# Modeling the Energy Consumption of Programs: Thermal Aspects and Energy/Frequency Convexity Rule

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# Why focussing on energy saving for mobile computing?

- **It is not *only* about the magnitude of saved energy:**
  - A smartphone CPU consumes between 60 to 500mW
  - There were about $7 \times 10^9$ smartphones sold in the last 5 years, there will be $50 \times 10^9$ 'smart objects' in 2022
  - A worldwide saving of 30% would roughly mean about 280 MW for the smartphones, about 3 GW for the smart objects
  - This would '*only'* save between one tidal and one nuclear power station worldwide

- **Saving energy at the software level also is about a natural-resource-free energy saving**

- **Focussing on mobile systems (*e.g. a baystation on a drone*): they are '*energy-critical*' : it is about being constantly looking for providing more autonomy with an unchanged QoS, with the same battery**



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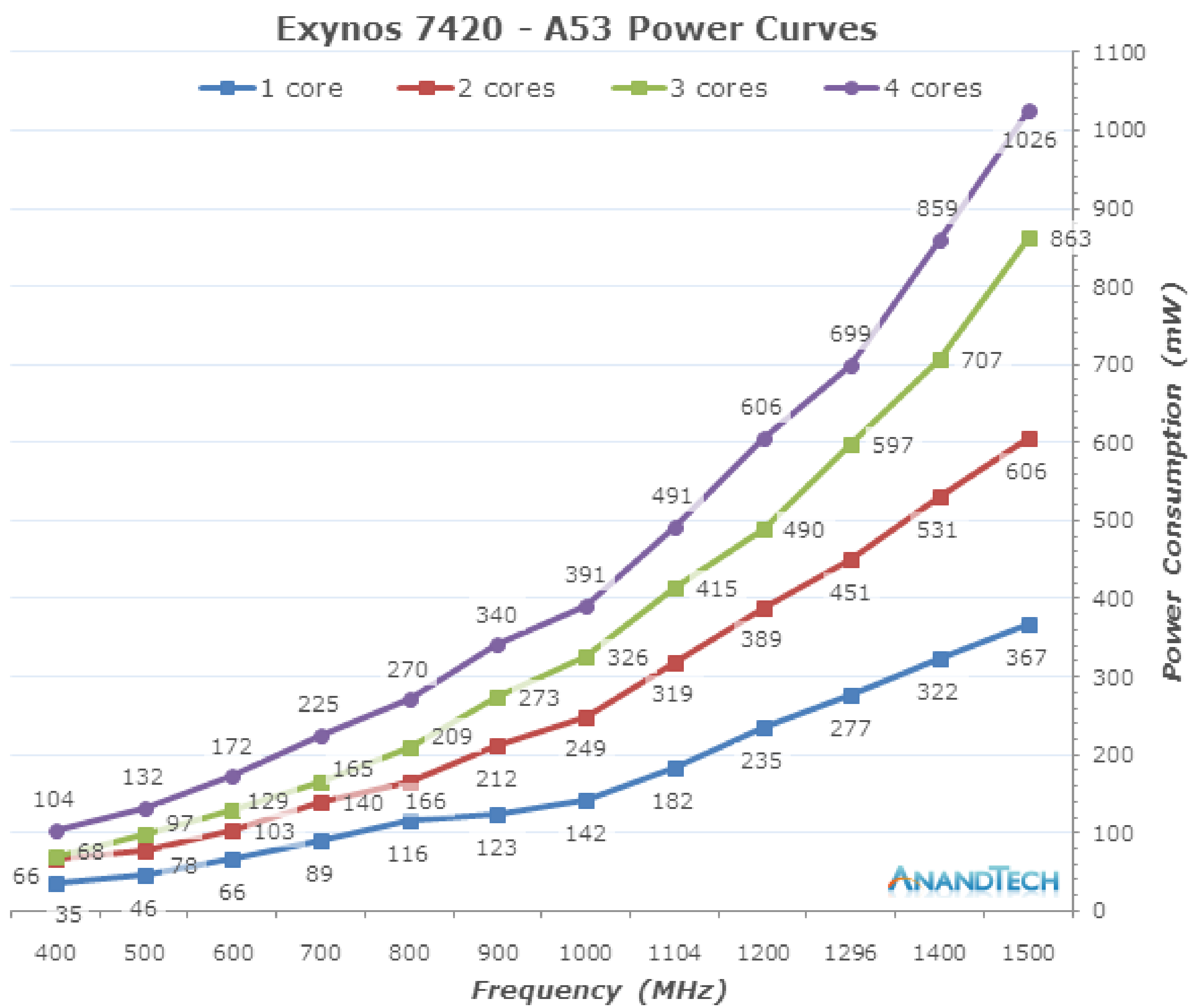
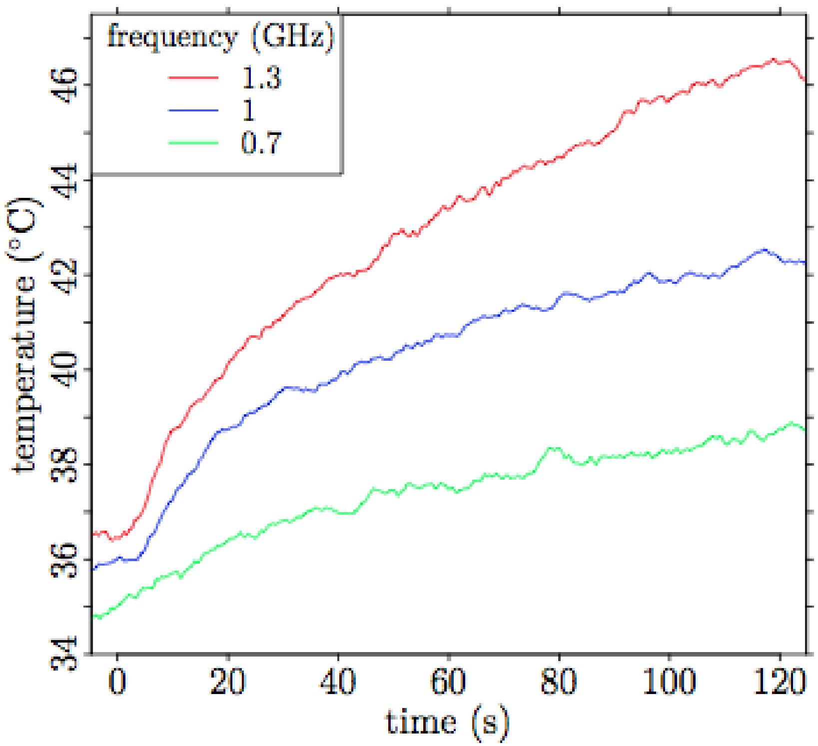
# The trend is moving towards providing more computational power



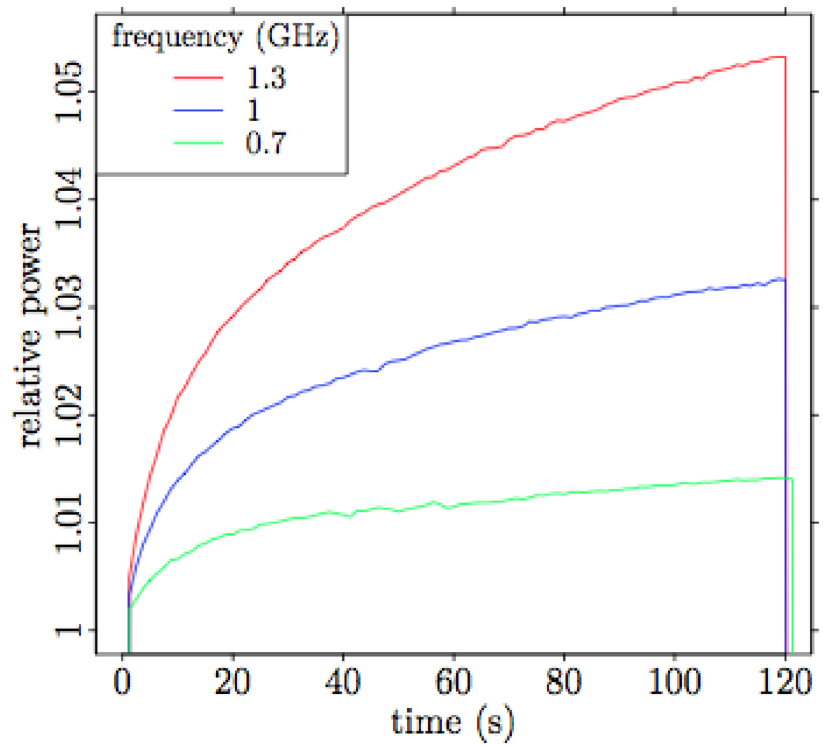
# Thermal Behavior:
# Power-temperature rule
# Passive Cooling rule

# Temperature impacts energy consumption

$$P = a_1 e^{T/a_2} + a_0$$




(a) Temperature




(b) Power

An increase of 10% of temperature generates an increase of 5% in power consumption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# Small size mobiles have no fan
# Passive Cooling Rule

The passive lumped system's transient thermal behavior is defined by

internal heat generation + radiation + convection

$$mC\frac{dT}{dt} = P(T) + \epsilon\sigma(T^4 - T_a^4) + h(T - T_b),$$

which has the solution

$$t(T) = -\frac{1}{\kappa_4}\Big(A\ln|T-\omega_1| + \frac{C}{2}\ln|(T-\alpha)^2+\beta^2| + B\ln|T-\omega_2| + \frac{\alpha C - D}{\beta}\arctan\left(\frac{T-\alpha}{\beta}\right) + c_o\Big).$$

Approximations do exist for small areas

# Contributions on thermal behavior

- Necessary for reproducible measurements and for accurate energy consumption models
- Power–temperature relationship
- Approximations for practical uses, particularly for online usages (embedded systems, radio mobiles,…)



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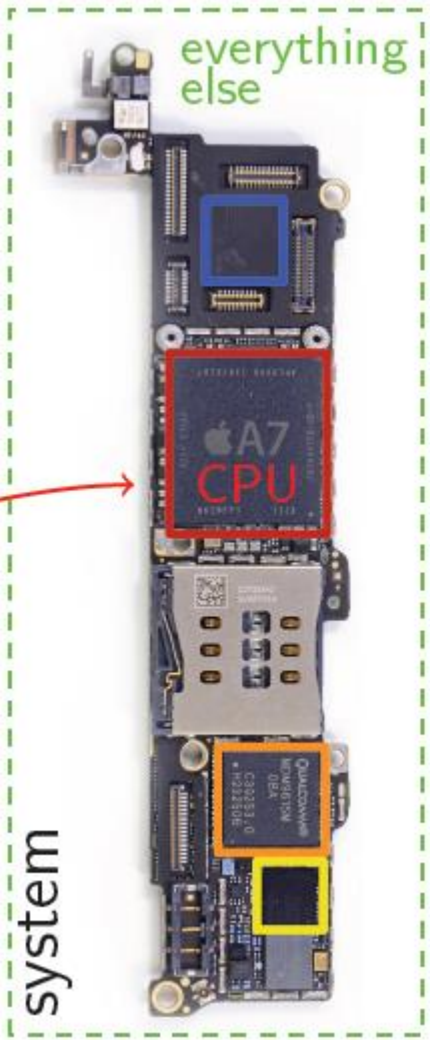
# EFCR: the energy – frequency convexity rule

# Fragmenting energy consumption per system module

- System's energy consumption $E_{\text{sys}}$ definition

$$E_{\text{sys}} = \int_0^{\Delta t} P_{\text{total}}\, dt = \int_0^{\Delta t} (P_{\text{cpu}} + P_{\text{back}})\, dt;$$




- Examples of $P_{\text{back}}$ include:
  - LCD screen,
  - radio interface,
  - power supply;
- If $P_{\text{cpu}}$ and $P_{\text{back}}$ are sufficiently constant over time

$$E_{\text{sys}} = (P_{\text{cpu}} + P_{\text{back}}) \cdot \Delta t;$$



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# Power and time model

## Microprocessor Power Model

CPU power $P_{\mathrm{cpu}}$ consists of:

- dynamic power $P_{\mathrm{dyn}}$,
- leakage current $P_{\mathrm{leak}}$,
- short-circuit current $P_{\mathrm{sc}}$;

$$
\begin{aligned}
P_{\mathrm{cpu}} &= P_{\mathrm{dyn}} + P_{\mathrm{leak}} + P_{\mathrm{sc}} \\
&= (1 + \gamma V) \cdot \eta \, \alpha C V^2 f \\
&= (1 + \gamma V) \cdot \xi V^2 f.
\end{aligned}
$$

## Execution Time Model

Execution time $\Delta t$ depends on:

- $cc_{\mathrm{b}}$ code size in clock cycles,
- $f$ CPU clock frequency,
- $f_{\mathrm{k}}$ frequency thieves,
- $\beta$ slack time per clock cycle;

$$
\Delta t = cc_{\mathrm{b}} \left( \frac{1}{f - f_{\mathrm{k}}} + \beta \right).
$$


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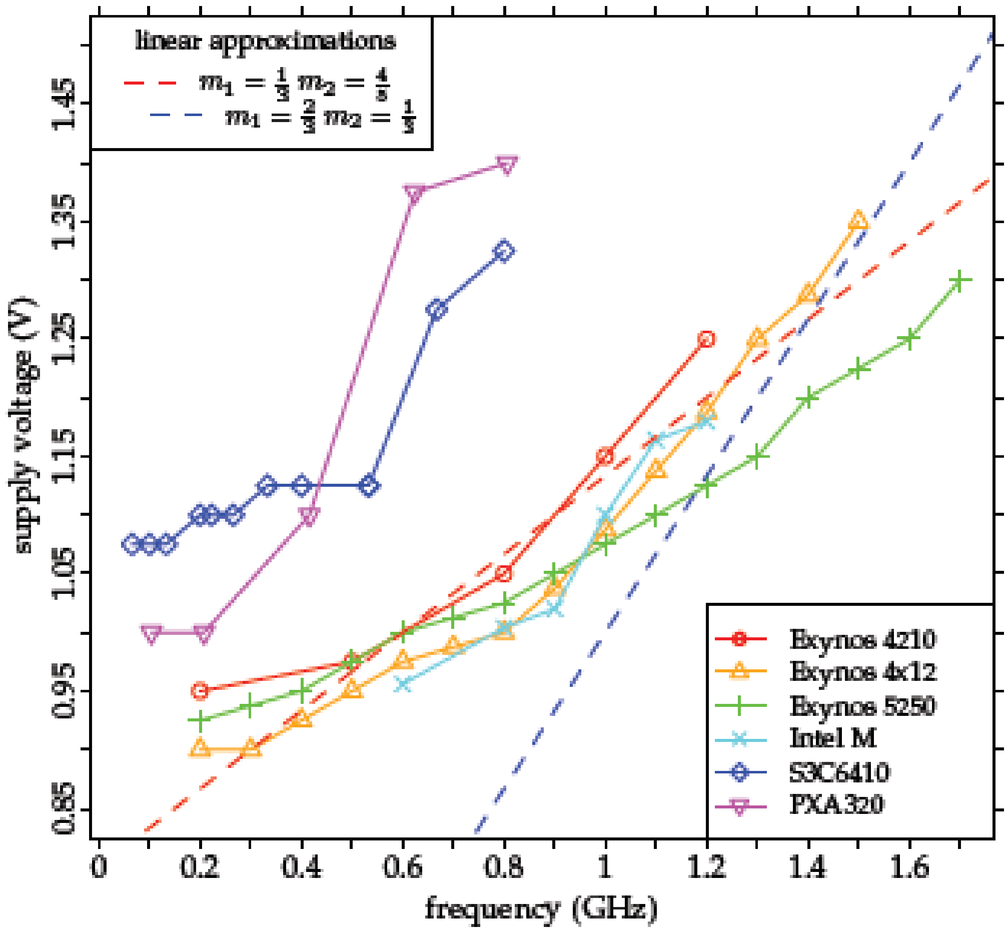
# V can be approached by a linear function of the frequency




$$V = m_1 f + m_2$$

# Optimal frequency and Convexity

- System's energy consumption model (EFCR)

$$\begin{aligned} E_{\mathrm{sys}}(f) &= (P_{\mathrm{cpu}} + P_{\mathrm{back}}) \cdot \Delta t \\ &= ([1+\gamma V]\xi V^2 f + P_{\mathrm{back}}) \cdot cc_{\mathrm{b}} \left( \frac{1}{f - f_{\mathrm{k}}} + \beta \right), \end{aligned}$$

where $\{\gamma, \xi, P_{\mathrm{back}}, cc_{\mathrm{b}}, f_{\mathrm{k}}, \beta\} \in \mathbb{R}^+$.

- A single minimum for $E_{\mathrm{sys}}(f)$ exists at $f_{\mathrm{opt}}$ when

$$\left( \frac{\partial E_{\mathrm{sys}}}{\partial f} \right)_{f=f_{\mathrm{opt}}} = 0, \quad \text{and} \quad \frac{\partial^2 E_{\mathrm{sys}}}{\partial f^2} \geq 0 \quad \text{holds;}$$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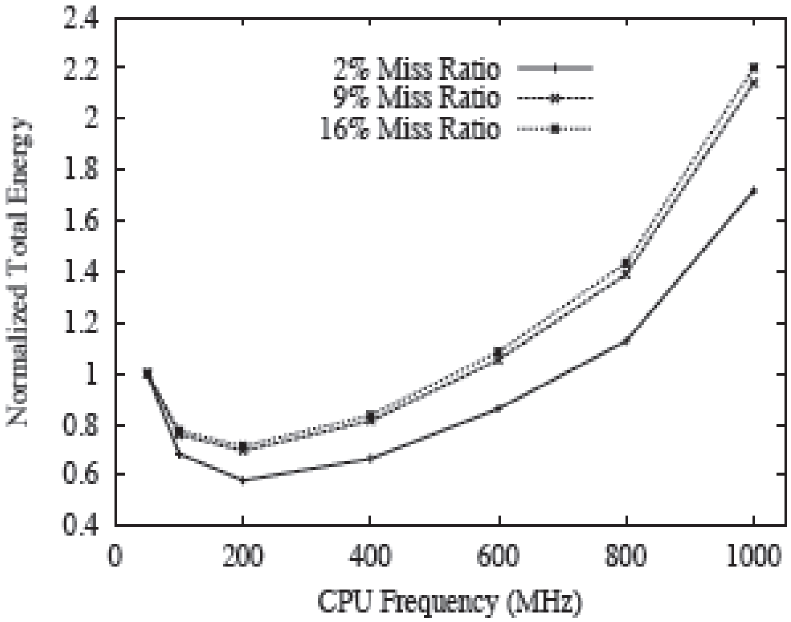
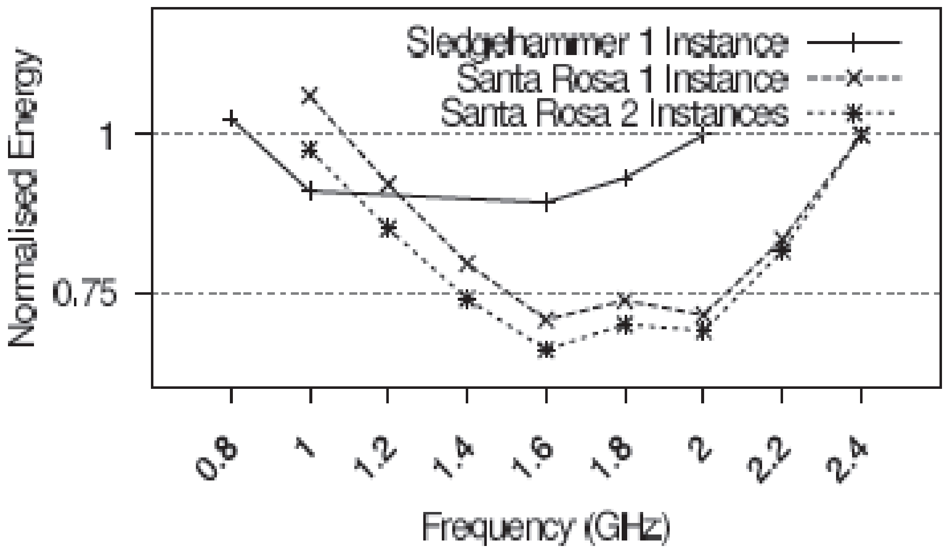
# State of the art

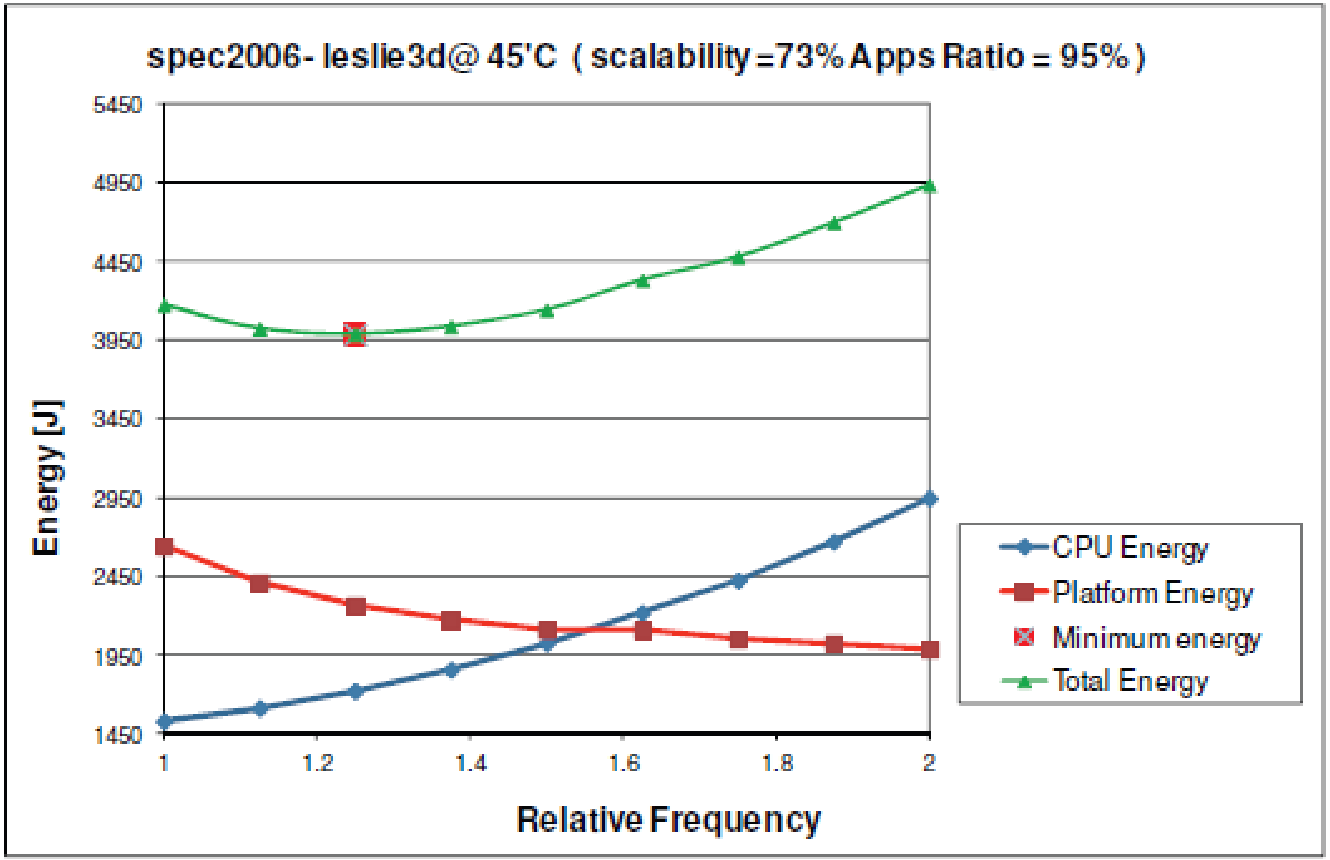
- **Convexity was already observable, however no analytical studies were performed**



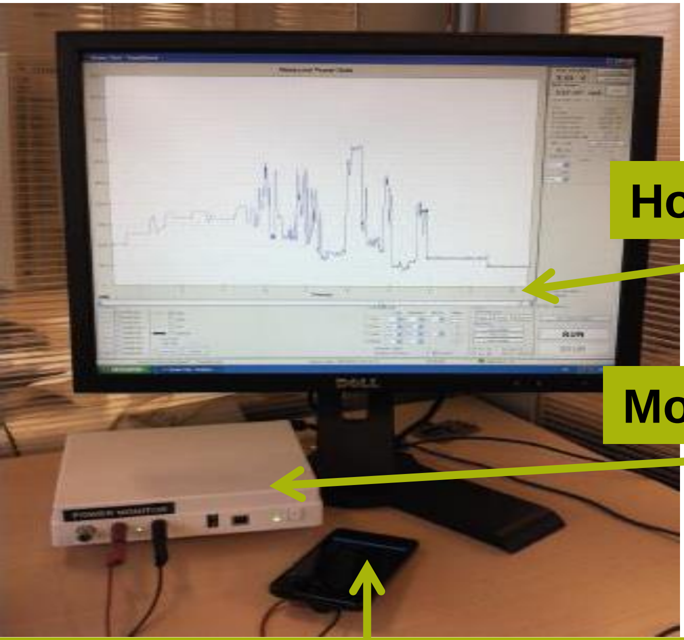

Fan, X., Ellis, C. S., and Lebeck, A. R.
The synergy between power-aware memory systems and processor voltage scaling. In PACS’04
Le Sueur, E., and Heiser, G.
Dynamic voltage and frequency scaling: the laws of diminishing returns. In *PACS’10*

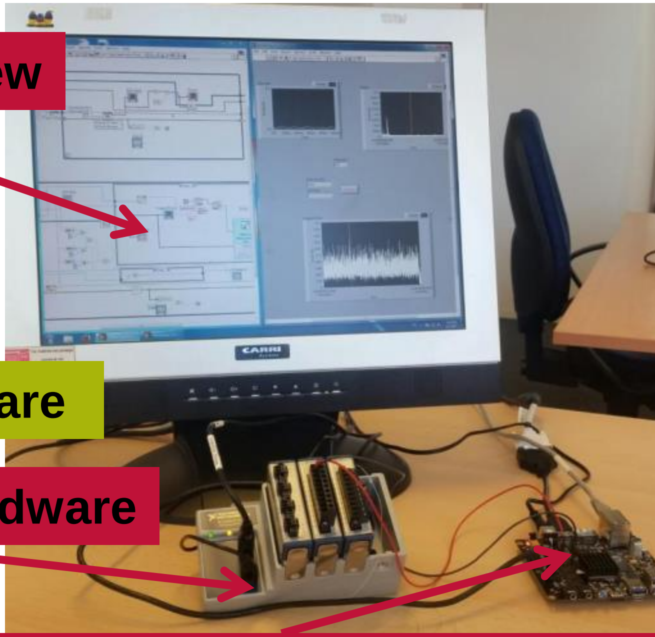
# Convexity shown on Intel Core 2 board




R. Efraim, R. Ginosar, C. Weiser, &A. Mendelson: "Energy Aware Race to Halt A down to EARtH Approach for Platform Energy Management", IEEE Computer Architecture Letter, 2012.

# Two Testbeeds





Host running Labview

Host running Analytics

Monsoon Monitoring Hardware

NI Monitoring Hardware

Samsung Galaxy SII under test

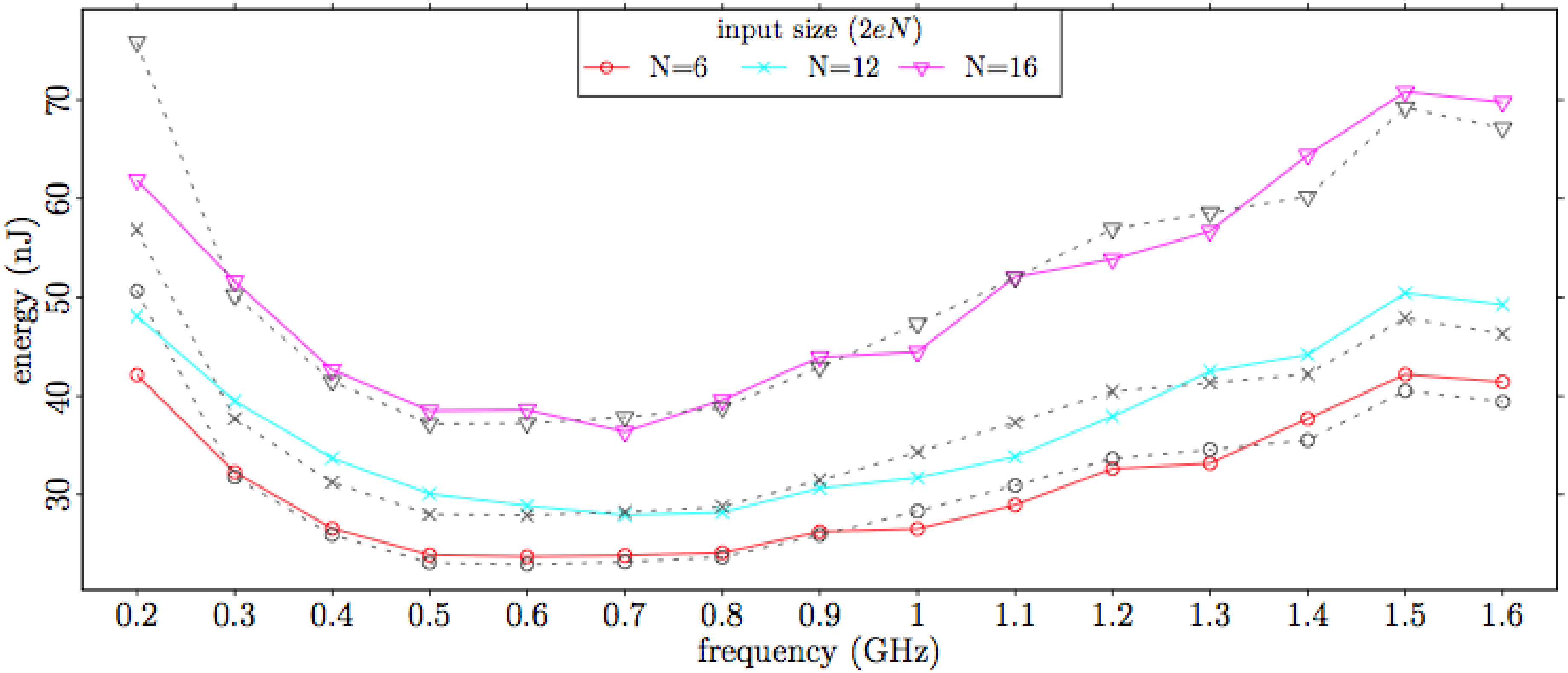
TI AM572x Board under test

- **Cheaper**
- **Easier to set up, easier to use**
- **Probes at the battery leve**
- **Home made analytics**

- **More expensive**
- **More accurate**
- **Probes location anywhere on the board**
- **Various SW analytics**


"Experimental Energy Profiling of Energy-critical Embedded Applications"
K. Vaddina, F. Brandner, P. Jouvelot, and G. Memmi
*IEEE SoftCom'17, Split, Croatia, 2017*.

# Experimental validation with the Samsung smartphone




In color: measurements

In doted lines: theoretical EFCR calculation

When N increases, $f_{opt}$ stays stable



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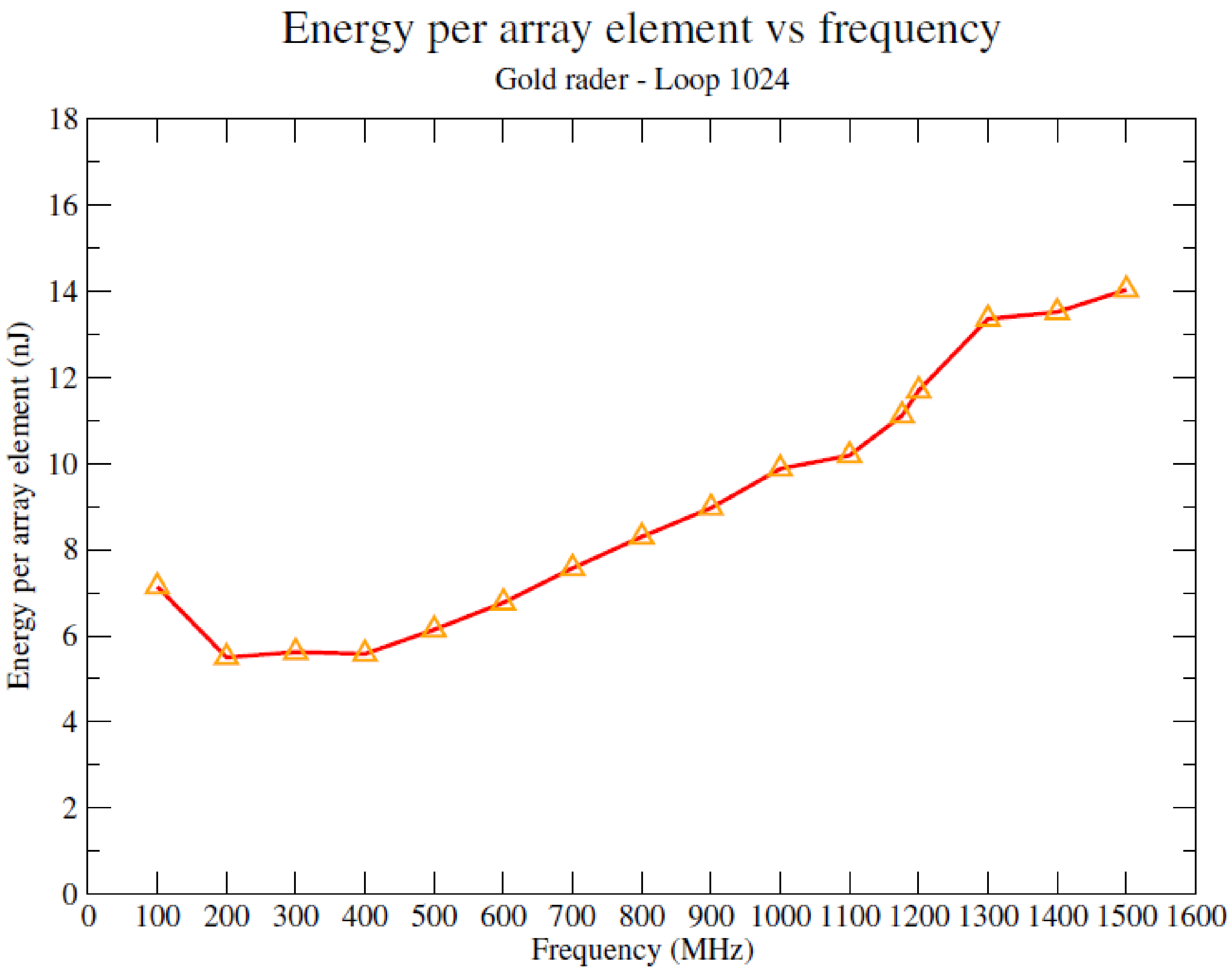
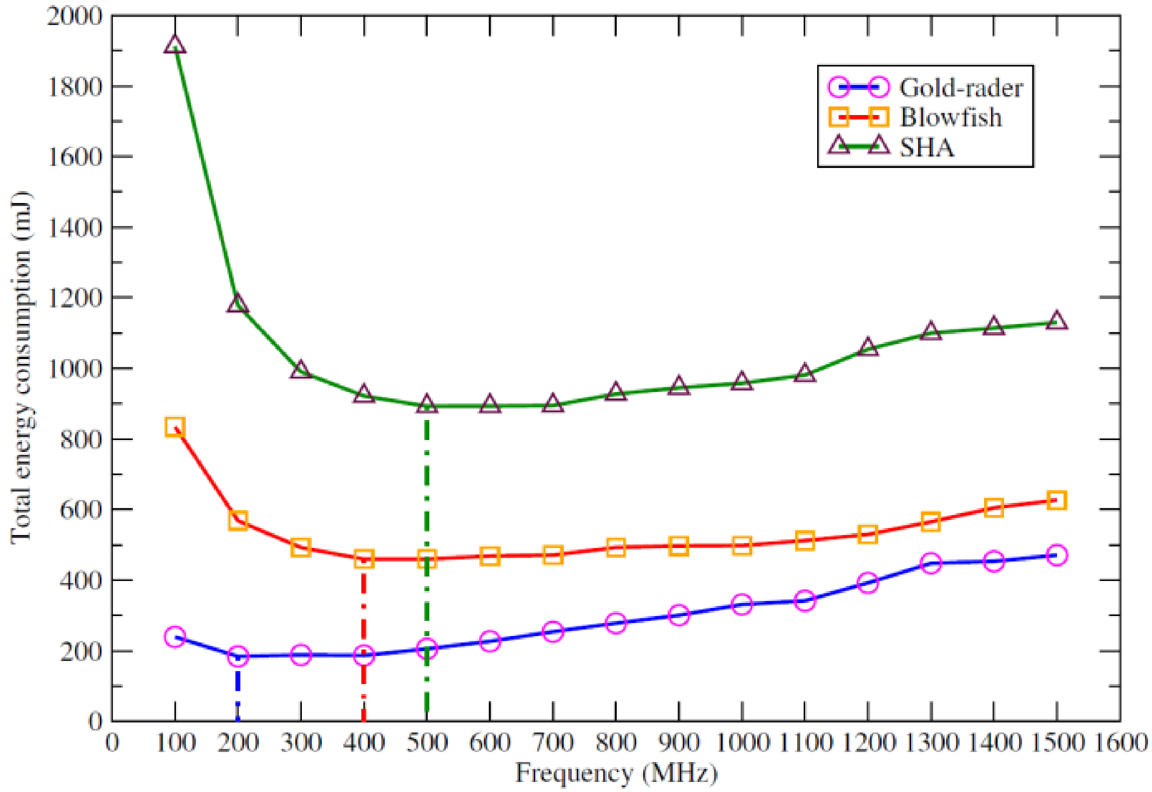
# Experimentation with TI AM572x board



# $f_{opt}$ sensitivity




- Energy consumption of three different programs running on TI AM572x platform showing different profiles with different $f_{opt}$.


"Parameter Sensitivity Analysis of the Energy/Frequency Convexity Rule for *Application Processors"*
*K. De Vogeleer, G. Memmi, and P. Jouvelot*
*J. of Sustainable Computing, Informatics and Systems, Elsevier B.V., September 2017.*

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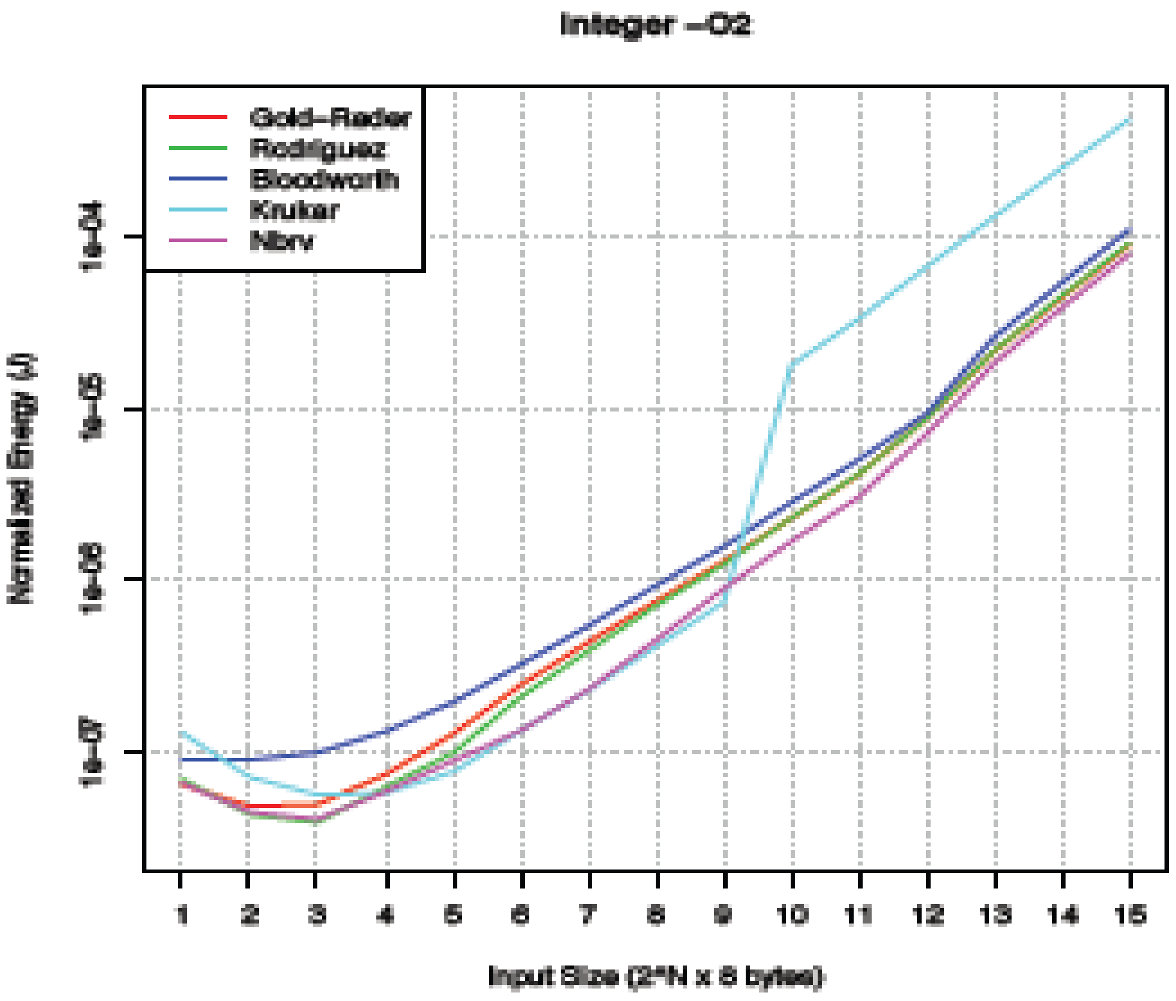
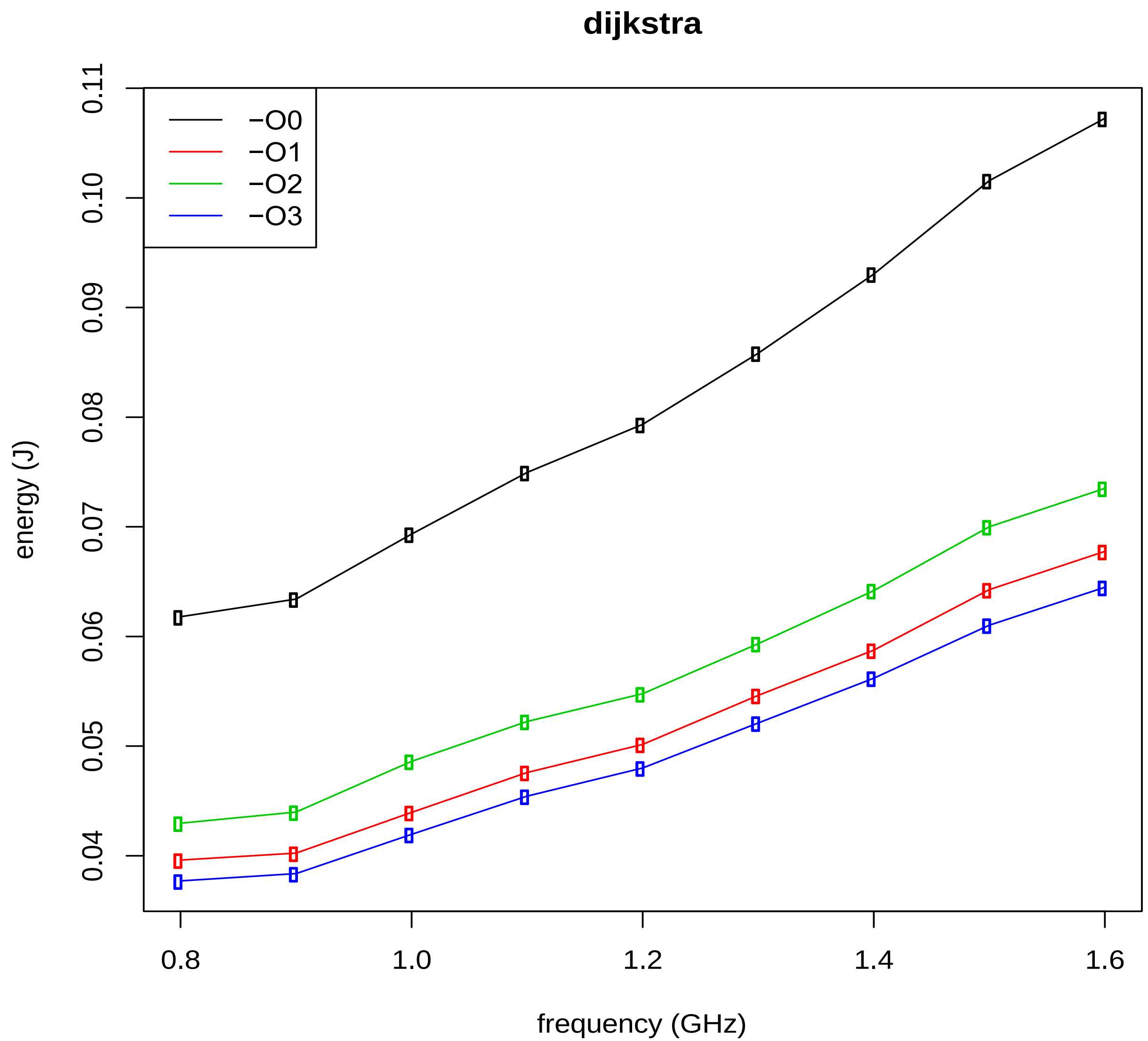
# Towards program energy profiling

# Energy profiles also can detect anomalies

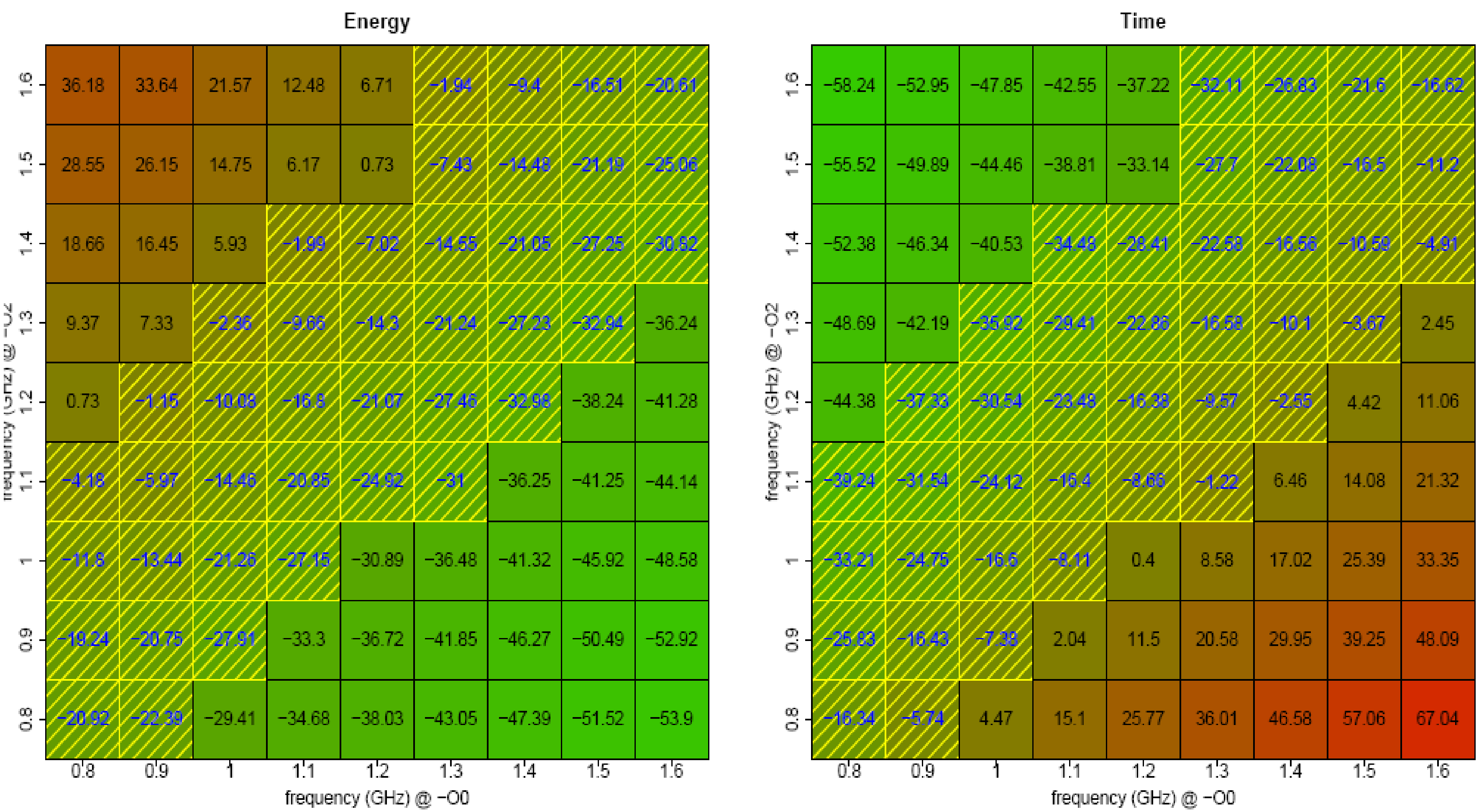


# Optimizing for performance also optimizes for energy cpu



# Drawing the best from the optimizer and DVFS

- Created by tuning clk frequency and performing standard program transformation



# Conclusion

# Energy-Oriented Environment

First measurements and results are setting expectations in the 10-40% saving range by:

- ✓ Exploiting energy-frequency convexity
- ✓ Integrating temperature impact in our models

- **Wider array of experimentation**
  - Using a wider and better controled temperature range
  - Setting a richer and more complete benchmark
- **More research on energy program profiling**
  - Handling various architectures (e.g. cache)
  - Understanding how where, and when to play with clock frequency changes (including overhaed data)
  - Temperature online monitoring

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# Thank you

# Bibliography


- “Experimental Energy Profiling of Energy-critical Embedded Applications” K. Vaddina, F. Brandner, P. Jouvelot, and G. Memmi *IEEE SoftCom’17, Split, Croatia, 2017*.
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- *“Modélisation de la consommation énergétique des programmes : aspects thermiques et loi de convexité énergie-fréquence” K. De Vogeleer, P. Jouvelot, and G. Memmi, ICSSEA’16 then Génie Logiciel 117 pp 47-59, June 2016.*
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- *“The Energy/Frequency Convexity Rule: Modeling and Experimental Validation on Mobile Devices” K. De Vogeleer, G. Memmi, P. Jouvelot, and F. Coelho 10th International Conference on Parallel Processing  and Applied Mathematics,* PPAM 2013, PEAC Workshop on "Power and Energy Aspects of Computation", Warsaw, Poland, pp 793-803, September 2013.