Simulation Modelling Practice and Theory 43 (2014) 1–15

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Energy-neutral networked wireless sensors

Soledad Escolar [a,*], Stefano Chessa [b], Jesús Carretero [a]

[a] Computer Science Department, University Carlos III of Madrid, Madrid, Spain
[b] Computer Science Department, University of Pisa, ISTI-CNR, Pisa, Italy

ARTICLE INFO

Article history:
Received 24 July 2013
Received in revised form 6 November 2013
Accepted 8 January 2014
Available online 28 January 2014

Keywords:
Power management
Wireless sensor networks
Quality of service
Solar cells
Adaptive duty cycling

ABSTRACT

Solar cells combined with power management algorithms enable the dynamic scheduling of Wireless Sensor Networks applications in a reference period, where the objective of the scheduling is to maximize the application quality level while conserving an energy level sufficient to constantly maintain the sensor operation. With the purpose of fulfillment of its activities the sensor may have alternative different applications with different costs and quality levels, which are intended to express how much the application meets the user requirements. In this paper we propose an algorithm that aims to find a (sub)optimal scheduling that maximizes the overall quality of service for two networked, solar cells powered sensors, and keeps the system energy neutral, thus ensuring that the system works uninterruptedly.

1. Introduction

A Wireless Sensor Network (WSN) comprises a large number of low-power wireless embedded devices, called sensors, which can be easily deployed in a given area, in order to collect environmental data and detect the occurrence of events of interest. Once an event is detected, the sensors send any related sensed data to a special node, called sink, that acts as a gateway between the WSN and external networks and that forwards the sensed data to the user.

Most of the commercial sensors available nowadays are powered by limited-capacity batteries that provide the energy required to sustain the operation of the sensor by feeding its circuitry. Consequently, the sensor lifetime is also limited: when the battery drops below a minimum charge level, the sensor stops working. There is great emphasis on the efficient use of energy to prolong battery life [3,17,9]. Such a limitation may be addressed by means of energy harvesting systems that use the energy obtained naturally from the environment to power on the sensors. However, since the energy production of the energy harvesting systems is generally not continuous, as it depends on the conditions of the environment, the sensors generally use a battery that is recharged when there is an excess of energy production (i.e. it is produced more energy than required) by the energy harvesting system, and that guarantees the operation of the sensors when there is insufficient production of energy. In other words, the battery acts as a limited-capacity buffer of the energy. In such a system, an efficient energy management is necessary in order to guarantee an infinite sensor's lifetime while maintaining the activities of the sensors.

In this work we model the sensors activities as tasks; for example, a task may define sensing, processing, and communication activities with a given rate. Each task is associated to a cost (defined in terms of energy required by the task per unit of time) and to a Quality of Service (QoS) level, which expresses how much the task meets the user needs/requirements. We also model the energy production from a solar cell, which can be used to estimate the maximum amount of energy that the sensor could waste. Based on these models, we devise a scheduling strategy that consists in finding an assignment of execution tasks

* Corresponding author. Tel.: +34 916249143.
E-mail addresses: mariasoledad.escolar@uc3m.es (S. Escolar), ste@di.unipi.it (S. Chessa), jesus.carretero@uc3m.es (J. Carretero).

1569-190X/$ - see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.simpat.2014.01.002

along a time frame, for instance one day, such that maximizes the QoS while keeping the sensor *energy neutral*, which means that within the time frame the energy production equals the energy consumption. Specifically, we address the problem considering a scenario that comprises two networked devices, one sensor and one sink, where both employ an energy harvesting system based on solar cells. Both the sensor and the sink perform a set of tasks that also include the communications among themselves. For this scenario we propose a low-complexity algorithm aimed at finding a (sub)optimal application scheduling that concerns both the sensor and the sink, such that the overall quality of the scheduling is maximized, the energy is preserved to guarantee the execution of applications even in conditions of darkness or low production, and the tasks selected at each time for the sensor and for the sink are compatible (i.e. they can work together). The optimization process is automatic and does not require human intervention.

In this paper we formulate the optimization problem for two networked sensors and present its evaluation. We have evaluated our approach by simulation and not by experimentation; note, however, that in order to construct more realistic models, both the energy consumption model from a sensor and the energy production model from a solar cell, are based on the parameters of real-world platforms: MicaZ and MSX-005F, respectively. Additionally, we discuss a generalization of the problem, which takes any number of sensors and a sink. It is important to point out that, even the scenario that we are addressing in this paper is limited to two nodes, to the best of our knowledge this is the first work that considers the optimization of the overall QoS of two networked sensors under the constraints of energy-neutrality and compatibility.

The remainder of this paper is organized as follows. After reviewing the related work in Section 2, we present in Section 3 our solar cell-based energy harvesting system, its energy production model and the energy consumption model of WSN applications. Section 4 describes our approach to schedule the applications to be executed on networked, solar cells powered wireless sensors, with the aim of optimizing their QoS. Section 5 provides the simulation results and Section 6 presents the generalization of the model for any number of sensors. Finally, Section 7 discusses the conclusions and further research.

2. Related work

Quality of Service (QoS) has been explicitly addressed under different perspectives in WSN. One of the most common approaches consists in looking for QoS at different layers of the network architecture, mainly MAC and routing layers. At MAC layer, several protocols [21] were proposed to improve the QoS based on service differentiation according to some static or dynamic criteria. At routing layer, QoS consists in finding the best path between a source and a destination node according to another metric, such as latency, bandwidth, packet loss, or fault tolerance. Some examples of these protocols are SAR [19], SPEED [11] and its evolution MMSPEED [10]. Ref. [20] discusses QoS at routing layer attending to the congestion control. QoS has been extensively studied at the scope of the application level, in such a way that the user is who may define application-specific performance metrics such as coverage, exposure, deployment, or reliability. In [13], for example, the optimum number of sensors that should send data is considered a QoS metric.

The sampling rate used by the application is another QoS metric with impact on the energy consumption of the sensor. Additionally, sampling could be provided simultaneously by different transducers able to monitor the same event but with different accuracy level and, in turn, different energy consumption. In this sense, several techniques focus on selecting the most appropriate transducer as well as its sampling rate according to the residual energy in order to balance sampling and energy [13,1]. Adaptive sampling techniques adjust the sampling rate of a sensor based on the spatial/temporal correlation of the data [1] to save energy. These techniques are often used in the sensors equipped with some energy harvesting system and able to estimate the energy that will be produced in a future time frame. For example, among the forms of energy harvested from the environment, it is known that the energy produced from the sun may be predicted with reasonable accuracy [2]. In [14] the authors present a theoretical model for planning and modeling micro-solar power systems. The model is validated by simulation and real experimentation, predicting with a minimal error the solar profile in different environments.

Several works combine adaptive sampling techniques and solar cells [18]. An example is [15], where the authors define the concept of *energy neutrality*, which states that the energy consumed by the sensor in a period of time is always less or equal to the energy harvested from the environment in the same period. Based on this, they propose an algorithm that divides the sensor lifetime in time slots, and that assigns to each slot the maximum sampling rate that keeps the system energy neutral. Although the authors do not mention explicitly QoS, we observe that increasing the sampling rate corresponds to rising the QoS of the application running on the sensor.

We have addressed the problem of QoS optimization while keeping the energy neutral condition in two previous works. Firstly, in [7], we propose an algorithm aimed at optimizing the QoS only attending to the duty cycle. We consider the re-optimization problem in [8], which considers an over/under production of energy with regard to the estimated production, and then find a (sub)optimal reassignment of applications to time slots that optimize the overall QoS while keeping the system energy neutral. Differently than the above works, in this paper we aim at the optimization of the QoS in a context of networked sensors, where the optimization should take into account also the compatibility of the scheduling plans of different devices and the fact that energy production and consumption is, in general, not the same on all devices. It is important to point out that, in this work, our view of QoS is rather different to the meaning used in the papers cited above. QoS enables to balance the application performance and its energy consumption, where performance is related to the use of different duty cycles, transducers and sampling rates, and/or communication patterns. To the best of our knowledge, this is the first work that consider the optimization of QoS in energy harvesting sensors under this perspective.