Adaptive Wireless Sensor Networks Powered by Hybrid Energy Harvesting for Advanced Environment Monitoring

François Philipp, Ping Zhao, Faizal A. Samman and Manfred Glesner
Microelectronic Systems Research Group
Technische Universität Darmstadt
Darmstadt, Germany
francoisp(at)mes.tu-darmstadt.de

Kithsiri Bandara Dasanayake, Suhinthan Maheswararajah and Saman Halgamuge
Melbourne School of Land and Environment and Department of Mechanical Engineering
University of Melbourne
Melbourne, Australia
s.maheswararajah(at)pgrad.unimelb.edu.au

Keywords—sustainable development, wireless sensor networks, energy harvesting, adaptive systems

I. INTRODUCTION

Advanced environment monitoring is a key technology for the progression of sustainable development. Thanks to tiny autonomous sensors capable of wireless communication and deployed in wide areas, a very precise knowledge of the evolution of an ecological system can be gained. This precious information helps to understand natural phenomena like animal tracking, prevent natural disasters like bushfires or flooding or allow a fine tuning of resources allocation in resource-constrained areas like irrigation control. However, management and installation of such wireless sensor networks is still a costly and complex operation. A current combined research project between the University of Melbourne and TU Darmstadt aims to address this issue by investigating a cost-effective, robust, and energy-efficient solution. An overview of an adaptive system combining a flexible hardware prototype, innovative energy harvesting techniques and optimized network organization techniques will be given in this paper.

II. FLEXIBLE SENSOR INTERFACE

Deployment costs of wireless sensor networks for precision agriculture, farming and similar outdoor applications are still very high. The context specificity necessitates the development of custom hardware that supports the requirements of a given application. This step, which involves high development costs, is mandatory to achieve very low power and energy-efficient operation with hardware specially adapted for the target environment. This run to energy-efficiency results in the development and the production of application-specific platforms that dramatically increase the deployment costs of such applications. Such expenses are still prohibitive for end users and limit the return on investment of these systems. A solution to this issue is the utilization of a generic hardware platform that may be adapted to a maximal range of situations. Large amount of such reusable modules can be produced in order to decrease the overall costs and make the installation affordable. The performance and power consumption cost induced by the genericity can be covered by novel heterogeneous energy-harvesting techniques as it will be demonstrated in the next section.

A. Modularity

The most obvious design feature to improve flexibility is modularity. A wireless sensor node is typically divided in four main components: the radio interface, the processing unit, the sensors and the power management unit. A current combined research project between the University of Melbourne and TU Darmstadt aims to address this issue by investigating a cost-effective, robust, and energy-efficient solution. An overview of an adaptive system combining a flexible hardware prototype, innovative energy harvesting techniques and optimized network organization techniques will be given in this paper. First, the modular sensor node hardware design is introduced in Section II. Novel energy harvesting circuits for outdoor environments are presented in Section III. The paper concludes with a strategy for elaborating the topology of large sensor networks for irrigation monitoring without orphan nodes in Section IV.

B. Adaptability

Each sensor used for the application requires a custom hardware (analog to digital converter or communication interface) and software interface. Besides, the limited connectivity of low power microcontrollers traditionally used with wireless sensor nodes highly restrict the number of pluggable sensors. These problems can be solved by extending the processor with a dynamically configurable component with a large number of I/Os. These requirements are fulfilled by Field Programmable Gate Arrays (FPGAs). These chips can be programmed with custom
digital hardware architectures allowing a energy-efficient and faster implementation of sensors interfaces. Moreover, the size of the configuration data of this family of devices may be reduced to a few amount of bytes. This enables dissemination of interfaces upgrades into low bandwidth wireless sensor networks. Thus, a new sensor may be dynamically plugged at runtime to a node and remotely activated via the base station of the network. This operation do not require programming hardware or complex manipulation and thus reduce the maintenance costs of the network.

For applications generating data at high sample rates, FPGAs can be used to preprocess the data at very low energy costs. Useful information is extracted from the data locally, thus reducing the traffic of the network and the global energy consumption. [3]

Maybe replace this with figure 2.1 from Ping Diss.

### III. ENERGY HARVESTING

Additional power consumption costs introduced by the generic platform solution may be compensated by an efficient power management based on energy harvesting. Sensor nodes powered only by batteries usually have a lifetime limited to some months. Using energy harvested from the surrounding environment, this lifetime may be extended to years, making the sensor node totally autonomous from the energy point of view [4]. For outdoor deployments, photovoltaics is the most common approach. However alternative sources exist and may be used instead of or in combination with solar panels when the energy scavenged from the sun is not sufficient:

- **Piezoelectric Harvester**: Using piezoelectric material, energy can be harvested from vibrating structures. Enough energy can be accumulated to recharge the battery of a sensor node by optimizing the power management circuit to work at the resonance frequency of the vibrating mass. Such systems can be used for example on animals: their movements will create the energy necessary to power the sensor nodes they are wearing. Other possible sources are pump motors used for irrigation.

- **Thermoelectric Harvester**: Thermogenerators are small planar modules that can generate energy from temperature difference. Based on the Seebeck effect, these thermoelectric converters may be used in addition to solar panels in very hot environments. The sun will directly heat one side of the generator, creating a potential difference large enough to contribute to the charging of the sensor node battery. Efficient isolation between the hot and the cold side as well as optimized circuitry will increase the performance of this solution.

- **RF Energy Harvester**: Should we include this? Input from Ping?

These energy sources can be used independently or together in order to reduce the maintenance of the sensor network. This autonomy makes the hardware more reliable and adaptable to a larger number of environments. Here the figure 2.27 from Ping Diss (maybe first figure becomes redundant)

#### A. Hybrid Energy Harvesting Circuit

A specific circuit has been developed at TU Darmstadt to combine thermoelectric and solar energy in a single system. Both converters are based on a single-ended primary-inductor DC/DC converter (SEPIC) controlled by a pulse-width modulated (PWM) signal. The duty cycle cycle of this signal has a direct influence on the efficiency of the conversion and on the amount of scavenged energy. For given environmental conditions (light and temperature for a solar panel for example), there is a maximum power output corresponding to a specific PWM duty cycle value. This is illustrated for a solar panel in Figure XXX with different light conditions (from cloudy weather up to direct summer sunlight). Here the figure 2.11 from Ping Diss

The duty cycle of the SEPIC must then be dynamically adapted according to changing environmental conditions in order to maximize the power output. This process is referenced as the Maximum Power Point Tracking (MPPT). For small scaled systems like wireless sensor nodes considered in the frame of this paper, the energy spent to adapt this duty cycle is not negligible and should be included in the balance for computing the efficiency of the whole energy harvesting circuit. Classical MPPT algorithms are based on “Perturb and Observe” methods. Different values of duty cycles are tested until the maximum is found. This may however requires a significant amount of measurements until the maximum point is found, which is undesirable for the energy efficiency and the response time of the system. We therefore base our approach on the relationship between the open circuit input voltage and the optimal input voltage at the maximum power point, also known as the fractional Open-Circuit voltage method. This further gives a relationship between the open circuit voltage and the optimal PWM duty cycle (as it can be observed in Figure YYY).

Maybe Here the figure 2.12 from Ping Diss?

Based on this relation, a Look-up-table has been elaborated to map measured open circuit voltages with duty cycles of the PWM generator circuit. This circuit has been realized with custom digital logic in a low-power FPGA (Microsemi...
Lower power consumption can be achieved by designing a mixed-signal Application Specific Integrated Circuit (ASIC) integrating all components. Because of the high production cost of such chips in small quantities and our desire to principally demonstrate a methodology and design concepts, we restricted the evaluation to the FPGA-based energy-harvesting circuit. The fabricated prototype of the whole system can be observed in Figure ZZZ.

Here the figure 2.30 from Ping Diss

If we also want to include the measurement results, this should be done here, but we may have space problems

IV. ORPHAN NODES

A sensor node delivers its measurements by establishing a connection to the base station (or coordinator) through single or multiple hop communication. To establish a network connection, it is required to obtain a network address from a router-capable parent node [4]. In practice, this might not occur, if the parent node is running out of network addresses due to inefficient address assignment or very low signal level received at the node caused due to obstacles and undesirable atmospheric conditions. The existence of large number of orphaned nodes adversely affects the performance of wireless sensor network applications such as real time sensor-based automated irrigation control systems where wireless sensor network is used not only to collect measurements from the environment but also to control the irrigation actuators. Considering a scenario where a sensor node, which controls the irrigation actuators, is not connected to the network resulting in lost of control signal from base station and caused damage to crops due to either shortage or excessive amount of water. Even though the impact of orphaned nodes on the system is the same as the exhausted or dead nodes, it is possible to restore them back to the network. However, connecting orphaned nodes back to the network may require some compromises since a parent node can possess only a limited number of children nodes. Developing protocols to manage the orphaned nodes in real time to optimise the performance of wireless sensor network is a challenging task in harsh environmental conditions.

V. CONCLUSION

The application of wireless sensor network in agriculture industry offers a wide range advantages over traditional techniques used for monitoring and irrigating large farms. However wireless sensor network suffers from various problems as addressed in this paper: inflexible in hardware/software interfaces, limited energy resources and presence of orphaned nodes. We are focusing on developing inexpensive, energy efficient and robust hardwares to support real-time reconfiguration of modules and protocols to increase the performance of the wireless sensor network while reducing the network traffic in harsh environmental conditions.