Steady-State Dynamic Temperature Analysis and Reliability Optimization for Embedded Multiprocessor Systems

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I. Steady-State Dynamic Temperature Analysis

Introduction

- Temperature is important.

Temperature Analysis

- Steady-State Temperature Analysis.
- Transient Temperature Analysis.
- Steady-State Dynamic Temperature Analysis.

Architecture Model

- Multiprocessor systems running periodic applications.

$$\Pi = \{\pi_i = (V_i,\ f_i,\ N_{gate\ i})\}$$

Core

Voltage

Frequency

Number of gates

Power Model

- Total Power = Dynamic Power + Leakage Power

$$P_{dyn} = C_{eff} \cdot f \cdot V^2$$

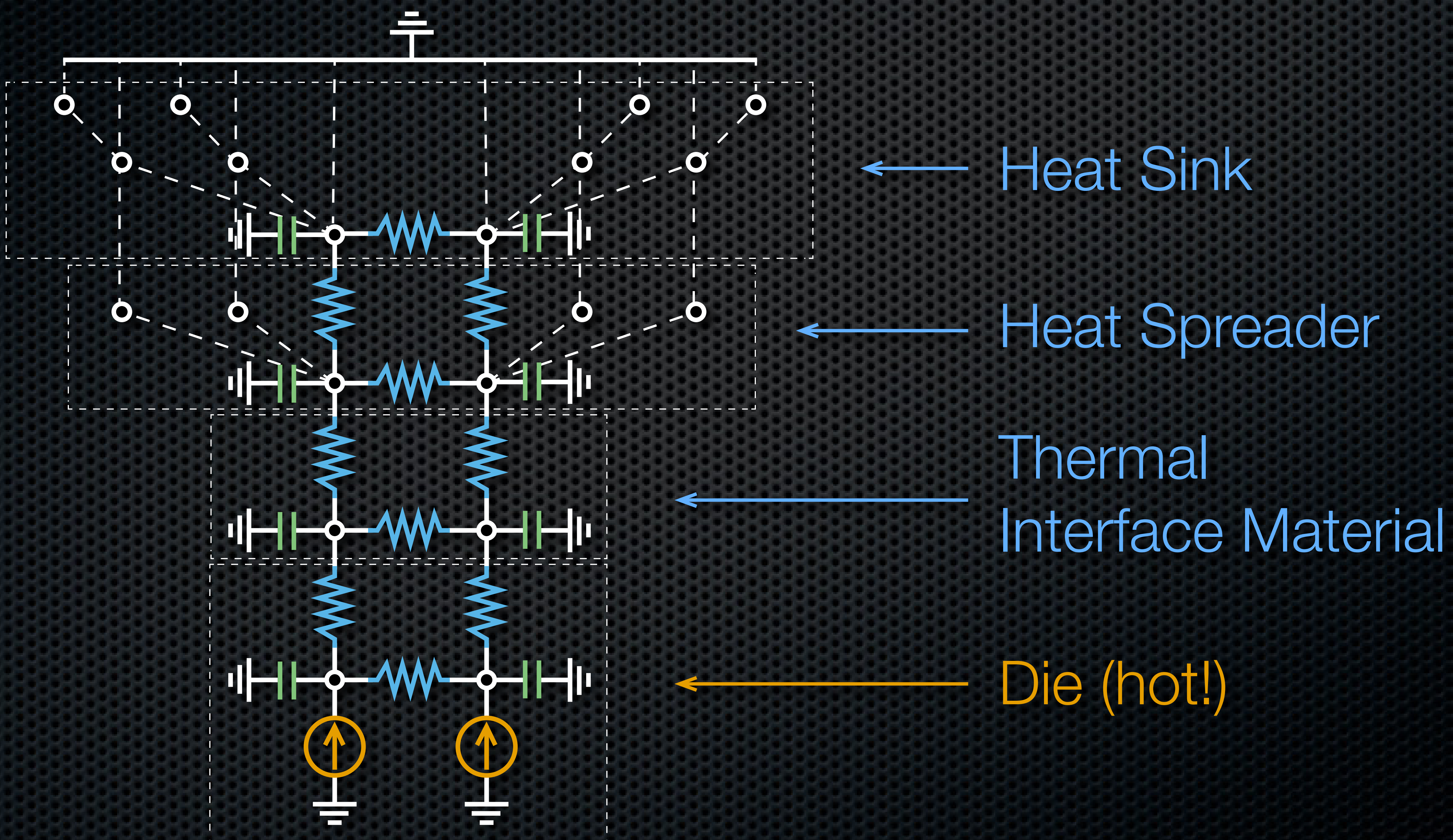
$$P_{leak}(T) = N_{gate}\, V\, I_0 \left[A\, T^2 e^{\frac{\alpha\, V + \beta}{T}} + B e^{(\gamma\, V + \delta)} \right]$$

Exponent

Temperature

Thermal Model: RC Analogy

- How to model temperature? Construct a circuit!



Thermal Model: Heat Equation

- System of differential equations.

$$\mathbf{C}\,\frac{d\mathbf{T}(t)}{dt} + \mathbf{G}\left(\mathbf{T}(t) - \mathbf{T}_{amb}\right) = \mathbf{P}(t)$$

Capacitance

Conductance

Temperature

Power

Power & Temperature Profiles

- Discrete dynamic power profile:

For all cores and all time intervals

$$\mathbb{P}_{dyn} \stackrel{\text{def}}{=} \{P_{ij} : \forall i, j\}$$

- Steady-State Dynamic Temperature Profile (SSDTP):

$$\mathbb{T} \stackrel{\text{def}}{=} \{T_{ij} : \forall i, j\}$$

Problem Formulation

Given:

- Multiprocessor architecture.
- Periodic dynamic power profile.
- Floorplan of the die.
- Configuration of the thermal package.

$$\mathbb{P}_{dyn}$$

$$\Downarrow$$

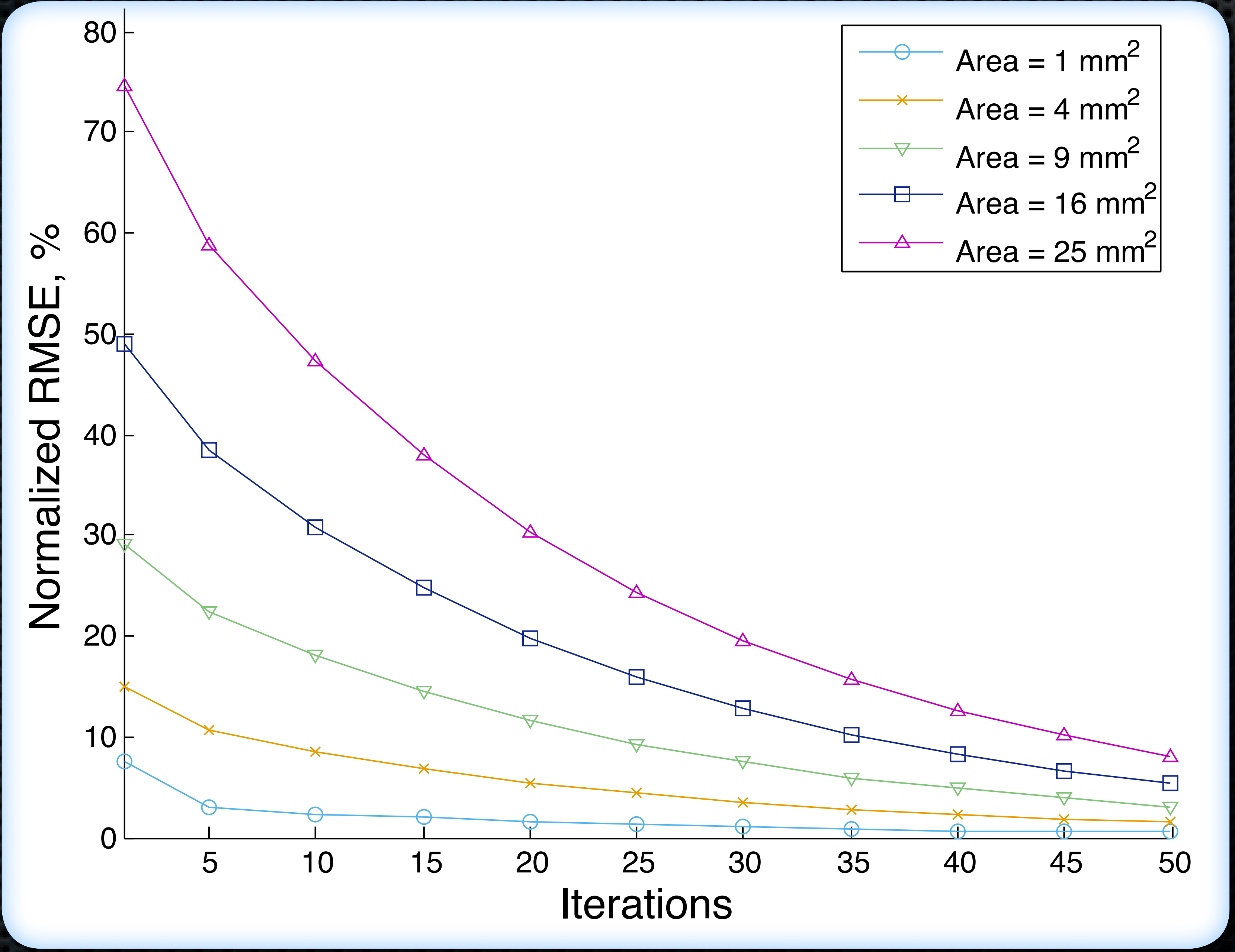
$$\mathbb{T}$$

Find:

- Periodic temperature profile (SSDTP).

State of the Art Solutions: TTA

- Looong transient temperature simulation.

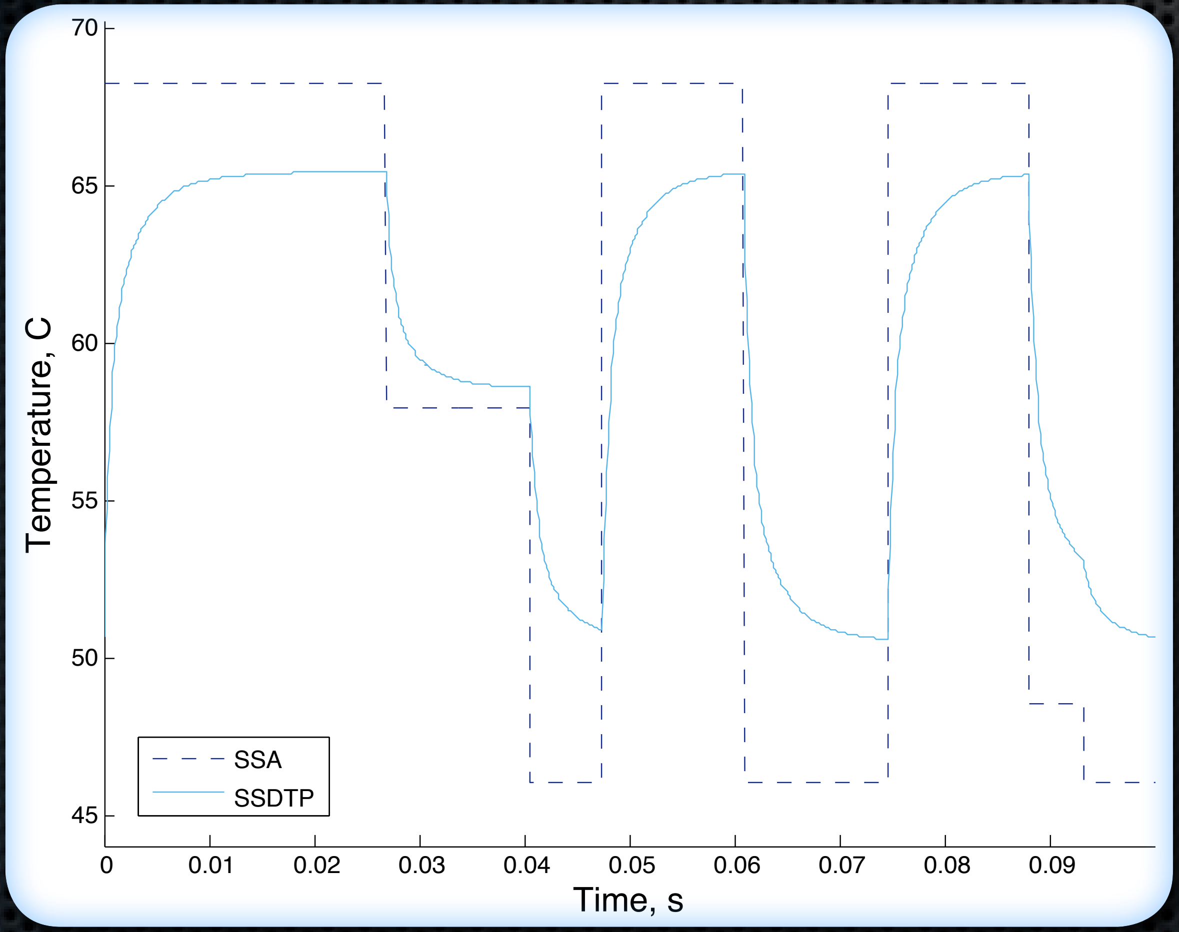


Error

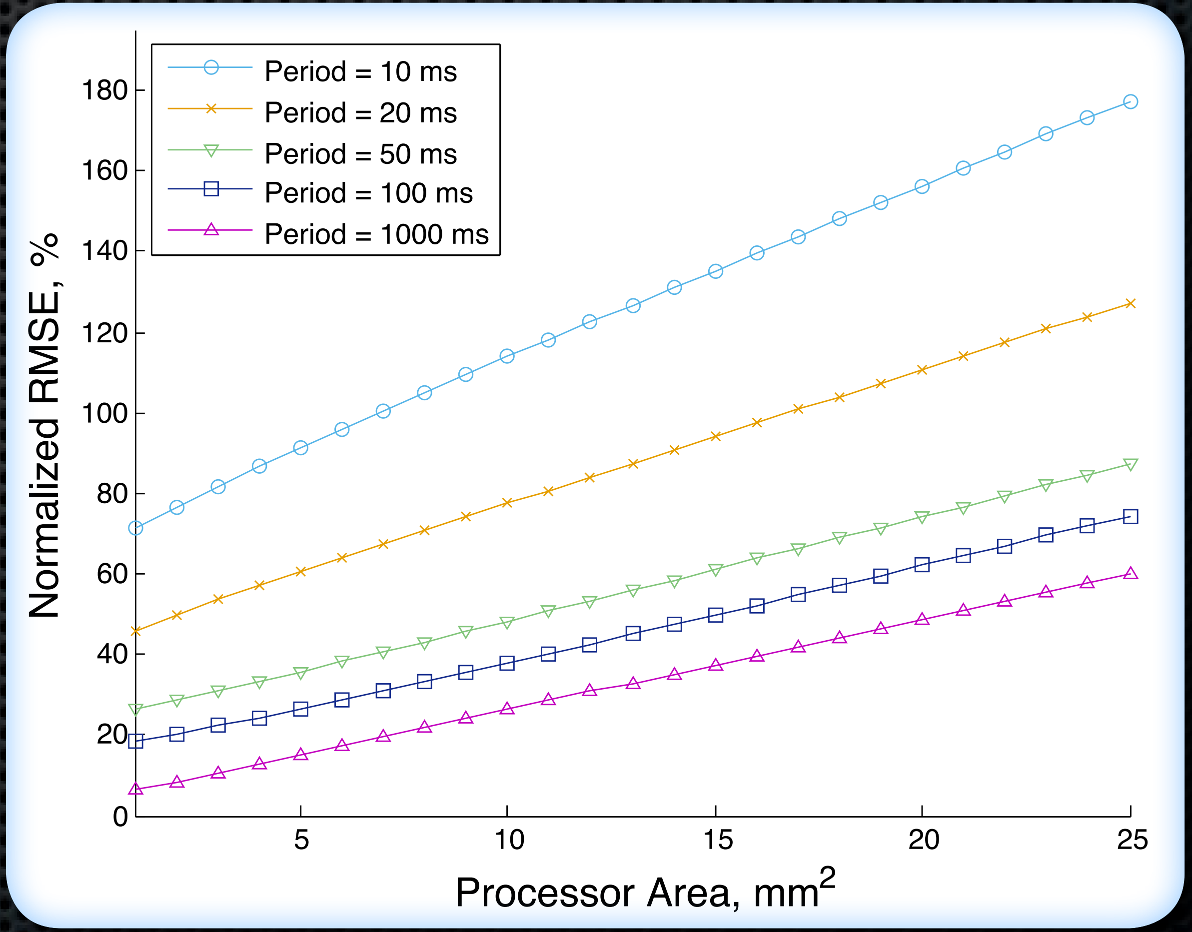
State of the Art Solutions: SSA

- Approximation with steady-state temperature.

Example



Error



Analytical Solution

- Heat equation can be solved analytically*.

$$\mathbf{T}(t) = e^{\mathbf{A}t}\,\mathbf{T}_0 + \mathbf{A}^{-1}(e^{\mathbf{A}t} - \mathbf{I})\,\mathbf{C}^{-1}\mathbf{P}$$

Transient Temperature Analysis

Steady-State Dynamic Temperature Analysis

Recurrence for SSDTP

- Recurrent equation with a boundary condition.

$$\mathbf{T}_{i+1} = \mathbf{K}_i\,\mathbf{T}_i + \mathbf{B}_i\,\mathbf{P}_i$$

$$i = 0, \ldots, N_s - 1$$

$$\mathbf{T}_0 = \mathbf{T}_{N_s}$$

Number of steps

Linear System

- System of linear equations.

$$\mathbb{A}\mathbb{X} = \mathbb{B}$$

$$N_n N_s \times N_n N_s$$

Number of nodes

Number of steps

Straight-Forward Solutions

- Direct dense and sparse solvers.
- Iterative solutions.
- Block Toeplitz and circulant approaches (e.g., FFT).

Do not consider the structure.
Do not consider the sparseness.

Slow

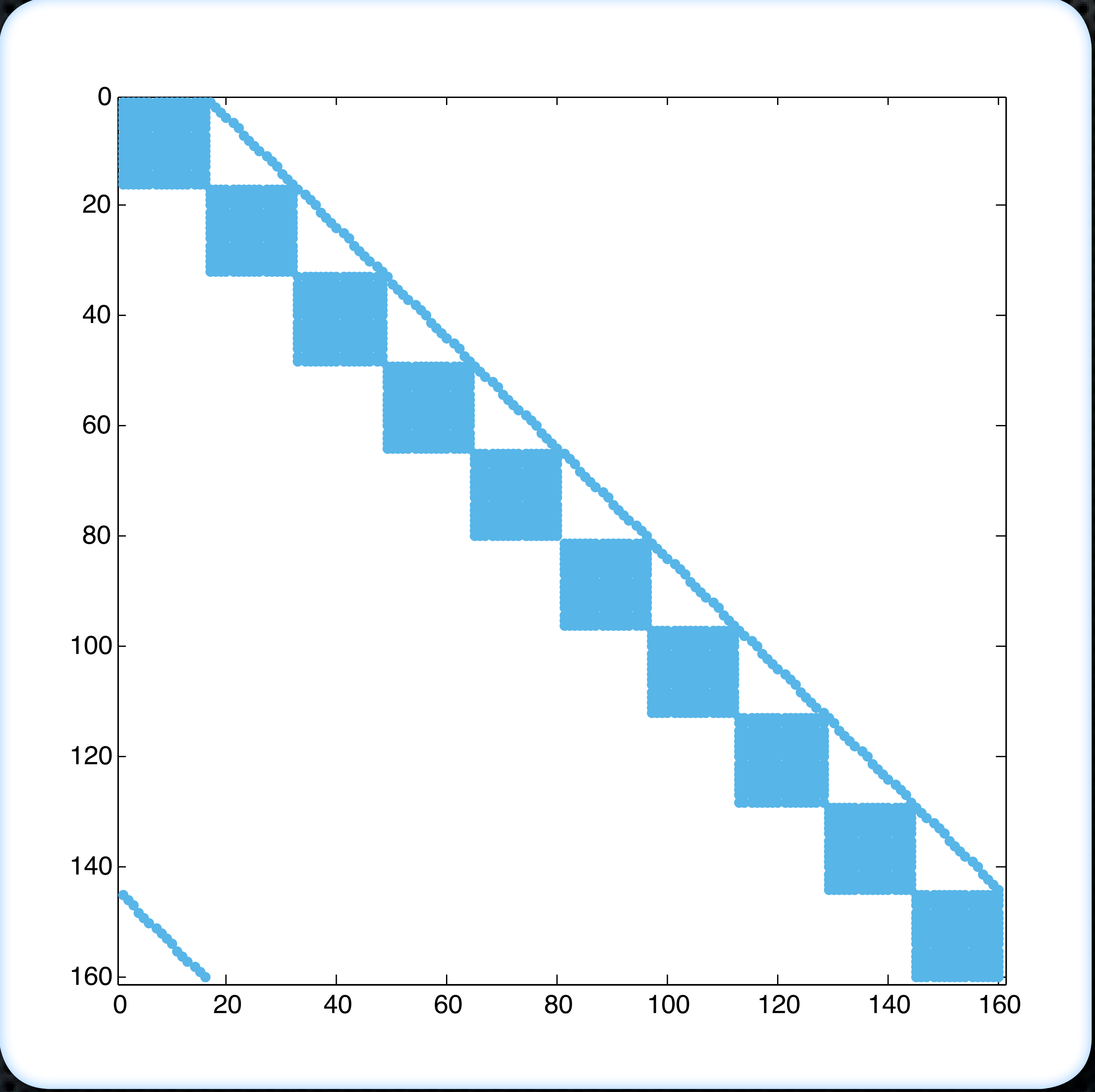
$\propto N_s^3 N_n^3$

Memory consuming

Inaccurate

Specific Structure

- One block diagonal + two subdiagonals.



Proposed Method (PM)

$$\propto \cancel{N_s^3} N_n^3$$

$$N_s \gg N_n$$

PM: Auxiliary Transformation

- Expensive operations with matrices.

Exponent

$$e^{\mathbf{A}}$$

$$\mathbf{A}^{-1}$$

Inverse

- But not with symmetric matrices.

Eigenvalue decomposition

$$\mathbf{A} = \mathbf{U}\,\boldsymbol{\Lambda}\,\mathbf{U}^T$$

PM: Condensed Equation

- Two successive recurrences.

$$\mathbf{W}_0 = \tilde{\mathbf{Q}}_0$$
$$\mathbf{W}_i = \tilde{\mathbf{K}}_i \, \mathbf{W}_{i-1} + \mathbf{Q}_i, \;\; i = 1, \ldots, N_s - 1$$

$$\tilde{\mathbf{T}}_0 = \mathbf{U} \left(\mathbf{I} - e^{\tau \boldsymbol{\Lambda}}\right)^{-1} \mathbf{U}^T \, \mathbf{W}_{N_s - 1}$$
$$\tilde{\mathbf{T}}_{i+1} = \tilde{\mathbf{K}}_i \, \tilde{\mathbf{T}}_i + \mathbf{Q}_i, \;\; i = 0, \ldots, N_s - 2$$

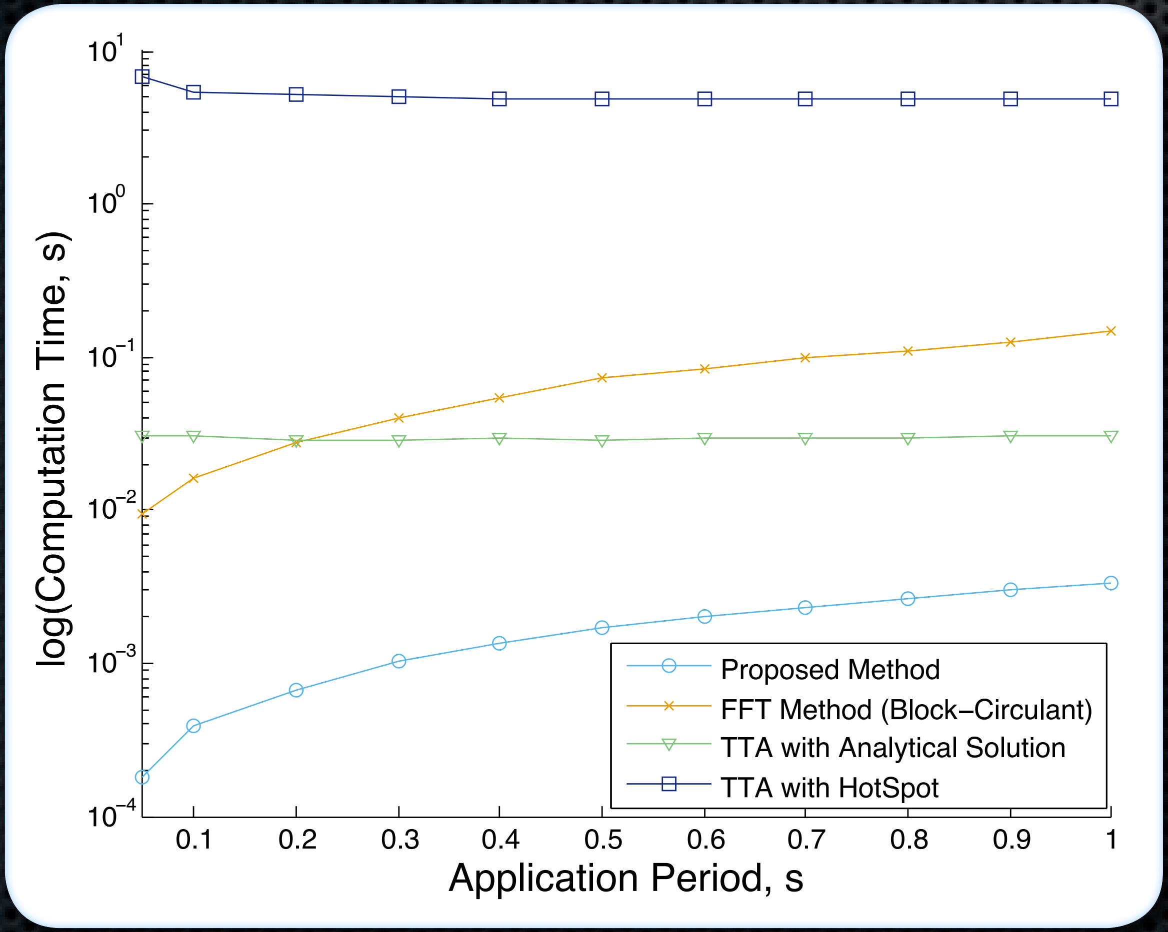
Features of the Proposed Method

- Takes into account the structure.
- Operates on a few small matrices.
- Linearly depends on the number of steps.
- One-time auxiliary work.

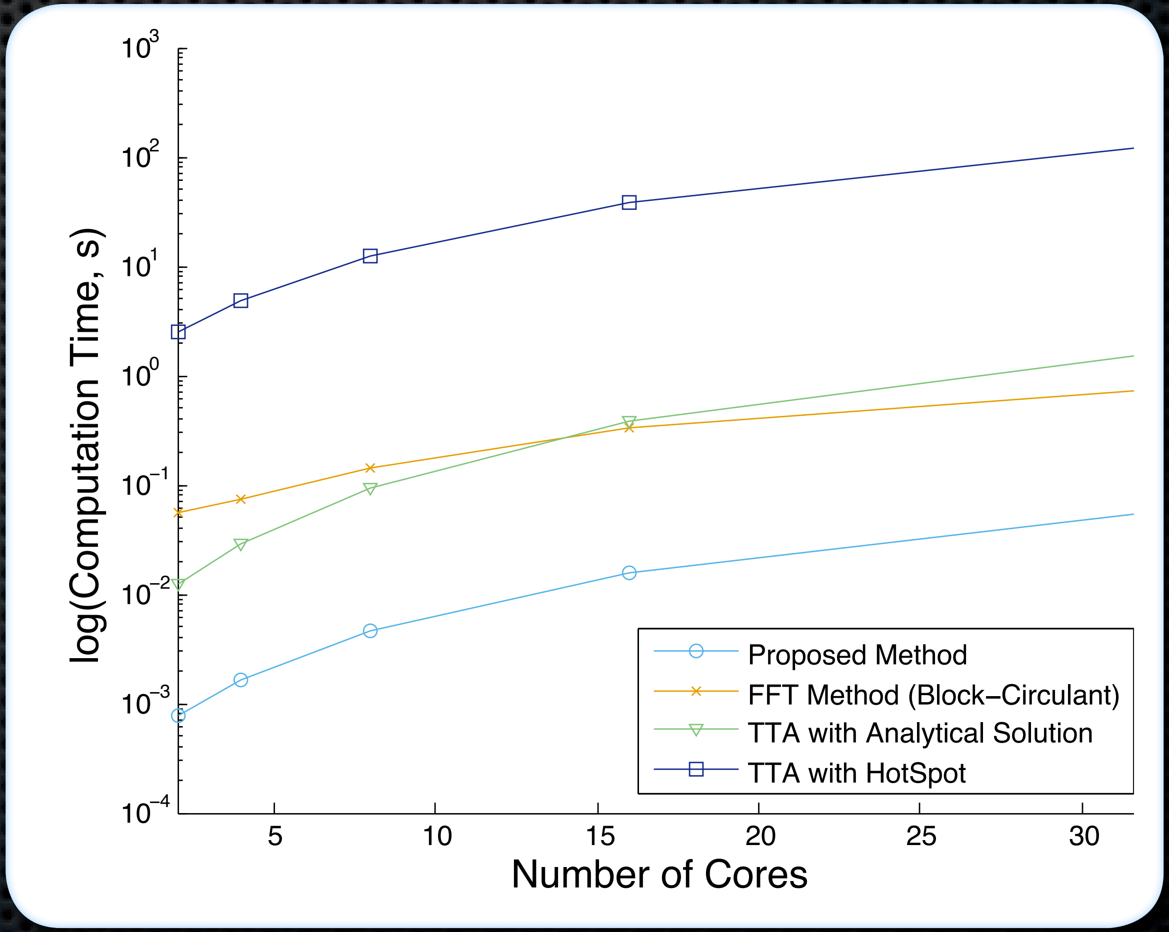
Performance

- 2000–5000 times faster than with HotSpot.

Scalability with period



Scalability with cores



II. Temperature-Aware Reliability Optimization

Application Model

- Task graph of data-dependent tasks.

Application period

$$G = (V,\ E,\ \tau)$$

Core $\pi_j \in \Pi$

Task $v_i \in V$

$$\rightarrow (N_{clock\,ij}, C_{eff\,ij})$$

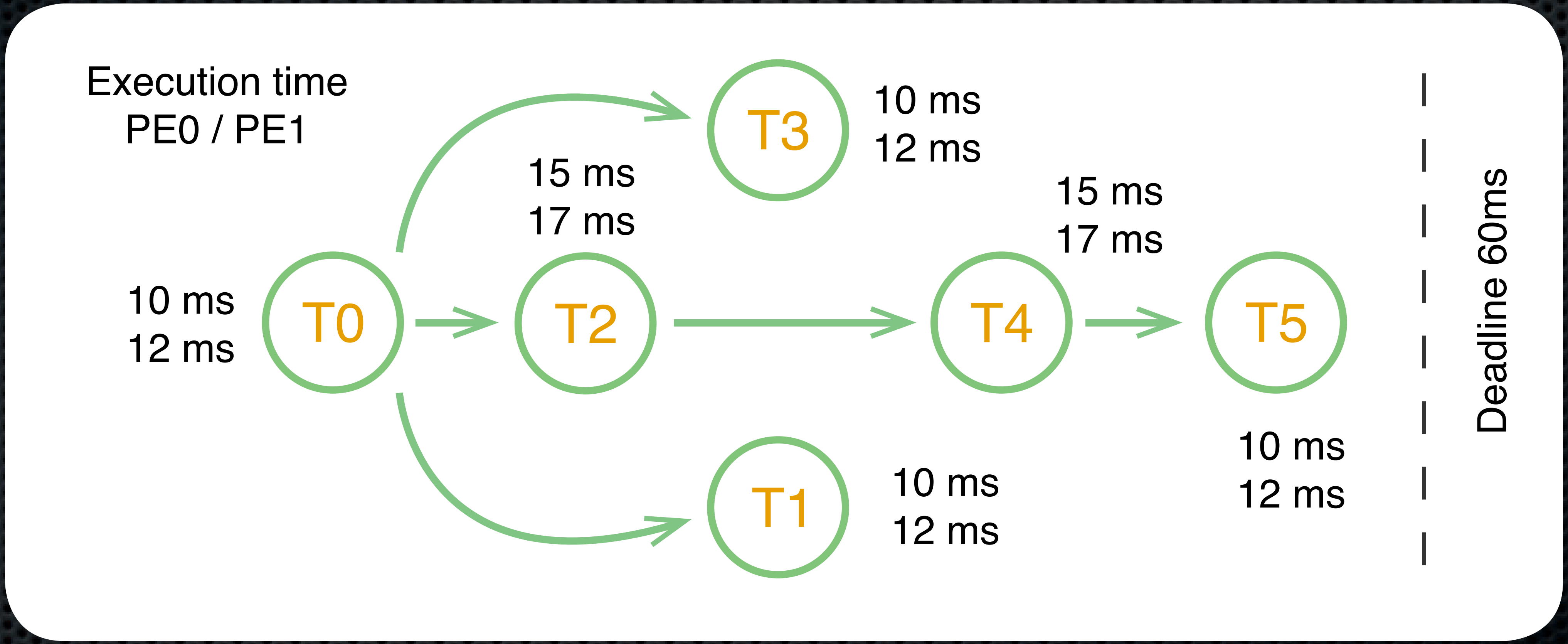
Reliability Model

- Thermal cycling failure mechanism.

$$\mathcal{T} \sim Weibull(\eta, \beta)$$

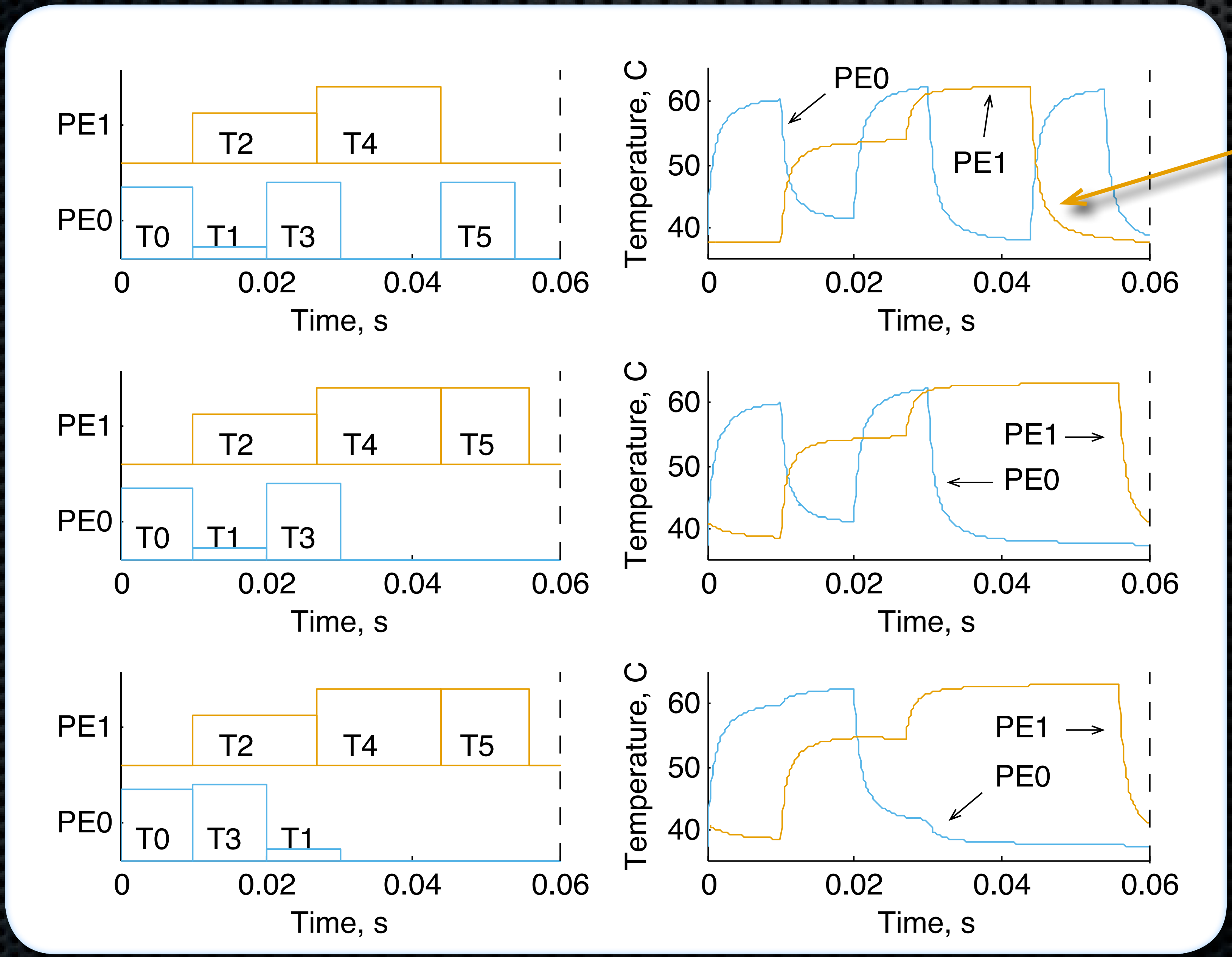
Motivational Example: Task Graph

- Consider 2 cores and an application with 6 tasks...



Motivational Example: SSDTPs

- Alternative mappings and schedules + their SSDTPs.



Thermal Cycling

+45% Lifetime

+55% Lifetime

Problem Formulation

- Maximize:

Lifetime

$$\mathcal{F} = \min_{i=0}^{N_p - 1} \theta_i$$

$$s.t.$$

$$t_{end\,i} \leq \tau \qquad \forall i$$

$$T_{ij} \leq T_{max} \qquad \forall i, j$$

Genetic Algorithm

- Chromosomes encode mappings and priorities.
- Tournament selection.
- Uniform mutation.
- 2-point crossover.
- Elitism model.

Experimental Results: Cores

- 20 tasks per core, 20 task graphs per each pair.

Lifetime improvement — Computational time

- 2 cores & 40 tasks — 51 times — 5 seconds.
- 4 cores & 80 tasks — 39 times — 34 seconds.
- 8 cores & 160 tasks — 28 times — 4 minutes.
- 16 cores & 320 tasks — 8 times — 36 minutes.
- 32 cores & 640 tasks — 4 times — 2 hours.

Experimental Results: Tasks

- Quad-core chip, 20 task graphs per each pair.

Lifetime improvement ↘ Computational time ↙

- 4 cores & 40 tasks — 61 times — 8 seconds.
- 4 cores & 80 tasks — 36 times — 32 seconds.
- 4 cores & 160 tasks — 29 times — 2 minutes.
- 4 cores & 320 tasks — 7 times — 7 minutes.
- 4 cores & 640 tasks — 4 times — 12 minutes.

Experimental Results: Techniques

- Comparison with the state of the art.

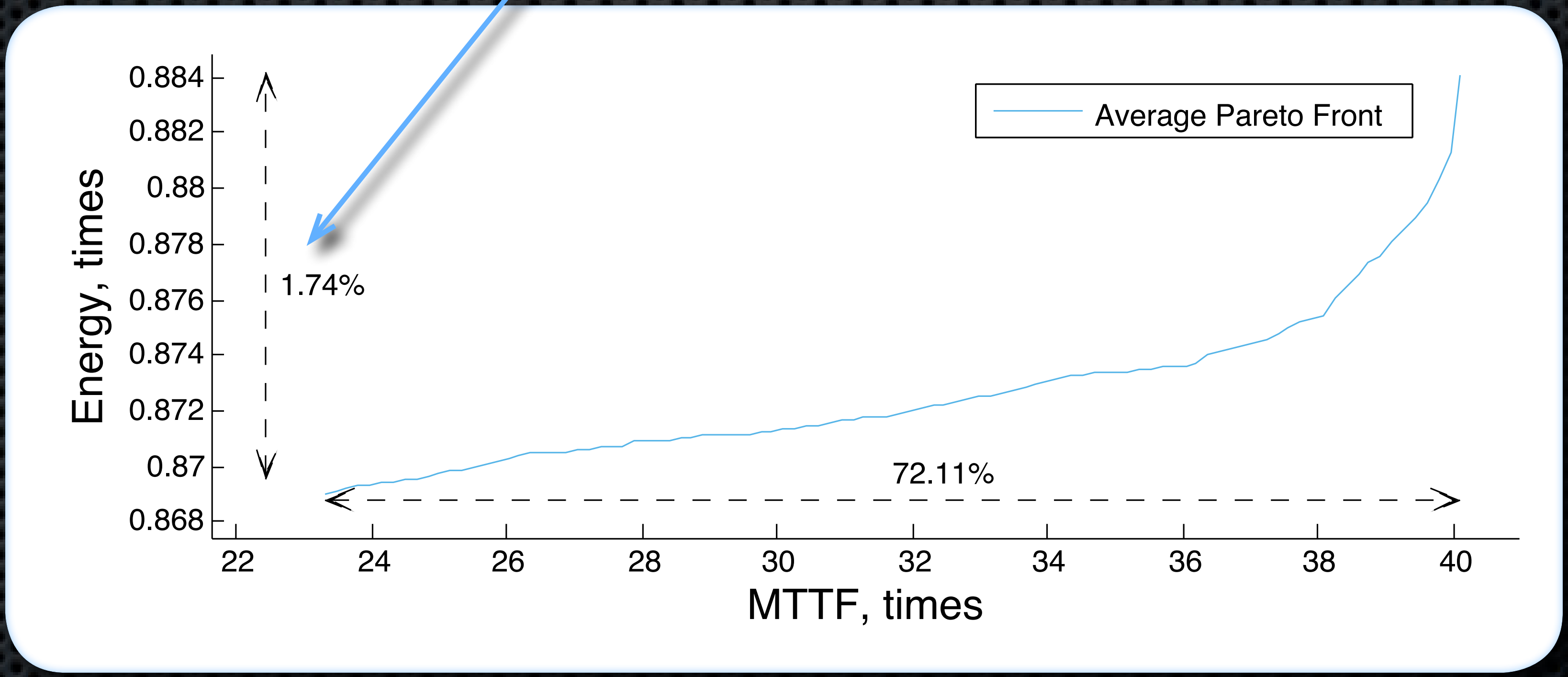
We are here — HotSpot — SSA

- 4 / 40 — 61 times — 1 times — 25 times.
- 4 / 80 — 36 times — 2 times — 14 times.
- 4 / 160 — 29 times — 2 times — 5 times.
- 4 / 320 — 7 times — 2 times — 4 times.
- 4 / 640 — 4 times — 1 times — 2 times.

Experimental Results: Energy

- Multi-objective optimization (NSGA-II).

Do not compromise the energy efficiency



Experimental Results: RLE

- Real-life example — MPEG2 decoder.
- 2 cores.
- 34 tasks.

- 24 times longer lifetime with the proposed method.
- 5 times with HotSpot.
- 11 times with the SSA.

Спасибо! Вопросы?

(не о девушках и кошках)