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Data retrieval time for energy-harvesting wireless sensor networks

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ABSTRACT

We consider an ad-hoc network of wireless sensors that harvest energy from the environment and broadcasts measurements independently, at random, provided sufficient energy is available. Clients arriving at the network are interested in retrieving measurements from an arbitrary set of sensors of some fixed size s. We show that the sensors broadcast measurements according to a phase-type distribution. We determine the probability distribution of the time needed for a client to retrieve s sensor measurements. We provide a closed-form expression for the retrieval time of s sensor measurements for an asymptotically large capacity of the sensor battery or the rate at which energy is harvested. We also analyze numerically the retrieval time of s sensor measurements under various assumptions regarding the battery capacity of the sensors, the energy harvesting and consumption processes. The results provide a lower bound for the energy storage capacity of the sensors for which the retrieval time of measurements is below a targeted level. It is also shown that the ratio between the energy harvesting rate and the broadcasting rate significantly influences the retrieval time of measurements, whereas deploying sensors with large batteries does not significantly reduce the retrieval time of measurements. Numerical experiments also indicate that our theoretical results generalize to non-identical energy harvesting rates, various amount of energy consumed upon a broadcast and non-exponential distributions of the energy harvesting and broadcasting processes.

1. Introduction

This paper considers the problem of retrieving measurements from an ad-hoc wireless sensor network. The measurements should originate from an arbitrary set of sensors, where the size of the set is predefined and fixed. The sensors harvest energy from the environment independently of the other sensors and at random points in time. This reflects the stochastic nature of the availability of the energy source. We further assume that the sensors store their energy in batteries of limited capacity. When sensors have energy, they broadcast measurements in a distributed manner. A broadcast implies energy consumption for the broadcasting sensor. Clients arrive at the network at random points in time and are interested in retrieving measurements from an arbitrary set of sensors. The size of the set is fixed and is considered to be the minimum number of measurements needed to compute an aggregate. Examples of applications are the case of sensors that estimate their position by combining several relative position measurements between themselves and the other sensors [1] or the case of users that obtain a reliable estimate of an attribute by combining noisy measurements from several sensors [2].

We determine the probability distribution of the time to retrieve measurements from an arbitrary set of sensors of fixed size. We also analyze the retrieval time of measurements when the capacity of the sensor battery or the rate at which energy is harvested are asymptotically large. These results show the impact of the energy availability, as well as the energy storage capabilities, on the process of measurement retrieval from an ad-hoc wireless sensor network with distributed data transmissions.

Energy harvesting for wireless communications has received significant attention in the last decade [3]. Energy harvesting brings new dimensions to the wireless communications problem in the form of intermittency and randomness of available energy [4]. Many authors have considered energy harvesting communication systems from the viewpoint of the communication channel of a single-transmitter to a single-receiver. For example, [5] studies the minimization of the time to transmit a fixed number of bits using an Additive White Gaussian Noise (AWGN) broadcast channel. Here, a single transmitter harvests energy and has a finite-capacity

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rechargeable battery. In [6] optimal transmission policies are derived to specify whether to transmit incoming data packets or to drop them. The policies are derived based on a value attached to each packet and on the energy available at a single transmitter. The energy arrival process is assumed to be known in advance, in an offline manner. In [7] a general framework is provided to maximize the amount of transmitted data by a given deadline when the battery of the transmitter suffers from energy leakage, under similar conditions. In [8–10] dynamic programming is employed to determine an optimal energy allocation policy over a finite horizon so that the number of transmitted bits is maximized.

Significant research has been conducted in the area of information theory, with a focus on impairments in the communication channel such as white noise, fading and interference. In [11,12] the minimization of the time to transmit a fixed number of bits using an Additive White Gaussian Noise (AWGN) broadcast channel is considered. However, the energy arrival process is assumed to be known in advance, in an offline manner. In [13,14] the process of energy harvesting is stochastic. However, in these references *centralized* transmission policies that minimize the mean delay of data transmission are derived. In [14], the average delay of data packets arriving according to a Poisson process at a *single* transmitter is considered.

The problem of maximizing the amount of data transmitted within a fixed time window is considered in [7–10]. In [15], the probability of successful reception of data packets and the energy cost per transmitted packet are determined for energy harvesting devices that broadcast using non-perfect transmission channels. The authors propose an erasure-based broadcast scheme to guarantee reliable transmissions. In [16] a game-theoretical approach is used to dynamically adjust the transmission power of sensors so that efficient use is made of the harvested energy. Such transmission policies require central coordination and, thus, may be difficult to implement for some ad-hoc wireless sensor networks. An interesting alternative viewpoint is taken in [17]. Power-neutral operations are proposed, where the instantaneous power consumption of the system must match the instantaneous harvested power (corresponding to very low energy storage capacity). Here, the focus is on processing and not on communications.

This paper contributes in the following way. Complementary to studies focusing on communication channel aspects, we further develop queueing theory in order to find analytical expressions describing fundamental performance trade-offs of an energy harvesting system, focusing on the impact of the energy harvesting process on the overall system (as opposed to only the communication channel). We analyze the time to retrieve measurements from a network of sensors (as opposed to a single source), with energy arriving according to a stochastic energy arrival process (not known in advance) to recharge the sensor batteries. Sensors transmit using a distributed (as opposed to centralized) protocol. Here a randomly arriving receiver needs to receive multiple distinct measurements (as opposed to a single measurement). We provide a formal analysis. Our viewpoint allows us to provide closed-form expressions for finite battery capacities, which, according to [4], is an important open research problem. We also conduct discrete event simulations for general energy harvesting and consumption models. The simulation results indicate that our theoretical results generalize to non-identical energy harvesting rates, various amount of energy consumed upon a broadcasting and non-exponential distributions for the energy harvesting and consumption processes. Overall, this work provides a formal theoretical support for the design of applications for ad-hoc sensor networks addressing the impact of energy arrival rate and storage capacity on the retrieval time of measurements under a distributed data transmission policy.

The remainder of this paper is organized as follows. In Section 2 we formulate the model and the problem statement. In Section 3 we determine the distribution of the time for a client to retrieve measurements from an arbitrary set of sensors of fixed size. We also determine the retrieval time of measurements when the rate at which energy is harvested and the maximum capacity of the sensor batteries are asymptotically large. We also conduct discrete event simulations to complement our numerical results and to investigate general energy harvesting and consumption models. In Section 4 we numerically compute the retrieval time of measurements from an arbitrary set of sensors of fixed size under various assumptions regarding the energy harvesting and consumption models. In Section 5 we discuss the results and provide conclusions.

2. Model and problem statement

We consider an ad-hoc network of N wireless sensors. Each sensor harvests one unit of energy from the environment at an exponential rate λ_e, independently of the other sensors. Sensors have a maximum storage capacity of B energy units. When the harvested energy exceeds the storage capacity of the battery, the excessive energy is discarded.

Each sensor broadcasts a measurement at an exponential rate μ/N, independently of the other sensors. Clearly, a sensor broadcasts a measurement only if it has energy. Upon a broadcast, the energy of the broadcasting sensor decreases by one unit. The assumption that each sensor broadcasts at an exponential rate μ/N could be interpreted as the situation when the entire network of sensors broadcasts measurements at an exponential rate μ and this rate is shared uniformly among the N sensors of the network. Also, for simplicity, the energy of a sensor is assumed to decrease or increase by one unit upon a broadcast and an additional energy harvest, respectively. However, similar techniques as in this paper can be employed for the case of general rates at which the energy of a sensor varies due to broadcasts or additional energy harvests.

Clients arrive at the sensor network according to a Poisson process with rate λ_a. Each client waits until receiving $1 \leq s \leq N$ measurements from an arbitrary set of sensors. Each measurement should originate from a distinct sensor. Based on the retrieved set of measurements, each client computes an aggregate. Upon a sensor broadcast, all clients present in the system receive the broadcasted measurement simultaneously. The clients leave the system as soon as they acquire s measurements.

We are interested in the time, denoted by W_s, for a client to retrieve s measurements from an arbitrary set of sensors of size s.

Lastly, we introduce some notation that will be useful when working with phase-type distributions. Let $\mathbf{e}$ be a column vector with all unit entries for which the dimensions are determined by the context. Let I_k denote the $k \times k$ identity matrix. For $n \times n$ matrix M_1 and $m \times m$ matrix M_2, let $M_1 \otimes M_2$ denote the Kronecker product of matrices M_1 and M_2 and let $M_1 \oplus M_2$ denote their Kronecker sum, i.e., $M_1 \oplus M_2 = M_1 \otimes I_m + I_n \otimes M_2$. Finally, let $M^{\otimes n}$ and $M^{\oplus n}$ denote the n-fold Kronecker product and the n-fold Kronecker sum with itself, respectively.

3. Analysis

In this section we first determine the distribution of the time for a single sensor to broadcast, given that the system is in steady-state. We show that this is a phase-type distribution. Using these results, we then determine the distribution of W_s. Lastly, we compute the $\mathbb{E}[W_s]$ for asymptotically large B, the maximum capacity of the sensor batteries, and λ_e, the rate at which a sensor harvests energy from the environment.

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