Ad Hoc Networks 29 (2015) 63–77

Contents lists available at ScienceDirect

Ad Hoc Networks

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

Asymptotic analysis of cooperative censoring policies in sensor networks

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ARTICLE INFO

Article history:
Received 26 June 2014
Received in revised form 29 January 2015
Accepted 12 February 2015
Available online 21 February 2015

Keywords:
Wireless sensor networks
Energy-aware systems
Censoring

ABSTRACT

The problem of cooperative data censoring in battery-powered multihop sensor networks is analyzed in this paper. We are interested in scenarios where nodes generate messages (which are related to the sensor measurements) that can be graded with some importance value. Less important messages can be censored in order to save energy for later communications. The problem is modeled using a joint Markov Decision Process of the whole network dynamics, and a theoretically optimal censoring policy, which maximizes a long-term reward, is found. Though the optimal censoring rules are computationally prohibitive, our analysis suggests that, under some conditions, they can be approximated by a finite collection of constant-threshold rules. A centralized algorithm for the computation of these thresholds is proposed. The experimental simulations show that cooperative censoring policies are energy-efficient, and outperform other non-cooperative schemes.

1. Introduction

Energy stands out as the most critical issue in Wireless Sensor Networks (WSNs) because sensors are usually battery-powered, and consequently, energy consumption limits their operational lifetime. Given the high energy cost of radio transmissions [1], a great number of methods to minimize the energy expenditure due to communication processes has been proposed in the literature (e.g. [2–6]).

Among all the state-of-the-art techniques, selective communication strategies, also known in the literature as *censoring* policies in the context of detection and cognitive radio networks (e.g., [7–9]), are a promising energy-saving approach. Such policies assume that nodes are able to quantify the relevance (importance) of the incoming messages and discard the low-importance ones to save energy, with the expectation of transmitting more relevant upcoming messages later. This importance value can be, for instance, the traffic priority of the routing protocol, the deviation from the mean in a distributed estimation scenario [10], or the likelihood ratio in a decentralized detection scenario [7].

These decisions about transmitting or censoring a message change the amount of energy stored in the batteries and, therefore, have an impact not only on the current state of the sensor battery but also on future ones. Intuitively, this implies that current decisions have to be made not only taking into account the instantaneous cost/reward, but also the (expected) impact on future costs/rewards. Mathematically, this implies that the sequential decision problem has to be handled using Dynamic Programming (DP) tools. In fact, the DP nature of the problem is also present in several works that deal with censoring communications strategies in WSNs. For instance, [11] uses a Markov Decision Process (MDP) formulation to design a congestion-aware medium access protocol. Ref. [12] exploits an

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http://dx.doi.org/10.1016/j.adhoc.2015.02.003
1570-8705/

MDP formulation to design transmission policies and adjusts the backoff according to the channel conditions. In the context of replenishable sensor networks, in [13] a Markov chain model to categorize the energy transition is used to derive an optimal single-hop transmission policy. Some other works also formulate energy-efficient communication policies by means of DP tools. The authors of [14] propose a transmission scheduling algorithm as a stochastic shortest path MDP. Another example is the energy-efficient MDP-based scheduling policies developed in [15], which choose the appropriate transmission mode in energy-harvesting scenarios.

Most of the censoring schemes currently available in the literature have been specifically designed for single-hop networks. The optimization of transmission policies in multihop networks is a more difficult problem because it requires the coordinated decision of all nodes involved in the communications from a source node to its destination. Censoring rules that optimize point-to-point communications can be shown to be suboptimal from the point of view of the global network performance (i.e., a collection of local optimizers is not a global optimizer).

Nevertheless, few algorithms that work in multihop scenarios have been proposed [16,17]. The main idea of these works consists of the simply use of local feedback coming from the decisions made by neighboring nodes, so that censoring policies for single-hop networks can be adapted to be more efficient in multihop networks: the policy used by a single node influences the transmission policies of other nodes and produces an overall beneficial coordination effect. Despite of this, the behavior of each node in these schemes is *selfish* in the sense that each node optimizes its own performance measure, which is based on the messages it only processes.

A very preliminary approach to the cooperative censoring problem has been proposed in [18]. In this approach, the analysis is restricted to very simple line networks, where it is assumed that the nodes closest to the sink will be the first ones that deplete batteries, and all nodes are assumed to use a common censoring threshold. Despite its simplicity, the experimental results show the potential benefit of exploiting node cooperation in order to save energy and optimize the global performance in multihop networks.

The main goal of this paper is to analyze the cooperative censoring problem in general multihop networks. In relation to the seminal work in [18], we carry out three major generalizations: (1) we do not make any assumption about the battery depletion order in the network, and any arbitrary node depletion order is allowed, (2) we remove any constraint on the threshold values, and, more importantly, (3) we extend the analysis to more general network topologies, with a special focus on tree networks.

Both the theoretical and experimental analysis suggest that the optimal censoring policies can be approximated by a collection of piecewise-constant threshold functions of the energy distribution. Unfortunately, the value of these thresholds depends on the expected evolution of the network topology during its whole lifetime. This finding makes the computation of the optimal thresholds difficult. For this reason, we propose a centralized threshold estimation algorithm that is particularized for a tree topology.

From a practical point of view, the proposed algorithm has some major limitations: (1) it works in a centralized manner, (2) it requires some knowledge about the network topology, and it depends on energy and data statistics that may be unknown during operation, and (3) it is computationally complex. Our main contribution in this paper is to show the potential advantages of cooperative censoring schemes, to understand the behavior underlying optimal cooperation, and to promote further research on decentralized adaptive schemes that could work on arbitrary topologies.

The rest of the paper is organized as follows: Section 2 describes the network model for WSNs using an MDP framework. The optimization problem under stationarity conditions is solved in Section 3 and the analysis of an illustrative scenario is presented. For large battery scenarios, an algorithm for computing the asymptotic thresholds, which is based on the stationary node lifetimes, is proposed in Section 4. Simulation results for different network configurations are presented in Section 5, and Section 6 wraps up the paper including some pointers for future work.

2. Network model

For the purpose of the analysis that follows, we consider a sensor network as a collection of sensor nodes $\mathcal{N} = \{i | i = 1, \ldots, N\}$ and a set of edges, $\mathcal{E} \subset \mathcal{N} \times \mathcal{N}$. We assume that the network operation time is divided into epochs, which are denoted by counter variable k. At each epoch, at most one message is generated by just one of the nodes. Messages are generated at different nodes, which are able to make decisions about routing (or not routing) these messages to their destination. Note that the assumption of one message per epoch is just for mathematical convenience and can be relaxed in real applications. The duration of each time epoch is assumed to be long enough to ensure that the message arrives to its destination generally after some hops. Some results of the treatment of simultaneous transmissions in censoring communications under more realistic scenarios can be found in [19].

As explained in the introduction, since we are interested in maximizing a long-term reward and current actions have an impact on future states, our problem will fall into the DP framework. Moreover, given that the state dynamics are assumed Markovian, the problem will be modeled as an MDP. In the following sections we present all the components of the MDP: state space, action space, state dynamics and rewards.

To facilitate the readability of this paper, the most relevant notation introduced here and in the following sections is summarized in Table 1.

2.1. Network state

The network state at epoch k will be characterized by three main variables: