Energy-Budgeting Sensor Networks with Renewable Energy Sources

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Abstract

Energy-aware scheduling, or *energy budgeting*, is an evolving research area of energy-harvesting sensor networks. This thesis will contribute to this field in three ways. Firstly, models for predicting the remaining energy of supercapacitors, which are frequently used for energy storage in harvesting devices, are developed and assessed. Secondly, existing prediction algorithms for future energy inflow are evaluated and enhanced to achieve an increased prediction horizon. Thirdly, an energy-aware scheduler will be devised that plans node and network tasks with respect to present and predicted future energy resources of individual nodes in the network.

1 Problem Domain

Perpetual operation of wireless devices, such as wireless sensor nodes, is a research goal being addressed with increasing frequency. Energy-efficient operation of these devices is important for an effective use of available energy resources. However, it can merely prolong a sensor node's lifetime, i.e., energy depletion will eventually occur. For battery capacities are not expected to rise in orders of magnitude within the near future, provided that larger-sized batteries are not an option, and since replacement of batteries is usually infeasible, research ought to embark on a different strategy.

Recent works have investigated the potential of harvesting energy from the environment and pointed out its feasibility. Various harvesting solutions can be employed, among the sources being sunlight, radio frequency, wind, vibration, or temperature differences. Particularly sunlight is highly promising, since it produces a sufficient amount of energy to supply wireless sensor nodes, which draw currents between several µA in the sleep state and some mA in full-operation mode.

Unfortunately, the amount of harvested energy is usually neither constant nor continuous. In the instance of solar harvesting, energy can only be harvested during the day, while its amount depends heavily on weather conditions, the time of the year, and the precise placement of the sensor node's solar cell. Hence, energy must be buffered in order to prevent nodes from temporal energy shortage and restricted periods of operation.

A prospective option for buffering energy are supercapacitors.

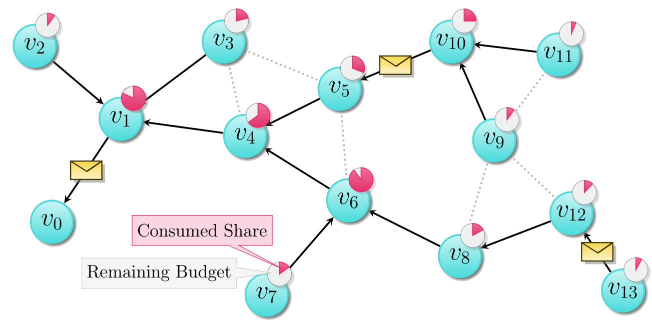

Figure 1. Energy-budgeting data-gathering application

While they are relatively small and can reliably supply a node for a few days, they reveal another strength: the stored energy can be estimated precisely with low computational effort. This is indispensable for what we refer to as *energy budgeting*: executing application tasks so that a given amount of energy per time—the energy budget—is used effectively. This implies that tasks are scheduled in order to comply with the needs and to maximize the yield of the application while not exceeding the energy budget. Corresponding techniques embrace adaptive duty-cycling and energy-aware scheduling, i.e., reducing the probability of accidental energy depletion caused by running a highly energy-consuming task during periods of low energy reserves.

In addition to local decisions, network aspects have to be considered for budgeting decisions. For example, consider a data-gathering application as illustrated in Fig. 1. Here, the closer a node is to the root of the tree, the more data it has to transport. Therefore, these nodes are responsible for trading off energy spent on local operations versus data forwarding. Even in this unspectacular plot, scheduling requires sharing of information among nodes to exploit all energy budgets as efficiently as possible.

1.1 Contribution of the Thesis

The main goal of the thesis is the development of models, methods, and an experimental system for energy-budgeted sensor networks with renewable energy sources, which allow for a theoretically endless lifetime in an energy neutral fashion. For this purpose, we will develop and evaluate

- estimation techniques for presently stored energy,
- enhanced prediction algorithms for future energy inflow, and
- an energy-aware scheduler that plans node and network tasks with respect to current and predicted future energy resources of the network and individual nodes.

Hence, this thesis makes a significant contribution to the current state of research on the subject of energy-budgeting sensor net-

Figure 2. Sensor node with our harvesting supply

works with renewable energy sources.

Moreover, a hardware suitable for energy budgeting is developed. On this basis, the practicability of the models and algorithms for energy budgeting will be demonstrated by using an experimental system, encompassing hardware, system libraries, and example applications. Finally, network aspects will be integrated into scheduling decisions.

2 Related Work

The emerging attraction of self-sustaining power supplies for wireless sensor nodes reveals itself by several works. Enviromote [6] is a platform equipped with a solar cell as power source and NiMH batteries for energy storage. The authors present charging and discharging characteristics of their power supply. Prometheus is based on a two-stage energy storage system consisting of a supercapacitor as the primary energy source and a rechargeable Li^+ battery. A solar cell serves as energy source. Charging and discharging behavior of the circuit and supercapacitors are examined, while taking a first step into the direction of energy-aware scheduling by adapting the duty cycle to the current supercapacitor voltage. Prometheus has been successfully deployed in the Trio testbed [3]. The Everlast platform stores energy harvested by a solar cell in a supercapacitor solely [10]. Maximum power point tracking (MPPT) is employed to increase the electrical power produced by the solar cell. Recently, we have developed a harvesting module (Fig. 2) with a solar cell and a supercapacitor, too, [8, 9]. A new release supports multiple harvesting sources [5].

These hardware platforms are enriched by prediction algorithms for the possible energy intake. The Weather-Conditioned Moving Average (WCMA), which predicts future energy resources by using the history of the last days and the current weather situation, has been investigated by Ali *et al.* [1]. Bergonzini *et al.* have improved this method by employing what they call a phase displacement regulator [2].

The energy-aware Nano-RK operating system [4] is a real-time operating system for wireless sensor nodes. Energy generated from a harvesting device is not supported. In [7], tools and methods that use multiparametric programming are suggested for achieving optimal performance in energy harvesting systems. For real hardware, an approximation algorithm is presented. Both simulational results and the evaluation of the algorithms on real hardware are discussed.

3 Intermediate Results

In order to pave the ground for an holistic assessment of the relevant design criteria for energy-aware scheduling, the author has already investigated estimation techniques for supercapacitors and prediction algorithms for solar harvesting devices. The results are presented in the following.

3.1 Energy Buffer Estimation

Supercapacitors have been chosen as energy storage devices for harvesting sensor nodes, because they exhibit many advantages. They can operate well in temperature regions between $-40\,^\circ$C and $60\,^\circ$C. They offer virtually infinite charge/discharge cycles, and the charging circuit is rather simple and cheap. Another very crucial advantages is that estimation of the remaining lifetime of a sensor node solely depends on the average node power consumption P_N and the efficiency η of the circuit. Further parameters are the current voltage $V_{C,0}$ of the capacitor, its actual capacity C and the minimum voltage V_{min} required to supply the circuitry:

$$T_{\text{life}} = \frac{\eta C}{2P_N}\left(V_{C,0}^2 - V_{\min}^2\right). \tag{1}$$

The author has also derived a more advanced formula, which incorporates the influence of leakage currents and reorganization processes inside the capacitor, which influence lifetime prediction for large values of V_C:

$$T_{\text{life}} = -\frac{\eta C}{2P_N}\left[V_C^2 - \frac{2V_C}{\alpha}\ln\left(1+\frac{P_0\exp(\alpha V_C)}{P_N}\right) - \frac{2}{\alpha^2}\sum_{n=1}^{\infty}\left(-\frac{P_0\exp(\alpha V_C)}{P_N}\right)^n\frac{1}{n^2}\right]_{V_{C,0}}^{V_{\min}} \tag{2}$$

Here, α and P_0 have to be determined empirically. The derivation of both formulae and a discussion of their preciseness has been carried out in [8].

As can be obtained from (1), the actual capacity of a supercapacitor influences energy estimation linearly. Unfortunately, it is subject to manufacturing variations and decreases with age. Therefore, its value has to be determined regularly or if a sensor node experiences wrong energy estimations. Capacity determination can be achieved via a controlled partial discharging procedure. This method has been proposed and evaluating in terms of the CapLibrate project [9].

3.2 Energy Intake Prediction

The employment of advanced energy intake prediction allows for refined scheduling techniques for sensor nodes. There are three particular cases that demonstrate its usefulness.

- When facing a low energy buffer, a node would have to either run fewer tasks, or it would risk accidental energy depletion. This is far from optimal, e.g., in a situation in which sunrise is close, but the energy of the buffer is almost worn out. Here, the low buffer level is no harm at all, since fresh energy can be harvested soon enough.
- In some instances, it is useful to start increasing a node's duty cycle well before the buffer gets close to being full. If the expected energy income would fill up the buffer to its maximum, some of the harvested energy will be lost, for it cannot be stored in the filled buffer. Take into consideration here that many harvesters can produce more power than can be consumed by a node even at a high load.
- Static a-priori assumptions about energy intake might not hold. A changed environment, damage to the harvester, or unexpected weather situations can severely influence the amount of actually harvested energy.

Recent algorithms are not capable of performing long-term predictions, i.e., their prediction horizon is in the range of minutes. To analyze the impact of different prediction strategies and their preciseness, a framework has been developed for simulating prediction algorithms based on real data. The latter has been recorded for a period of six month using a sensor node equipped with the harvesting board developed at TUHH. Furthermore, a set of TinyOS interfaces and components has been developed recently for simulation and real-world analysis of existing and to be developed algorithms.

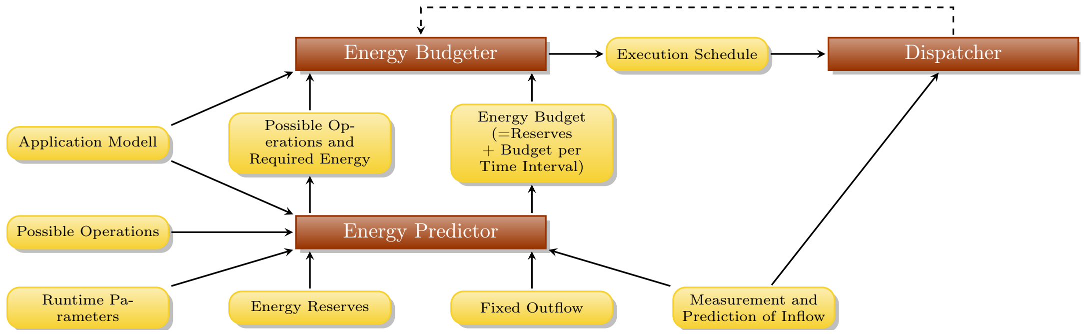

Figure 3. Building blocks of an energy-budgeting scheduling system

4 Enhancements

To improve the ability of energy-aware scheduling in sensor networks, the following three enhancements using the intermediate results are intended as fundamental parts of the thesis:

- The models for lifetime prediction are being refined by a more thorough investigation of the leakage behavior and the influence of the ambient temperature on the supercapacitors. Here, we plan to particularly focus on the distinction between leakage and internal reorganization processes. For this purpose, we are currently conducting measurements.
- All available harvesting predictors abide by the principle of equally distributed slots. Most harvesters however exhibit times of low and high dynamics, e.g., consider nighttime versus noon in the instance of solar cells. To keep memory consumption as low as possible and to avoid dynamic memory allocation (if available at all), we are exploring the design of prediction algorithms with variable-length slots.
- Lifetime prediction (cf. (1)) requires a detailed knowledge of the power consumption. This encompasses the analysis of different power levels and the efficiency of the whole circuit, which depends on the input voltage and output current of the power supply. We are currently seeking to convert recorded data into appropriate models for the estimation of power consumption in various situations.

5 Energy-Aware Scheduler

The enhanced energy resource and power consumption estimation plus the revised prediction models are three major cornerstones of an energy-aware scheduler that we will develop next. The scheduler will be modeled as sketched in Fig. 3. A first, partly finished, version runs periodical tasks and scales the periods depending on the current energy buffer fill level. For the next development cycle, we will integrate additional task models, e.g., tasks with deadlines and priorities. A fundamental step will be the incorporation of network tasks, among these being clustering and routing decisions.

Long-term prediction of the energy inflow and a new scheduling core will also be installed. Yet, before these steps can be taken, additional effort on application models and reward maximization have to be carried out. On this ground, we will particularly focus on low-end, cheap charging circuits as found in our harvesting supply. We believe that these simple circuits perform as well as their maximum-power-point counterparts. This stems from experiments with a different hardware. However, the energy delivered by the solar depends on the state-of-charge of the energy buffer—in our case, the voltage of the supercapacitor—, so that finding an optimal schedule requires more attention.

We plan to base our scheduling system on the findings from [7]. Concrete scheduling approaches are yet to be determined. The scheduling algorithms will be evaluated in a real-world test deployment, and their efficiency will be compared with simulational models and results. In addition, pointing out the applicability to other platforms or application fields with embedded devices will be considered and explored.

6 References

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Biography

Christian Renner was born in Winsen/Luhe, Germany, on September 2, 1982.

He graduated from Alexander-von-Humboldt-Gymnasium (highschool), Hamburg, Germany, in 2002. After his ten-month civil service, he studied Informatics and Engineering (Diploma Degree) from 2003 until 2008 at Hamburg University of Technology (TUHH). In the winter term 2006 / 2007 he spent six month with studies at ETH Zurich, where he also wrote his Studienarbeit (project work) under supervision of Prof. Kay Römer. He finished his studies in June 2008 with his diploma thesis under supervision of Prof. Volker Turau.

Christian has been working on the field of sensor networks since 2005, mainly concentrating on medium access control, energy-efficient protocols, and neighborhood management. He has been part of the inter-disciplinary sensor-network research project *SomSeD* at Hamburg University of Technology.

Christian was accepted for the scholarship program of the German National Academic Foundation (Studienstiftung des deutschen Volkes) in 2006. He received an additional scholarship for his studies at ETH Zurich. He was awarded the *Philips Undergraduate Prize* for finishing his undergraduate studies among the top students in 2005, and he was awarded the *Diploma Prize* by the Foundation for Promoting the TUHH (Stiftung zur Förderung der TUHH) for his excellent studies and social engagement in 2008.

Christian is with the Institute of Telematics at Hamburg University of Technology since July 2008. His thesis adviser is Prof. Volker Turau. Submission of the thesis is scheduled for the end of the year 2011.