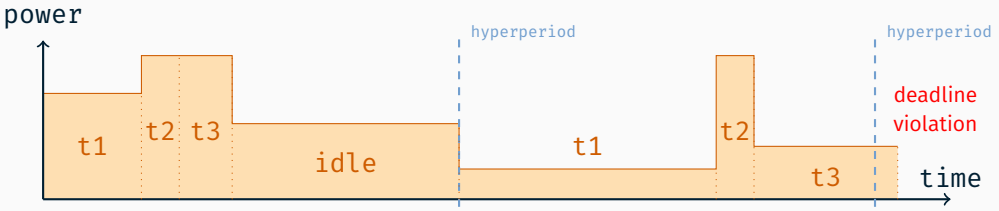
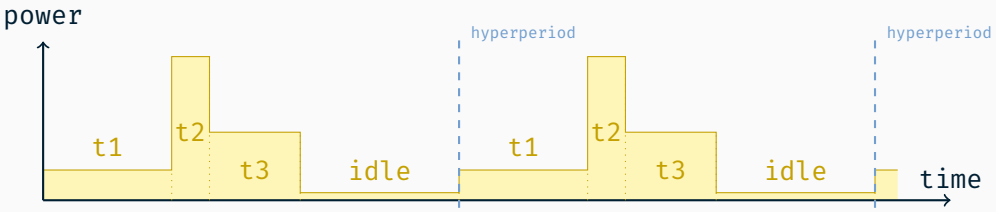


feedback-based approach: reconfigurations during execution

- minimzation of energy consumption
- × real-time guarantees

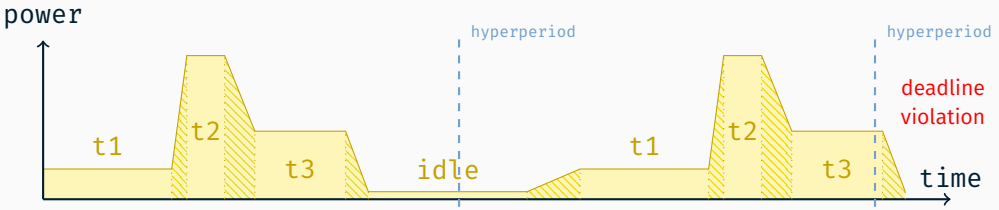
Problem Analysis



static approach: analysis before execution

- minimzation of energy consumption
- real-time guarantees

Problem Analysis



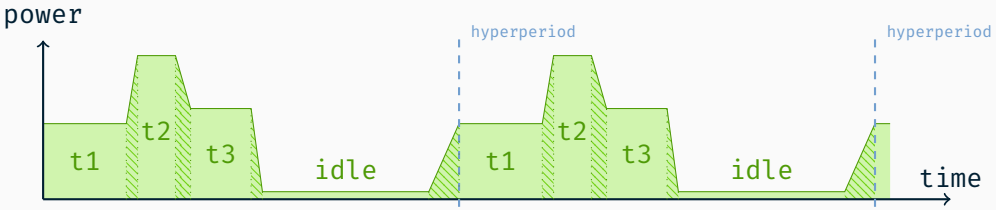
static approach without reconfiguration penalties

- minimzation of energy consumption
- × real-time guarantees
- × consideration of reconfiguration costs

Problems

1. CPU-only approaches...
   - neglect energy consumption of **devices**
   - ignore **dependencies of devices** and **clock-tree configurations**
2. **no guarantees** of feedback-based approaches
3. missing **reconfiguration penalties**

Concept of FusionClock



static approach with reconfiguration penalties

- ✓ minimzation of energy consumption
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- ✓ consideration of reconfiguration costs

The FusionClock Approach

Overview over the FusionClock Approach

clock-tree model + device constraints

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clock-tree model + device constraints

resource-consumption model

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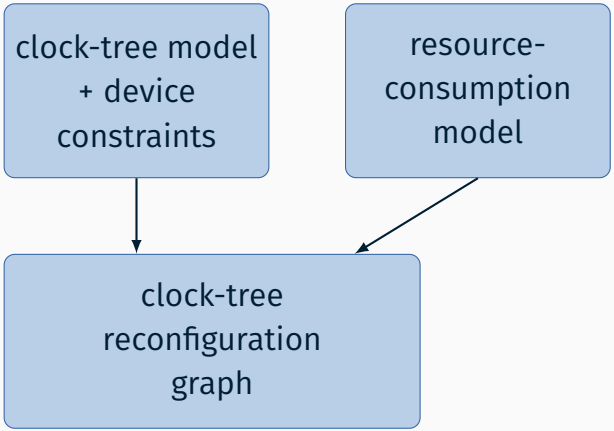

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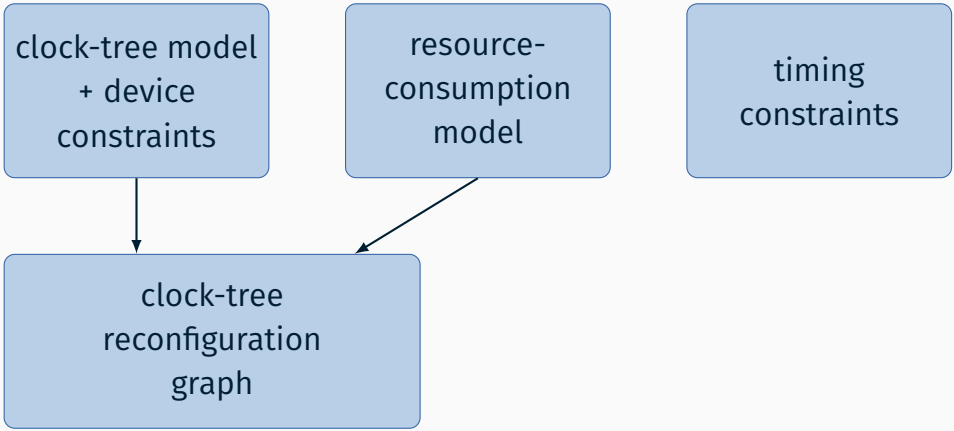

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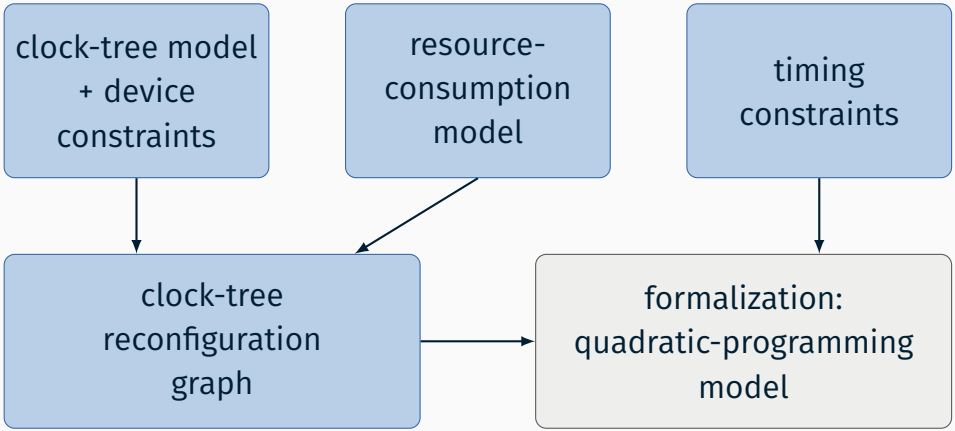

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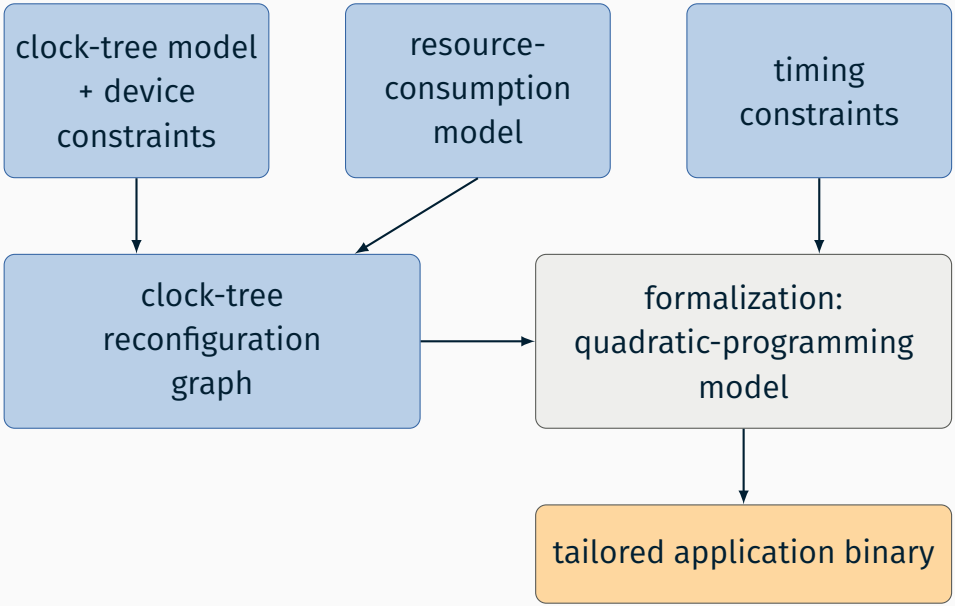

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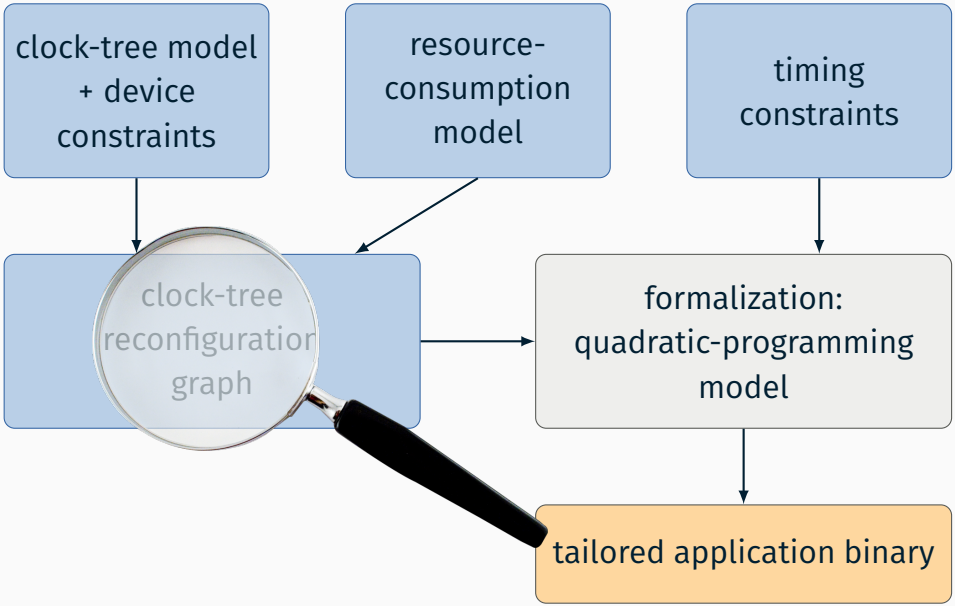

Clock-Tree Reconfiguration Graph

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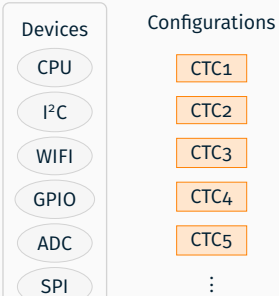

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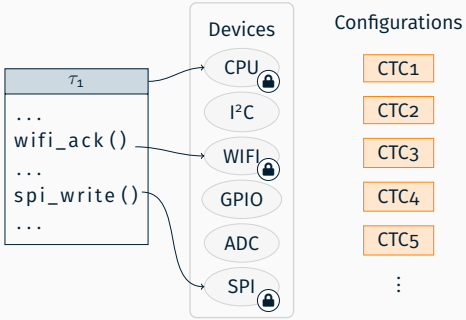

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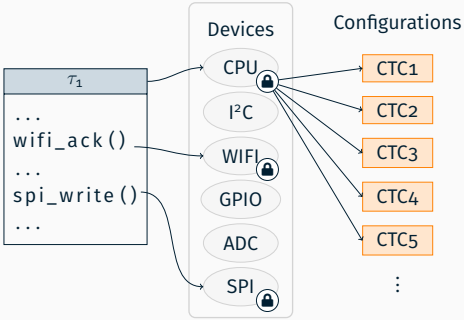

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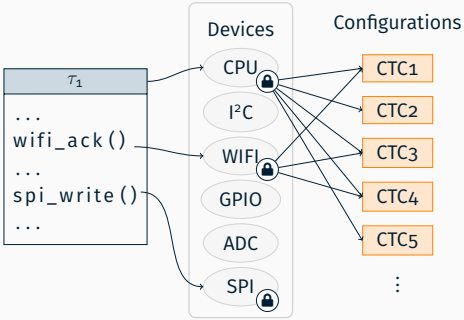

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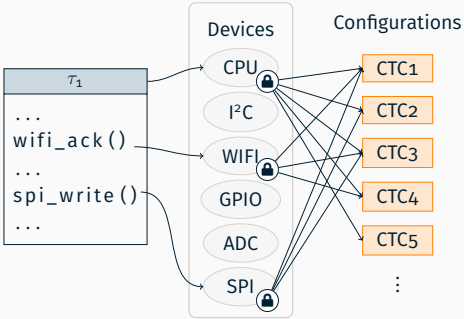

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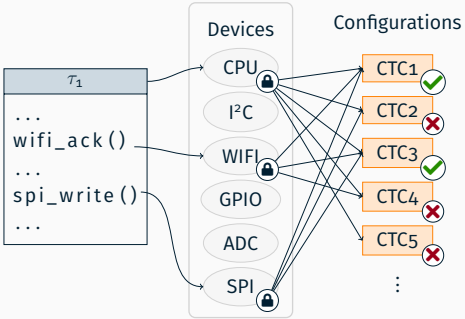

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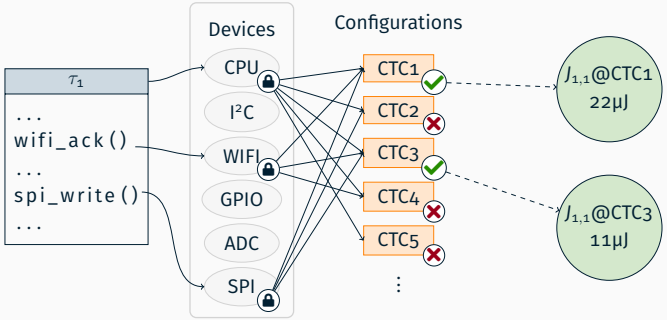

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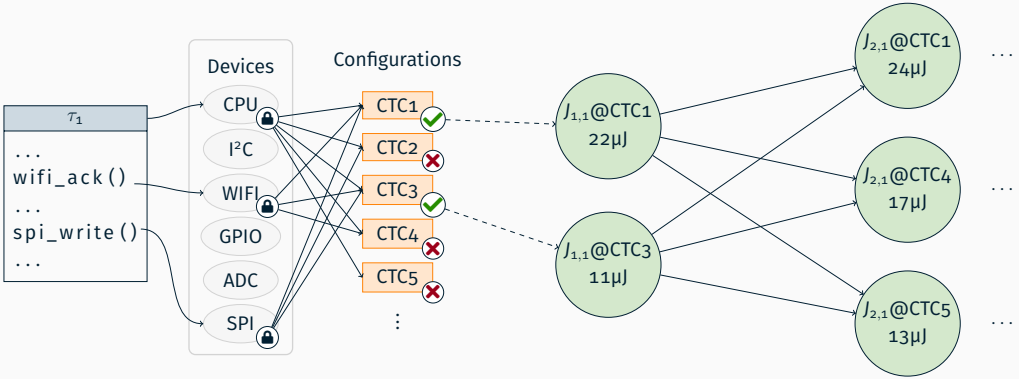

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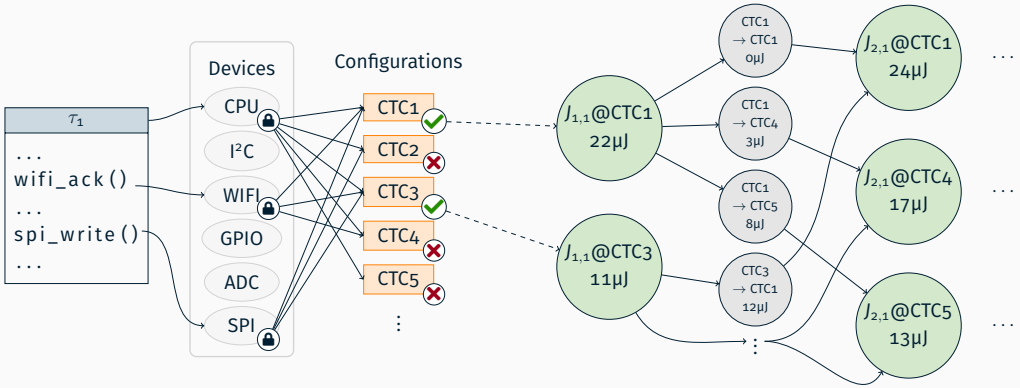

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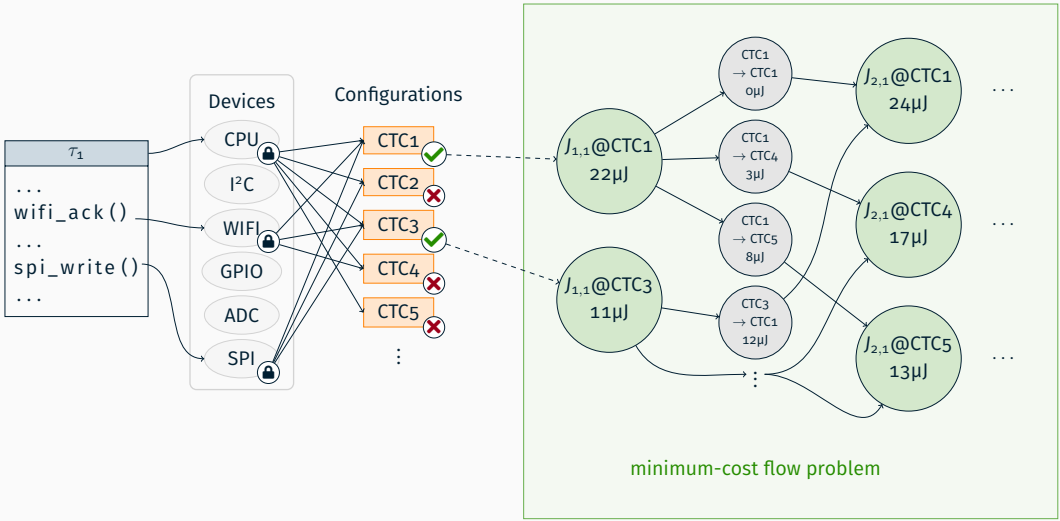

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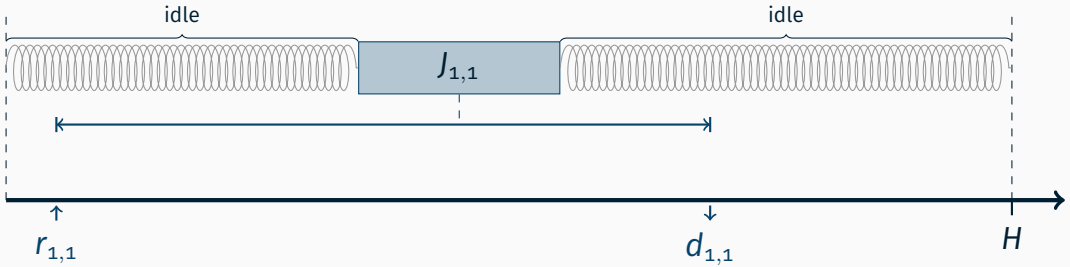

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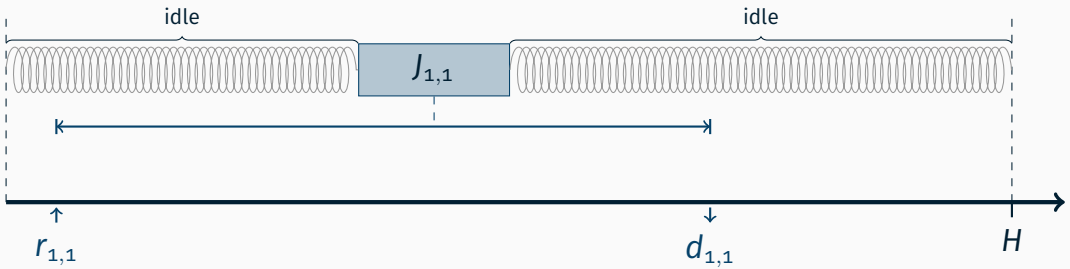

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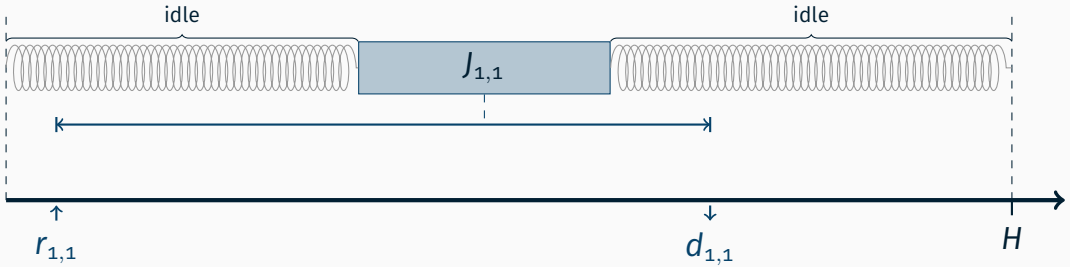

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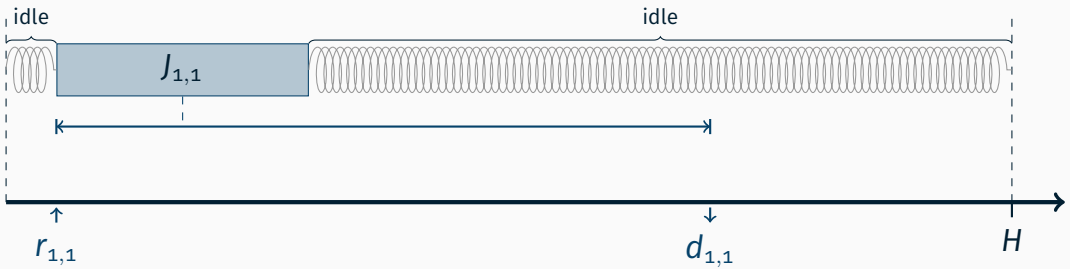

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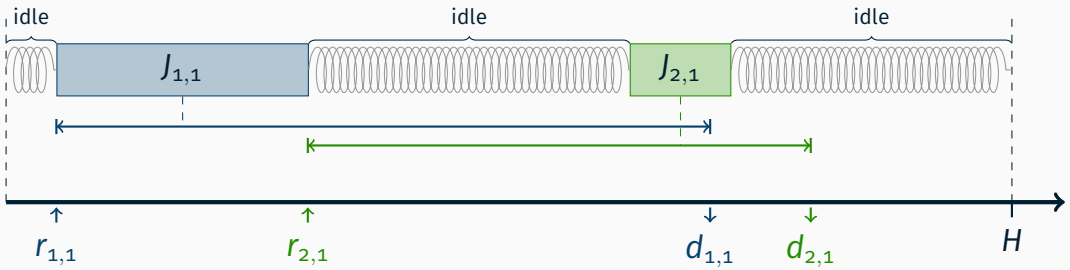

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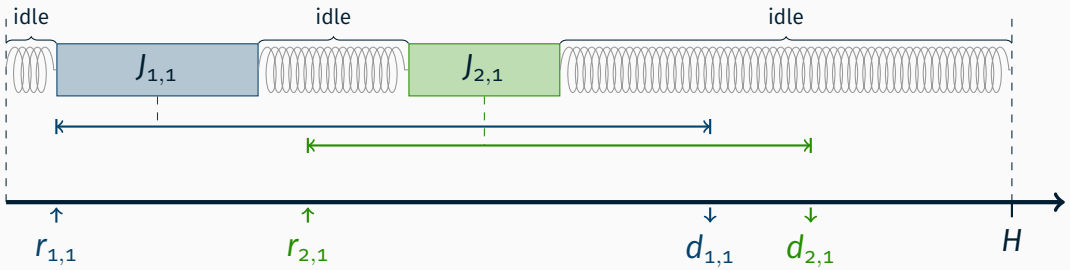

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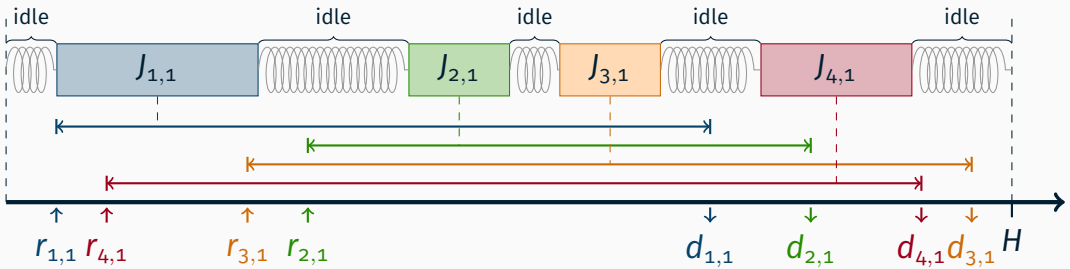

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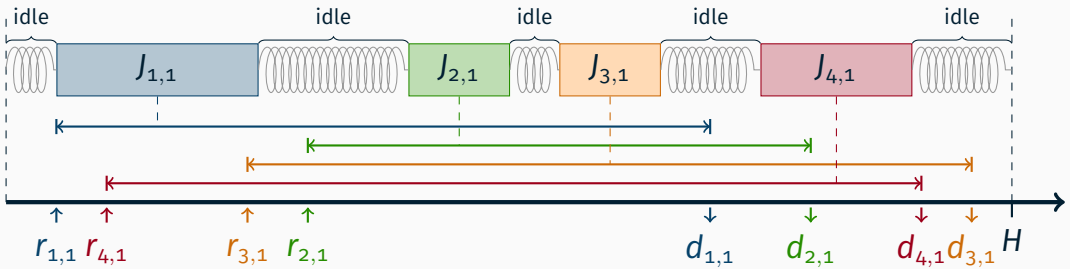

Distributing the slack:

- **reconfiguration penalties**
- **idling**: start times, durations, and configurations

Formalization

min **energy costs** of jobs and idling options
+ **energy penalty** for reconfiguration

w.r.t.
constraints in the **clock-tree reconfiguration graph**
all times **sum up** to **hyperperiod**
each job **starts** at or after its **release time**
each job **finishes** before or at its **deadline**

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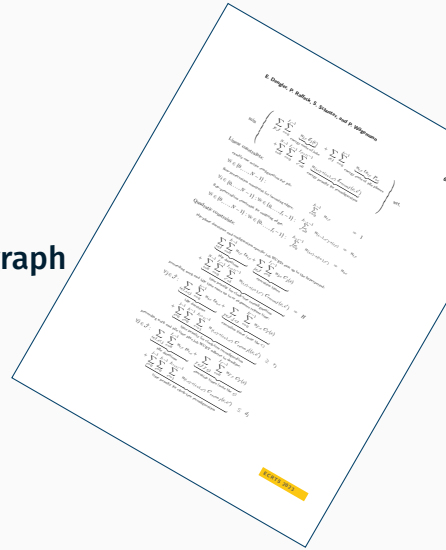
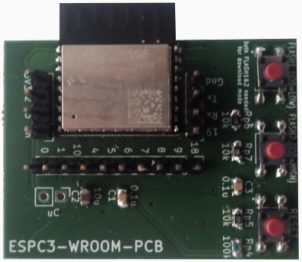


Evaluation

Evaluation Hardware



Evaluation: Break-Even Point Analysis

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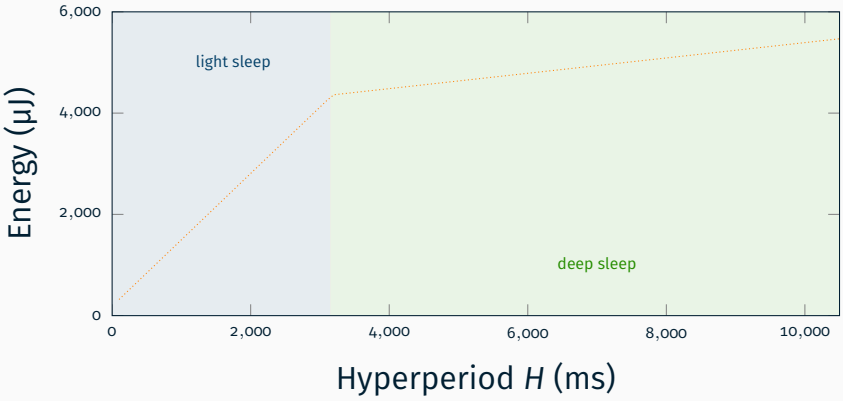
- 5 CTCs: which one is used for the compute task?
- 3 idle options: when do the energy savings outweigh the reconfiguration penalties?
- how do actual measurements compare to the predicted energy consumptions?

Evaluation: Break-Even Point Analysis



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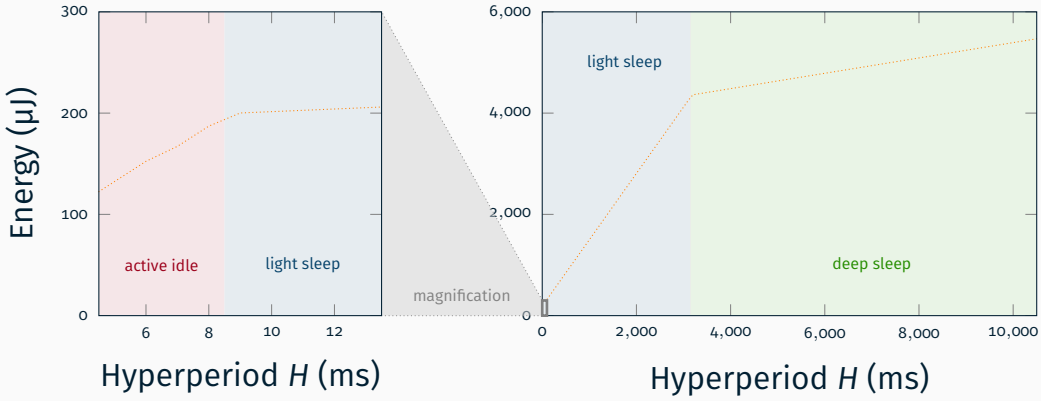

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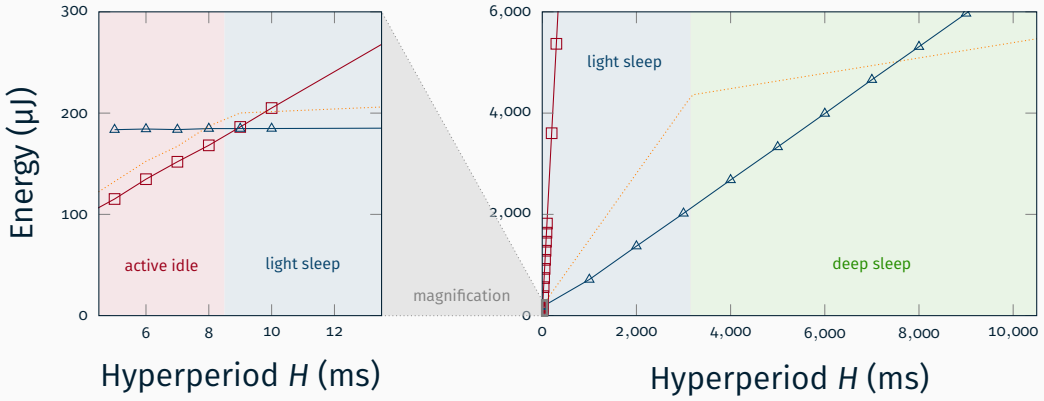

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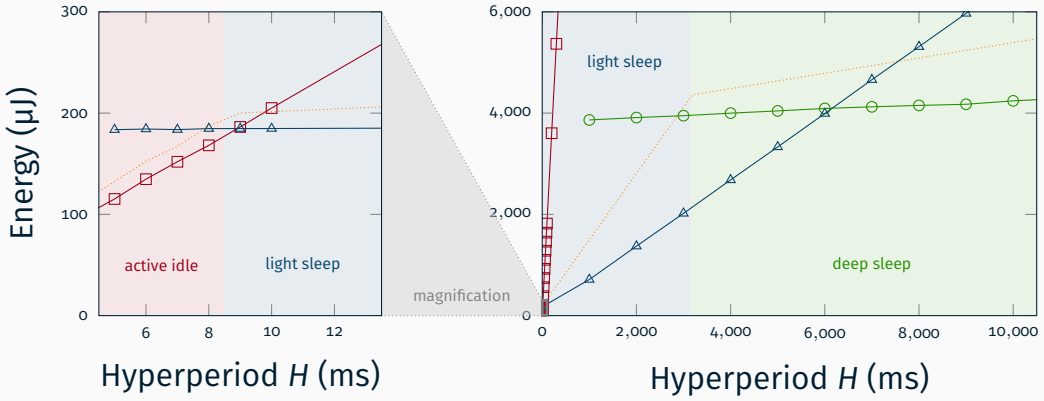

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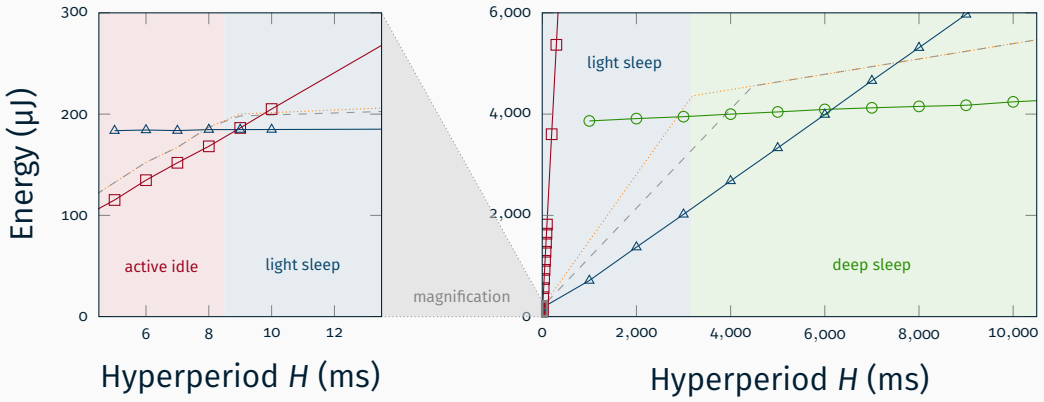

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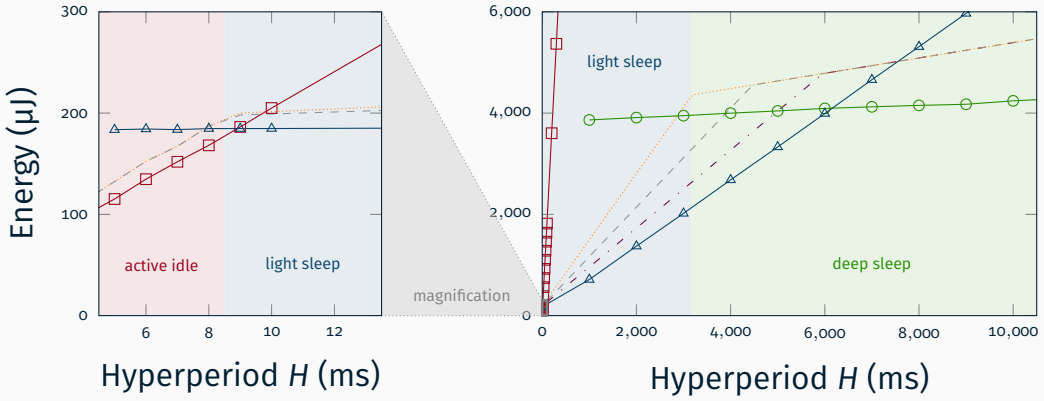

Evaluation: Taskset Generation

Does FusionClock ...

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- ... minimze energy consumption in comparison to device-unselective approaches?

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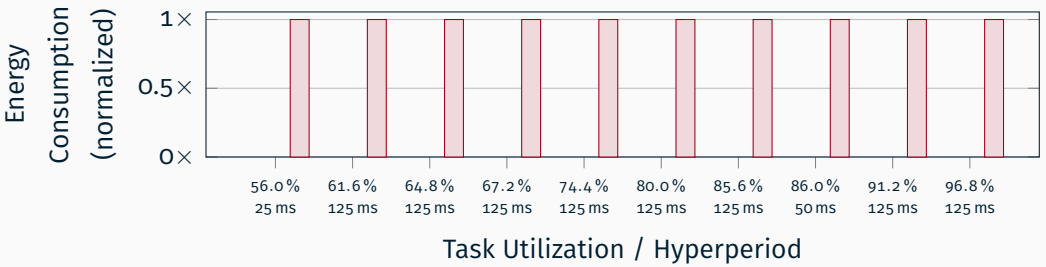
Evaluation with generated tasksets:

- simulate device usage: sense, compute, actuate
- 5 active modes
- 2 idle modes: light sleep, deep sleep
- 9 to 18 tasks

Evaluation: Taskset Generation



binary without clock-tree reconfigurations

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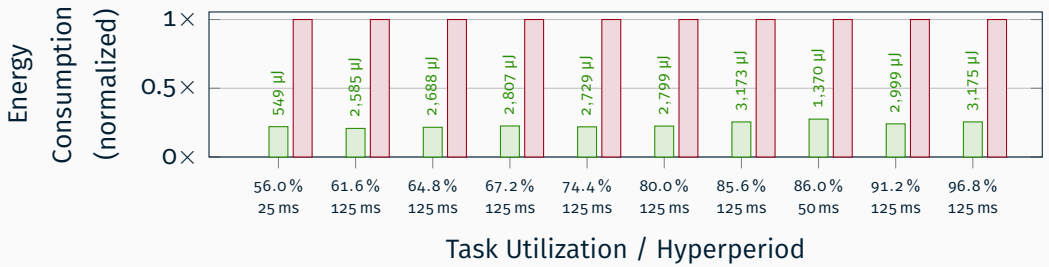

predicted energy consumption

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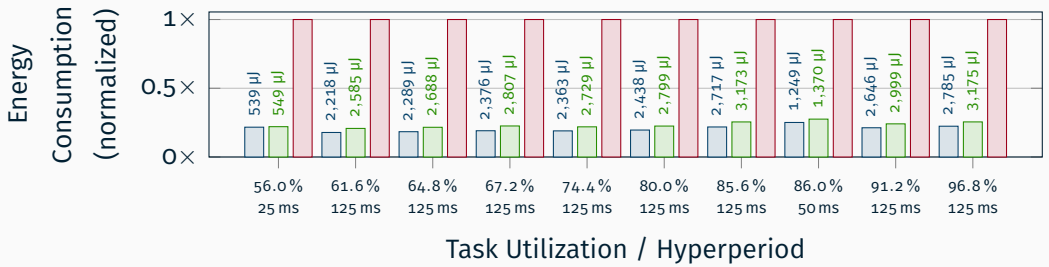

tailored application binary

predicted energy consumption

binary without clock-tree reconfigurations

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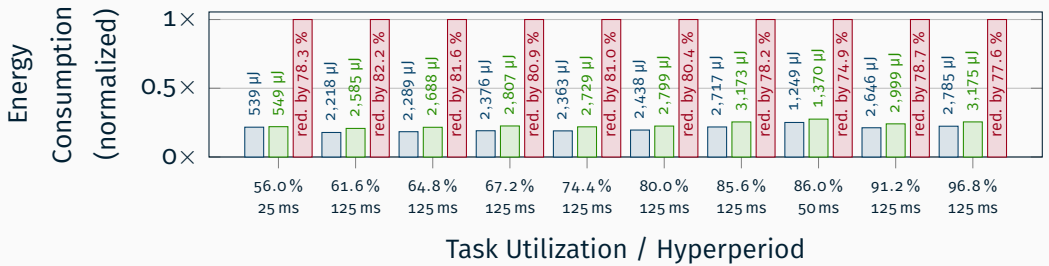

tailored application binary

predicted energy consumption

binary without clock-tree reconfigurations

Problems solved by FusionClock

1. CPU-only approaches...
   - neglect energy consumption of devices
   - ignore dependencies of devices and clock-tree configurations
2. no guarantees of feedback-based approaches
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   ✓ **inclusion of clock-tree reconfiguration costs in optimization**

Questions?

Source Code and Artifact Evaluation of FusionClock

`https://gitlab.cs.fau.de/fusionclock`

E. Dengler, P. Raffeck, S. Schuster, and P. Wägemann.
FusionClock: WCEC-Optimal Clock-Tree Reconfigurations (Artifact).
Dagstuhl Artifacts Series, 9(1):2:1–2:3, 2023.