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Energy-efficient data collection in wireless sensor networks with time constraints

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ABSTRACT

We consider the problem of retrieving a reliable estimate of an attribute from a wireless sensor network within a fixed time window and with minimum energy consumption for the sensors. The sensors are located in the plane according to some random spatial process. They perform energy harvesting and follow an asleep/awake cycle. A sink, at a random location in the plane, requests measurements from the awake sensors in order to retrieve an estimate of an attribute. The sink has to collect a sufficient number of measurements within a fixed time window. Moreover, the sink aims to minimize the energy that the sensors use to transmit their measurements. We determine a closed-form expression for the expected energy consumption of the sensors when measurements are retrieved according to a Greedy schedule. We also provide an upper bound on the maximum expected distance over which a sensor transmits under this Greedy schedule. Furthermore, we formulate a Markov Decision Process (MDP) to determine a sensor transmission schedule with general time constraints. We also develop a heuristic that schedules the sensors for transmission. We compare numerically the performance of the MDP schedule with the heuristic and with an offline, optimal schedule, where the asleep/awake state of the sensors is assumed to be known ahead of time. We show that the energy consumption under the MDP schedule converges to the energy of the offline schedule as the size of the time window for measurement collection increases. We also show that the heuristic performs close to the MDP schedule in terms of energy consumption.

1. Introduction

Wireless sensor networks (WSNs) consist of a large number of low-cost, small devices that sense the environment and that transmit the data to a sink or a specialized gateway for further use. In typical applications such as geographical monitoring or fire detection in forests [1,2], the wireless sensors are randomly placed over the terrain and collect measurements about an attribute such as temperature, humidity level, noise level, etc. In most studies on wireless sensor networks, the sink is assumed to have a fixed location in the network. This enables the development of dedicated routing, data aggregation and data fusion algorithms that make efficient use of the fixed network topology. In this paper, we assume that the sink has a random location in the plane. This could be the case, for instance, of a user with a mobile device that enters the area in which the sensors are deployed to collect measurements.

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We consider the case when the sensors have noisy measurements of one attribute. The sink is interested in collecting from the sensors a sufficiently large set of measurements of this attribute. Based on the collected measurements, the sink computes a reliable estimate of this attribute.

The network is assumed to consist of energy harvesting sensors, i.e. the sensors have batteries with limited storage capacities and that the energy gets replenished over time according to a random process. When a sensor does not have enough energy to transmit or receive messages, it enters a sleep state. Once sufficient energy has been harvested, the sensor enters the awake state and is able to transmit messages again. Since the sensors perform additional tasks (for example, transmitting measurements to other sinks), a new sleep cycle can be entered even if no messages have been transmitted to the sink. Summarizing, the sensors follow an asleep/awake pattern according to a random process and measurements can be obtained by the sink only if a sensor is awake.

We further assume that a beaconing mechanism is in place from which the sink can infer which sensors are awake in each time slot. The sink can then request a measurement from an awake sensor. Moreover, to avoid collecting multiple times the same measurement from the same sensor, which could lead to a biased estimate of the attribute, the sink requests a measurement only from an awake sensor which is distinct from the ones that have already transmitted their measurements.

The sink aims to minimize the energy which the sensors use for transmission. We will consider the general setting in which the energy of a sensor is an increasing function of the distance between the sensor and the sink. Therefore, the sink aims to collect measurements from sensors which are as close as possible to it.

In addition, the sink has a predefined time window within which it can collect sufficient measurements for a reliable estimate. This time constraint ensures that the estimate is based on the most up-to-date measurements of the attribute available in the network.

The sink could reduce the energy consumption of the sensors by waiting for close sensors to become awake and request them to transmit their measurements. However, the time until some of these sensors become awake could exceed the predefined time window for measurement collection. Consequently, the sink could collect too few measurements. Alternatively, to collect sufficient measurements within a predefined time window, the sink could request the sensors to transmit as soon as they become awake, without taking into account how far these sensors are from the sink. In this case, however, the energy consumption needed to retrieve a reliable estimate could be significantly high. Our interest is in which sensors should be scheduled for transmission and when, so that the sink retrieves sufficient measurements for a reliable estimate within a predefined time window and with minimum energy consumption for the sensors.

Summarizing, we have the following sensor scheduling problem:

- Sensors are randomly located in the plane. Each sensor has a noisy measurement of one and the same attribute. Each sensor follows an asleep/awake cycle.
- One sink is placed at a random location in the plane. The sink has a limited, predefined time windows within which it requests a sufficiently large set of sensors to transmit their measurements. Only awake sensors, that have not transmitted previously, are requested to transmit.
- Objective: Schedule sensors for transmission such that the energy consumption of the transmitting sensors is minimized. The energy consumption of a sensor is an increasing function of the distance between this sensor and the sink.

1.1. Related work

The problem of reliable and energy-efficient data collection for WSNs has been addressed in [1–9]. In most studies, however, energy-efficient data collection does not take into account both time deadlines for the period within which sensor data is collected and the geometry of the sensors in the plane, as in our paper. In [3] a survey on energy conservation schemes in WSNs is provided. In [2] cluster heads collecting sensor data are dynamically selected such that the energy used for data transmission is minimized. However, no constraints on the time during which the data collection must be done, are considered in [2], as in our paper. In [4] energy minimization is considered in WSN with multiple sinks and multiple aggregation nodes. Using stochastic geometry, the expected energy consumption associated with an optimal organizational hierarchy is determined. In contrast to our paper, where we collect measurements from a subset of sensors, in [4] the sink compresses the data from all sensors. Moreover, the authors do not consider any time constraints for the data compression at the sink. In [5] energy harvesting nodes are considered. These nodes transmit data to an access point in the uplink only if they have sufficient energy stored in a buffer. The authors determine the limiting distribution of the stored energy in finite and infinite energy buffers. In [6] a collision-free schedule for data aggregation in WSNs is proposed based on maximal independent sets. A bound on the delay of the schedule is provided. In [7], we analyzed the Pareto front of the expected delay and expected energy consumption to retrieve a reliable estimate of an attribute from a WSN. In this paper, we will consider a fixed number of time units within which a reliable estimate must be retrieved from the sensors. In [8] the problem of reliable and energy efficient data collection from a sparse sensor network to a mobile data collector, is considered. The authors consider a limited contact time within which data can be transmitted from the sensors to the collector. This contact time depends on the time the mobile collector is within the transmission range of a sensor. In [9], the authors consider the case of a single transmitter that transmits a fixed number of packets to a receiver within a predefined time window. An energy-efficient transmission schedule is derived. This schedule specifies for when the transmitter must transmit a packet or keep silent. The energy consumption of the transmitter depends on the transmission channel. In comparison, in our model,