


Energy Aware Software

Principal investigator: Dr. Simon Holmbacka
Project starting time: 01.09.2018
Duration of the project: 48 months

Site of research:
Åbo Akademi University, Turku, Finland
Faculty of Science and Engineering
Embedded Systems Laboratory

Sites for research cooperation:

IETR - INSA Rennes 
Institut d'Electroniques et de Télécommunications
Rennes, France

FernUniversität in Hagen 
Fakultät für Mathematik und Informatik
Hagen, Germany

TU Wien 
Institute for Software Technology and Interactive Systems
Vienna, Austria

Uppsala University 
Department of Information Technology
Uppsala, Sweden

1 Rationale

Energy consumption is currently a challenge in all domains of computer systems. IoT, cyber physical systems and other mobile systems demand solutions to lower the energy consumption while keeping the same amount of computations, and high end systems, servers and exa-scale computing demand more computations for the same energy. These problems were traditionally solved by the hardware evolution, but since we now witness the end of the Dennard scaling [DGR⁺74] this development is no longer feasible. As the improvement in semi-conductors no longer keep the required pace, evolution in energy efficiency must be shifted over to the software. The vision behind this research is to significantly improve the energy efficiency of computer systems by involving the application software in the decision of allocating resources – this branch of self-awareness is called “**making the software energy aware**”. Energy aware software form a stronger link between applications and the runtime system by means of an information flow used to steer the allocation of resources, which increases the self awareness of software. This advancement in software design is required for the research community to take the next step into energy efficient computing.

From tiny embedded systems to large scale server farms and diverse IoT systems, energy efficiency is becoming the main struggle for system usability, expansion, reliability and scalability. The drivers for solving the issues differ depending on the area of focus; the very usability of battery powered devices depends on its ability to provide the user with the satisfactory experience while consuming the minimal amount of energy. Desktop and laptop systems require high levels of energy efficiency in order to (a) lower noise levels from active cooling, (b) increase the reliability by reducing the heat and (c) minimize the electric bill. Taking into account the bigger picture, the rapid expansion of large scale servers is not in line with ecological development, and now contributes to over 2% of the total energy consumption in the US¹, with Facebook alone releasing 650k tonnes of carbon annually². Lastly, without increased energy efficiency, high performance computing centers cannot reach exa-scale performance. The US Department of Energy³ have defined a maximum power envelope of 20 MW for a single data center, but with current technology, a modern exa-scale computing center would require over 7000 MW.

In order to provide a continuous performance improvement in computing systems, the clock frequency wall was avoid in the beginning of the 2000s by the introduction of multi-core based systems. This led to a new challenge in mid-2000s: the CPU power wall [DKM⁺12, WS13]. Indeed, due to physical limitations of semiconductor materials, the power dissipation of a fixed chip area is limited. With the evolution in the fabrication of semiconductor devices, from a 10 μ m manufacturing process in the 70s until the commercialization of 14nm based technology in 2015, more transistors are squeezed into a smaller silicon area which increases power density [PV07]. This eventually leads to dark silicon, when all the components of a chip can not be operated at the same time due to both its power dissipation and generated heat. The effects of the power wall was until now limited by the design of more energy

¹Statistics according to the U.S. Office of Energy Efficiency & Renewable Energy: <http://energy.gov/eere/femp/resources-data-center-energy-efficiency>

²<https://sustainability.fb.com/en/our-footprint/>

³<http://ascr-discovery.science.doe.gov/2014/11/exascale-road-bumps/>

efficient transistors with for example lower voltage levels, which has led to an increase in the transistor efficiency in proportion to an increase of transistor density – a phenomenon called the Dennard scaling [DGR⁺74]. However the current increase of the transistor efficiency is not any more proportional to the increase of transistor density [WS13], and the semiconductor device fabrication is currently in a post-Dennard scaling area, where a substantial increase of the performance of computing systems cannot be achieved until both the current power dissipation and the related energy consumption issues are res.

In eradicate the above-mentioned constraints in this interdisciplinary domain, specific software must inevitably be introduced to make computer systems energy efficient again! The key challenge is to utilize the available hardware resources as efficiently as possible. Since general purpose applications behave in a very dynamic way, a runtime environment must continuously adjust the usage of the resources based on the execution of the applications. In Linux based systems, attempts have been made to incorporate this behavior by using clock frequency scaling and deep sleep states to scale the hardware resources according to the demand. The limitations with the existing approaches are that the resources are allocated based on poor metrics. There is no interoperability between applications and the runtime system, and resources are usually allocated based on indirect metrics such as the system *workload*. Such a metric does not describe performance demands in applications, and therefore often causes incorrect resource allocation, which, in turn, leads to and additional waste of energy [HNP⁺14, HLL15].

In this research project we will enhance the application software with the inclusion of *energy awareness*. This new property will enable applications to get directly involved in the allocation of resources. Energy aware software is able to continuously report the performance demand in its own specific metric to the runtime system. With this new vial information, the runtime system is able to allocate resources (usually with clock frequency scaling and with sleep states) with a much greater accuracy than using indirect metrics such as the workload. As a result of the inclusion of energy awareness in software on real-world Linux platforms in our previous research [Hol15], an impressive saving of 50%-60% in energy was achieved – without compromising on the performance! We are therefore confident that adding energy awareness in general purpose software can reduce the energy consumption significantly.

Figure 1 illustrates the purpose of the research: part A) shows the current approach without any interoperability between applications and the resources. Using this approach, resources are allocated based on the level of workload or other indirect means of metric. Part B) Figure 1 illustrates the inclusion of energy awareness. This is the added interface between the application and the runtime system through which the application communicates. It produces the following benefits (a) a better accuracy of resource allocation, (b) an increase in self awareness and (c) lower energy consumption.

The research area in energy efficient computing is a broad domain spanning several levels of hardware from IoT to Exascale. The commonality is, however, the ability to propagate information from the highest software layer to the runtime system, and to the hardware. Throughout all computing domains in the area of energy efficient computing, we have identified three critical challenges to address in our research further specified in sections 1, 1 and 1.

Challenge 1: Self awareness Applications must be able to properly express their intentions in terms of performance requirements during an execution. Such requirements are added to the application software in form of performance meta-data – a performance goal the application is due to achieve. The challenge is therefore to provide a framework with the capability of handling and expressing performance meta-data in an interdisciplinary domain. As previously mentioned, the traditional way of solely monitoring the workload is a very inaccurate and often counter-productive both in terms of performance and energy. We tackle this challenge by allowing the applications to express the resource requirements internally. This means that the application should include a small part of code – the meta-data – which expresses the intention of the application in its own understanding of performance. For example, the end user of a video decoder is satisfied in case the decoder produces a framerate of 25 fps because of properties in the human eye and the understanding of moving pictures. A higher framerate is therefore energy

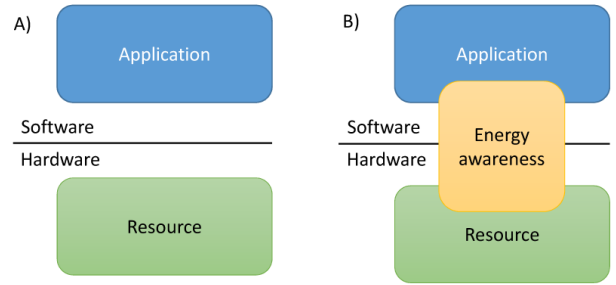


Figure 1: A: No connection between the application and the resources B: Resource allocation based on self-awareness [TODO ADD THE ENERGY SAVINGS SOMEHOW HERE!!]

waste while not producing any higher satisfaction for the end user. Therefore, we will investigate the types of meta-data needed to describe the intentions of an application sufficiently accurately. These types of meta-data will have to have a sufficiently descriptive form, which can be generalized to any new- or legacy application. Once the meta-data descriptions have been established, the injection of the data into both new- and legacy applications must be achieved fairly effortlessly in order for the programmers to make the additional effort. A trade-off between descriptiveness and programmer effort is to be expected.

Challenge 2: Interoperability for energy efficiency The interoperability challenge in the domain of energy awareness in application software is to create an ecosystem capable of exchanging information about the intentions of an application to the runtime software layer. Secondly, the exchanged information must be interpreted by the runtime layer to make sensible decisions regarding the resource allocation. Since applications in general are dynamic, the performance of the application depends on a wide set of factors such as memory intensity, use of caches, user interrupts, the data sizes and data types used, interaction with other applications etc. This means that the performance of an application cannot be guaranteed with fixed resources. In order to adapt the resources allocated to the application, the performance of the application must be monitored at runtime. In case the currently allocated performance is either too high or too low, the monitor reports this issue to the controller which allocates or deallocates resources to accommodate for the real resource requirement. We recognize therefore the need for a proper monitoring framework to insure the interoperability between applications and the runtime system. Such a framework must be detailed enough and provide sufficient tools for measuring performance, but simple enough to reduce programmer effort for using it. Since the monitoring framework is a runtime system, a considerably low overhead must be guaranteed to avoid interference with the energy consumption and performance of the host system.

Challenge 3: Smart adaptivity Given a proper dataflow from applications to the runtime system, the final challenge is the allocation of resources. Allocating resources efficiently means having a knowledge of how the resources of one form affect the performance of the application requesting the resources. Even though feedback control loops is a well established area of research, the methods must be adapted and applied to the general purpose computing domain. Together with machine learning, big data and pattern recognition, smart adaptivity in the control loop helps to bring the framework of energy aware software to a broader domain of computing systems from IoT to exa-scale systems.

1.1 Previous work

The embedded systems lab in the Åbo Akademi University has for the last seven years focused on low power and energy aware software. During these years a special interest had been put in mobile phone processors and their significance for energy awareness in general. This is because it has been noted that the trend of performance requirements by far exceeds the battery capacity of a mobile device, especially since the mobile multi-core revolution [Epe15, Tri15]. This means that the performance of the hardware and the demand for performance of the user is greater than the energy a battery with limited dimensions can physically store. Because of the slow capacity increase in batteries, the available energy must be used more efficiently in order for such a mobile device to retain its usability. In the thesis of the PI “*Energy Aware Software for Many-Core Systems*” two guidelines were presented for creating energy aware software on modern many-core hardware. Implementing the recommendations in software has proven to reduce the energy consumption up to 50% without degrading the performance [HLL15], especially on mobile multi-core hardware. The recommendations called “Energy aware mapping” and “Energy aware resource allocation” are used to tailor the resource allocation to the software executing, and a prototype runtime system was implemented as a phase of the PhD thesis. More specifically, the recommendations allow the system to use the optimal number of cores and the optimal clock frequency according to the performance requirement of the running application. Using this software, practical state-of-the-art demonstrators were created, for example a low power video transcoding cloud system⁴ demonstrated in the Millennium Pavilion SHOK Summit 2014 in Helsinki, and in the DIGILE Workshop 2013 “Rolling up the Sleeves”. Also, the Android app “Low Energy Player” was implemented as a state-of-the-art demonstrator and is available on Google store⁵ This research project reaches

⁴Picture of the ESLab demonstrator available at <https://dl.dropboxusercontent.com/u/5260559/ClusterDemo.jpg>

⁵<https://play.google.com/store/apps/details?id=org.videolan.vlc.LEL.lite.green>

beyond the state-of-the-art by the development of a programming framework for energy aware software ready to use by the everyday-programmer, which has not been available to this date.

Therefore, the proposed research project has a perfect fit with the PI's previous involvement in research and the ability for a breakthrough in the field is expected.

1.2 Related work

The concept of “low energy programming” or “low power programming” has previously existed in the form focusing on the programming paradigm or on the programming syntax. Guidelines from Intel [BSA11] suggests the use of a certain level of loop unrolling, vectorization, memory intensity cache usage etc. for achieving maximum energy efficiency in combination with Intel compiler tools. Such recommendations are applied only on the algorithms in the program, and do not cover, the intention of the program for functioning efficiently together with the runtime system allocating the resources. The low power programming guidelines from Intel also require the programming to construct the program in a certain way in order to become energy efficient, and the underlying hardware architecture must be known. In the thesis “Developing Energy-Aware Software” by Brinke [tB15] the author describes programming languages for modularity and modeling resource consumption for software. The *awareness* of energy, is tightly bound to the application code and the programmer is expected to follow certain programming patterns to make the software energy aware. On the contrary, the planned framework for energy efficient software requires only the insertion of meta-data in the software. This means minimal effort of the programmer and the application algorithms can be implemented without interference from the energy awareness framework. The resource requirements are specified using a simple library, where after the runtime environment allocates the required resources.

Related projects. Our newly funded AKA project **Efficient Stream Computing (2017-2021 799k €)** introduces a formal and practical paradigm of measuring efficiency of software execution through the notion of *Fitness*, which characterizes how much of the microarchitecture the task is able to exploit. This will enable the optimization of Stream Computing systems for energy efficiency, performance or cost with minimal overhead in the development. The commonality of this project is energy efficient execution, but while ESC focuses more on *where to map* a task, the primary goal of this project is to optimize resource allocation and how software can influence this decision.

The **Carbon Research Group**⁶ at MIT has developed a heartbeat framework to evaluate performance as a generic parameter in software construction. The framework is capable of measuring performance of any application as a generic parameter by user inserted API calls to the heartbeat library. Measuring performance is the necessary first step when constructing a feedback-based control system. For example it enables the possibility to measure the framerate in a video decoder, but a controller is then needed to allocate the resources in order to keep the performance on a given setpoint. We consider using the heartbeat framework for measuring generic performance in our energy awareness framework, but we plan to extend the framework considerably in order to add the controller for allocating resources.

The **Hardkernel** project⁷ creating the Odroid family boards recently released the Global Task Scheduling (GTS) support for the ARM big.LITTLE devices. “High performance threads” are scheduled to the big high performance cores and “Low performance threads” are scheduled to LITTLE energy efficient cores based on the workload activity of the threads in order to save energy. Even though the activity level of a thread is an early attempt introduce energy awareness in the system, the practical results are poor. In other words, the scheduler most often schedule a thread on *the wrong core*. This results not only in energy inefficiency, but also in poor performance of the applications and an unsatisfactory user experience. We will use this platform as one of the reference models for our energy awareness framework because its SoC is very popular and is being used in millions of Android devices worldwide.

Our research group is currently a partner in the **INTERSYS (2016-2017 496k €)** project⁸ dedicated to standardize and optimize interconnected IoT devices handling streaming data. Since the number of IoT devices are expected to rapidly increase in the near future, the project is extending interoperability notions for handling the massive amount of data streams from small devices to gateways and servers. Still missing is the notion of energy

⁶<http://groups.csail.mit.edu/carbon/>

⁷<http://www.hardkernel.com/main/main.php>

⁸<http://iot4health.utu.fi/?p=374>

awareness, which is a crucial point as most devices operate on battery-only power. We intend to work closely with this project and we plan to introduce the benefit of energy awareness into IoT systems.

EMBECOSM⁹ focus on providing the GCC compiler with the notion of energy efficiency, in practice this means learning which compiler flags minimize the energy consumption for a selected architecture. The outcome of this project is similar to OpenTuner¹⁰ from MIT, which is capable of offline optimization of multi-criteria problems. Both projects provide a metric for offline optimization but runtime support, which we suggest, is not stated in their scope. Runtime optimization is critical in virtually any environment containing multi-node and heterogeneous multi-node platforms. This is because the data used in especially streaming applications like multi-media software is arbitrary or very difficult to predict. Compile time optimizations can for example not predict what kind of video format is being used in a video decoder.

The **StarPU**¹¹ project at INRIA Bordeaux and the **PEPPHER**¹² project has presented a runtime system to minimize the performance for heterogeneous architectures. The system builds a performance model of the implemented CUDA or OpenCL kernels based on benchmarking on CPUs and GPUs, after which the system is able to schedule the kernels onto the most performance efficient device. However, they only consider the optimizations in form of performance, not energy efficiency.

Therefore, whilst there are a number of ongoing projects researching energy efficiency in general, none of them so far has endeavored to solve the problem of increasing energy efficiency with energy aware applications.

Related work. In previous work, Eyerman et al. [EEKS09] claim that no single throughput metric is fundamentally generic for multiprogram workloads. Performance should instead be expressed as related to the internal single case-study; a direction adopted in this research. However, we plan to integrate this direction of thinking into user defined meta-data that expresses resource requirements in software.

A high-level language CQML [Aag01] was suggested for describing QoS requirements integrated in UML. CQML links a high level QoS description to system performance, and can describe system actions based on the result. Applications specify a performance setpoint and a lower bound acceptable performance level in context of the application. Applications then monitor own performance and signal this value to the QoS manager periodically. We will consider a similar structure to define QoS in our framework, but more focus will put on the link between applications and hardware resources in a single computer system. On the contrary, our methods for energy aware programming will not be strongly tied to a certain programming language and the framework itself will have the flexibility to be integrated from various environments such as servers and PCs and Android.

Runtime systems for minimizing energy consumption in computer systems have been previously proposed. The PowerDial [HSC⁺11] approach allows graceful degradation in applications based on current application performance measured in heartbeats [HES⁺10]. The system transforms application parameters (such as peak-signal-to-noise in a video) into dynamic control variables stored in the application itself. A callback function is inserted into the application, which the controller uses to adjust the control variables according to performance and policies. A heartbeat feedback monitors the execution and reports on the updated performance of the application. Also, the work by Segovia [Seg11] suggests graceful degradation of the application QoS by monitoring a *happiness* value in the application. Based on this value, the runtime system can degrade quality points in the application in order to achieve the requested QoS. Our planned runtime system is inspired by the same approach to treat input signals from applications: the performance is transformed into a generic parameter QoS upon which the controller acts. In contrast, our controller uses no graceful degradation in the applications, but the actual hardware actuators to allocate resources.

There has previously been a strong separation between monitor and control. Several research projects offer the opportunity to monitor an executing application, but supports no control of the hardware. On the other hand, many controller-based research project do not support any proper framework for declaring meta-data requirements and monitoring of the execution. This research project will tie both parts together with the main focus on reducing the energy consumption with minimal programmer effort – an effort not previously emphasized. Our research project will also ensure a proper balance between academic research and practical usability, which means that there is both

⁹<http://www.embecosm.com/>

¹⁰<http://opentuner.org/>

¹¹<http://starpu.gforge.inria.fr/>

¹²<http://www.peppher.eu/>

a focus on planning the long term usage of the framework in terms of capabilities and scalability, but also practical efforts to enable a programmer to pick up the tools and start developing energy aware software in the industry.

2 Scientific Objectives and Expected Impact

2.1 Scientific objectives

Objectives of the project and their theoretical and methodological underpinnings. Our objective is to solve the energy consumption problem in computer systems, and to develop a complete framework for programming energy aware software. In most recent systems, power managers have been implemented to scale the performance of the system according to the current resource demand. Various implementations exist depending on whether the system is a large cloud farm or a small IoT system, but main constraint in current solutions is the inability to accurately express resource demands. In mainstream Linux systems, the resource demand is measured as the utilization caused by the workload of the CPU. Workload in operating systems is measured as a sliding window average over an active and idle CPU as illustrated in Figure 2. A high workload indicates that the system needs more resources, and the clock frequency is scaled up to decrease the workload of the CPU. Setting the frequency can be based on different policies implemented in *frequency governors*, and the most common policy is called “ondemand” [Sta06]. This frequency governor scales the clock frequency to the maximum value as soon as a workload threshold is reached. After this it step-wise decreases the clock frequency to the lowest frequency not exceeding the threshold.

The problem with this approach is that the workload does not describe the performance of the applications accurately enough. High workload does not necessarily mean that an application requires more performance, it simply describes how much the application is using the CPU. It is merely an indirect effect of executing an application as illustrated in Figure 2. Incorrect resource allocation results in either poor performance or in energy waste.

Other work on attempting to refine the functionality of the frequency governors was presented in [SKK11]. Their frequency governor the “Green Governor” scales the clock frequency not only based on the workload, but also in the memory intensity. The assumption made was that higher memory intensity stalls the CPU enough to not benefit from high clock frequency. The fundamental problem, however, still remains unsolved because the governor models the performance requirement of the application indirectly. Therefore, if the model does not fit the application, either excessive or insufficient resources are allocated to the application.

What we propose is to make the application software itself energy aware and **the objectives of this research** is to

develop a complete framework for programming energy aware software. Using this software, applications become involved in the resource allocation which is a necessary step for reaching the next level of energy efficiency in computer systems. A power management system compatible with energy aware software requires therefore an interface between application and runtime system, which is current non-existing. This research is aimed to provide such an interface, and the necessary tools needed to use it. Our current design recommendations for energy aware programming extends the application to signal resource requirements to the runtime system, which allocates the hardware resources based directly on the requirements rather than indirect metrics like the workload. With this framework, resources can be allocated more efficiently leading to a lower energy consumption.

Hypotheses. The project states the following Hypotheses:

- a. Performance requirements in computer systems will continue to increase significantly faster than transistor technology and battery technology development, software must thus utilize the resources more efficiently.

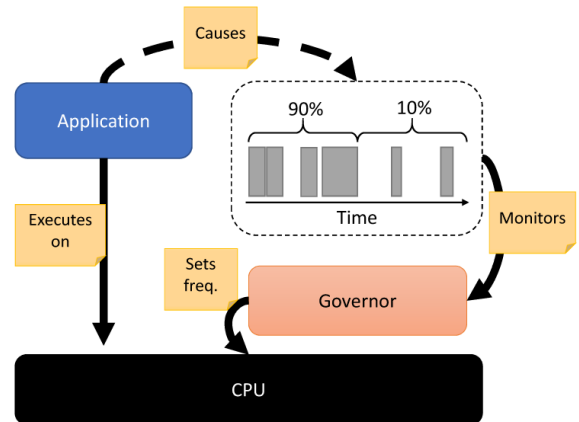


Figure 2: Current power management systems: The application causes a workload (illustrated by the gray rectangles), and the frequency governor scales the clock frequency according to the load level.

- b. Energy aware software can utilize the hardware resources more efficiently because hardware resources are allocated based on actual performance requirements.
- c. Software can be made energy aware with minimal performance overhead and minimal programmer efforts.
- d. 50% of energy can be saved using energy awareness in software.

These hypotheses can be verified by comparing SoA power managers (for example in Linux) to our framework, which supports energy awareness in software. Real-world applications are executed and real energy measurements are obtained by hardware sensors. The overhead of our framework is determined by load measurements directly in the OS kernel or in user space.

Expected research results and their anticipated scientific impact. Our expected impact on the research community is to introduce energy awareness to software. In other words, the need for communication between the application layer and the runtime environment. Our potential breakthrough is to introduce **energy awareness as natural part of programming**. For decades it has been a natural step to introduce meta-data in the software for creating parallel programs. The programmer has been willing to add `#pragmas` in OpenMP, Keywords in Cilk or Initializations in OpenCL to create parallel software because of the minimal programming effort and significant performance gain. We intend to extend this notion to energy awareness, and demonstrate the potential reward in terms of energy efficiency. Furthermore, the development of runtime systems becomes more straight forward. Without energy aware programming as the underlying notion, runtime systems in any domain have no common ground on which the decision making is based. Optimizations remain based on ad-hoc ideas and “hacked” hard-code which is usually not portable between either domains or even between different architectures. Even though the implementation of the runtime systems between domains can be different, the core idea of resource allocation decisions based on energy aware programming remains common. With this common denominator, runtime systems engineers between projects and domains can incorporate shared ideas for implementing new, or improving existing runtime systems. By introducing the notion of energy aware programming, the development of runtime systems needed in any modern computer system has the potential to shift from an ad-hoc single-purpose environment to a sharing environment where engineers have a common platform to cooperate on.

2.2 Effects and impact beyond academia

Reach and potential utilization value of the research beyond the scientific community.

Impact on power dissipation. There are currently 2.3 billion smart phones in the world it is estimated this could more than 3 billion by 2020. Not included in this number is all the tablets and entertainment system, as well as over 6.4 IoT systems world-wide. The power dissipation for such amount of devices connected to the electrical grid is predicted to give noticeable impact on the energy consumption. The proposed energy-awareness strategy will result in less generated power and heat, which in turn lowers the energy consumption and increases the lifespan of the devices. Even more crucial to the usability for off-grid devices is the battery lifetime. The very usability of battery operated mobile devices is completely dependent on its energy efficiency. This research project will generate methods to minimize the charge interval which requires personnel effort and additional electrical energy.

Impact on the sustainability of the planet. In accordance with the Paris Agreement, countries are encouraged to foster climate resilience and low greenhouse gas emissions development. As for impact on the greenhouse emissions, this research project contributes by lowering the overall energy consumption in critical parts of computer systems. With a higher efficiency grade on IT infrastructure, lower energy consumption achieved for server machines and even desktop machines impacts on the CO₂ emitted from producing the electricity. It also leads to a lower demand for IT infrastructure cooling facilities.

Impact on the industrial sector. The project has a transversal impact on the industrial sector by reducing the input barriers to developing energy efficient systems. The research project will make energy aware programming accessible to any enterprise independently of its size and sector by reducing the cost and technology complexity. In fact, the research project is based on an open architecture and it will provide tools devoted to aid software engineers in the development of software. It paves the way to improve the technology and to simplify its use.

Self-assessment of the expected societal impact of the research in the long or short term. The project solution will be demonstrated via several different channels. First and foremost, the PI will attend international

high ranking conferences for assessment and feedback of the project. Technical assessment from both academia and the industry will be performed during the project and ensure the robustness of all the introduced technologies. Different alternative technologies will be proposed to cover possible inconsistencies. Networking activity consisting of collecting feedback from technical and theoretical actors will be done, and project knowledge will be shared for mutual benefits.

2.3 Publication plan

We intend to publish at the top journals and conferences based on the JuFo listings, and we will select publication venues that use some form of open access model, most likely green open access. To this end a lump yearly sum is included to cover the publication fees. Further, we plan to also be visible in industrial event and fares to both demonstrate and get feedback on our research work. The publication rate with regard to the project is approximately 3–4 high-quality peer-reviewed publications per year.

3 Research Methods and Material, Support from Research Environment

Research methods. We are working extensively within the *streaming applications* paradigm for a number of reasons. Firstly, streaming systems are usually implemented in environments in which energy efficiency is of essence like video playback systems, web servers, digital filtering systems, telecommunications systems and other multi-media or IoT systems. Secondly, since the content of the streaming data is to a large extent arbitrary, no compiler based optimization (or other static solution) can solve the energy problem. Thirdly, streaming systems are extremely common and is thus providing a large market to work on from tiny IoT systems up to large cloud server systems. To prove our hypotheses for everyday-applications, we will include the framework for energy aware software in commonly used streaming applications, and verify the correctness of the software with respect to performance and usability. We verify our hypotheses by physically measuring the energy consumption for a wide range of applications and configuration parameters. To prove our hypotheses for extreme cases, we will develop specific benchmarks that can obtain corner case execution characteristics such as very high, very low or customized load patterns. By covering both extreme- and everyday cases, we can confidently present a range of potential energy savings by using energy aware software.

Management of research material and data. The project will create two kinds of concrete results: 1. Software, and 2. Measurement data. We subscribe to the idea of open reproducible science. The computer architecture area has suffered from problems with reproducibility in that often neither the software nor the full measurement data are available. We intend to be as open as possible about our research. All software will be released under an open-source license. Zenodo¹³ has been selected as the platform where we plan to publish measurement results and each submission in Zenodo can get a citable DOI.

Support form research environment. The research team will be well supported by infrastructure available at through the Centre for Computer Science (TUCS). TUCS boasts a long history of high-level achievements of its affiliated researchers, in terms of articles in high-level journals and conferences and a high number of citations. TUCS has been a Center of Excellence of Research of the Academy of Finland in the very first round of such centers in Finland, 1995-1999 and in 2002-2007. The PI is an active member of the COST action IC1305 Network for Sustainable Ultrascale Computing and the Energy Efficient High Performance Computing Working Group (EE HPC Working Group). Joint articles have been published in the COST action between the PI and the group in TU Wien led by Ivona Brandić, which was published in IEEE Transactions and one between the PI and the group in University of Tirana led by Neki Frasheri.

The PI together with EIT Digital recently released an online Coursera course on the subject in “Development of Real-Time Systems”¹⁴ currently followed by over 7000 students world-wide. Our team has a full time lab technician constructing specialized equipment needed in our experimental work. The team therefore has strong knowledge in

¹³<http://zenodo.org/>

¹⁴<https://www.coursera.org/learn/real-time-systems/>

manufacturing measurement tools for externally probing and measuring running systems. Crucial to our experiments is our open hardware datalogger with full Linux tool support capable of high-sample power measurement measurements with 0% performance overhead in the host system. The team is experienced in building tools based on the theoretical models that enable the use of the models in practice. Some of the previous programming tools created by Åbo Akademi University is the Canals data-flow language and the RVC-CAL to OpenCL translator. This competence will be put to good use in creating the energy aware programming framework. The PI is currently working in Elisa OYJ on the PoDoCo¹⁵ grant, which is of great importance to gain insights into the industrial needs of solving the problem of energy efficiency, and how the framework of energy aware programming can be used in practice.

Utilization of research infrastructure. Since our research is mainly based on theoretical computer engineering and implementation work, no major research infrastructure is expected. We utilize mainly opensource tools or other free software from our own research community. For the evaluation and demonstration efforts we require the latest hardware technology especially in the embedded domain and eventually access to larger cloud systems.

Critical points for success. Our intension is not only to provide theoretical insights into energy aware software, but also the framework needed to enable the programming. To ensure success, the critical points and risk factors are listed as follows:

- *Software design is infeasible.* With an infeasible design, the intended research results cannot be achieved without a major re-design. With our previous experience in energy aware software, and the results gathered we are confident about the main directions in the research. Although we intend to monitor the feasibility early in the project to ensure an eventual re-design in as early stages as possible.
- *Learning curves lead to delays.* Learning new methods and tools is always a challenge. By exceeding the time budget in methods and tools, the project can be delayed. Our lab environment keep up-to-date with tools and methods by weekly discussions internally in the whole lab group. Practical questions about research can be posted in such sessions, and people share their experience.
- *Relocation of research partners.* This project is relying on international cooperation. In the event of relocation of key persons, mobility can be postponed and the research ultimately delayed. By having a large network of contacts, we have a safety net in case of relocation events. Work and timelines can be re-adjusted while keeping the core research intact.
- *Access to hardware platforms.* Without appropriate hardware, the results in evaluation are inadequate and insufficient. For covering this, risk The PI has connections to the energy efficient middleware group in ARM Cambridge, the leader of which was invited to one of our project workshops in the PARALLAX project. On the large scale side, our team has previously obtained the Amazon EC2 grant¹⁶ twice enabling access to large scale servers.

4 Ethical Issues – This research project has no ethical issues.

5 Implementation: schedule, budget, distribution of work

The schedule of the research work is summarized in Figure 3.

5.1 Work packages

WP1 – State of the art and exposing the meta-data. The initial part of the project is to determine how to expose the meta-data to the programmer.

Therefore the project begins with a state-of-the-art re-

view of currently proposed solutions for defining performance requirements and self-awareness. The WP is intended to firstly define what exactly should be included in the meta-data to get a proper description of performance in

Task 1.1 State-of-the-art review and defining the meta-data
Task 1.1 State-of-the-art review and defining the meta-data
Task 1.3 Tools for introducing meta-data in software

¹⁵<http://www.podoco.fi/>

¹⁶<https://aws.amazon.com/grants/>

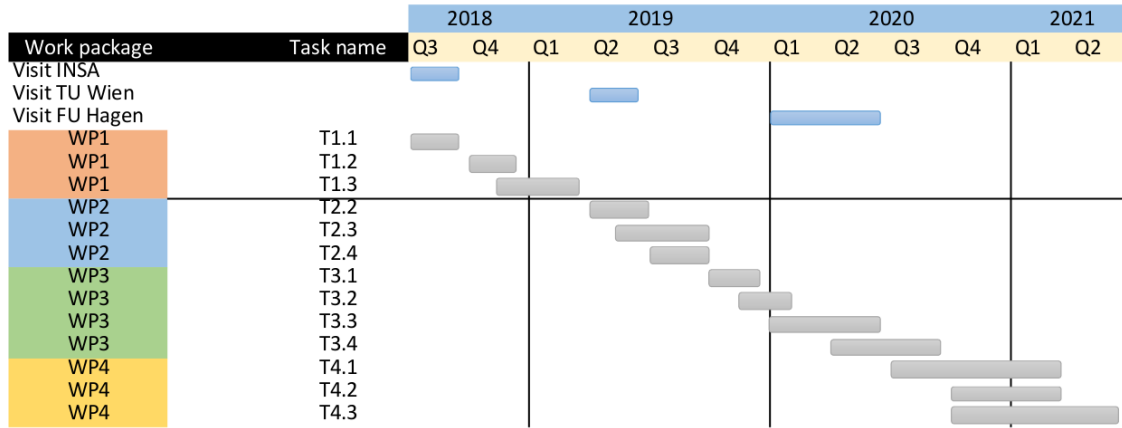


Figure 3: Time schedule for the project

applications. Further, what must be determined is guidelines for how, where, and when the meta-data should be injected in software to ensure stability and minimal performance overhead. Included in this WP is tool support for automatic meta-data injection based on earlier findings.

WP2 – Feedback monitor. WP2 covers the monitoring of the application software. This includes how to interconnect the monitor with the application, determine the information flow between the application and the monitor and also how to forward this information to the resource allocation controller. The main challenge to tackle is how the application software can be monitored without affecting the functionality or the performance of the system. State-of-the-art monitoring systems such as the MIT heartbeats [HES⁺10] will be evaluated as complementary research to the proposed energy awareness monitor. A monitoring interface will be developed and its cross-domain applicability will be evaluated on Android, PC and server systems.

Task 2.1 Evaluate complementary work and possible integration
Task 2.2 Construction of the monitoring interface and framework
Task 2.3 Cross-domain evaluation of monitoring system

WP3 – Energy aware controller. WP3 is about using the self-awareness provided by WP1 and the monitoring data from WP2 and use it for smart optimizations by a runtime system controller. The main challenge in WP3 is to define the resource allocation to achieve maximal energy efficiency without performance loss. Several well established optimization methods based on system models will be evaluated. This means firstly modeling the underlying system and secondly applying mathematical optimization methods on the model. The work was initiated in the thesis of the PI, and WP3 is intended to refine the optimization methods for a larger selection of platforms and improve on existing optimization methods. WP3 also include the implementation of tools for automatic model generation for increasing the portability of the framework and finally the implementation of the runtime system controller itself.

Task 3.1: Modeling energy consumption
Task 3.2: Tools for generating energy models
Task 3.3: Adopting optimization methods for energy efficiency
Task 3.4: Implementation of runtime controller

WP4 – A framework for energy aware programming and demonstrator. The final stage of the research is to bind the previously created methods into a package usable for the programmer. Construction of the API framework used for energy aware programming is defined as the first item in WP4. The API is a result from the meta-data declaration in WP1, the monitor interface in WP3 and the runtime system in WP3. Additional efforts in this WP is especially put on supporting interdisciplinary domains of platforms. A software library, pragma or other interface is the final deliverable and is the link between the application software and the runtime. Additionally, we demonstrate its usability with single small scale use-cases, which also function as evaluation of the API. Lastly a large scale demonstrator is created running a complete version of the energy aware

software on an off-the-shelf consumer device such as an Android phone or tablet.

Budget. The budget of the project is defined in Table 1.

	2018	2019	2020	2021
Salary Post-doc	34434	106172	107607	72694
Travel	5500	5500	5500	5500
Equipment	0	2500	1000	2000
Open access fees	0	1000	1000	1000
Mobility	1000	2000	1000	0
Total	40934	117172	116107	81194
Project total				355407

6 Research Team and Collaborative Partners

Merits of research team. The PI was awarded the honorary degree for his thesis as well as the *Researcher of the Year award* by Åbo Akademi University for best PhD thesis during the year 2016; this project is a continuation of this thesis. The PI has published over 25 high ranking articles in the area of energy aware software during the past five years and additional articles in various workshops, and received the *Best Paper Award* at the 2014 DASIP conference. Our lab and the PI has worked within several international and national research projects such as ESC, RECOMP, ParallaX and INTERSYS with close ties to Finnish industry like Nokia, ABB, Kone, Ericsson etc.

Table 1: The budget of the project in neuroses

The PI has published over 25 high ranking articles in the area of energy aware software during the past five years and additional articles in various workshops, and received the *Best Paper Award* at the 2014 DASIP conference. Our lab and the PI has worked within several international and national research projects such as ESC, RECOMP, ParallaX and INTERSYS with close ties to Finnish industry like Nokia, ABB, Kone, Ericsson etc.

Key national and international collaboration. The research in the thesis of the PI consisted of contributions from 17 co-authors in 7 universities in 6 countries. The cooperation between Prof. Jean-Francois Nezan, INSA de Rennes, and Åbo Akademi University has concentrated on the run-time management of dataflow networks, and has been executed through exchange of PhD students. The PI visited INSA de Rennes for 4 months in 2013-2014, which resulted in two journal publications and two proceedings publications. INSA de Rennes has a strong background in tool support. The previously developed PREESM¹⁷ tool which was used to determine parallelism in data-flow programs to be used in a power optimizer developed by the PI. A cooperation between Holmbacka and Prof. Jörg Keller at the FernUniversität in Hagen started in 2014, since when we have worked on energy efficient scheduling for multi-core systems. The PI has worked in Hagen as a Post-doc researcher, and the cooperation with FernUni is currently very active. One scientific journal and three proceedings publication about energy efficient scheduling has been published during this cooperation. The PI has been cooperating with the Electronic Commerce Group in TU Wien led by Prof. Ivona Brandić since spring 2015 inside the COST action IC1305 framework. Work on cost and energy efficient cloud scheduling was done by extending the Philharmonic cloud simulator¹⁸ created at TU Wien with a multi-core model developed by the PI at Åbo Akademi University. A journal has been accepted in the IEEE Transactions journal as a result of this cooperation. We have an active collaboration with Prof. Alexandra Jimborean from Uppsala University in Sweden. Their lab group is working on compile-time and runtime code analysis and transformation for performance and energy efficiency using LLVM. Her group has developed a monitoring and feedback system for re-organizing instruction calls based on their memory intensity. The PI is actively involved in minor collaborations with many universities and companies such as Uni. Carlos III Madrid, Uni. Gronningen, TU Eindhoven, Uni. Uppsala, Uni. Turku, NTNU Trondheim, Uni. Tirana, Elisa Inc., Treelogic Inc., Ingenarius Inc., Comsel systems Inc., Hipperos Inc., RISE Inc., TXT E-Solutions Inc. Additional collaboration and mobilities is expected among the other partners.

7 Research Careers and Research Training

Advancing the research career of the applicant and researcher training. The supervision of PhD students are carried out as teamwork within participating senior researchers, but every student has also official supervisors with whom the student makes a study and research plans according to the university regulations. Each laboratory consists of researchers at various levels of their research career. It is paramount for all of them (including professors, researchers and staff) to periodically participate in the researcher training programs and renew their education/training. With the current application, we seek funding for a post-doc researcher to work full-time within

¹⁷<http://preesm.sourceforge.net/website/>

¹⁸<http://philharmonic.github.io/>

the project. Combined with the international co-operation, exchange period and close interaction between participating institutes, the project gives to the involved post-doc good basis to proceed in the academic career after the project.

8 Mobility Plan for the Funding Period

The mobilities among the main partners are planned as follows and illustrated in Figure 3, but the exact details will be defined later in the project based on the availability of the collaborators and their time schedule.

- The PI will visit Prof. Jean-Francois Nezan for 3 months in the beginning of WP1 to bring early tool integration of meta-data injection in WP1, and to determine the meta-data model needed for such tool integration. In the later stages of the project, the utilization of PREESM is expected in form of a demonstration environment for WP4.
- The PI will visit Prof. Ivona Brandić for 3 months in the beginning of WP2 after the meta-data framework has been established in WP1 in order to adapt and evaluate our framework in cloud environments.
- The PI will visit Prof. Jörg Keller for 6 months in the middle of WP3 mainly for the energy optimization in WP3 and the construction of the controller in WP3.

References

- [Aag01] Jan Aagedal. *Quality of Service Support in Development of Distributed Systems*. PhD thesis, University of Oslo, Twente, Netherlands, March 2001.
- [BSA11] Teigerwald Bob S and Agrawal Abhisek. Developing green software, June 2011.
- [DGR⁺74] R.H. Dennard, F.H. Gaensslen, V.L. Rideout, E. Bassous, and A.R. LeBlanc. Design of ion-implanted mosfet’s with very small physical dimensions. *Solid-State Circuits, IEEE Journal of*, 9(5):256–268, Oct 1974.
- [DKM⁺12] Andrew Danowitz, Kyle Kelley, James Mao, John P. Stevenson, and Mark Horowitz. Cpu db: Recording microprocessor history. *Queue*, 10(4):10:10–10:27, April 2012.
- [EEKS09] Stijn Eyerman, Lieven Eeckhout, Tejas Karkhanis, and James E. Smith. A mechanistic performance model for superscalar out-of-order processors. *ACM Trans. Comput. Syst.*, 27(2):3:1–3:37, May 2009.
- [Epe15] Epec Engineered Technologies. New battery technology developments, May 2015.
- [HES⁺10] Henry Hoffmann, Jonathan Eastep, Marco D. Santambrogio, Jason E. Miller, and Anant Agarwal. Application heartbeats: A generic interface for specifying program performance and goals in autonomous computing environments. In *Proceedings of the 7th International Conference on Autonomic Computing, ICAC ’10*, pages 79–88, New York, NY, USA, 2010. ACM.
- [HLL15] Simon Holmbacka, Sébastien Lafond, and Johan Lilius. Performance monitor based power management for big.little platforms. In Dimitrios Nikolopoulos and Jose-Luis Nunez-Yanez, editors, *Workshop on Energy Efficiency with Heterogeneous Computing*, page 1 6. HiPEAC, 2015.
- [HNP⁺14] Simon Holmbacka, Erwan Nogues, Maxime Pelcat, Sébastien Lafond, and Johan Lilius. Energy efficiency and performance management of parallel dataflow applications. In Ana Pinzari and Adam Morawiec, editors, *The 2014 Conference on Design & Architectures for Signal & Image Processing*, page 1 8. ECDI Electronic Chips & Systems design initiative, 2014.
- [Hol15] Simon Holmbacka. *Energy Aware Software for Many-Core Systems*. PhD thesis, Åbo Akademi University, December 2015.
- [HSC⁺11] Henry Hoffmann, Stelios Sidiroglou, Michael Carbin, Sasa Misailovic, Anant Agarwal, and Martin Rinard. Dynamic knobs for responsive power-aware computing. *SIGPLAN Not.*, 46(3):199–212, March 2011.
- [PV07] M. D. Powell and T. N. Vijaykumar. Resource area dilation to reduce power density in throughput servers. In *Low Power Electronics and Design (ISLPED), 2007 ACM/IEEE International Symposium on*, pages 268–273, Aug 2007.
- [Seg11] Vanessa Segovia. *Adaptive CPU resource management for multicore platforms*. Licentiate thesis, Lund University, Sep. 2011.
- [SKK11] V. Spiliopoulos, S. Kaxiras, and G. Keramidas. Green governors: A framework for continuously adaptive dvfs. In *Green Computing Conference and Workshops (IGCC), 2011 International*, pages 1–8, July 2011.
- [Sta06] Venkatesh Pallipadi Alexey Starikovskiy. The ondemand governor. In *Proceedings of theLinux Symposium*, 2006.
- [tB15] Steven te Brinke. *Developing Energy-Aware Software*. PhD thesis, Universiteit Twente, Oslo, Norway, Juni 2015.
- [Tri15] Rob Triggs. How far we’ve come: a look at smartphone performance over the past 7 years, July 2015.
- [WS13] L. Wang and K. Skadron. Implications of the power wall: Dim cores and reconfigurable logic. *IEEE Micro*, 33(5):40–48, 2013.