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Prediction free energy neutral power management for energy harvesting wireless sensor nodes

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ABSTRACT

Current power management mechanisms for energy harvesting wireless sensors typically rely on predicted information about the amount of energy that can be harvested in the future. However, such mechanisms suffer from inevitable prediction errors, which in turn degrade the overall performance in real implementations. To circumvent such problems, we propose a fundamental framework to efficiently manage the harvested energy in a prediction free manner. In particular, we theoretically derive a set of Budget Assigning Principles (BAPs) to maximize the amount of harvested energy that can be utilized by a sensor in the presence of battery energy storage inefficiencies, which in turn maximize the sensor's performance level in terms of the sensor's average duty cycle. A Prediction FREE Energy Neutral (P-FREEN) power management mechanism is then proposed to implement the BAPs based solely on current observed energy harvesting rate and battery residual energy level. The performance of P-FREEN is verified via theoretical analysis and extensive computer simulations using real life energy harvesting data sets.

1. Introduction

Powered by batteries with finite energy storage capacity, traditional wireless sensors usually have a limited *Lifetime*, which is defined by the period of time elapsed before a sensor's *Battery Residual Energy Level* (BREL) reaches zero. The BREL indicates the amount of residual energy in the battery. When its BREL reaches zero, a sensor node is called *dead* and it stops performing any more tasks. Thus, conventional researches [1–4] focus on extending the lifetime of a sensor by utilizing the energy stored in the batteries more efficiently. However, due to the finite energy storage capacity of a battery, no matter how carefully the power management mechanisms or communication protocols are designed, sensors will eventually stop working. Battery replacement is required for these sensors, which may be costly and difficult to be done due to environmental or physical constraints [5].

In view of this, energy harvesting techniques have been introduced for wireless sensors in recent years to provide an additional source of energy. Sensor nodes are equipped with energy harvesting devices (solar panels, etc.) to harvest energy from the ambient environment. The harvested energy can be used to re-charge the sensor's battery if necessary. As a result, the lifetime of a sensor is less of a critical issue as it is possible for sensors to operate perpetually in an *Energy Neutral* [6] state, in which the amount of energy consumed by the sensor is no more than that can be harvested in a given period of time. Several energy management mechanisms, such as those in [7–9], have been proposed to provide such energy neutral operations. Besides maintaining the energy neutral status of a sensor, these mechanisms also aim at maximizing the sensor performance levels, such as the sensor average duty cycle or communication channel throughput, by efficiently utilizing the harvested energy.

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However, one common problem with the above power management mechanisms is that they are all offline optimization mechanisms. In particular, they all make use of predicted energy harvesting information or assume the energy harvesting statistics to be known in advance to provide optimized system performance level and energy neutral operation. While energy harvesting information may be predictable for various energy sources such as solar power and wind power, getting such predicted information for each sensor might be time consuming. Even if the predictions are available upon deployment of sensors, these predictions may not be easily done with high level of accuracy. As a matter of fact, the actual amount of energy harvested at a given period of time usually deviates greatly from the predicted value. Fig. 1 shows the observed 2 weeks' solar radiation power information obtained from US Texas Solar Radiation Lab [10]. From this figure we can see that the amount of energy that a sensor can actually harvest shows a large fluctuation. As a result, a system operating with a prediction based power management mechanism may underuse or overuse the energy harvested. The system performance will be sub-optimal as there may not be sufficient amount of energy available at a given period of time due to overusage of energy resource. In addition, batteries with larger capacities have to be used to accommodate the larger fluctuations in the battery residual energy levels caused by these prediction errors, which will increase the size and cost of the wireless sensors.

To circumvent the problems stated above, a Prediction FREE Energy Neutral (P-FREEN) power management mechanism with maximized sensor average duty cycle is proposed in this paper. In order to develop a theoretical power control framework for P-FREEN, we firstly formulate the sensor's average duty cycle maximization as a Non-Linear Programming (NLP) problem. However, it is well known that solving a NLP problem is computationally intense. Hence, instead of solving this NLP problem directly, we define a Harvested Energy Utilization (HEU) efficiency to represent the fraction of the harvested energy that can be effectively utilized by the system in the presence of battery energy storage inefficiencies. By analysing the characteristics of HEU efficiency, we propose a set of Budget Assigning Principles (BAPs) that maximize the HEU efficiency, which in turn maximize the average duty cycle of a sensor. With the assumption that two consecutive time slots usually experience similar energy harvesting condition, P-FREEN implements BAPs based solely on the observed energy harvesting rate and current battery residual energy level. The novel features of P-FREEN are:

- Energy Neutral power management without the need to predict future energy harvesting profile.
- Improved sensor performance level (average duty cycle), which is achieved through fast adaption to the fluctuations of the energy harvesting power rate, in the presence of battery energy storage inefficiencies.
- Reduced Battery Residual Energy Level variations, which reduces the capacity of the battery required and improves battery cycle life.
- Low computational complexity and easy implementation.

The rest of the paper is organized as follows. We review the recent researches that are related to our proposed mechanism in Section 2. Section 3 discusses the system model and some preconditions we assumed. In Section 4, the condition to maximize the sensor average duty cycle is theoretically analysed. The details about the implementation of P-FREEN are presented in Section 5. Theoretical analysis and computer simulations that evaluate the performance of P-FREEN are presented in Section 6. The paper concludes in Section 7.

2. Related Works

In the literature, recent power management mechanisms for energy harvesting wireless sensors can be classified according to their performance maximization goals, such as communication channel throughput maximization, source rate maximization, the sensor duty cycle maximization, etc.

In [11], optimal sleep and wake up policies that maximize the channel throughput for wireless sensors are

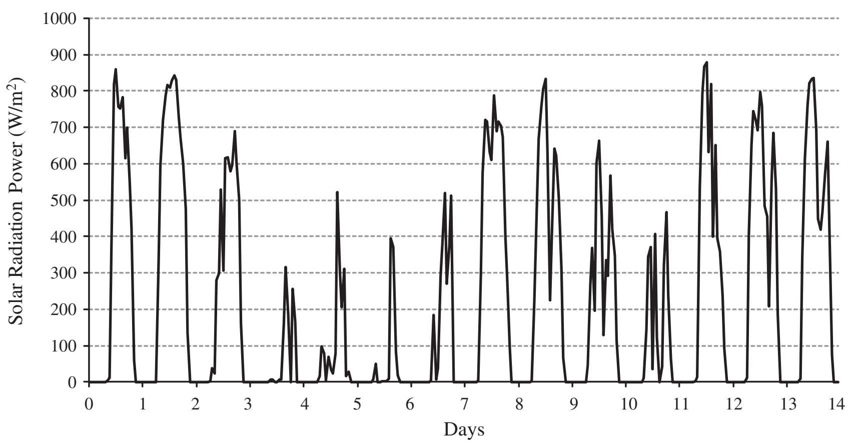

Fig. 1. Observed solar radiation power.