Modeling Impact of Power- and Thermal-aware Fans Management on Data Center Energy Consumption

Wojciech Piątek¹, Ariel Oleksiak¹,², Micha vor dem Berge³

1Poznan Supercomputing and Networking Center
2Poznan University of Technology
3Christmann Informationstechnik & Medien
Problem and motivation

► Problem
  ▶ Impact of micro servers on the overall data center energy consumption
  ▶ PUE is not sufficient in minimizing data center energy consumption

► Motivation
  ▶ Complexity and time requirements of Computational Fluid Dynamics methods

► The approach
  ▶ Models for transient simulations of data center
  ▶ Reflecting correlations between PUE and savings
  ▶ Fan management to minimize overall energy consumption and high temperature excesses
FiPS Project

FiPS – Field-Programmable Servers

► Heterogeneous servers
  ▶ CPU, embedded CPU, FPGA
  ▶ Cluster architecture
  ▶ 100 – 10k processing elements

► Application to hardware mapping methodology

► Goal: Performance/Energy +40%
Outline

► Power and thermal models of data center

► How PUE can be misleading…

► Simulation experiments - fans power management
POWER AND THERMAL MODELS OF DATA CENTER
Power use modeling

• Data Center

\[ P_{DATA\_CENTER} = \sum_{i=1}^{n} P_{RACK} + P_{COOLING} \]

• Cooling*

\[ P_{COOLING} = \frac{P_{IT\_LOAD}}{CoP} \]

• Rack

\[ P_{RACK} = \left( \sum_{i=1}^{l} P_{NODE\_GROUP} + c \right) / \eta_{PSU} \]

Power use modeling

- **Node group (e.g. blade center)**
  \[ P_{\text{NODE\_GROUP}} = \sum_{i=1}^{m} P_{\text{NODE}} + \sum_{j=1}^{k} P_{\text{FAN}} \]

- **Fan**
  \[ P_{\text{FAN}} = \frac{V \times dp}{\mu} \quad P_{\text{FAN}} = k_f \times V^3 \]

- **Node (server)**
  \[ P_{\text{NODE}} = \sum_{i=1}^{n} P_{\text{CPU}} + P_{\text{MEM}} + P_{\text{NET}} + P_{\text{HDD}} \]

- **Processor**
  \[ P_{\text{CPU}}(f,l) = (P_{\text{CPU}}(idle) + l \times (P_{\text{CPU}}(f,100) - P_{\text{CPU}}(idle))) \times g(T_{\text{CPU}}) \]
Thermal modeling

\[ P_{\text{node}} \]

\[ T_{\text{cpu}} \]

\[ P_{\text{cpu}} \]

\[ T_{\text{amb}} \]

\[ T_{\text{in}} \]

\[ P_{\text{fan}} \]

\[ T_{\text{out}} \]
Thermal modeling - processor

\[ T_{\text{cpu}}(t + \Delta t) = T_{\text{cpu}}^\infty + (T_{\text{cpu}}(t) - T_{\text{cpu}}^\infty) e^{-\frac{\Delta t}{RC}} \]
Thermal modeling - processor

\[ T_{cpu}(t + \Delta t) = T_{cpu}^\infty + (T_{cpu}(t) - T_{cpu}^\infty) e^{-\frac{\Delta t}{RC}} \]

\[ T_{cpu}^\infty = P_{cpu} \ast R + T_{amb} \]

\[ R = R_{cond} + R_{conv} \]

\[ R_{conv} = \frac{1}{k_h \ast V^n} \]

\[ V = \sqrt[3]{k_f \ast P_{fan}} \]

\[ T_{amb} = (T_{cpu} + 2 \ast T_{in}) / 3 \]
Thermal modeling - outlet

\[ T_{out}(t + \Delta t) = T_{out}^\infty + (T_{out}(t) - T_{out}^\infty)e^{-\frac{\Delta t}{RC}} \]

\[ T_{out}^\infty = \frac{P_{node} + P_{fan}}{K} + T_{in} \]

\[ R = R_{cond} + \frac{1}{k_h * V^n} \]

\[ K = \rho * V * C_p \]

\[ T_{out}^\infty = \frac{\sum_{i=1}^{n} P_{node_i} + P_{fan}}{K} + T_{in} \]
Thermal modeling - evaluation

- Tin = 20.5 °C

- Monitoring: f = 1Hz

- Intel Core i5-4400E
  - stress workload generator -> stress workload generator
  - fan speed: 30%, 70%, 100%
Thermal modeling - evaluation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_cond</td>
<td>1,06 °C/W</td>
</tr>
<tr>
<td>R_conv</td>
<td>0,28-0,7 °C/W</td>
</tr>
<tr>
<td>K_h</td>
<td>49 [W][s]/°C[m^3]</td>
</tr>
<tr>
<td>n</td>
<td>0,77</td>
</tr>
<tr>
<td>C</td>
<td>8 [W][s]/°C</td>
</tr>
</tbody>
</table>

### Thermal Performance

<table>
<thead>
<tr>
<th>Fans speed</th>
<th>Avg. temperature difference</th>
<th>Avg. relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>1,91°C</td>
<td>2,75%</td>
</tr>
<tr>
<td>70%</td>
<td>1,95°C</td>
<td>3,14%</td>
</tr>
<tr>
<td>100%</td>
<td>1,04°C</td>
<td>1,86%</td>
</tr>
</tbody>
</table>
HOW PUE CAN BE MISLEADING…
How PUE can be misleading... - Levels of PUE

PUE Level 1
PUE Level 2
PUE Level 3

Different PUE for the same energy use!

PUE = 1.88
PUE = 1.6
PUE-Level 4:
- Subtracting fans and PSU consumption
- To quantify efficiency at IT level

\[
PUE = \frac{\text{Total load}}{\text{IT load}}
\]

\[
PUE \text{ Level 4} = \frac{\text{Total load}}{\text{IT load} - \text{Fans inside racks} - \text{PDUs}}
\]
SIMULATION EXPERIMENTS
Simulation experiments

- Simulations with SVD Toolkit
- Resource: 10 racks, 42 1-unit enclosures with Intel Core i5-4400E
- Cooling model*
  \[ CoP = 0.0068 \times T_{in}^2 + 0.0008 \times T_{in} + 0.458 \]
- Load: 7200s, 10 periods (uniform distribution) with 0-100% utilization -> 46%

Simulation experiments

- Constant fan speed - 30%
- Constant fan speed - 100%
- Variable fan speed - 3 speed levels: 30%, 70% and 100%
- Dynamic fan speed control - 8 speed levels; tuning the fan speed in advance
## Simulation experiments \( T_{in}=22^\circ C \)

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Const = 30%</th>
<th>Const = 100%</th>
<th>Variable</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Leakage [kWh]</td>
<td>14,49</td>
<td>4,17</td>
<td>4,91</td>
<td>5,22</td>
</tr>
<tr>
<td>Avg temp, exceeded time (90 C) [s]</td>
<td>1311</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Processors energy [kWh]</td>
<td>87,78</td>
<td>77,46</td>
<td>78,2</td>
<td>78,51</td>
</tr>
<tr>
<td>Enclosure fans energy [kWh]</td>
<td>2,7</td>
<td>33,27</td>
<td>17,86</td>
<td>14,26</td>
</tr>
<tr>
<td>Racks energy [kWh]</td>
<td>149,23</td>
<td>172,55</td>
<td>155,69</td>
<td>151,91</td>
</tr>
<tr>
<td>Cooling energy [kWh]</td>
<td>40,08</td>
<td>42,58</td>
<td>39,93</td>
<td>39,35</td>
</tr>
<tr>
<td>Total energy [kWh]</td>
<td>192,3</td>
<td>218,58</td>
<td>198,73</td>
<td>194,3</td>
</tr>
<tr>
<td>PUE</td>
<td>1,288</td>
<td>1,266</td>
<td>1,276</td>
<td>1,279</td>
</tr>
<tr>
<td>PUE Level 4</td>
<td>1,512</td>
<td>1,87</td>
<td>1,69</td>
<td>1,648</td>
</tr>
</tbody>
</table>
Simulation experiments Tin=22°C
# Simulation experiments Tin=24C

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Const = 100%</th>
<th>Variable</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Leakage [kWh]</td>
<td>4.91</td>
<td>5.37</td>
<td>5.88</td>
</tr>
<tr>
<td>Avg temp, exceeded time (90 C) [s]</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Processors energy [kWh]</td>
<td>78.2</td>
<td>78.66</td>
<td>79.17</td>
</tr>
<tr>
<td>Enclosure fans energy [kWh]</td>
<td>33.28</td>
<td>21.37</td>
<td>15.25</td>
</tr>
<tr>
<td>Racks energy [kWh]</td>
<td>173.41</td>
<td>160.25</td>
<td>153.80</td>
</tr>
<tr>
<td>Cooling energy [kWh]</td>
<td>36.7</td>
<td>34.91</td>
<td>34.07</td>
</tr>
<tr>
<td>Total energy [kWh]</td>
<td>213.58</td>
<td>198.37</td>
<td>190.95</td>
</tr>
<tr>
<td>PUE</td>
<td>1.231</td>
<td>1.237</td>
<td>1.241</td>
</tr>
<tr>
<td>PUE Level 4</td>
<td>1.631</td>
<td>1.566</td>
<td>1.531</td>
</tr>
</tbody>
</table>
Conclusions

► Holistic model of data center including power and thermal models (accuracy: 1.86-3.14%)
► PUE Level 4 as a way of representing fan impact on DC effectiveness
► Thermal-aware fans management led to:
  ▶ Up to 8% reduction on cooling
  ▶ Up to 12% savings on total energy
  ▶ … all with keeping the processor temperature below the given threshold
► Next steps
  ▶ Model improvement, analysis of denser and heterogeneous architectures