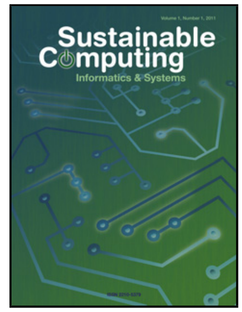
Accepted Manuscript



Title: Parameter Sensitivity Analysis of the Energy/Frequency Convexity Rule for Application Processors

Author: Karel De Vogeleer Gerard Memmi Pierre Jouvelot

PII:	S2210-5379(16)30157-3
DOI:	http://dx.doi.org/doi:10.1016/j.suscom.2017.05.001
Reference:	SUSCOM 166

To appear in:

Received date:	12-9-2016
Revised date:	20-3-2017
Accepted date:	1-5-2017

Please cite this article as: Karel De Vogeleer, Gerard Memmi, Pierre Jouvelot, Parameter Sensitivity Analysis of the Energy/Frequency Convexity Rule for Application Processors, *<![CDATA[Sustainable Computing: Informatics and Systems]]>* (2017), http://dx.doi.org/10.1016/j.suscom.2017.05.001

Parameter Sensitivity Analysis of the Energy/Frequency Convexity Rule for Application Processors

Karel De Vogeleer, Gerard Memmi, and Pierre Jouvelot

Abstract—Theoretical and experimental evidence is presented in this work in order to validate the existence of an Energy/Frequency Convexity Rule, which relates energy consumption and microprocessor frequency for application processors. Data gathered during several month-long experimental acquisition campaigns, supported by several independent publications, suggest that energy consumed is indeed depending on the microprocessor's clock frequency, and, more interestingly, the curve exhibits a clear minimum over the processor's frequency range. An analytical model for this behavior is presented and motivated, which fits well with the experimental data on mobile-specific ARM processors. A parameter sensitivity analysis shows how parameters affect the energy minimum in the clock frequency space. The conditions are discussed under which this convexity rule can be exploited, and when other methods are more effective, with the aim of improving the energy management efficiency of computer systems. We show that the power requirements of computer systems, besides the microprocessor, and the overhead affect the location of the energy minimum the most. The sensitivity analysis of the Energy/Frequency Convexity Rule puts forward a number of simple guidelines to save energy consumption for energy-critical systems, such as battery-powered or embedded systems.

Index Terms—DVFS, energy optimization, Energy/Frequency Convexity Rule, SoC.

1 Introduction

The execution time characteristics and power requirements of a code sequence are the main drivers that define its final energy consumption. This is a direct result of the definition of electrical energy consumption: the integral of electrical power over time. The execution time is influenced by the type and the amount of operations contained by the code sequence of concern. For example, register-based operations will require less energy to execute compared to external memory-based instructions. As such, each functional unit within a microprocessor and, more generally, each component of the computer system have their own respective power and execution time profiles. As a result, every code sequence has different power and execution time demands. For example, Carroll and Heiser [1] showed that, for an embedded system running `equake`, `vpr`, and `gzip` from the SPEC CPU2000 benchmark suite, the microprocessor energy consumption exceeds the RAM memory consumption, whereas `crafty` and `mcf` from the same suite showed to be straining more energy from the device RAM memory.

In previous work, the authors have shown that the energy consumption of code sequences exhibits, under certain assumptions, convex properties, which is henceforth referred to as the Energy/Frequency Convexity Rule [2]. The rule states that there exists an optimum clock frequency for the execution of each sequence of code that minimizes the energy consumption of that code sequence. Under certain conditions, this optimal clock frequency, minimizing energy consumption, lies between the minimum and maximum clock frequencies. The existence of a minimum energy point results from the behavior of the microprocessor's power and the execution time w.r.t. the clock frequency. The microprocessor's power increases about linearly with clock frequency, meaning that more energy is consumed when the microprocessor's speed is increased. On the other hand, the slower the clock frequency, the longer execution time will increase the energy expenditure.

The energy saving gained by running at the optimal clock frequency is a trade-off with the performance of the system, in terms of execution time. For applications requiring human interaction, it has been shown by Seeker *et al.* [3], however, that the clock frequency can be scaled down considerably without affecting the user's experience. More generally, this kind of energy savings can be obtained for code sequences where a limited slowdown can be tolerated and time is not critical. For example, such slowdowns could be applied to code sequences in multithreaded programs that are not on the critical path [4], [5].

In this paper, which builds upon the authors' previous work presented in [2], detailed experimental evidence is presented, supported by several independent publications, for the existence of an Energy/Frequency Convexity Rule that relates energy consumption and microprocessor clock frequency on mobile devices. This convexity rule seems to ensure the existence of an optimal frequency where energy consumption is minimal. This existence claim is based on both theoretical and practical evidence on a Systems-on-Chip (SoC). Data gathered via acquisition campaigns on multiple ARM-based platforms suggest that the energy consumed per input element is strongly correlated with

- *K. De Vogeleer and Gerard Memmi are with Université Paris Saclay, Telecom ParisTech, LTCI, France. Email: {karel.devogeleer,gerard.memmi}@telecom-paristech.fr*
- *Pierre Jouvelot is with MINES ParisTech, PSL Research University, France. Email: pierre.jouvelot@mines-paristech.fr*