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On the Lifetime and Usability of Environmental Monitoring Wireless Sensor Networks

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Abstract:

Wireless sensor networks have been demonstrated, at an early stage in their development, to be a useful measurement technology for environmental monitoring applications. Based on their independence from existing infrastructures, wireless sensor networks can be deployed in virtually any location and provide sensor samples in a spatial and temporal resolution, which otherwise would only be achievable at high cost or involve significant work by humans. The feasibility of the usage of wireless sensor networks in real-world applications, however, is only maintained if certain technological challenges are overcome. Amongst these challenges, are the limited lifetime of the distributed sensor nodes, and user interfaces, which allow for the technology to be utilized in an efficient manner. Contributions to the solution of these challenges have been the objective of this thesis.

After an analysis of the contributions wireless sensor networks can provide to the application domain of environmental monitoring, and the introduction to the restrictions, which are posed by a limited operational lifetime and low system usability, these issues are addressed at the system level of sensor node devices.

The lifetime of sensor nodes, which is closely linked to the lifetime of the complete wireless sensor network, is addressed with regards to the energy efficiency of nodes, as well as the utilization of solar energy harvesting in order to increase the available energy resources. With respect to energy efficiency, an analysis has been performed of the contributions to the energy consumption of environmental monitoring sensor nodes, which leads to the desire to minimize the nodes' duty cycles and quiescent currents. A sensor node design is presented, which features energy efficiency as a key attribute by utilizing modern semiconductor architectures. Moreover, an argument for the usage of synchronization-based, contention-free communication is made in order to reduce active communication periods and, thus, the duty cycle of a sensor node. A synchronization method with its focus on low protocol overhead is introduced as a basis for such communication forms.

After an initial feasibility study in relation to using battery-less solar energy harvesting architectures in locations with limited solar irradiation, multiple architectural implementations are analyzed in a comparative manner. Among these comparisons is an analysis of short-term energy storage devices in the form of double-layer capacitors and thin-film batteries, which provide prolonged component lifetimes than those for conventional secondary batteries, but which can only buffer for short periods of time due to their limited energy capacity. In order to be able to dimension such energy harvesting systems with respect to the individual application constraints at hand, state of charge simulations are proposed.

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A method for such simulations is presented and demonstrated for the implementation of an energy harvester model on a component basis. While the modeling in this manner is time consuming, the model can predict the state of charge of the energy buffer in the architecture with a high level of accuracy. Finally, a method for the systematic evaluation of solar energy harvesting architectures is presented. The presented method can be summarized as a solar energy harvesting testbed, which utilizes configurable energy harvesting circuits in order to create a deploy-once-test-many type of system. The output results of this testbed can significantly improve the efficiency of architecture comparisons and system modeling.

Contributions to the improvement of the usability of wireless sensor nodes are made on two separate levels, namely, developer usability and end user usability. A method for the programming of sensor nodes based on hierarchical finite state machines is presented, which improves the usability of software development by creating familiarity for technically experienced users. Moreover, the utilization of finite state machine principles allows for the software to be developed in a systematic and modular manner. As implemented applications typically require to be verified, which, in the environmental monitoring domain, usually results in outdoor deployments, usability considerations for sensor nodes are presented, which can simplify this process. Special attention has been paid in order for these improvements to be achieved with low overheads.

While software development is a familiar concept for most system developers, this is not the case for the end users of these systems, who are typically domain experts. In order to allow for wireless sensor nodes to be operated by domain experts, a method for the configuration of sensor nodes has been proposed. The method uses a combination of graphical specification of the node behavior and a configurable sensor node. The evaluation of this method, which has been based on a proof-of-concept implementation, demonstrated that the performance can remain high, while end users, without technical experience, are enabled to configure sensor nodes without prior training.

In summary, the contributions, presented in this thesis, address system lifetime and usability with regards to the sensor node level. The results have led to the implementation of an energy efficient sensor node, which allows for the operation from battery-less solar energy harvesting sources. Furthermore, support tools for the implementation of these nodes, both on the hardware and software level, have been proposed.