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

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12th July 2023

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Friedrich-Alexander-Universität Erlangen-Nürnberg

Supported by the DFG under the grant WA 5186/1-1 (Watwa)

Lehrstuhl für Verteilte Systeme
und Betriebssysteme

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Application Scenarios

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- embedded real-time systems: worst-case execution time (WCET), worst-case energy consumption (WCEC)

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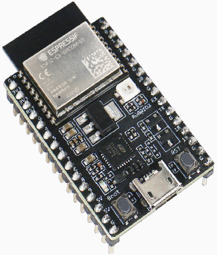
- devices massively influence timing and energy behaviour
  ⇒ reduce energy consumption for longer battery life

Devices on Embedded Systems



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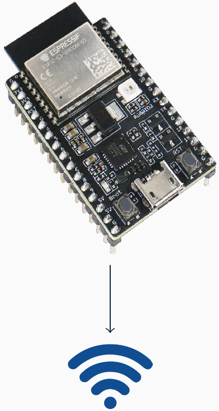

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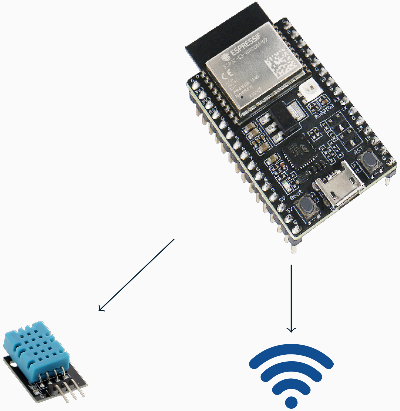

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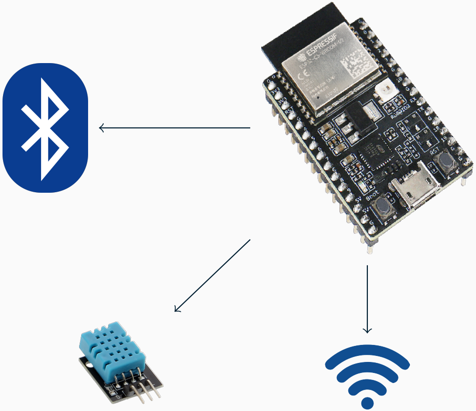

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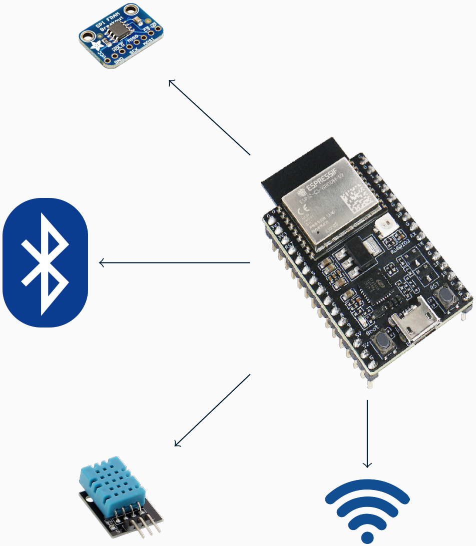

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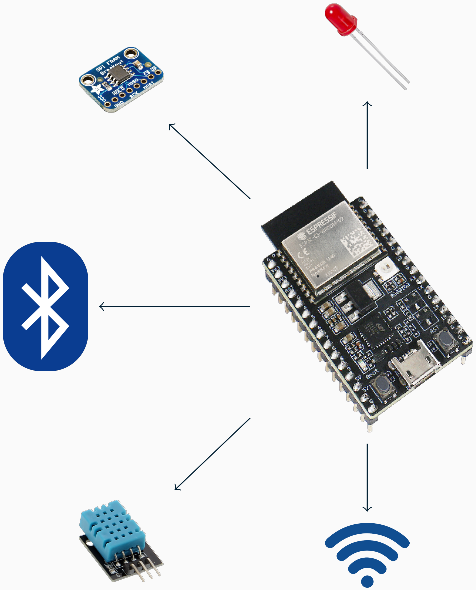

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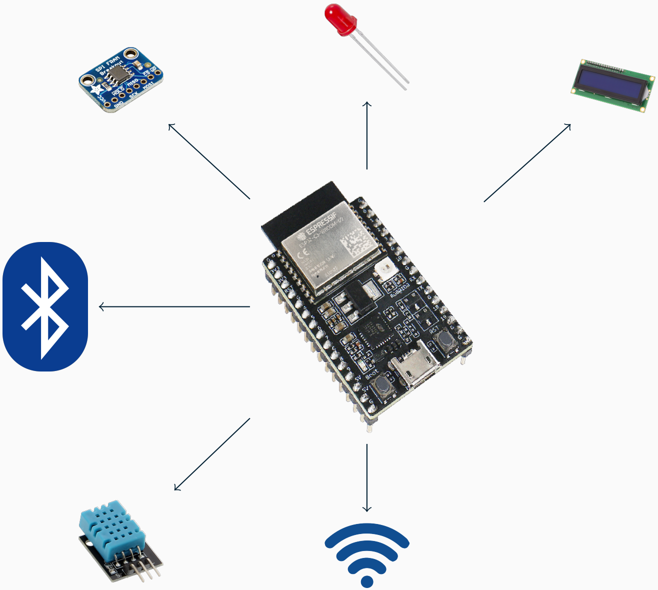

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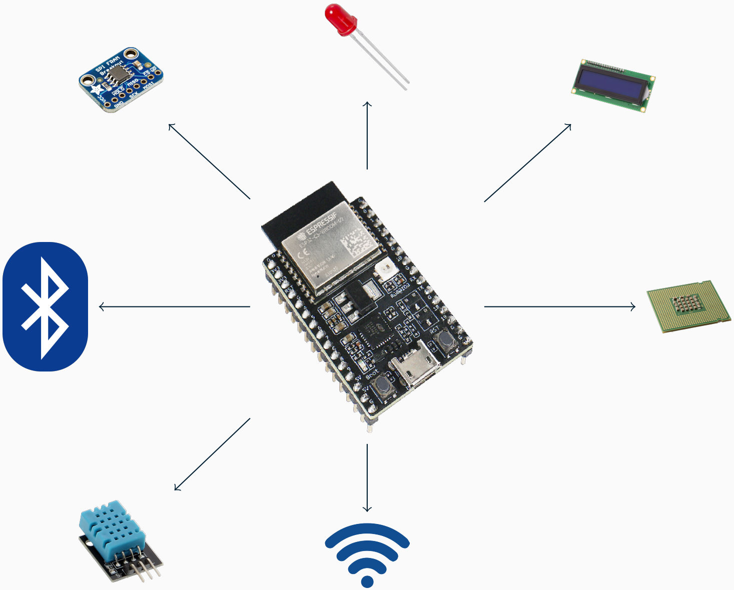

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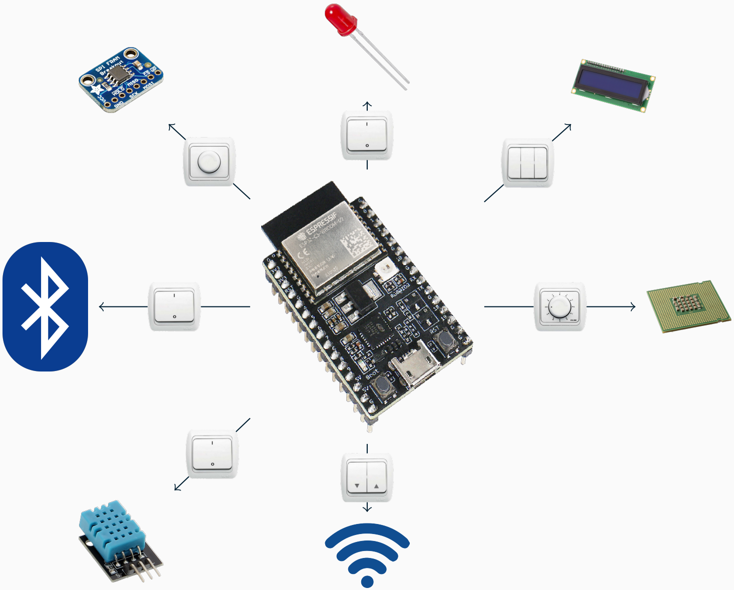

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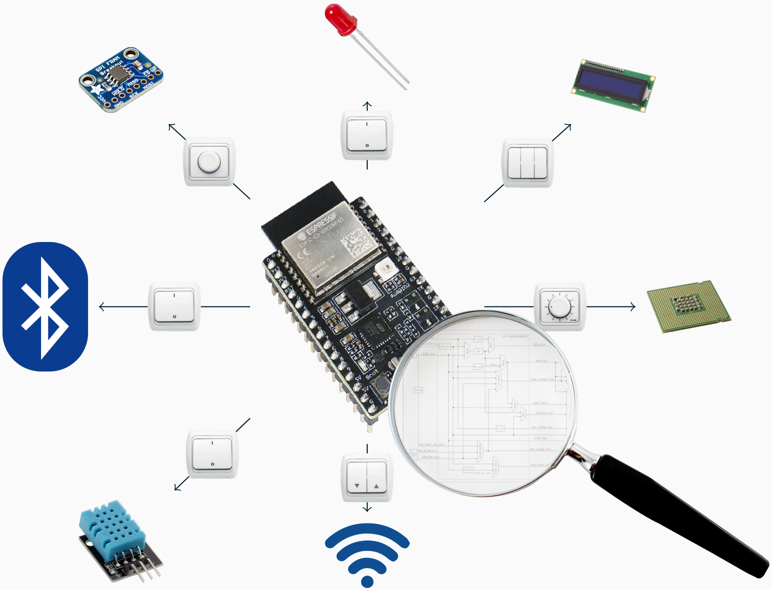
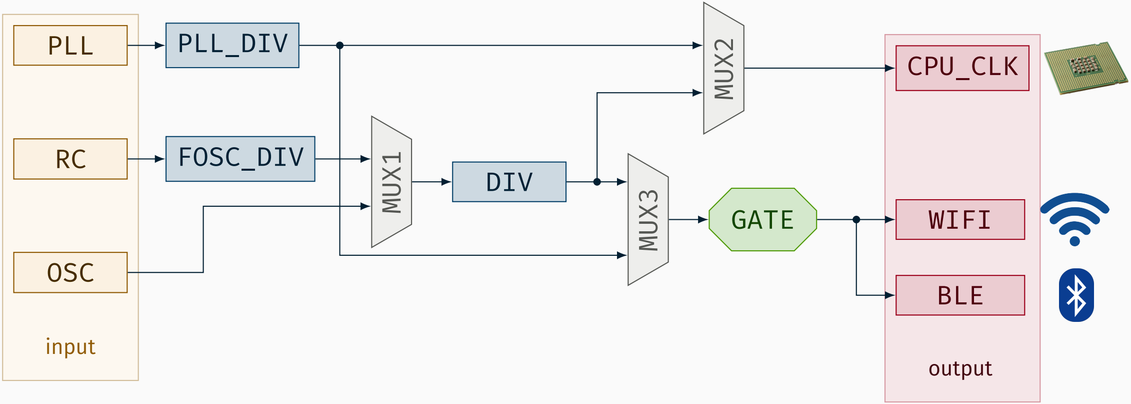


The Clock Tree



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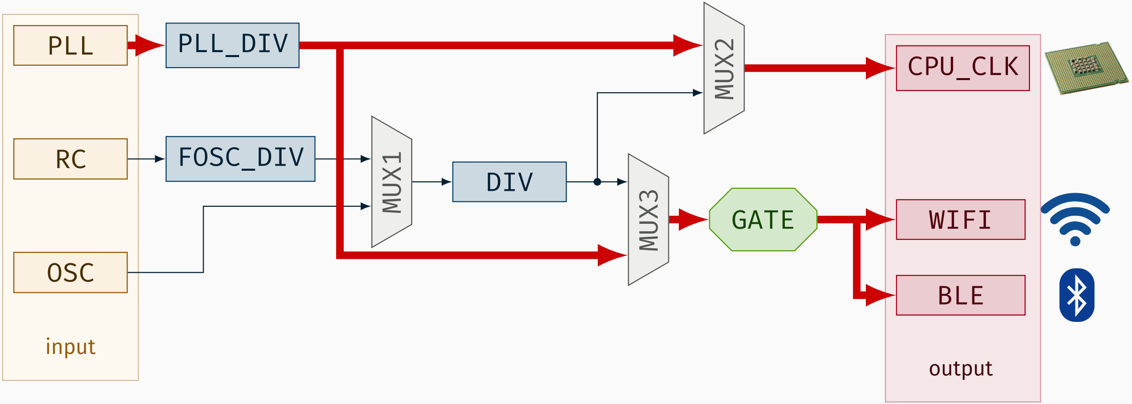

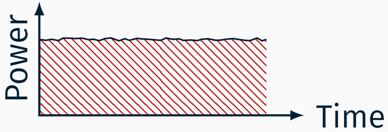

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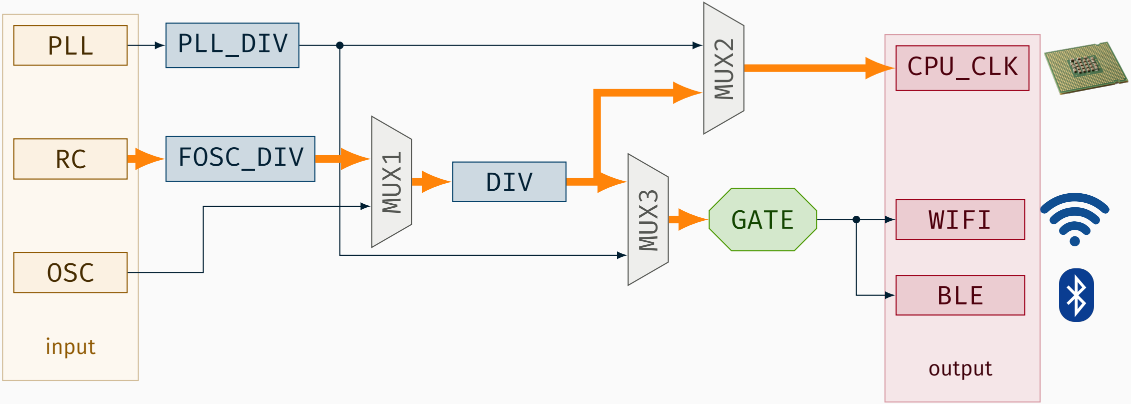
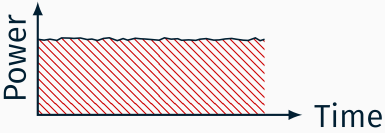
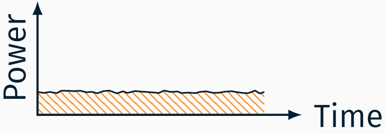




v.s.



Problem Description

System Model / Requirements for FusionClock

- single-core platforms

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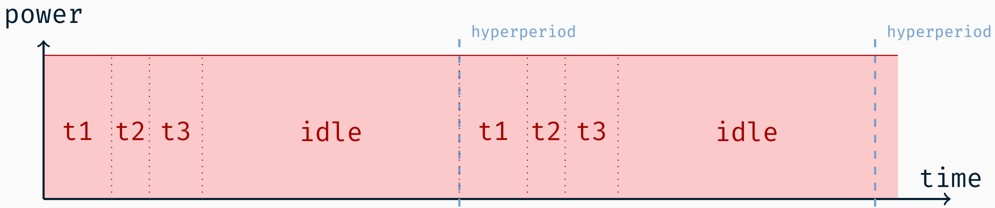
- single-core platforms
  - configurable via **clock tree**
- static and sound model of the system for WCET/WCEC analyses
  - including the **devices** of the system
- strictly periodic, cyclic task model
  - **time-triggered schedule**

Problem Analysis



all-always-on approach

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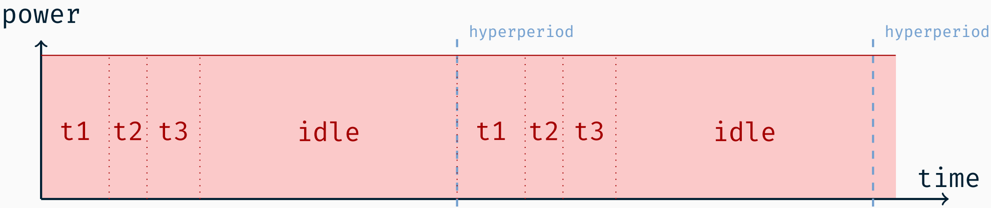

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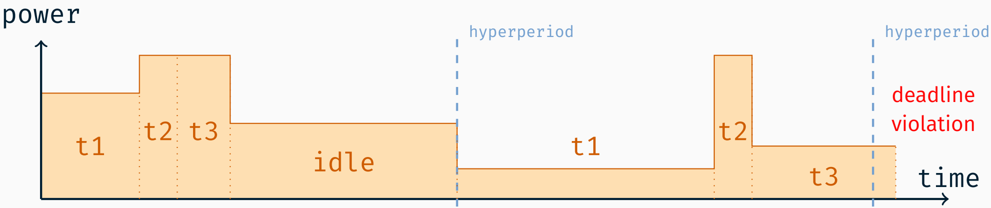
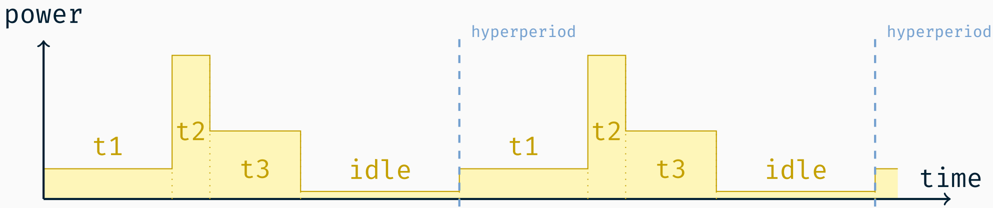


feedback-based approach: reconfigurations during execution

- minimzation of energy consumption
- × real-time guarantees

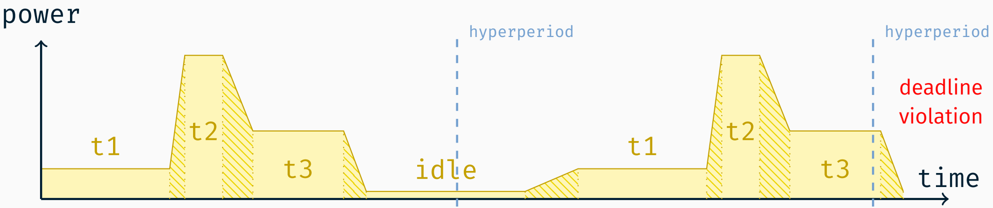
Problem Analysis



static approach: analysis before execution

- minimzation of energy consumption
- real-time guarantees

Problem Analysis



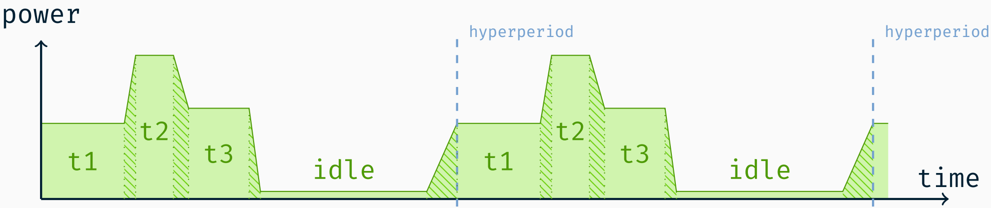
static approach without reconfiguration penalties

- 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



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- ✓ 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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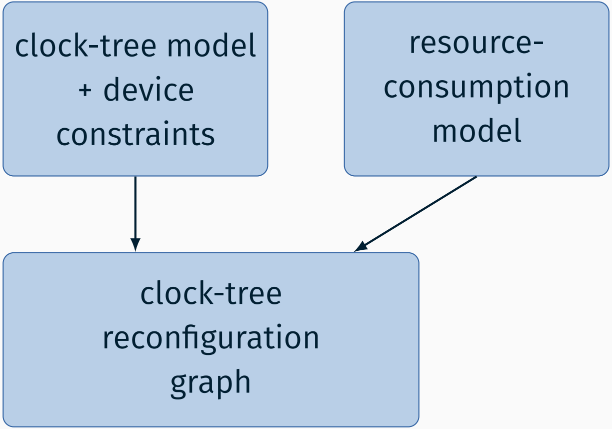

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resource-consumption model

clock-tree reconfiguration graph

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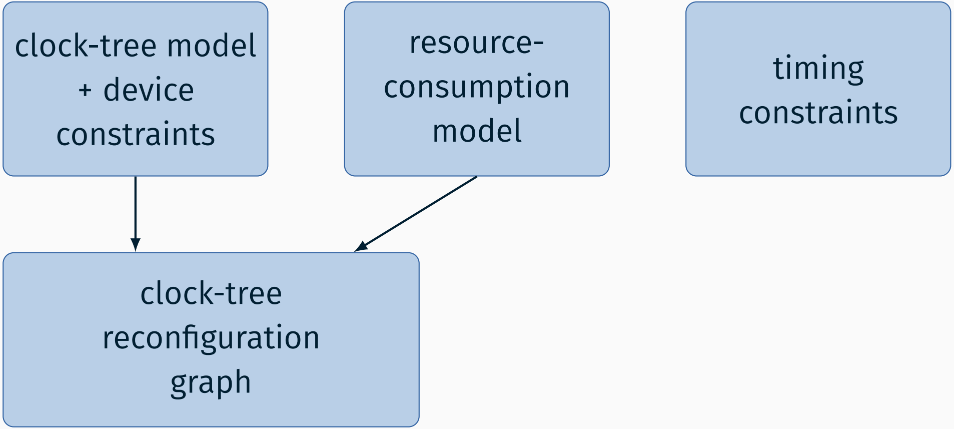
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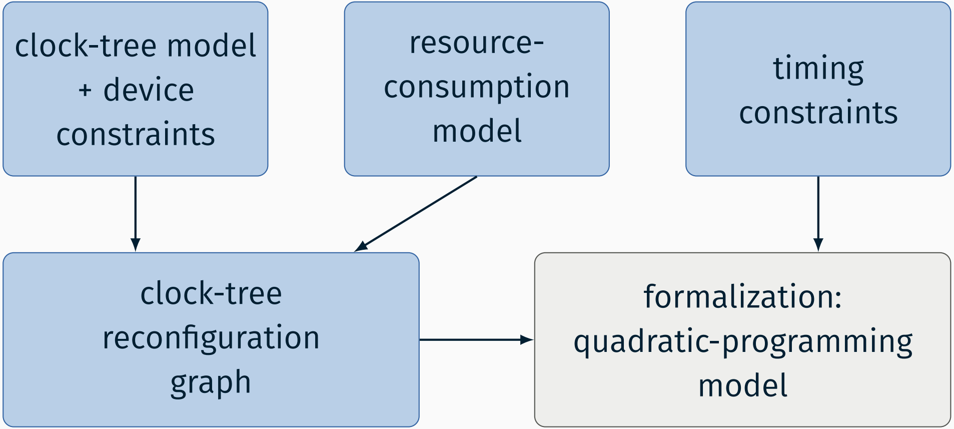
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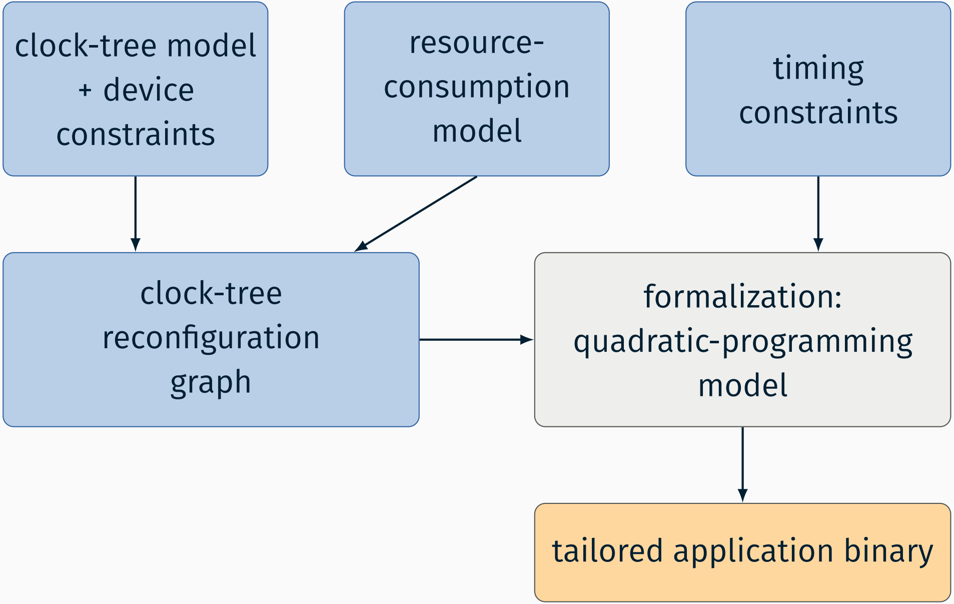

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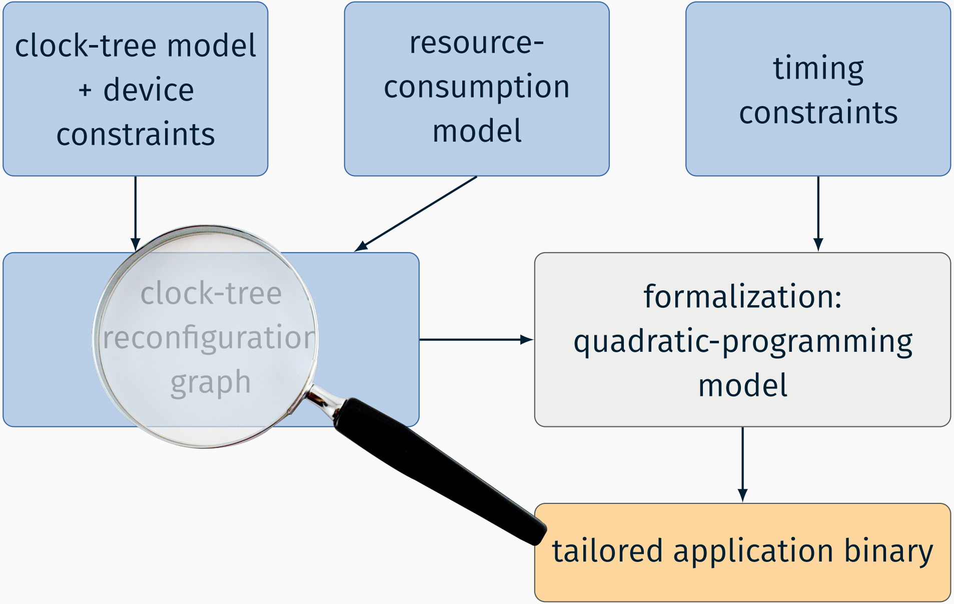

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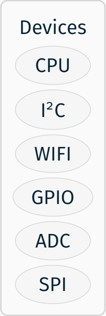
Clock-Tree Reconfiguration Graph



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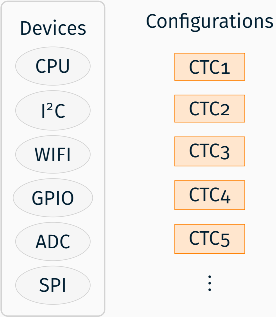

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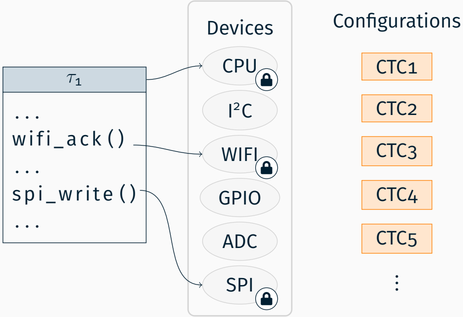

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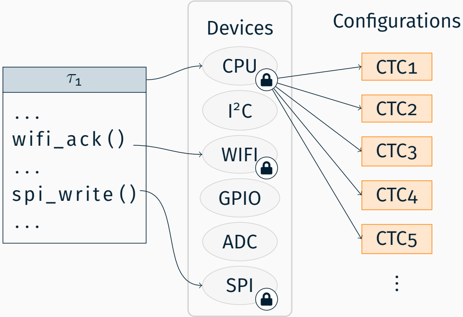

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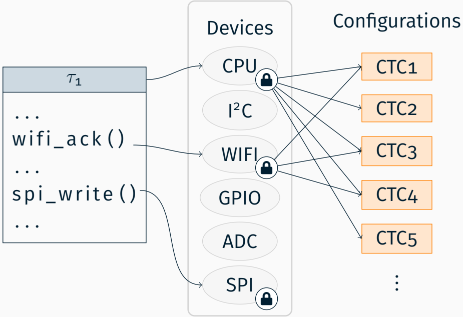

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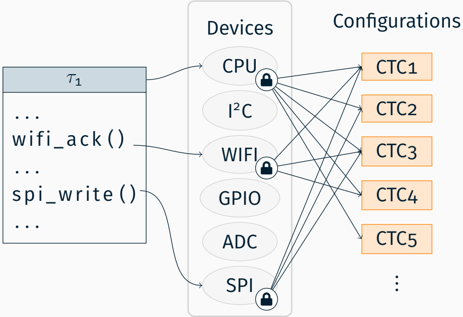

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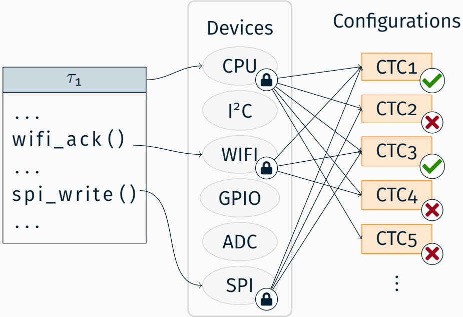

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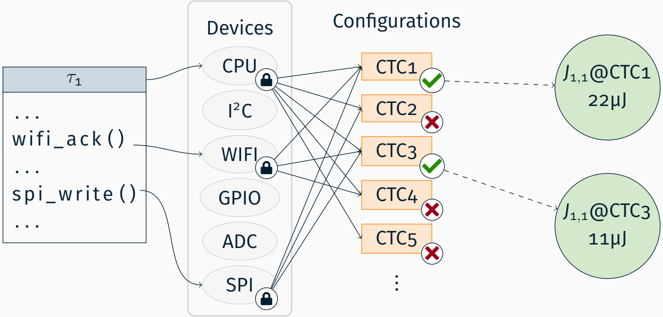

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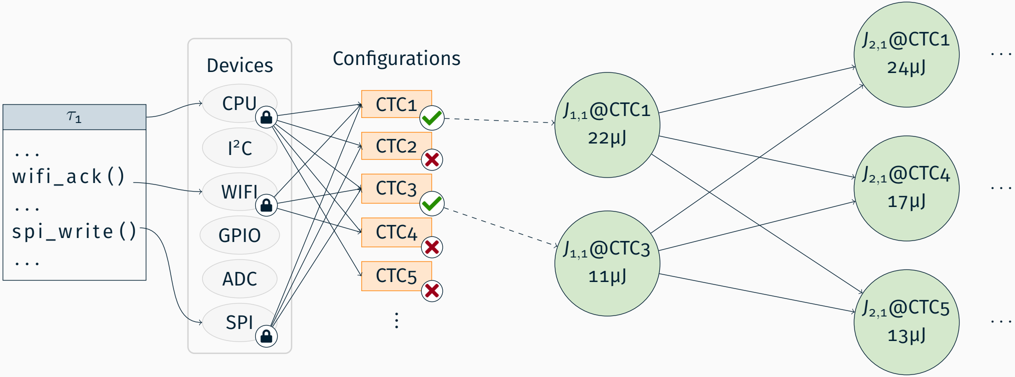

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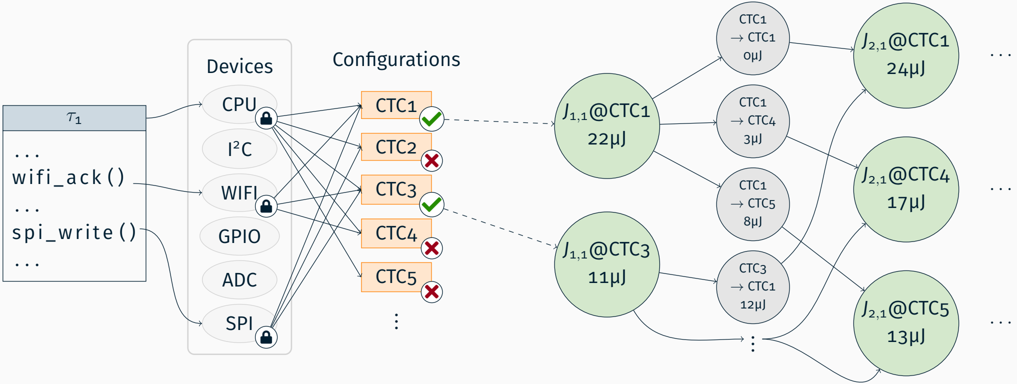

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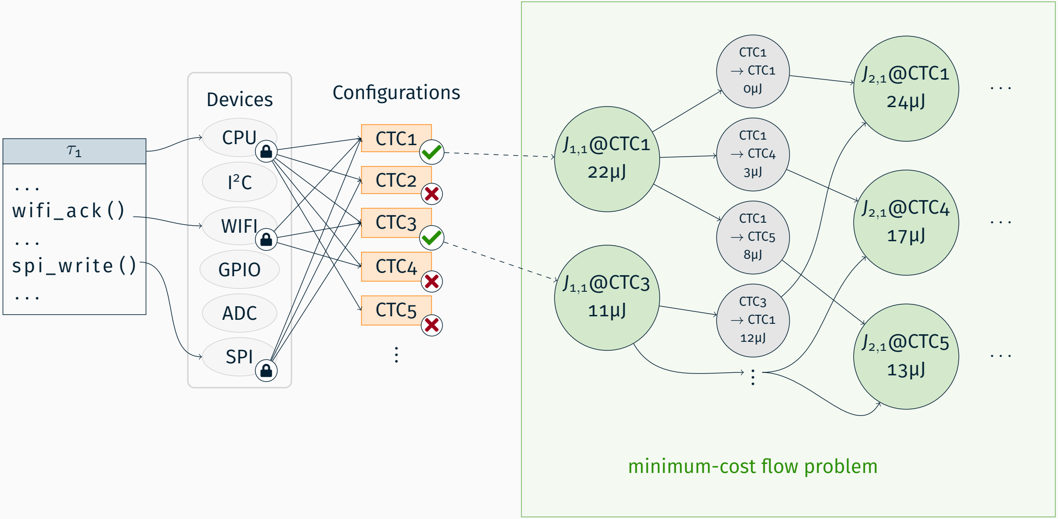
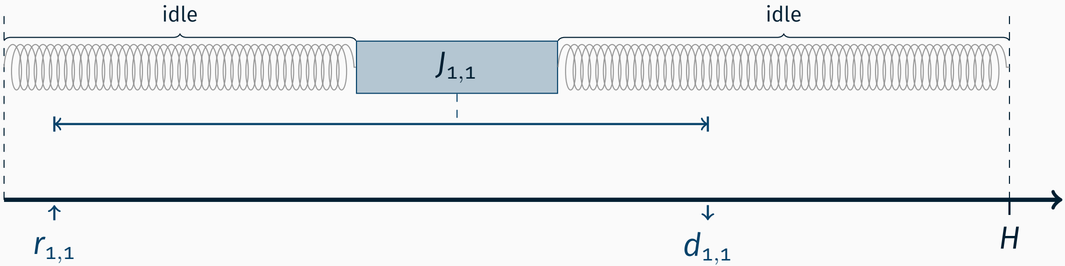


Incorporation of a Time-Triggered Schedule



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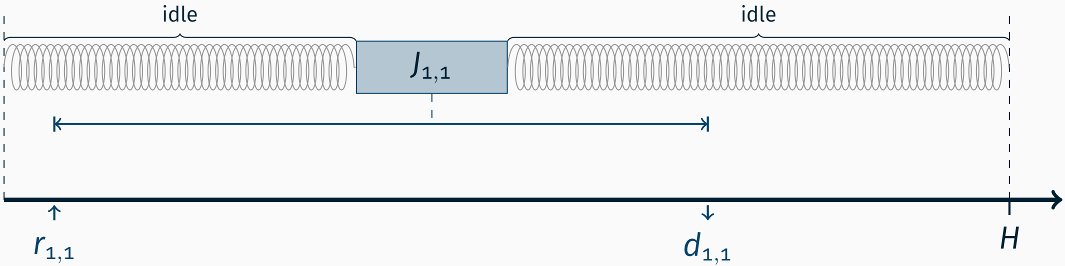

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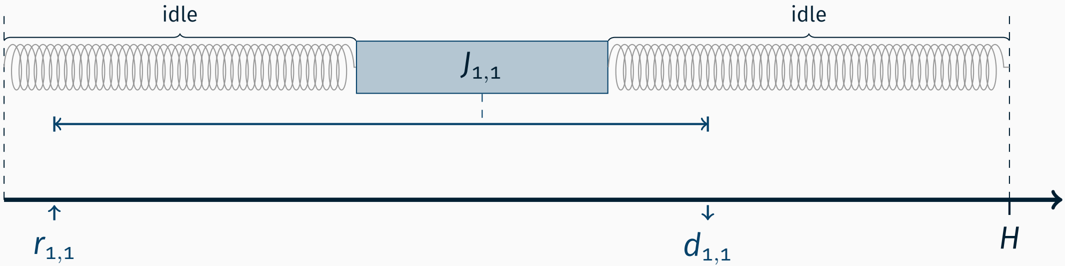

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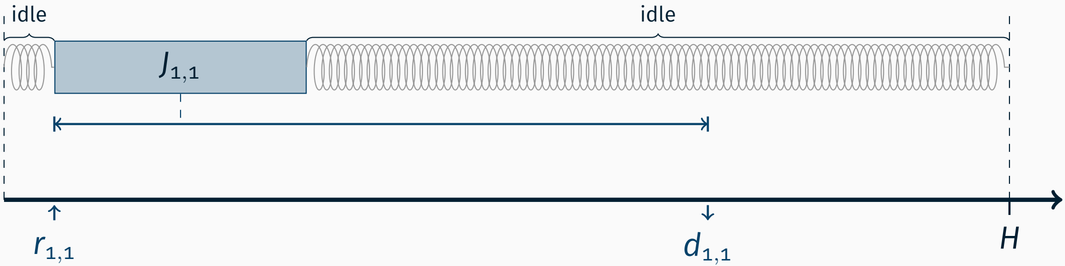

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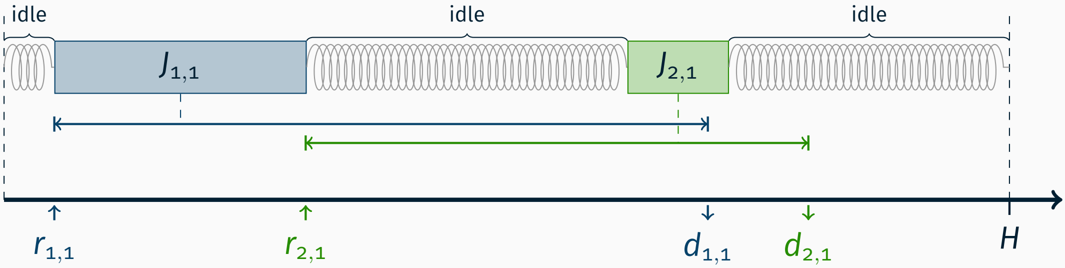

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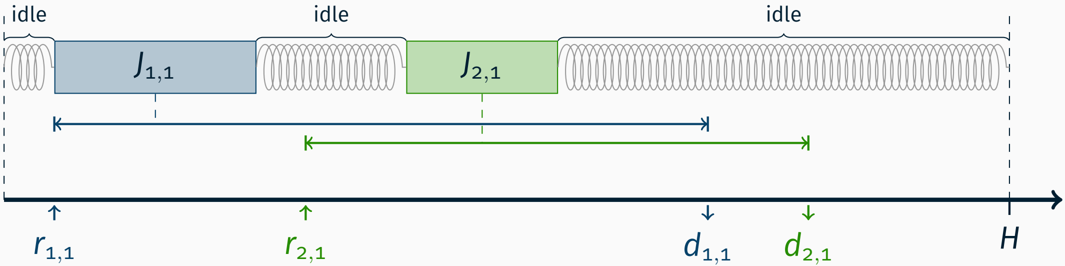

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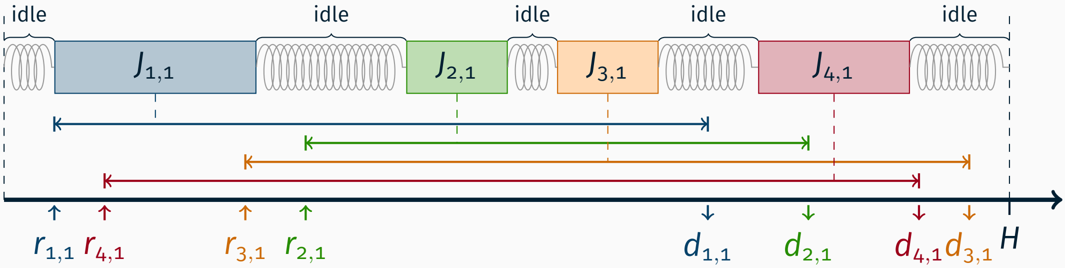

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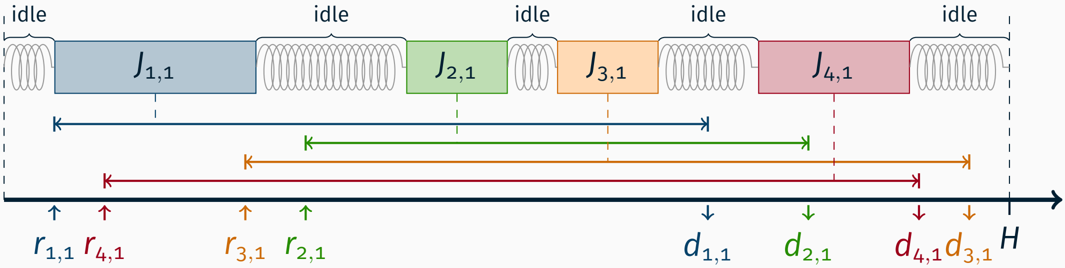

Distributing the slack:

- **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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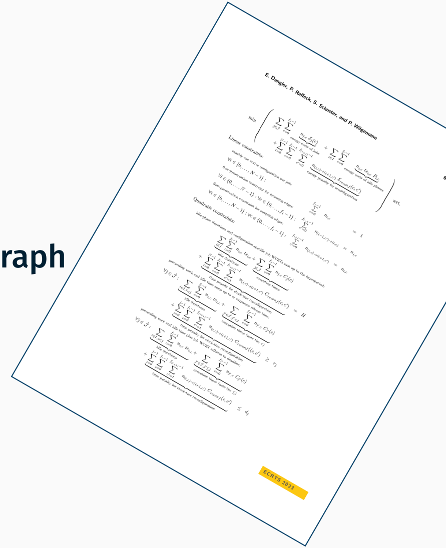

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$$\min \left(\sum_{j\in\mathcal{J}} \sum_{c=0}^{f_j-1} \underbrace{n_{j,c}\,\mathcal{E}_j(c)}_{\text{energy costs of jobs}} + \sum_{i\in\mathcal{I}} \sum_{c=0}^{f_i-1} \underbrace{n_{i,c}\,ts_{i,c}\,P_{i,c}}_{\text{energy costs of idle phases}} + \sum_{i=0}^{N-1} \sum_{c=0}^{f_i-1} \sum_{c'=0}^{f_{(i+1)}-1} \underbrace{n_{(i,c)\to(i+1,c')}\,\mathcal{E}_{reconf}(c,c')}_{\text{energy penalty for reconfiguration}} \right) \text{wrt.}$$

Linear constraints:

exactly one active configuration per job:

$$\forall i \in \{0,\dots,N-1\}: \quad \sum_{c=0}^{f_i-1} n_{i,c} = 1$$

flow-preservation constraint for incoming edges:

$$\forall i \in \{0,\dots,N-1\}: \forall c \in \{0,\dots,f_i-1\}: \quad \sum_{c'=0}^{f_{i-1}-1} n_{(i-1,c')\to(i,c)} = n_{i,c}$$

flow-preservation constraint for outgoing edges:

$$\forall i \in \{0,\dots,N-1\}: \forall c \in \{0,\dots,f_i-1\}: \quad \sum_{c'=0}^{f_{i+1}-1} n_{(i,c)\to(i+1,c')} = n_{i,c}$$

Quadratic constraints:

idle-phase durations and configuration-specific job WCETs sum up to the hyperperiod:

$$\underbrace{\sum_{i\in\mathcal{I}} \sum_{c=0}^{f_i-1} n_{i,c}\,ts_{i,c}}_{\text{idle durations}} + \underbrace{\sum_{j\in\mathcal{J}} \sum_{c=0}^{f_j-1} n_{j,c}\,C_j(c)}_{\text{execution times}} + \underbrace{\sum_{i=0}^{N-1} \sum_{c=0}^{f_i-1} \sum_{c'=1}^{f_{(i+1)}-1} n_{(i,c)\to(i+1,c')}\,C_{reconf}(c,c')}_{\text{time penalty for clock-tree reconfiguration}} = H$$

preceding work and idle time sums up to or surpasses release time:

$$\forall j \in \mathcal{J}: \quad \underbrace{\sum_{i\in\mathcal{I},i<j} \sum_{c=0}^{f_i-1} n_{i,c}\,ts_{i,c}}_{\text{idle durations}} + \underbrace{\sum_{j'\in\mathcal{J},j'<j} \sum_{c=0}^{f_{j'}-1} n_{j',c}\,C_{j'}(c)}_{\text{execution times (note the <)}} + \underbrace{\sum_{i=0}^{j-1} \sum_{c=0}^{f_i-1} \sum_{c'=1}^{f_{(i+1)}-1} n_{(i,c)\to(i+1,c')}\,C_{reconf}((c,c')}_{\text{time penalty for clock-tree reconfiguration}} \geq r_j$$

preceding work and idle time plus job WCET adheres to deadline:

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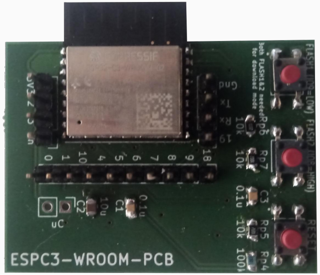
Evaluation

Evaluation Hardware



Evaluation: Break-Even Point Analysis

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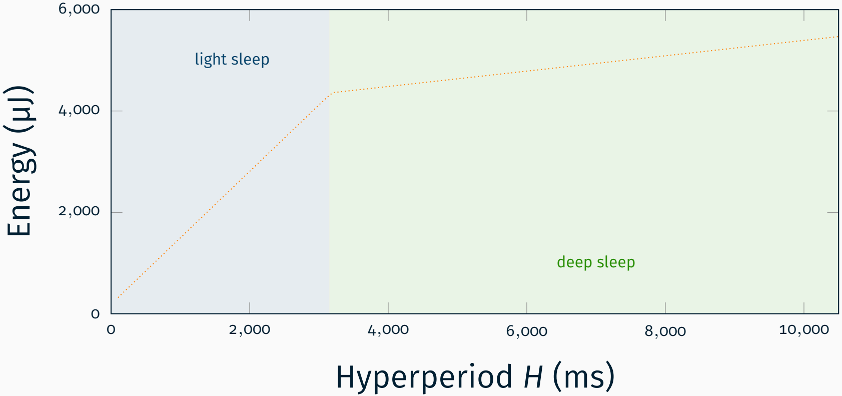
- 5 CTCs: which one is used for the compute task?
- 3 idle options: when do the energy savings outweigh the reconfiguration penalties?
- how do actual measurements compare to the predicted energy consumptions?

Evaluation: Break-Even Point Analysis



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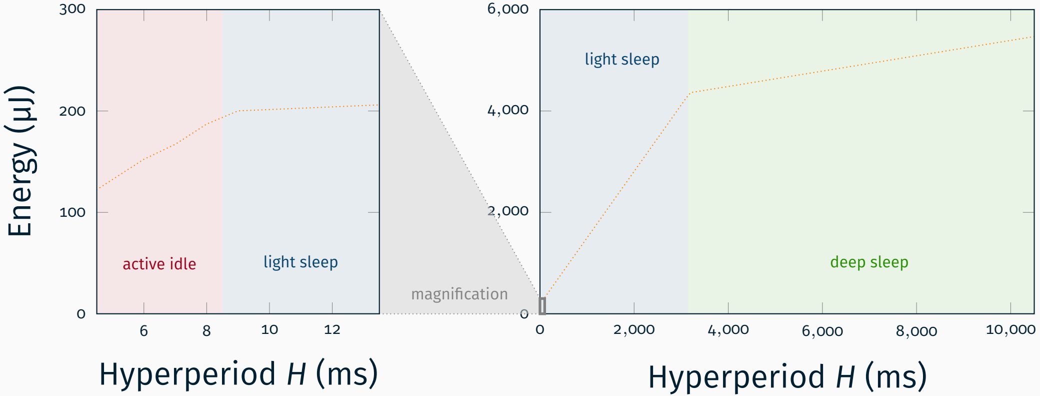

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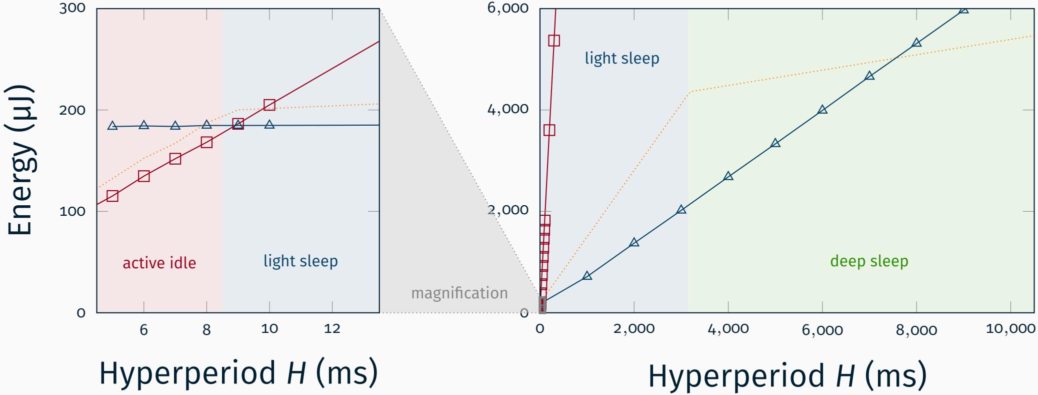

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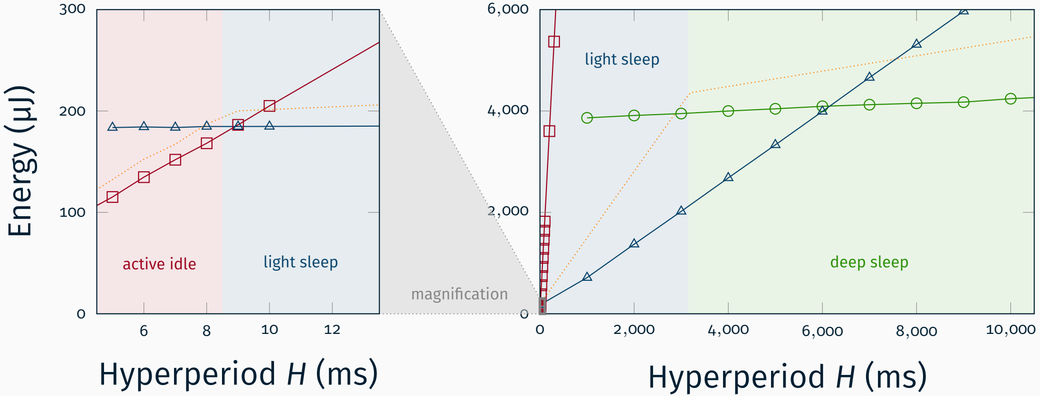

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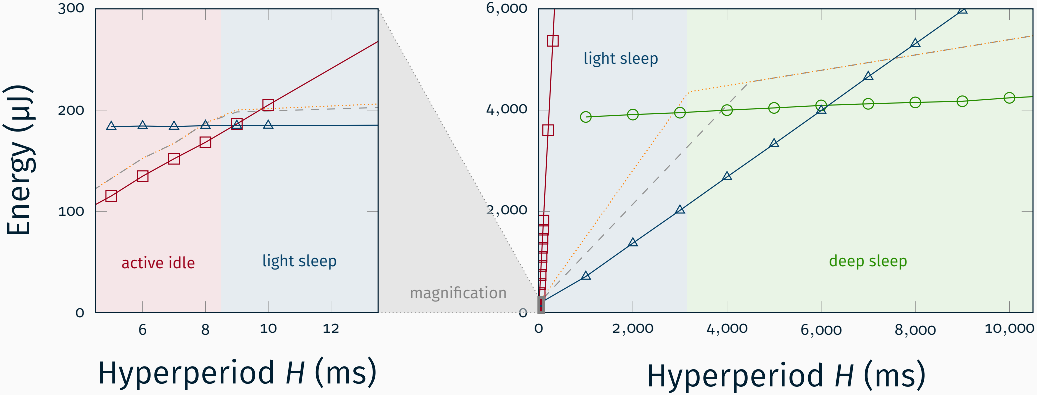

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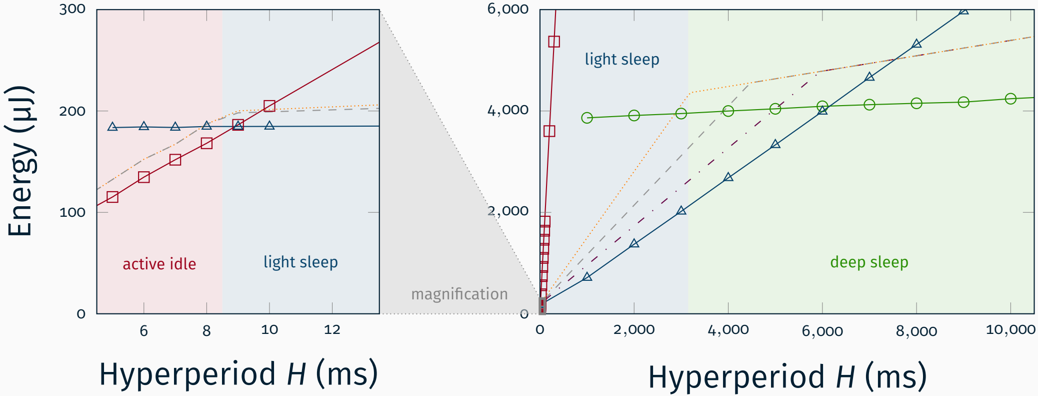

Evaluation: Taskset Generation

Does FusionClock ...

- ... determine a reliable upper bound?
- ... minimze energy consumption in comparison to device-unselective approaches?

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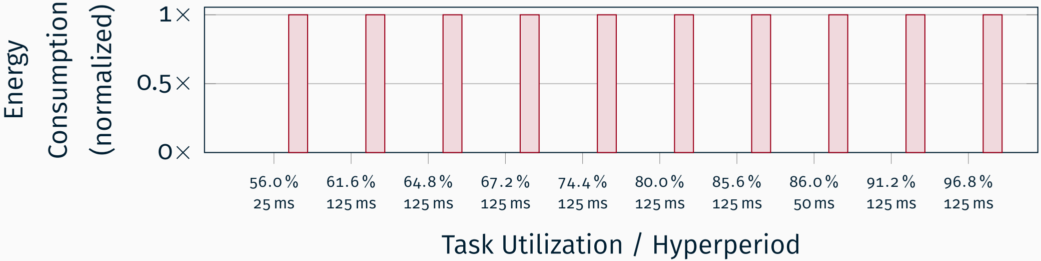
Evaluation with generated tasksets:

- 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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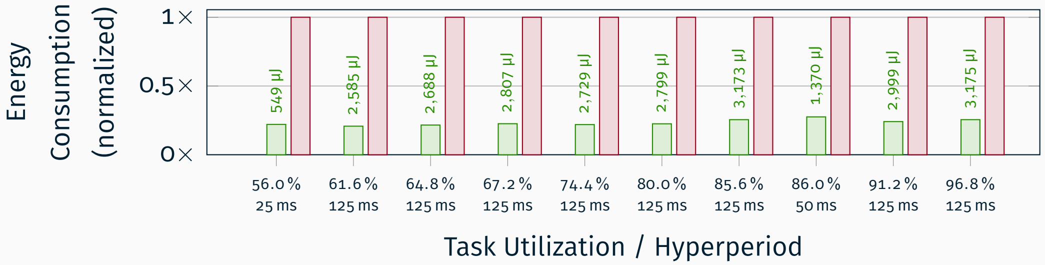

predicted energy consumption

binary without clock-tree reconfigurations

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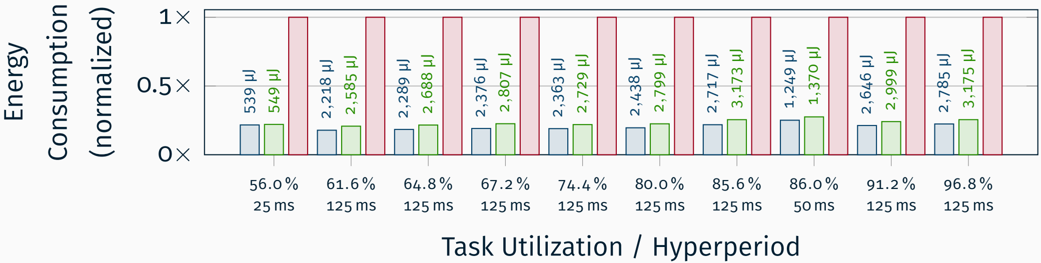

tailored application binary

predicted energy consumption

binary without clock-tree reconfigurations

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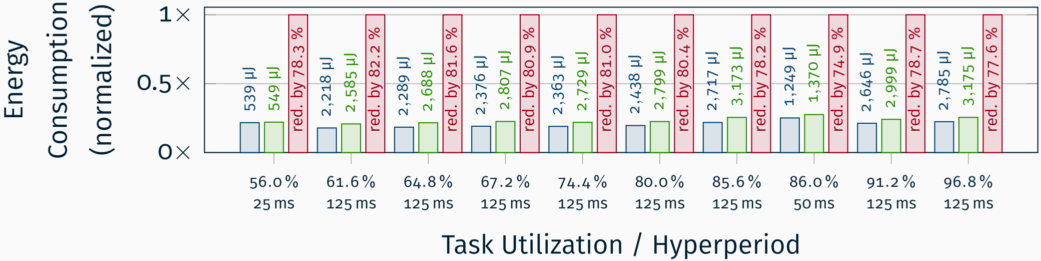

tailored application binary

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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
3. missing reconfiguration penalties

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   ✓ **inclusion of clock-tree reconfiguration costs in optimization**

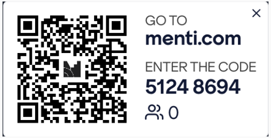
Questions?

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.

ECRTS * Artifact * AE * Evaluated *
Consistent * Complete * Well Documented * Easy to Reuse *



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