Compact Interleaved Thermal Control for Improving Throughput and Reliability of Networks-on-Chip

Tong Cheng, Zirui Xu, Xinyi Li, Li Li, Yuxiang Fu

Nanjing University
Nanjing, Jiangsu, China

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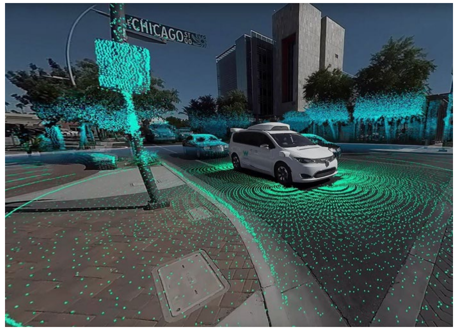
➢ Outline

- Background
- Motivation
- Interleaved Thermal Control —— **The scope of a particular node**
- Optimal Control Phase Assignment —— **The scope of the whole system**
- Experiment Results and Analysis

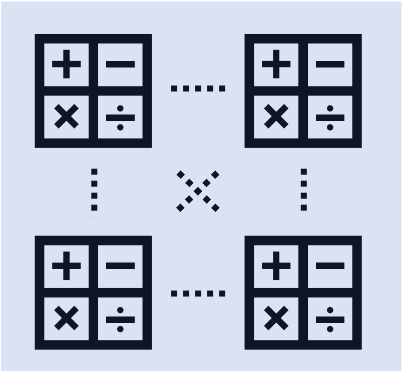
Background

Emerging Applications

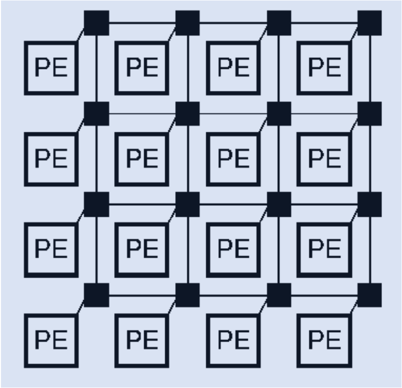


- Pattern Recognition
- LLM
- ADAS
- ……

Powerful Computing Arch

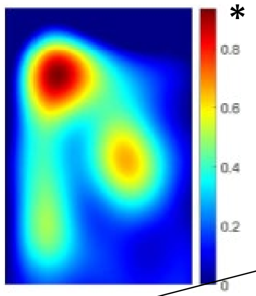


- Increasing PEs: more computing power

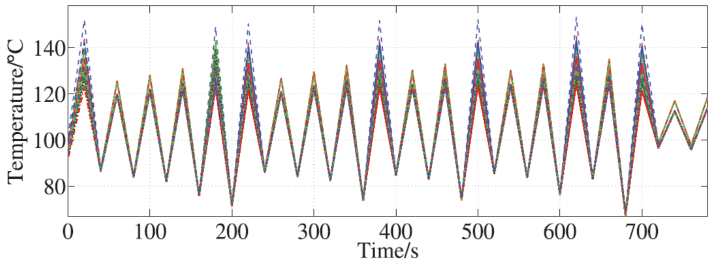


- NoC: higher interconnect bandwidth

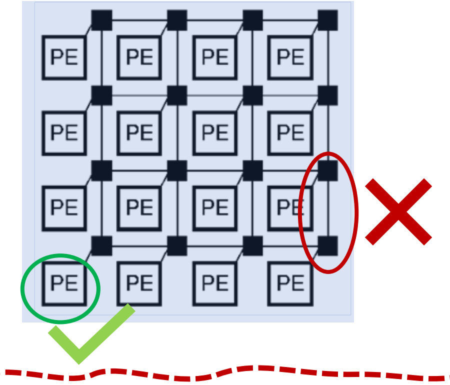
Severe Thermal/Reliability Problems



- thermal hotspots
- thermal gradients
- **thermal cycling**



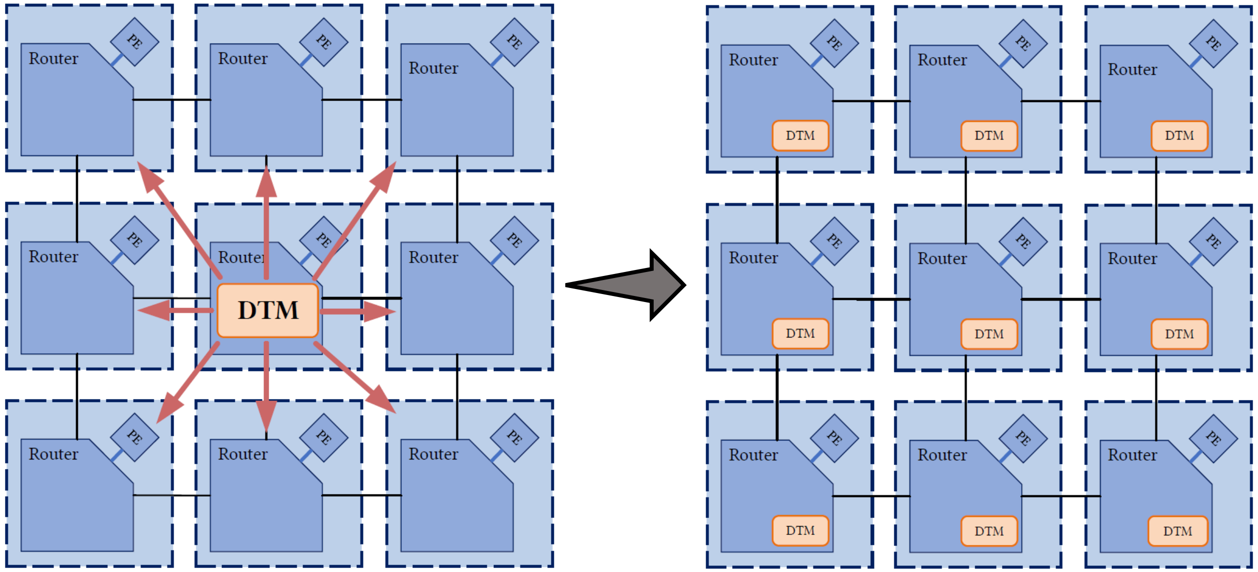
- Reliability problems



*Zhang, J., et al. (2022). "Hot-Trim: Thermal and Reliability Management for Commercial Multi-core Processors Considering Workload Dependent Hot Spots." IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems: 1-1.

➢ Motivation

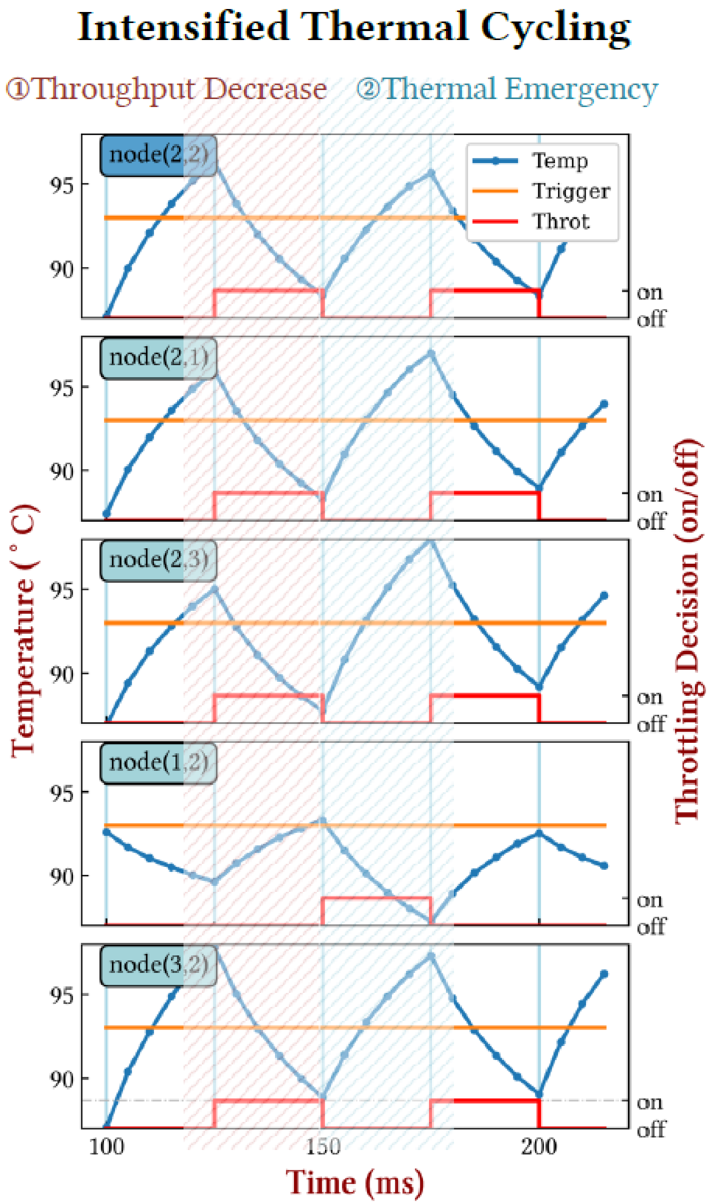
- The NoC system is inherently **distributive** and achieves excellent **scalability**



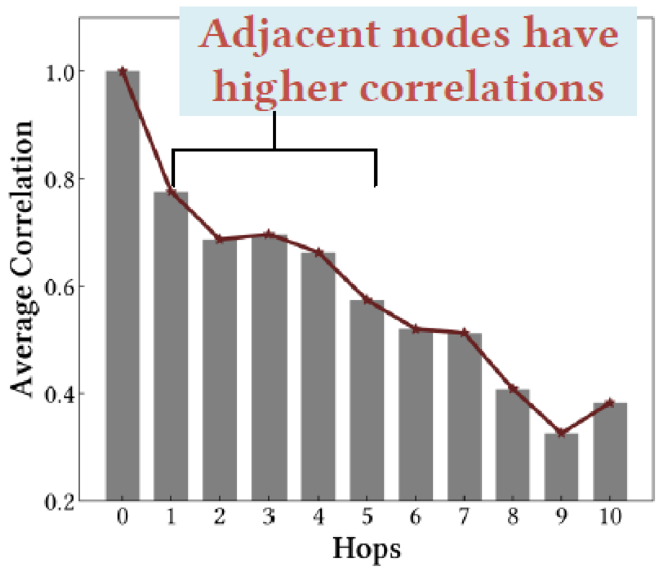
- centralized thermal management → distributed thermal management

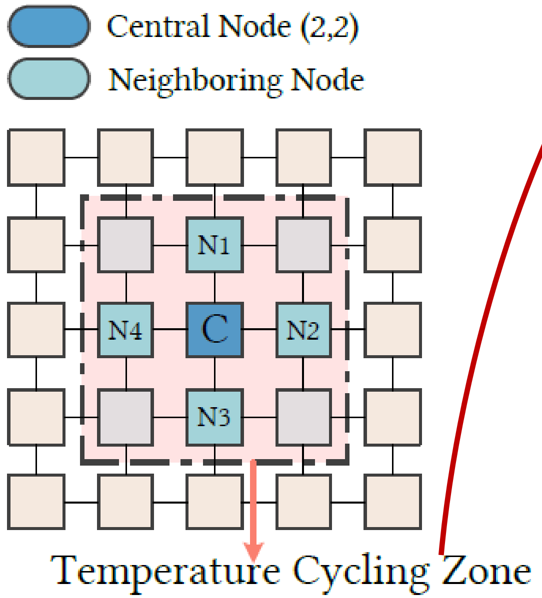
- Current distributed DTMs (Dynamic Thermal Management):
  - Deploy identical control mechanisms at each node
  - Initiate control mechanisms synchronously

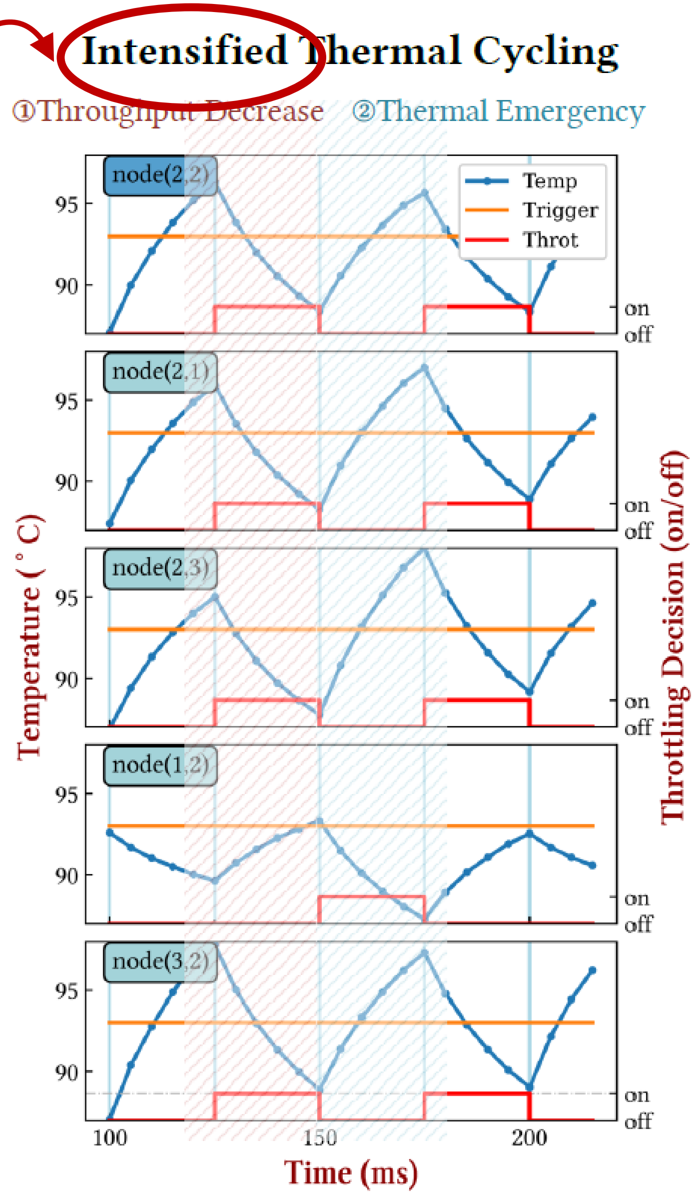
System Oscillation !!



➢ Motivation







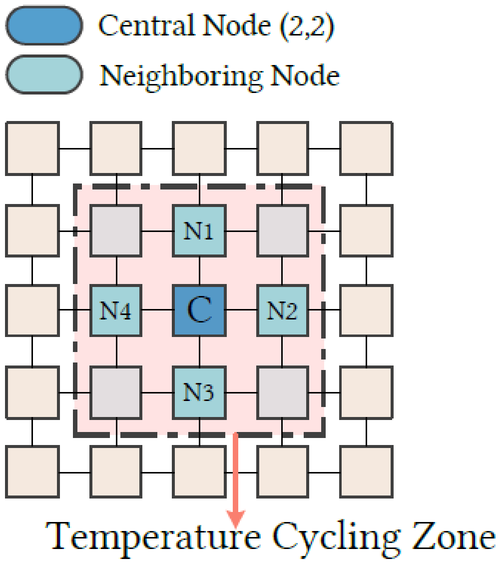
Preliminary experiment

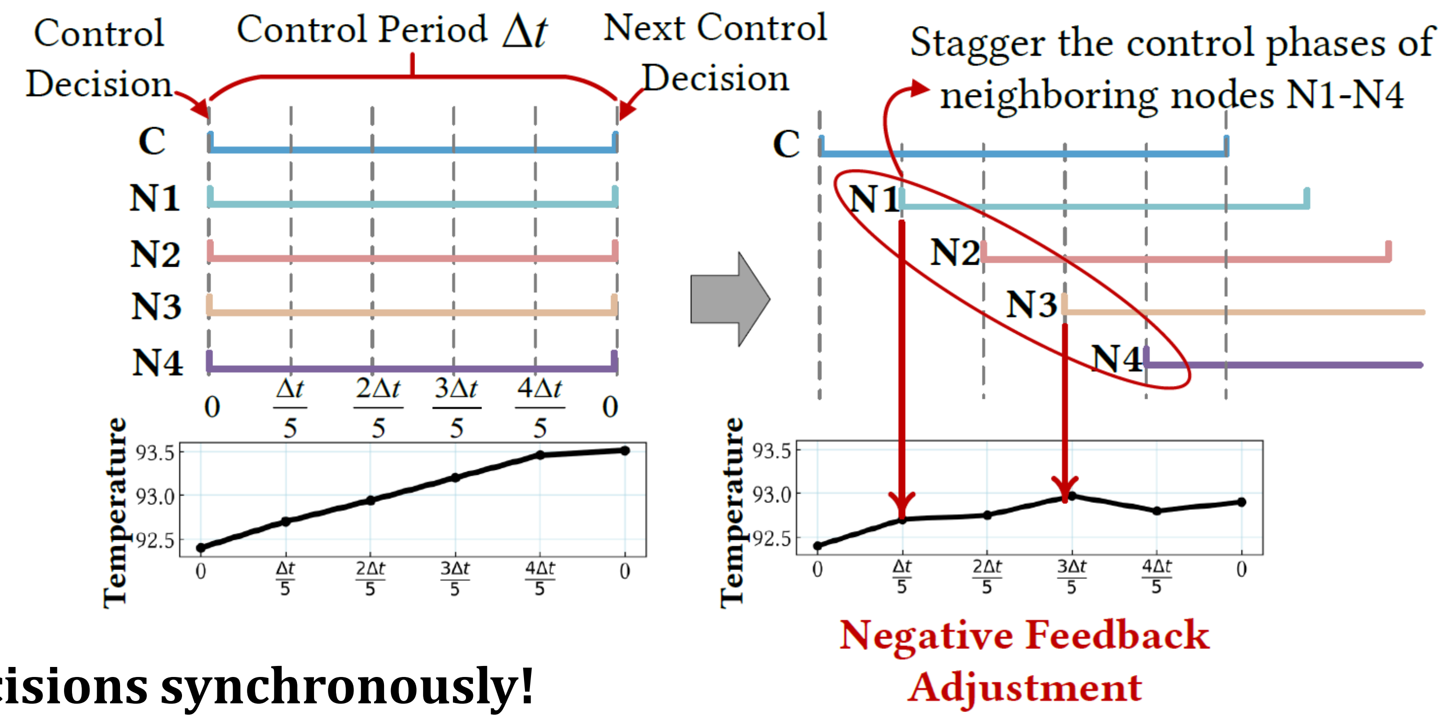
- The adjacent nodes exhibit higher traffic correlation and share more similar thermal characteristics

Intensified Thermal Cycling

- Result in significant ***performance losses during temperature drops*** and pose high ***thermal risks during temperature rises***

➢ Interleaved Thermal Control —— The scope of a particular node





- **Do not make control decisions synchronously!**

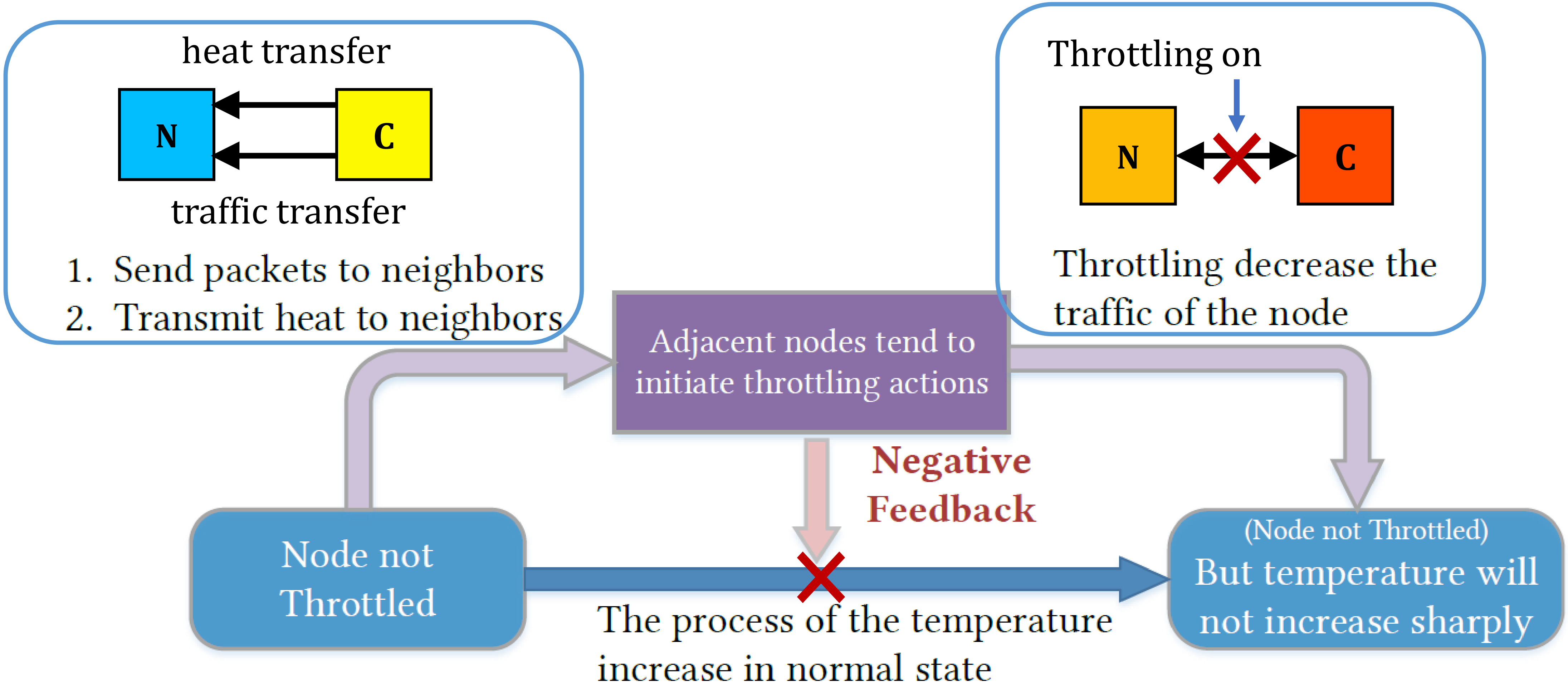
  ——***Staggers the control phases*** of neighboring nodes to evenly divide the control period

  ——Give more chances to adjust: ***divide a period evenly***.

- **Source node throttling**
  - Make routing decisions based on each node's throttling mark

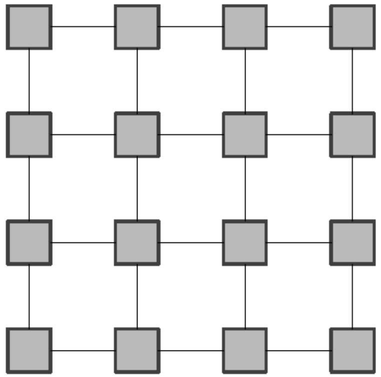
➢ Interleaved Thermal Control —— The scope of a particular node

- **Negative Feedback Control**

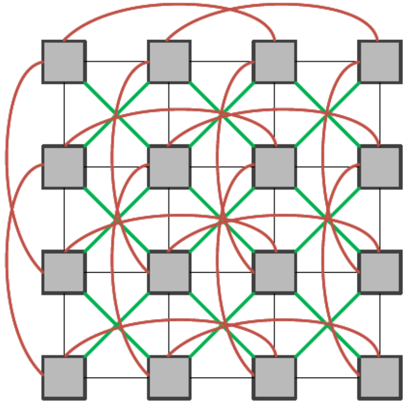


➢ Optimal Control Phase Assignment —— The scope of the whole system

Mesh-based NoC



$G = (V, E)$



Original Problem Statement

- each node and its closest neighboring nodes are assigned with different node types
- the minimum number of node types needed

Graph Coloring Problem

PROBLEM 2. *Given an undirected graph $G = (V, E)$ as shown in Fig. 4(b) and a color set S, find the smallest size of S and the map $c : V \to S$ such that $c(v) \neq c(w)$ whenever v and w are adjacent vertices in V.*

$$Phase_n = \frac{Type_n \cdot \Delta t}{N} (Type_n = 0 \cdots N-1)$$

➢ Optimal Control Phase Assignment —— The scope of the whole system

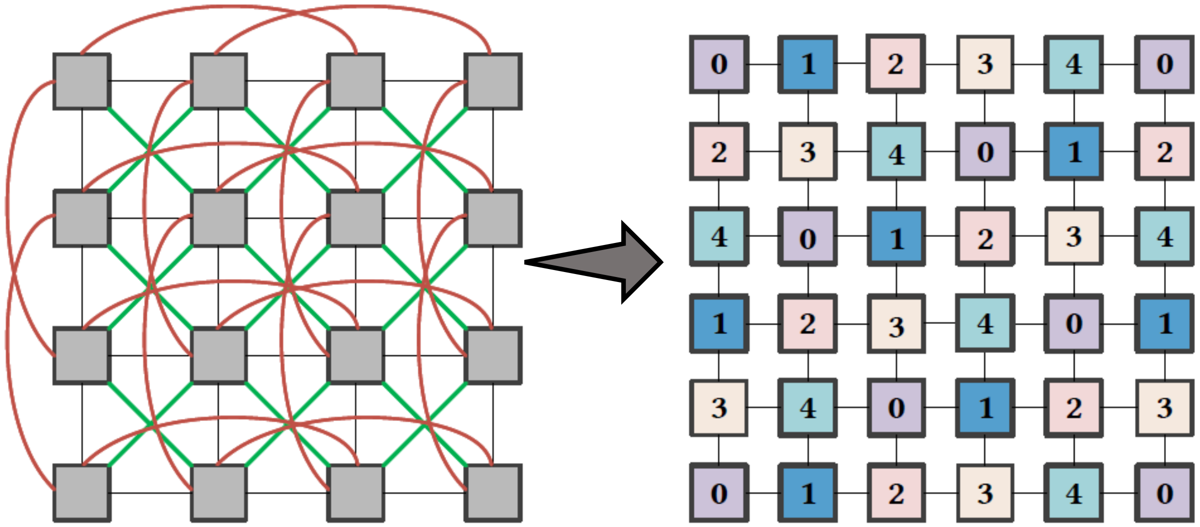
Backtracking Based Solution

Algorithm 1: Control Phase Assignment Algorithm

Input: undirected graph $G = (V, E)$

Output: chromatic number of the graph $\chi(G)$, all possible optimal mapping $c : V \rightarrow S$

```
1  Convert the NoC topology to the input graph G = (V, E);
2  Set the exploration range of the color number list_k to [5-10];
3  foreach color number k in list_k do
4      if search to the last vertex then
5          χ(G) ← k ;
6          save the current mapping c : V → S;
7      else
8          foreach color in S = {1, . . . , k} do
9              add mapping c(v) = color;
10             if curret mapping c : V → S is valid then
11                 search the next node ;    /* A recursive
                    call that move to line 4 */
12             end
13             remove the mapping;
14         end
15     end
16 end
17 return χ(G) and all possible mapping;
```



Rules:

- The chromatic number is 5
- horizontal axis following the pattern {0,1,2,3,4}
- vertical axis following the pattern {0,2,4,1,3}

➢ Experiment Results and Analysis

Experimental Setup

- **Platform**: AccessNoxim (Noxim ✗ Hotspot)
- **Traffic Patterns**
  - Synthetic traffic
  - PARSEC benchmark traffic
  - Neural network traffic

Simulation Platform Configuration

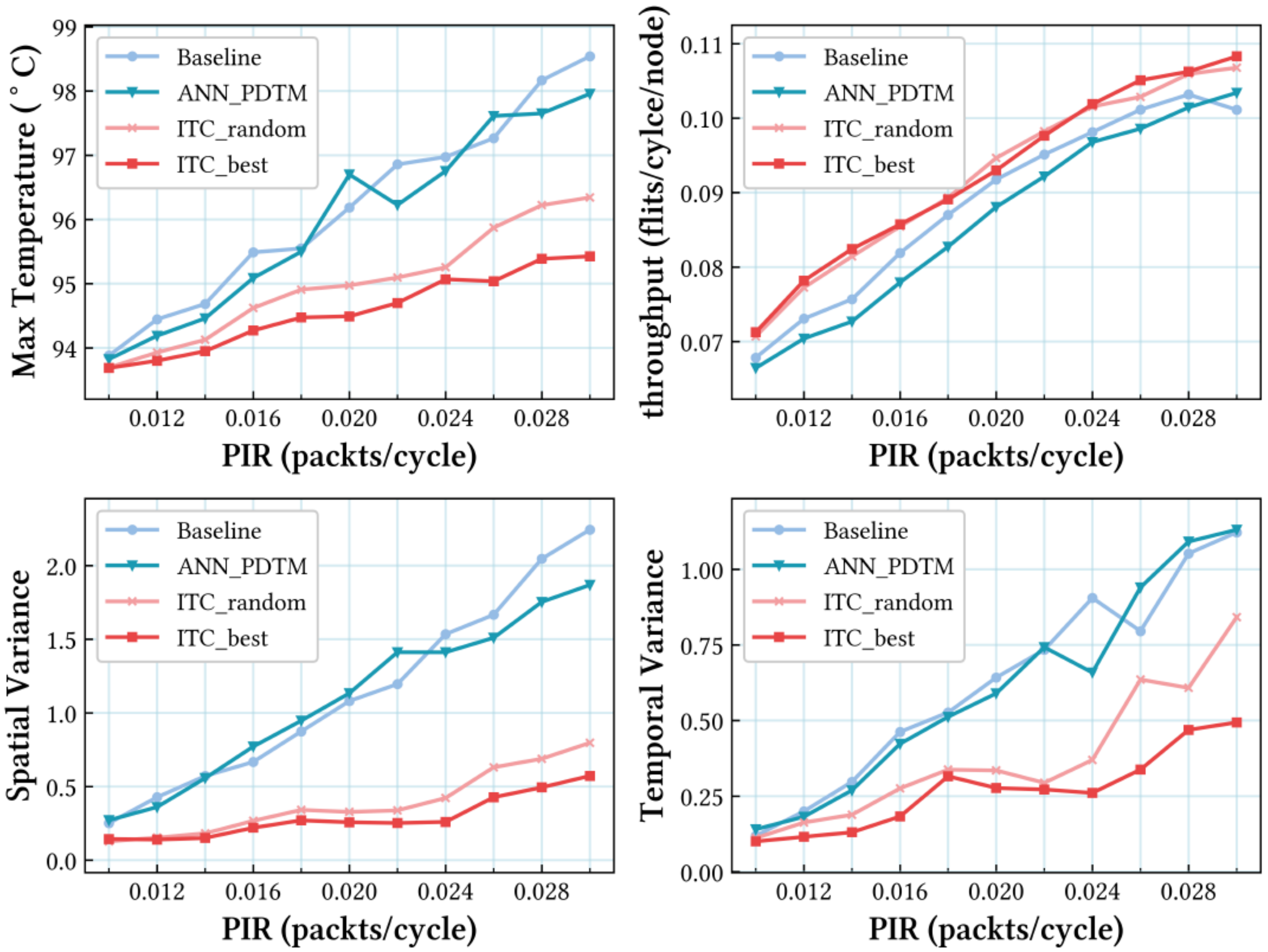
Parameters	Settings	Parameters	Settings
	NoC Configurations		
Topology Buffer Depth Flow Control	8×8 mesh 4 Flits Wormhole	Routing Packet Length Arbitration Policy	XY 8 Flits Round-robin
	System Configurations		
Frequency Warm-up Time	1 GHz 10000 cycles	Control Period Initial Temperature	10 ms 85 °C

Abbr. of different works to be compared

- **Baseline**: reactive dynamic control method
- **ANN_PDTM**: ANN-based proactive method *
- **ITC_random**: Interleaved Thermal Control with the random control phase assignment
- **ITC_best**: Interleaved Thermal Control with the best control phase assignment

*Chen, K. C., et al. (2023). "Adaptive Machine Learning-Based Proactive Thermal Management for NoC Systems." IEEE Transactions on Very Large Scale Integration (VLSI) Systems 31(8): 1114-1127.

➢ Experiment Results and Analysis ——under incremental PIR levels



Analysis

- Significant enhancement in peak temperature, temporal and spatial temperature variance
- A notable advantage in throughput
- Best control phase assignment works
- Do better under a high workload

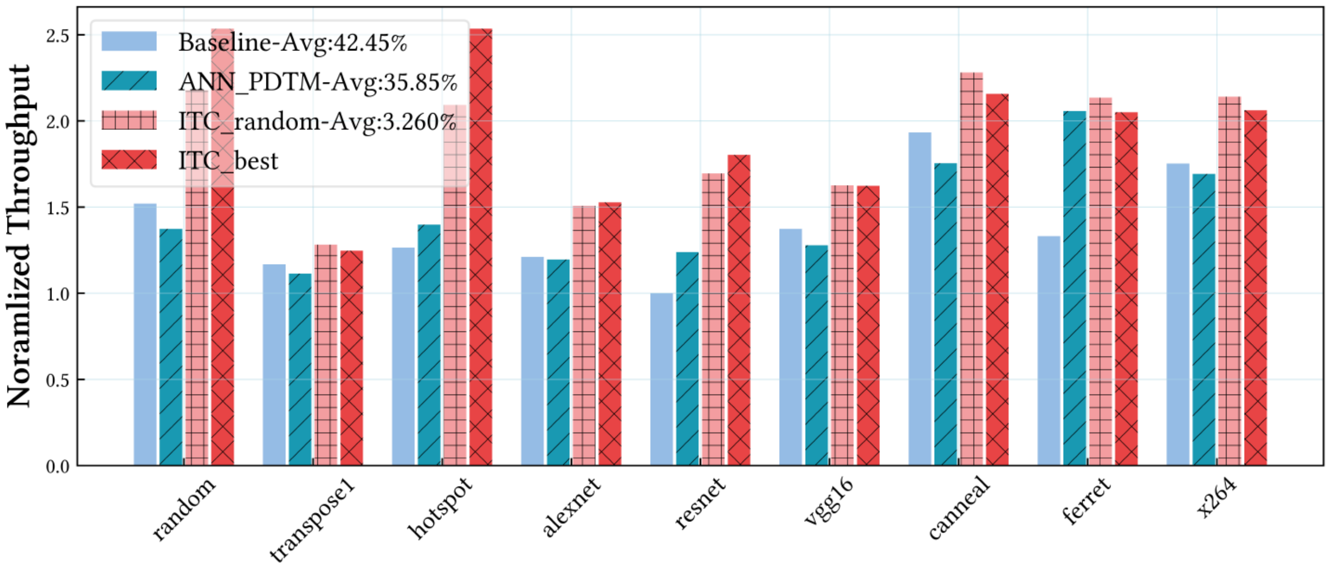
(PIR: packet injection rate)

Comparison on throughput, maximum temperature, temporal variance, and spatial variance under incremental PIR levels.

➢ Experiment Results and Analysis ——under different traffic patterns

Table 2: Thermal Metrics Comparison under Different Traffic Patterns.

	Max Temp				Spatial Variance				Temporal Variance			
Traffic Patterns	Baseline	ANN_PDTM	ITC_random	ITC_best	Baseline	ANN_PDTM	ITC_random	ITC_best	Baseline	ANN_PDTM	ITC_random	ITC_best
random	97.55	98.66	96.34	95.43	1.901	2.300	0.797	0.572	1.124	1.613	0.842	0.494
transpose1	97.49	97.65	97.09	96.89	3.242	3.515	3.727	2.690	1.201	1.447	2.277	0.895
hotspot	98.40	98.30	97.32	95.41	2.123	2.135	1.026	0.501	1.246	1.202	0.602	0.407
alexnet	98.32	98.57	97.51	97.34	2.238	2.195	1.576	1.452	0.999	1.364	1.625	1.052
resnet	98.47	98.19	96.84	96.13	2.457	2.205	1.162	1.236	1.606	1.669	1.264	0.881
VGG16	98.18	98.73	97.00	97.31	2.026	2.294	1.198	1.394	1.385	1.564	1.801	1.242
canneal	97.62	97.63	96.45	96.80	2.382	2.320	0.818	0.744	1.383	1.224	0.544	0.669
ferret	97.65	97.49	97.51	97.35	2.755	1.887	0.854	0.706	1.224	1.192	0.579	0.816
x264	98.24	97.73	96.88	96.56	2.030	1.777	0.702	0.724	1.290	1.186	0.582	0.625
Avera. Improv.	1.614 °C	1.425 °C	0.432 °C	-	71.17%	70.75%	20.50%	-	50.23%	51.47%	25.04%	-



Analysis

- Thermal Metrics: validate the generalization
- Normalized Throughput:
  - Improves by 6.81% to100.62%, averagely **42.46%**, compared with the baseline
  - averagely **35.85%** compared with the ANN-based PDTM

➢ Experiment Results and Analysis ——thermal cycling-based system reliability

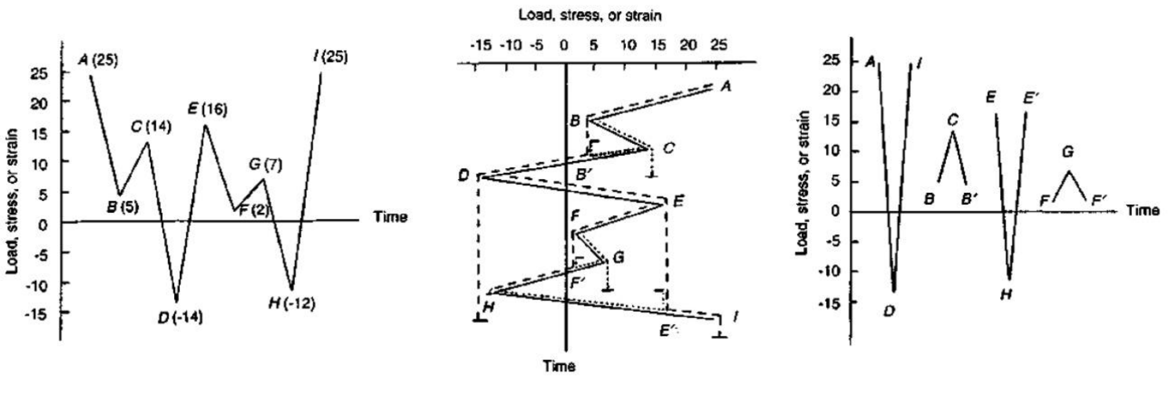
Calculate MTTF

- rain-flow counting method
- Coffin-Manson equation

$$N_{TC}(i) = A_{TC}(\delta T_i - T_{th})^{(-b)} e^{\frac{E_{aTC}}{kT_{Max}(i)}}.$$

- Miner's rule

$$N_{TC} = \frac{m}{\sum_{i=1}^{m} \frac{1}{N_{TC}(i)}}, \quad MTTF = \frac{N_{TC} \sum_{i=1}^{m} T_i}{m}.$$

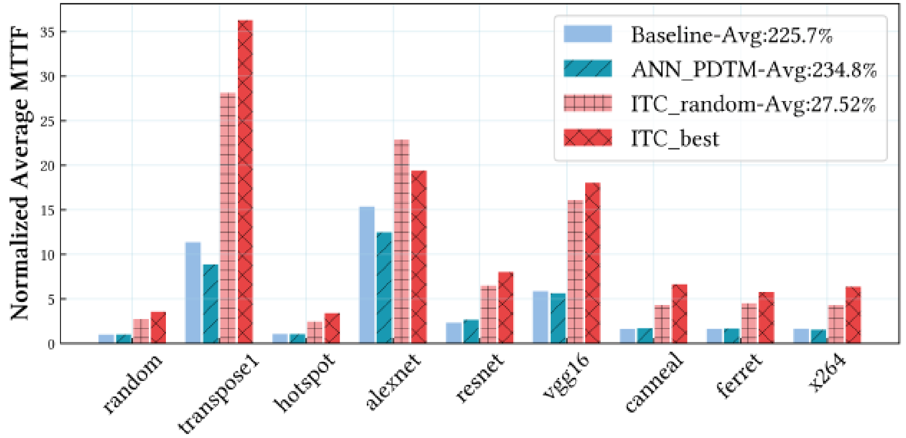


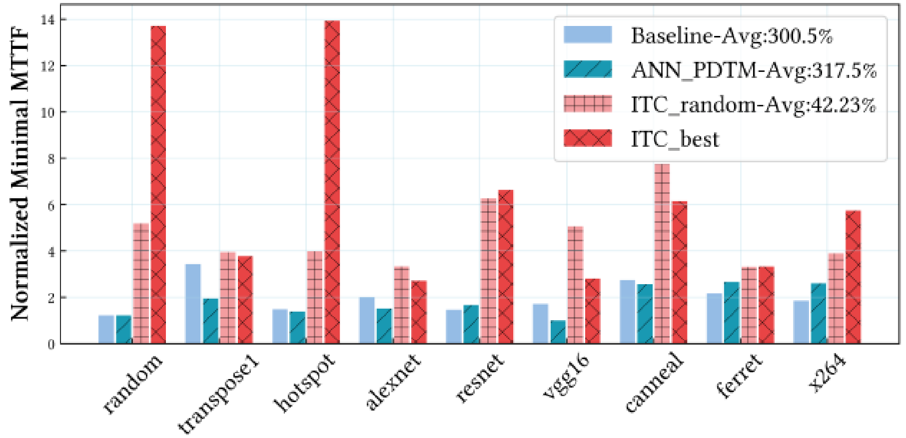
(a) (b) (c)

Analysis:

Stable Feedback control

- Improves the ***average TC-related MTTF*** by **27.52%, 234.83% and 225.69%**
- improves the ***minimum TC-related MTTF*** by **42.23%, 317.50% and 300.49%**





Thanks for Listening!

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