Energy Models for DVFS Processors

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1 Introduction and Motivation

2 Energy Measurement techniques for DVFS processors
   - Power measurement with power-meters
   - Power measurement with RAPL sensors
   - Comparison of the measurement techniques

3 Runtime and energy performance
   - SPEC CPU2006 benchmarks
   - PARSEC benchmarks

4 Energy models with frequency scaling
   - Physical energy models
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Introduction and Motivation

- **Energy consumption** is an important concern in today’s consideration of parallel programs especially for HPC.
- Several different energy acquisition methods based on hardware, software and simulation approaches have been proposed in a large variety of different setups.
- Current commodity processors provide the dynamic voltage-frequency scaling (DVFS) technique. Processors can dynamically adjust voltage and frequencies of cores to reduce power consumption.
- Reducing the frequency leads to a smaller power consumption. However, longer computation times result due to the reduced frequency.
- It would be valuable to be able to choose a suitable frequency before running a larger HPC program.
Introduction and Contribution

- We investigate **two energy measurement techniques** for DVFS processors
  hardware-based measurement with **power-meters** and **RAPL sensors**
  accessing MSR hardware counters.

- As application programs, we have chosen the **SPEC CPU2006**, the
  **PARSEC benchmarks** and the **SPLASH benchmarks**, which
  represent a **broad range of sequential and multithreaded application codes**.

- We also compare **three different energy models** for DVFS
  concerning their ability to **capture** the energy consumption of the
  benchmarks.
  **physical energy models** and a new heuristic model

- An **experimental investigation** is provided comparing the **energy prediction capabilities** of the energy models.
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Modern microprocessors such as the Intel Core i7 processors incorporate a sophisticated power management technology, including performance states (P-states), throttle states (T-states), idle states (C-states) and sleep states (S-states).

- **P-states** are predefined sets of frequency and voltage combinations at which an active core can operate.
- A **C-state** is an idle state in which parts of the processor are powered down to save energy.
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Power measurement with power-meters (NI9205 device)

The NI9205 enables a fine-grain power measurement of different components of a computer system.
Power acquisition and profiling with LabView

**Challenge**: relate the power data measured to the application program whose energy consumption is to be determined;

**User-configured modules** operating in a client-server fashion had to be written

Detailed measurement for different pins supplying different components of the computer system.
Example: PARSEC benchmark x264 on Core i7 Ivy Bridge

Power Hardware Measurement x264 3.2GHz Ivybridge

Mainboard 24 PIN 3.3V (memory)
Mainboard 24 PIN 12V
Mainboard 24 PIN 5V
Mainboard EPS 12V (CPU)
Harddisk (5V+12V)

power [watt]
time [s]

Time interval between 20 and 20.5 sec
## Platforms for Experimental Evaluation

<table>
<thead>
<tr>
<th></th>
<th>Core i7-2600</th>
<th>Xeon E3-1225V2</th>
<th>Core i7 4770</th>
</tr>
</thead>
<tbody>
<tr>
<td>architecture</td>
<td>Sandy Bridge</td>
<td>Ivybridge</td>
<td>Haswell</td>
</tr>
<tr>
<td>min. frequency</td>
<td>1.6 GHz</td>
<td>1.6 GHz</td>
<td>0.8 GHz</td>
</tr>
<tr>
<td>max. frequency</td>
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<td>3.4 GHz</td>
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<td>200 MHz</td>
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<tr>
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<td>256 KByte</td>
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<tr>
<td>L3 shared cache</td>
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<tr>
<td>RAM size</td>
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<td>8 GByte</td>
<td>8 GByte</td>
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Power measurement with RAPL sensors

- Runtime and energy measurements for different Intel Core i7 processors (Sandy Bridge, Ivy Bridge, Haswell).
  access to Model Specific Registers (MSRs) via rdmsr and wrmsr instructions

- The RAPL (Running Average Power Limit) interface provides mechanisms to control power consumption;

- The MSRs provide information about the energy status of the PP0 and PP1 power planes via specific registers.

- likwid-powermeter from the likwid tool-set (Version 3.0) to access the MSRs.

- The cpufreq-set tool has been used to set the core frequencies.
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Comparison of the measurement techniques

only the $+12$VDC EPS connector power is shown left

**observation**: the two alternative measurement techniques coincide qualitatively and quantitatively for a **wide range of frequencies**

**small difference** as the 24 PIN 5V connector **also supplies the CPU**

(in and other mainboard devices)

in the following: measurement with RAPL
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SPEC CPU2006 benchmarks

integer and floating-point benchmarks from different application areas runtimes on Core i7 Haswell for integer benchmarks using different frequencies:

more-than-linear increase of the execution time for smaller frequencies
SPEC CPU2006 integer benchmarks: power consumption on Haswell

different applications lead to different power consumption
SPEC CPU2006 integer benchmarks: energy consumption on Haswell

no large variation of the energy consumption with the frequency
SPEC CPU2006 floating point benchmarks: runtime on Haswell

more-than-linear increase of the execution time for smaller frequencies
different applications lead to different power consumption
slightly larger power consumption as for the integer benchmarks
SPEC CPU2006 floating point benchmarks: energy consumption on Haswell

energy consumption of SPEC FIPoint benchmarks on i7 Haswell

no large variation of the energy consumption with the frequency
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PARSEC benchmarks – runtime Haswell

12 programs from different application areas
different parallel models for shared address spaces are used

Execution time increases more than linearly for smaller frequencies (below about 1.7 GHz).
large variation of the power consumption for different benchmarks
Benchmarks with a sequential workload typically lead to smaller power values
PARSEC benchmarks – energy consumption Haswell

The graph shows the energy consumption of Parsec benchmarks on Core i7 Haswell. The x-axis represents frequency in GHz, while the y-axis represents energy consumption in Joule.

The graph indicates that the smallest energy consumption between 2 GHz and 2.5 GHz is achieved by the benchmarks.

Rauber, Rünger, Schwind, Xu, Melzner  Energy Measurement and Prediction for Multi-threaded Programs
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Energy models with frequency scaling

- Energy models usually take the **dynamic power consumption** and the **static power consumption** into consideration.

- The **dynamic power consumption** is related to the supply voltage and the **switching activity** during the computing activity of the processor.

- The **static power consumption** is intended to capture the **leakage power consumption** as well as the power consumption of peripheral devices.

- The **total power consumption** of the CPU is obtained as the sum of these two components.

- For **DVFS processors**, the power consumption depends on the **operational frequency** $f$. 
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Physical energy models

- The **energy consumption** of an application program can be described as $E = \int_{t=t_0}^{t_{max}} P(t) \cdot dt$.

- The **dynamic power consumption** is often approximated by $P_{dyn} = \alpha \cdot C_L \cdot V^2 \cdot f$
  
  $\alpha$: switching probability; $C_L$: load capacitance; $V$: supply voltage; $f$: operational frequency.

- Modeling of the **static power consumption due to leakage power**: $P_{static} = V \cdot N \cdot k_{design} \cdot I_{leak}$
  
  $N$: number of transistors; $k_{design}$: design-dependent parameter; $I_{leak}$: technology-dependent parameter.

- The frequency scaling can be expressed by a **dimensionless scaling factor** $s \geq 1$, which describes $\tilde{f} < f_{max}$ as $\tilde{f} = f_{max}/s$.

- The frequency $f$ depends linearly on the supply voltage $V$: $V = \beta \cdot f$.

- Thus, the dependence of the **dynamic power** on $f$ is approximated by $P_{dyn} = \gamma \cdot f^3$ with $\gamma = \alpha \cdot C_L \cdot \beta^2$. 
Modeling the static power consumption

- For **earlier processors**, the static power consumption was considered to be **neglectable**.
- For **recent processors**, the static power consumption may be **too large** to be ignored.
- **Model 1**: static power depends **linearly on the frequency**:
  \[ P_{\text{static}} = \delta \cdot f \]
  with \( \delta = N \cdot k_{\text{design}} \cdot I_{\text{leak}} \cdot \beta \).
- **Model 2**: static power is **constant**, independently of \( f \).
- **Reducing the operational frequency** of a processor by a scaling factor of \( s \), \( s \geq 1 \), **increases the execution time** of a program by the same factor.
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Heuristic energy model

- A (new) heuristic model considers the entire power consumption and uses **least squares methods** to derive a formula describing the power consumption in **closed form**.

- **Observation** from the experiments: there is an **almost linear dependence** of the power on the frequency $f$: $P_{heu}(f) = a + bf^{1+\epsilon}$

- The parameter $a$ can be interpreted as the **static part** of the power consumption that **does not change** with the frequency.

- The parameter $b$ captures the **dynamic part** of the power consumption that **increases with the operational frequency** of the CPU.

- For the parameter $\epsilon$, several **fixed values** have been tested and the computation of $a$ and $b$ is done by the least squares method.

- **Different benchmarks** may have **different values** for these parameters $a$ and $b$ due to their specific computational and memory access behavior.
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Validating the energy models

- Comparison of the **measured energy values** with energy values **predicted by the models** for different frequencies.

- For the **analytical model**, the parameters $\gamma$ and $\delta$ have been determined by curve fitting using the least squares method.

- For different benchmarks, the resulting values for the parameters $\gamma$ and $\delta$ are **quite similar** for most of the benchmarks on the same architecture (the difference is typically below 10%).

- Thus, in principle, the **average of the parameters** for the different benchmarks could be used and would lead to a similar correspondence between measured and predicted values.

- For the different architectures, different values for the parameters $\gamma$ and $\delta$ result.

- For the **heuristic model**, $\epsilon = 0.2$ has been used.
SPEC: Comparison for Haswell $f = 2.5$ GHz

measured vs predicted energy consumption $f=2.5$ GHz Haswell

energy consumption [J]

measured
predicted 1
predicted 2
predicted 1 av
predicted 2 av
SPEC: Comparison for Haswell $f = 0.8$ GHz

measured vs predicted energy consumption $f=0.8$ GHz Haswell

energy consumption [J]
Model 1: parameter $\gamma$ (dynamic part) lies between 12 and 31 for different benchmarks; parameter $\delta$ (static part) lies between 7 and 13.5;
PARSEC: Comparison for Haswell $f = 0.8$ GHz

Best predictions by the heuristic model
Observations

- For most situations, **both the analytical and the heuristic energy models are well suited** to describe the energy consumption of most benchmark programs.
  The deviations usually lie **below 10%**.

- The two **analytical models** both provide reasonable predictions with slight advantages for Model 1.

- Using the analytical models, **larger deviations** between the measured and predicted values can be observed for **smaller frequencies** on the Haswell architecture.
  The **heuristic model** leads to better predictions in this situation.

- Only for **smaller frequencies**, there are some deviations between the models. In this context, the **heuristic model** provides better predictions.

- **Summary**: the energy models are able to capture the energy consumption with **reasonable accuracy** for most situations.
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Conclusions

- **Frequency scaling** provides the possibility to choose an energy and runtime efficient state for processing an application program.
- We have studied various hardware, software and simulation approaches.
- Both *measurement methods* considered (power-meters, hardware counters) provide *qualitatively and quantitatively corresponding data*.
- **Large variation** of power consumption for the different benchmarks; *speedup* plays an important role, variations are *smaller* for *sequential workloads*.
- **Energy models** are suitable for an *energy performance prediction*. 
References

