Task Migration Policy for Temperature-Aware Management of Many-Core Systems

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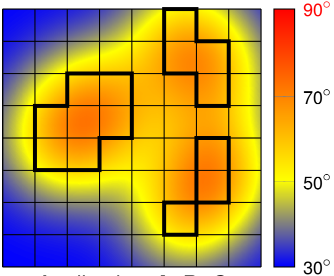
Motivation

Many-Core Systems

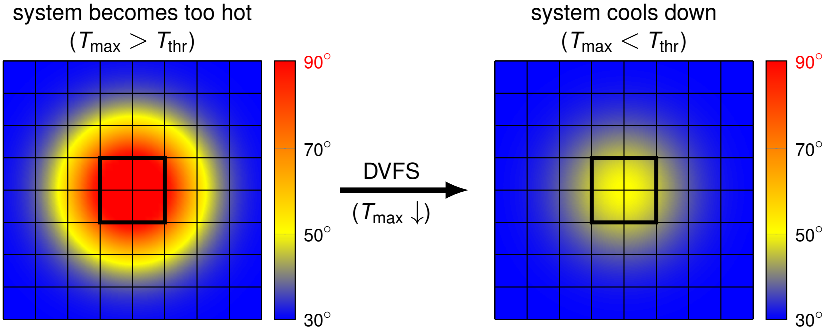
- Many-Core Systems
  - Large number of processing resources
  - Parallel execution of applications
  - Dynamic workload
  - Dynamic resource management
- The thermal Issue
  - Increased on-chip temperature
    - Dense integration of transistors
    - High density of power consumption
    - Requires thermal control
  - Dynamic thermal distribution
    - Dynamic workload
    - Dynamic Thermal Management (DTM)



Application ***A***, ***B*** ,***C***
running on 8x8 core system

Dynamic Thermal Management (DTM)

- Predefined **temperature constraint**: T_{thr}
  - Thermally safe operation as long as $T_{\text{max}} < T_{\text{thr}}$
  - Enforced using DVFS or power gating if $T_{\text{max}} > T_{\text{thr}}$



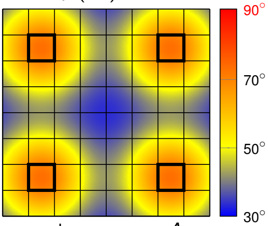
Thermal Safe Power (TSP)

- TSP analysis provides a **core power constraint**: P_{thr}
  - Function of the location of active cores (Q), heat flow, T_{thr}, etc.
  - Thermally safe operation as long as $P_{\text{core}} < P_{\text{thr}}$
  - Enforced using DVFS or power gating if $P_{\text{core}} > P_{\text{thr}}$

$$Q_A = [0,0,0,0,0,0,0,0,0,1,0,0,0,0,1,0,\\ 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,\\ 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,\\ 0,1,0,0,0,0,1,0,0,0,0,0,0,0,0,0]$$

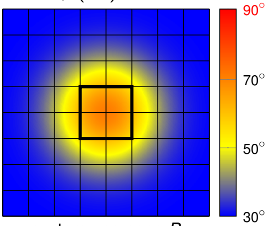
$$Q_B = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,\\ 0,0,0,0,0,0,0,0,0,0,0,1,1,0,0,0,\\ 0,0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,\\ 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]$$

$P_{\text{thr}}(Q_A) = 20$



system use-case A

$P_{\text{thr}}(Q_B) = 12$



system use-case B

Temperature-Aware Task Migration Policy

Task Migration Policy

- Migration policy decides which migration must be performed.
- Large decision space
  - N-core system $\rightarrow$ up to $\binom{N}{2} \times \binom{N}{2}$ migration options!
  - Heuristic is required

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Two-Step Heuristic

- Step 1: Select a promising active core (migration source)
  $\rightarrow$ Goal: maximum increase in P_{thr} if it becomes idle
- Step 2: Select a promising idle core (migration destination)
  $\rightarrow$ Goal: minimum decrease in P_{thr} if it becomes active

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  $\rightarrow$ Goal: maximum increase in P_{thr} if it becomes idle
- Step 2: Select a promising idle core (migration destination)
  $\rightarrow$ Goal: minimum decrease in P_{thr} if it becomes active
- TSP analysis* is required to calculate P_{thr}
  - Time-consuming analysis
    $\rightarrow$ Goal: single analysis to select both source and destination

∗ Pagani, Santiago, Heba Khdr, Jian-Jia Chen, Muhammad Shafique, Minming Li, and Jörg Henkel. *Thermal safe power (TSP): Efficient power budgeting for heterogeneous manycore systems in dark silicon.* IEEE Transactions on Computers (TC) 66, no. 1 (2016): 147-162.

TSP Analysis: Homogeneous Many-Core

- Calculates core power constraint $P_{\text{thr}}(\boldsymbol{Q})$ for system use-case $\boldsymbol{Q}$

$$A\,T' + B\,T = P + T_{amb}G \tag{1}$$

$$T_i = \sum_{j=1}^{N} b_{i,j}^{-1} \cdot p_j^{cores} + \sum_{j=1}^{N} b_{i,j}^{-1}\left(p_j^{blocks} + T_{\text{amb}} \cdot g_j\right) \tag{2}$$

$$P_{\text{thr}}^{\star}(\boldsymbol{Q}) = \min_{\forall i \in L} \left\{ \frac{T_{\text{thr}} - P_{\text{inact}}^{\text{core}} \cdot \sum_{j=1}^{M} b_{i,k_j}^{-1}(1-q_j)}{\sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot q_j} + \frac{-\sum_{j=1}^{N} b_{i,j}^{-1}(p_j^{\text{blocks}} + T_{\text{amb}} \cdot g_j)}{\sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot q_j} \right\} \tag{3}$$

TSP Analysis: Heterogeneous Many-Core

- Calculates core **power-density** constraint $P_{\text{thr}}^{\rho}(\boldsymbol{Q})$ for system use-case $\boldsymbol{Q}$

$$A\,T' + B\,T = P + T_{amb}G \tag{1}$$

$$T_i = \sum_{j=1}^{N} b_{i,j}^{-1} \cdot p_j^{cores} + \sum_{j=1}^{N} b_{i,j}^{-1}\left(p_j^{blocks} + T_{\text{amb}} \cdot g_j\right) \tag{2}$$

$$P_{\text{thr}}^{\rho\star}(\boldsymbol{Q}) = \min_{\forall i \in L} \left\{ \frac{T_{\text{thr}} - \sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot p_{\text{inact},j}^{\text{core}}(1-q_j)}{\sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot \text{area}_j^{\text{core}} \cdot q_j} + \frac{-\sum_{j=1}^{N} b_{i,j}^{-1}(p_j^{\text{blocks}} + T_{\text{amb}} \cdot g_j)}{\sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot \text{area}_j^{\text{core}} \cdot q_j} \right\} \tag{4}$$

Algorithm 1: TSP(Density) for a system use-case $\boldsymbol{Q}$

Input: $\boldsymbol{Q}, \boldsymbol{P}^{\text{blocks}}, T_{\text{amb}}, T_{\text{thr}}, P_{\text{max}}, \text{area}_j^{\text{core}}$ & $p_{\text{inact},j}^{\text{core}}$ (for $j = 1, 2, \ldots, M$), and floorplan;

Output: Uniform TSP(Density) constraint for mapping $\boldsymbol{Q}$;

$P_{\text{thr}}^{\rho\star}(\boldsymbol{Q}) \leftarrow \infty$;

for *all* $i \in \boldsymbol{L}$ **do**

  $auxP \leftarrow T_{\text{thr}} - \sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot p_{\text{inact},j}^{\text{core}} (1 - q_j)$;

  $auxP \leftarrow auxP - \sum_{j=1}^{N} b_{i,j}^{-1} (p_j^{\text{blocks}} + T_{\text{amb}} \cdot g_j)$;

  $auxP \leftarrow \frac{auxP}{\sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot \text{area}_j^{\text{core}} \cdot q_j}$;

  if $auxP < P_{\text{thr}}^{\rho\star}(\boldsymbol{Q})$ **then**

    $P_{\text{thr}}^{\rho\star}(\boldsymbol{Q}) \leftarrow auxP$;

if $P_{\text{thr}}^{\rho\star}(\boldsymbol{Q}) \leq R^{\rho}(\boldsymbol{Q})$ **then**

  $P_{\text{thr}}^{\rho}(\boldsymbol{Q}) \leftarrow P_{\text{thr}}^{\rho\star}(\boldsymbol{Q})$;

else

  $P_{\text{thr}}^{\rho}(\boldsymbol{Q}) \leftarrow R^{\rho}(\boldsymbol{Q})$;

return $P_{\text{thr}}^{\rho}(\boldsymbol{Q})$;

Complexity: $O(ZN)$, with $Z = \#\text{blocks}$, $N = \#\text{nodes}$

Source-Core Selection

Possible Methods

1. Exhaustive search
   - For each active core c, calculate $P_{\text{thr}}^{\rho}(\boldsymbol{Q})$ assuming c is idle
   - Choose the core which results in greatest $P_{\text{thr}}^{\rho}(\boldsymbol{Q})$

     $\rightarrow$ Complexity: $O(MZN)$, $M = \#\text{cores}$

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2. Random search
   - Select x active cores randomly as potential candidates
   - For each randomly selected core c, calculate $P_{\text{thr}}^{\rho}(\boldsymbol{Q})$ assuming c is idle
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     $\rightarrow$ Complexity: $O(XZN)$, $X =$ subset size

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     $\rightarrow$ Complexity: $O\big(XZN\big)$, $X =$ subset size

3. Proposed Method
   - Find the best candidate with a single TSP analysis for current $\boldsymbol{Q}$

     $\rightarrow$ Complexity: $O\big(ZN\big)$

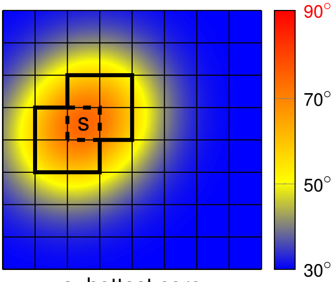
Source-Core Selection: Proposed Idea

Temperature Awareness:

- Enabling the source-core search to see the heat distribution in the system

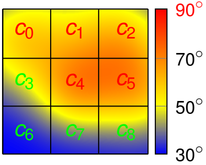
Concept

- Generate the heatmap of the system
- Rank all active cores by their temperature
- Select from all active cores the hottest one as source core
- Deactivating the selected core results in the maximum gain in P^{ρ}_{thr}
  - Better thermal balance in the system
  - Enables maximum frequency increase for active cores



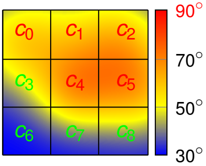
s=hottest core

Source-Core Selection: Proposed Procedure



Source-Core Selection: Proposed Procedure

core	c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
auxP	29	28	24	33	22	18	41	38	35
P^{ρ}_{thr}:	18								



$$P^{\rho\star}_{\text{thr}}(\mathbf{Q}) = \min_{\forall i \in L} \left\{ \frac{T_{\text{thr}} - \sum_{j=1}^{M} b^{-1}_{i,k_j} \cdot p^{\text{core}}_{\text{inact},j}(1-q_j) - \sum_{j=1}^{N} b^{-1}_{i,j}(p^{\text{blocks}}_j + T_{\text{amb}} \cdot g_j)}{\sum_{j=1}^{M} b^{-1}_{i,k_j} \cdot \text{area}^{\text{core}}_j \cdot q_j} \right\}$$

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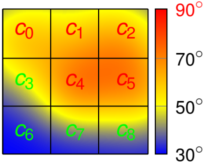

switch off

c_5

$$P_{\text{thr}}^{\rho\star}(\boldsymbol{Q}) = \min_{\forall i \in L}\left\{ \frac{T_{\text{thr}} - \sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot p_{\text{inact},j}^{\text{core}}(1-q_j) - \sum_{j=1}^{N} b_{i,j}^{-1}(p_j^{\text{blocks}} + T_{\text{amb}} \cdot g_j)}{\sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot \text{area}_j^{\text{core}} \cdot q_j} \right\}$$

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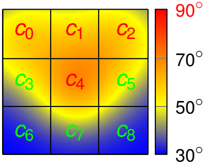

Destination-Core Selection: Intuitive Approach

Proposed Method

- Using TSP Analysis as the base for the heuristic
- Destination-core selection heuristic:
    1. Perform the TSP analysis for the current system use-case (***Q***)
        - generate a map of inactive cores and their auxP value
    2. Sort the map by auxP values from high to low
    3. Choose the first core-auxP pair (the coolest core) as the best destination core for migration
- The rest of the map can be used as alternative options

$$P_{\text{thr}}^{\rho\star}(\boldsymbol{Q}) = \min_{\forall i \in L} \left\{ \boxed{\frac{T_{\text{thr}} - \sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot p_{\text{inact},j}^{\text{core}} (1 - q_j) - \sum_{j=1}^{N} b_{i,j}^{-1} (p_j^{\text{blocks}} + T_{\text{amb}} \cdot g_j)}{\sum_{j=1}^{M} b_{i,k_j}^{-1} \cdot \text{area}_j^{\text{core}} \cdot q_j}} \right\} \quad (4)$$

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Problem: Selection quality not as good as expected!

Destination-Core Selection: Proposed Approach

Proposed Method

- Using TSP Analysis as the base for the heuristic
- Destination-core selection heuristic:
  1. Perform the TSP analysis for the current system use-case (***Q***)
     - generate a map of inactive cores and their $\frac{\text{auxP}}{\text{area}^{\text{core}}}$ value
  2. Sort the map by auxP values from high to low
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- The rest of the map can be used as alternative options

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Experiments

Experiment Setup

Platform

- Heterogeneous (52 cores, 3 types)
- All TSP parameters are given
  $\boldsymbol{B}, \boldsymbol{G}, T_{\text{amb}}, T_{\text{thr}}, p^{\text{core}}_{\text{inact},j}, p^{blocks}_{j}, \ldots$

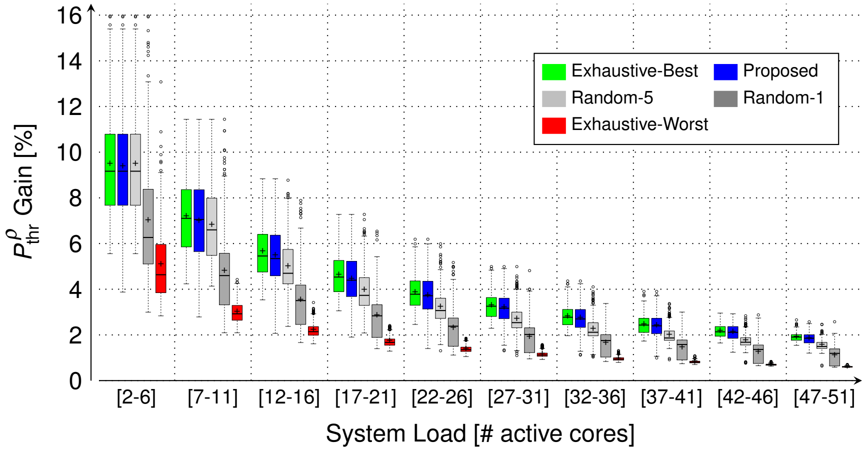
Compared Approaches

- Exhaustive search
  - Best
  - Worst
- Random selection (x=5)
- Random selection (x=1)
- Proposed

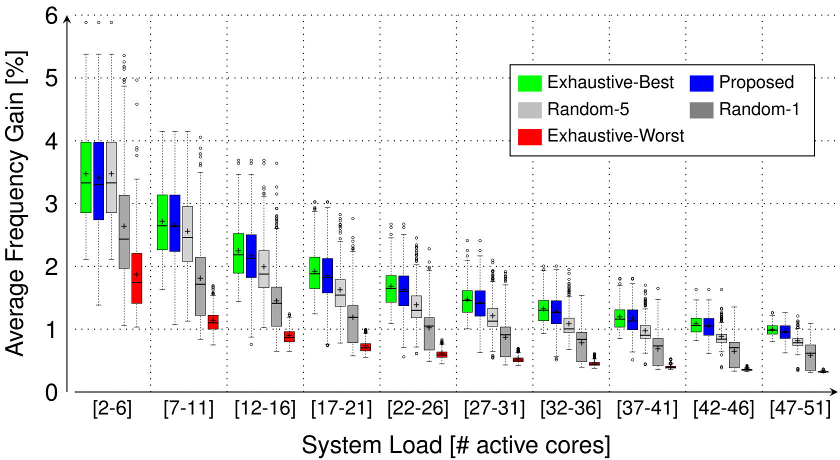
Evaluation

- P^{ρ}_{thr} gain
- Average Frequency gain

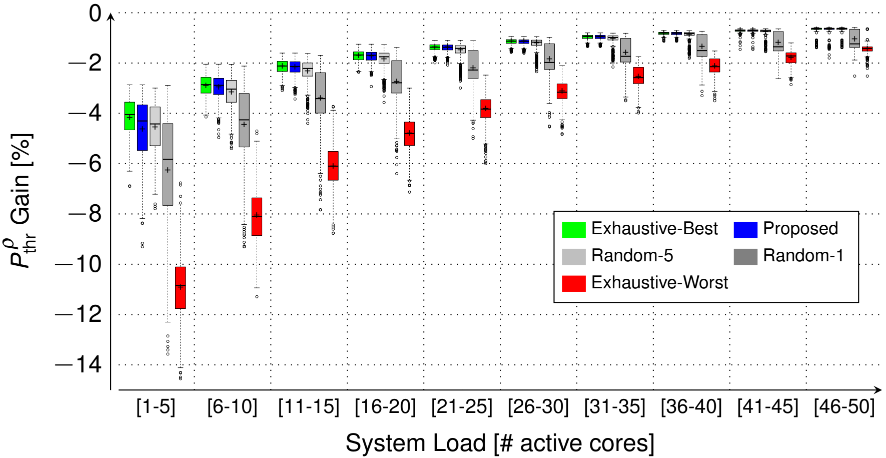
Source-Core Search: Thermal Balance



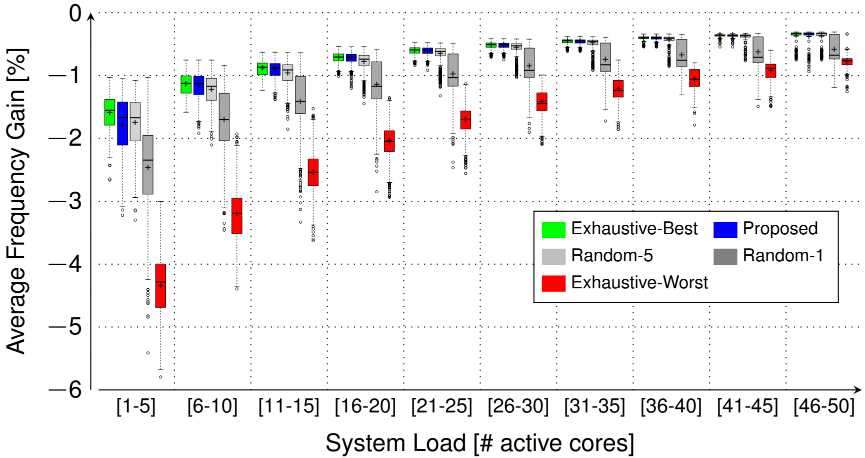
Source-Core Search: Performance Gain



Destination-Core Search: Thermal Balance



Destination-Core Search: Performance Gain



Investigated Migration Approaches

- **Holistic search**
  - finds the best pair of source and destination cores for migration (exhaustive)

  → (1) *Holistic* (optimal reference)

- **Two-Step search**
  - performs a TSP analysis to find the best source core
  - performs a second TSP analysis based on an updated Q to find the best destination

  → (2) *Exhaustive* (heuristic reference)

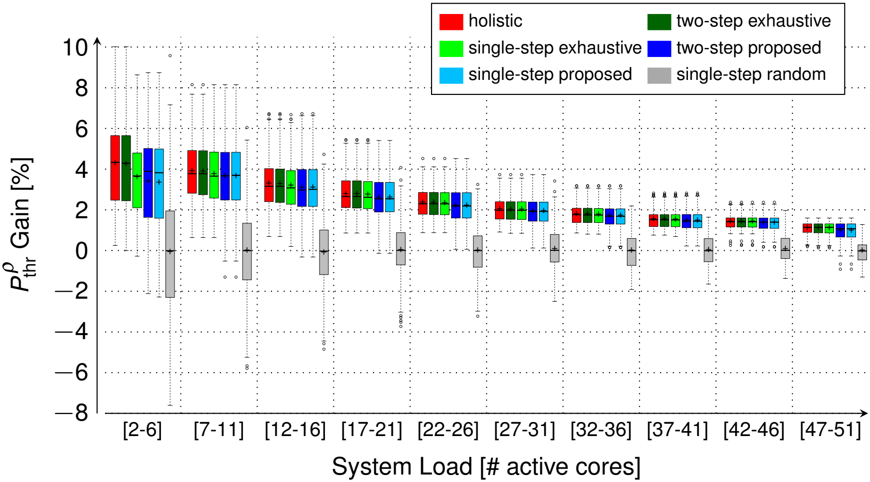
  → (3) *Proposed*

- **Single-Step search**
  - performs a single TSP analysis to find the best source and the best destination cores

  → (4) *Exhaustive* (heuristic reference)

  → (5) *Proposed*

Migration Effectiveness: Thermal Balance



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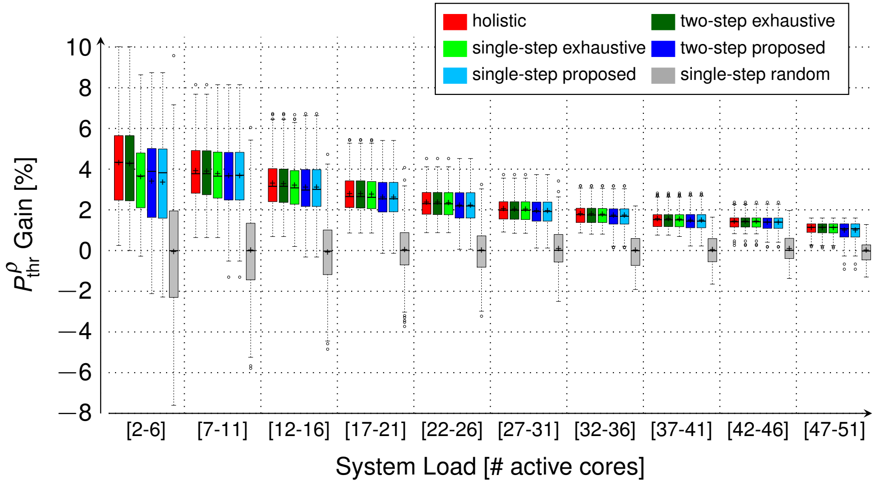
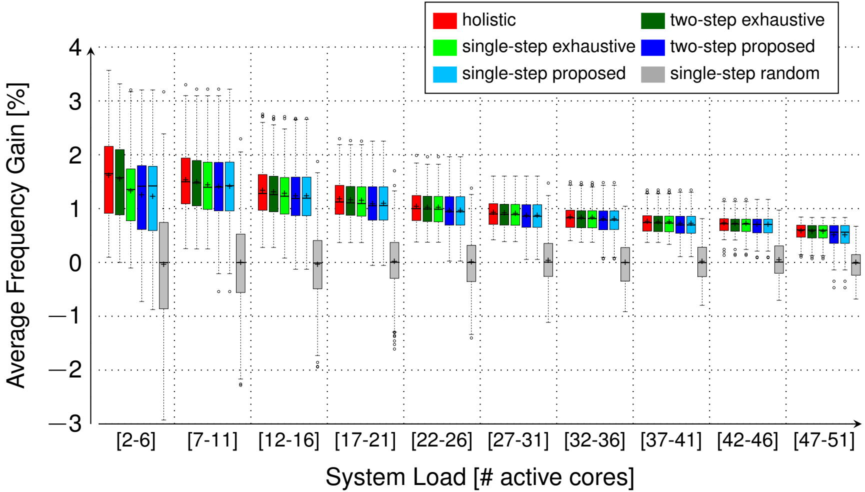


Best Compromise: Single-Step S/D search using proposed method

Migration Effectiveness: Performance Gain



Conclusion

Conclusion

- Many-core systems rely on dynamic thermal management
  - Thermal safety at the cost of performance loss
- Task migration is a promising solution
- Designing an **efficient migration policy** is challenging
- Proposed **temperature-aware task migration policy** is
  - Lightweight
  - Effective
  - Near optimal

Thanks for listening.

Any questions?

Backup Slides

Homogeneous Formulas

$$P_{\text{thr}}(\boldsymbol{Q}) = \begin{cases} P^{\star}_{\text{thr}}(\boldsymbol{Q}) & \text{if} \quad P^{\star}_{\text{thr}}(\boldsymbol{Q}) \leq R\left(\sum_{i=1}^{M} q_i\right) \\ R\left(\sum_{i=1}^{M} q_i\right) & \text{otherwise.} \end{cases} \tag{5}$$

$$P^{\star}_{\text{thr}}(\boldsymbol{Q}) = \min_{\forall i \in L} \left\{ \frac{T_{\text{thr}} - P^{\text{core}}_{\text{inact}} \cdot \sum_{j=1}^{M} b^{-1}_{i,k_j}(1 - q_j)}{\sum_{j=1}^{M} b^{-1}_{i,k_j} \cdot q_j} + \frac{-\sum_{j=1}^{N} b^{-1}_{i,j}(p^{\text{blocks}}_j + T_{\text{amb}} \cdot g_j)}{\sum_{j=1}^{M} b^{-1}_{i,k_j} \cdot q_j} \right\} \tag{3}$$

$$R(m) = P^{\text{core}}_{\text{inact}} + \frac{P_{\max} - \sum_{i=1}^{N} p^{\text{blocks}}_i - P^{\text{core}}_{\text{inact}} \cdot M}{m} \tag{6}$$

Algorithm 2: TSP for a Given Mapping (from [1])

Input: $\boldsymbol{Q}, \boldsymbol{P}^{\text{blocks}}, T_{\text{amb}}, T_{\text{thr}}, P^{\text{core}}_{\text{inact}}, P_{\text{max}}$, and floorplan;

Output: Uniform TSP power constraint for mapping $\boldsymbol{Q}$;

$P^{\star}_{\text{thr}}(\boldsymbol{Q}) \leftarrow \infty$;

for all $i \in \boldsymbol{L}$ **do**

  $auxP \leftarrow T_{\text{thr}} - P^{\text{core}}_{\text{inact}} \cdot \sum_{j=1}^{M} b^{-1}_{i,k_j}(1 - q_j)$;

  $auxP \leftarrow auxP - \sum_{j=1}^{N} b^{-1}_{i,j}(p^{\text{blocks}}_j + T_{\text{amb}} \cdot g_j)$;

  $auxP \leftarrow \frac{auxP}{\sum_{j=1}^{M} b^{-1}_{i,k_j} \cdot q_j}$;

  if $auxP < P^{\star}_{\text{thr}}(\boldsymbol{Q})$ **then**

    $P^{\star}_{\text{thr}}(\boldsymbol{Q}) \leftarrow auxP$;

  end if

end for

if $P^{\star}_{\text{thr}}(\boldsymbol{Q}) \leq R\left(\sum_{i=1}^{M} q_i\right)$ **then**

  $P_{\text{thr}}(\boldsymbol{Q}) \leftarrow P^{\star}_{\text{thr}}(\boldsymbol{Q})$;

else

  $P_{\text{thr}}(\boldsymbol{Q}) \leftarrow R\left(\sum_{i=1}^{M} q_i\right)$;

end if

return $P_{\text{thr}}(\boldsymbol{Q})$;

Heterogeneous Formulas

$$P_{\text{thr}}^{\rho}(\boldsymbol{Q}) = \begin{cases} P_{\text{thr}}^{\rho\star}(\boldsymbol{Q}) & \text{if} \quad P_{\text{thr}}^{\rho\star}(\boldsymbol{Q}) \leq R^{\rho}(\boldsymbol{Q}) \\ R^{\rho}(\boldsymbol{Q}) & \text{otherwise.} \end{cases} \tag{7}$$

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$$R^{\rho}(\boldsymbol{Q}) = \frac{P_{\max} - \sum_{i=1}^{N} p_i^{\text{blocks}} - \sum_{j=1}^{M} p_{\text{inact},j}^{\text{core}}(1-q_j)}{\sum_{j=1}^{M} \text{area}_j^{\text{core}} \cdot q_j} \tag{8}$$

Dynamic Voltage and Frequency Scaling with Power Density

$$P_{total} = P_{static} + P_{dyn} \tag{9}$$

$$= I_q \cdot V_{dd} + \alpha \cdot \hat{C}_{eff} \cdot V_{dd}^2 \cdot f \tag{10}$$

$$P_{density} = \frac{P_{total}}{A} \tag{11}$$

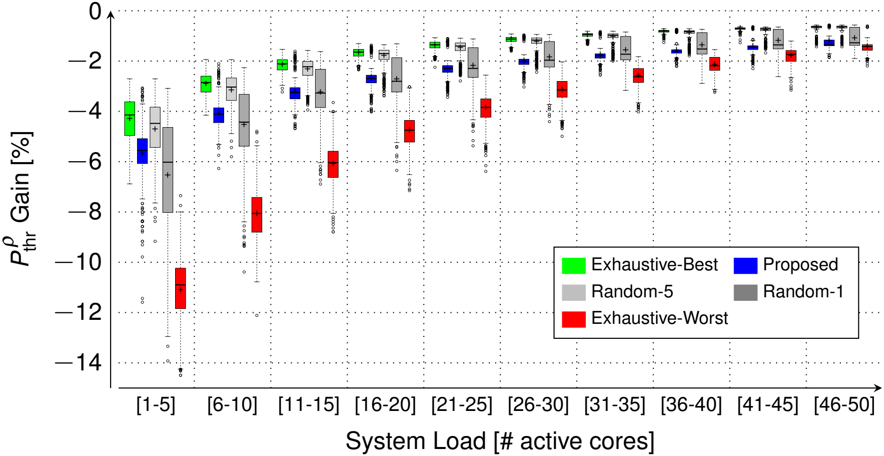
$$P_{dyn} = A_i \cdot P_{density} - P_{stat,i} \tag{12}$$

$$\frac{P_{dyn}^{(a)}}{P_{dyn}^{(b)}} = \frac{V_{dd}^{(a)} \cdot V_{dd}^{(a)} \cdot f^{(a)}}{V_{dd}^{(b)} \cdot V_{dd}^{(b)} \cdot f^{(b)}} = \left(\frac{f^{(a)}}{f^{(b)}}\right)^3 \tag{13}$$

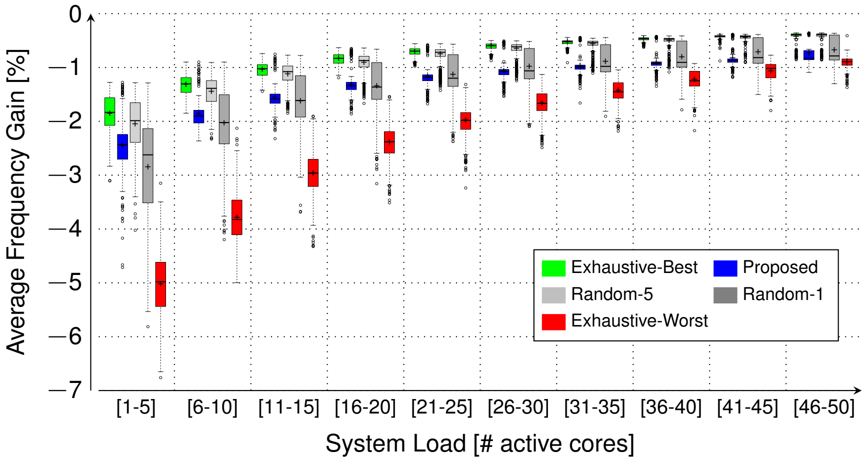
$$\text{avg freq gain per core} = \left(\frac{1}{|C|} \cdot \sum_{i \in C} \frac{f_i^{(a)}}{f_i^{(b)}}\right) - 1 \tag{14}$$

$$= \left(\frac{1}{|C|} \cdot \sum_{i \in C} \left(\frac{A_i \cdot P_{density}^{(a)} - P_{stat,i}}{A_i \cdot P_{density}^{(b)} - P_{stat,i}}\right)^{\frac{1}{3}}\right) - 1 \tag{15}$$

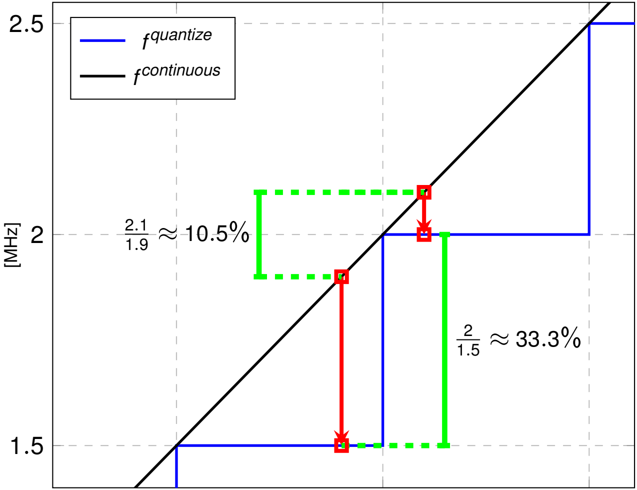
Result: Destination-Core Search - Bad Ranking



Result: Destination-Core Search - Bad Ranking



Realistic Approach



Result: Migration Approaches