Energy Efficient Application Mapping to NoC Processing Elements Operating at Multiple Voltage Levels

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Outline

• Motivation
• Problem Formulation
• Computational Complexity
• Optimal Solution - Mixed Integer Linear Program
• Heuristic based on LP relaxation and randomized rounding
• Experimental results
Motivation

- Minimization of energy consumption subject to performance constraint has become one of the most important objectives.
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  - Mapping of the PEs to the NoC router nodes.
  - Assignment of Operating voltages of the PEs.
  - Routing of traffic over NoC links.
Motivation (cont’d)

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- Results over small examples show potential room for improvement.
Motivational Example

Application Task-graph:

Mesh Specification
- Dimension: 3 x 3
- Supply Voltage = 2.5 V
- Frequency (f) = 500 MHz
- Clock Period (T) = 2 ns

Application Deadline = 122 us
Motivational Example (cont’d)

Mapping generated by sequential approach:

Mapping generated by unified approach:

**Mapping:**
- T0 → P2 → r0
- T1 → P1 → r3
- T2 → P0 → r1
- T3 → P3 → r4

**Comp. Energy** = 3.8124 uJ  
**Comm. Energy** = 0.952 uJ  
**Total Energy** = 4.7644 uJ

**Mapping:**
- T0 → P2 → r0
- T1 → P1 → r3
- T2 → P2 → r0
- T3 → P3 → r1

**Comp. Energy** = 3.8575 uJ  
**Comm. Energy** = 0.0159 uJ  
**Total Energy** = 3.8734 uJ
Motivation

- Energy consumption can be further reduced by scaling down voltage level of non-critical PEs.
- There will be energy, area overhead due to level shifters.
- Excessive number of voltage islands is not desirable from the physical design perspective.
Problem Formulation

Given:

- Application task graph $G_T(V_T, E_T)$ ($V_T$: set of tasks and $E_T$: set of task dependencies)
- Communication volume $w_{ij}$ on each edge $e_{ij} \in E_T$.
- Set of potential PEs $P_t$ for each task $t \in V_T$.
- Set of allowable voltage levels $V_p$ for each PE $p$.
- NoC topology $G_R(V_R, E_R)$.
- Execution time and energy consumption parameters.
Problem Formulation (cont’d)

Solve the application mapping problem, along with voltage assignment, such that:

• All tasks finish execution before application deadline \( D \).
• Task dependencies maintained.
• Bandwidth constraint on each NoC link is satisfied.
• Total number of created voltage islands does not exceed \( \kappa \).
• Total energy consumption (computation + communication + voltage transition) is minimized.
Theorem 1: Voltage assignment problem is NP-hard and inapproximable within any constant factor. Proof obtained by using reduction from the known NP-hard problem \textit{GRAPH 3-COLORABILITY with no vertex degree exceeding 4}. Application mapping problem, which is a superset of the voltage assignment problem, is at least as hard as this.
Optimal Solution

• Mixed Integer Linear Program (MILP)
• **Objective**: minimize \( E = E_c + E_r + E_l + E_{vt} \)
  • \( E_c \): computation energy consumption
  • \( E_r \): communication energy consumption on router ports
  • \( E_l \): communication energy consumption on links
  • \( E_{vt} \): level shifter energy consumption

• such that all constraints are satisfied.
Optimal Solution (cont’d)

\[ E_c = \sum_{t \in V_T} \sum_{p \in P_t} \sum_{v \in V_p} (\delta_{tp}^v e_{tpv}) \]

\[ E_r = \sum_{e_{xy} \in E_R} \sum_{e_{ij} \in E_T} (f_{xy}^{ij} w_{ij})(\psi_i + \psi_o) \]

\[ E_l = \sum_{e_{xy} \in E_R} \sum_{e_{ij} \in E_T} ((f_{xy}^{ij} w_{ij})L_{xy})\psi_l \]

\[ E_{vt} = \sum_{v_1 \in V} \sum_{v_2 \in V} \sum_{e_{xy} \in E_R} (\zeta_{xv_1} \zeta_{yv_2})\alpha_{v_1 v_2} \]
Heuristic Solution

1: Relax all the integer constraints in the MILP /* relaxation */
2: Solve the relaxed LP using CPLEX
3: while (Solution NOT Integral) do
   4: Set the integral variables in LP solution as constants and leave them unaltered during further iterations /* variable fixing */
   5: Round a variable to integer with probability equal to its value
   6: Solve modified LP
   7: if (NO Constraint Violation) then
      8:   if (Integer Solution) then
      9:      Solution Found - break out of outer while loop
   10: end if
   11: else
   12:   Eliminate constraint violations by modifying the rounding
   13: end if
14: end while
15: return Solution
Experimental Setup

• E3S benchmark applications (auto-industry, consumer, networking and office-automation)

• Three real applications: MPEG4, MWD(Multi-Window Display) and OPD(Object Plane Decoder).

• Five discrete voltage levels used.

• ILOG CPLEX used for solving MILP.

• Evaluations:
  • Optimal for variable voltage setup vs. Optimal for fixed voltage setup.
  • Optimal solution using proposed unified approach vs. sequential approach.
  • Quality of heuristic solution vs. optimal solution.
Experimental Results

Feasibility of solutions: **Case I** is variable voltage settings, whereas **Case II - VI** are fixed voltage settings (Low to High)

<table>
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<th>Case I</th>
<th>Case II</th>
<th>Case III</th>
<th>Case IV</th>
<th>Case V</th>
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</table>
Experimental Results (cont’d)

Optimal at Variable Voltage vs. Optimal at Fixed Voltage:

- Auto-industry
- Networking
Experimental Results (cont’d)

Optimal at Variable Voltage vs. Optimal at Fixed Voltage:

- Consumer
- Office-automation
Experimental Results (cont’d)

Optimal at Variable Voltage vs. Optimal at Fixed Voltage:

- **MPEG4**
- **MWD**
- **OPD**
Experimental Results (cont’d)

Optimal using Unified approach vs. Sequential approach:

- auto-industry
- networking
- office-automation
Experimental Results (cont’d)

Optimal vs. Heuristic at Variable Voltage:

- auto-industry
- networking
Experimental Results (cont’d)

Optimal vs. Heuristic at Variable Voltage:

- **consumer**
- **office-automation**

![Bar graphs comparing optimal vs. heuristic energy consumption for consumer and office-automation](image-url)
Experimental Results (cont’d)

Optimal vs. Heuristic at Variable Voltage:

MPEG4

MWD

OPD
Thank you!