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Satisfying the target network lifetime in wireless sensor networks

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ABSTRACT

Generally, the lifetime of a wireless sensor network (WSN) is defined as the duration until any sensor node dies due to battery exhaustion. If the traffic load is not properly balanced, the batteries of some sensor nodes may be depleted quickly, and the lifetime of the WSN will be shortened. While many energy-efficient routing schemes have been proposed for WSNs, they focus on maximizing the WSN lifetime. In this paper, we propose a scheme that *satisfies* a given 'target' lifetime. Because energy consumption depends on traffic volume, the target lifetime cannot be guaranteed through energy-efficient routing alone. We take an approach that jointly optimizes the sensing rate (i.e., controlling the sensor-traffic generation or duty cycle) and route selection. Satisfying the target lifetime while maximizing the sensing rate is a *NP-hard* problem. Our scheme is based on a simple Linear Programming (LP) model and clever heuristics are applied to compute a near-optimal result from the LP solution. We prove that the proposed scheme guarantees a *1/2-approximation* to the optimal solution in the worst case. The simulation results indicate that the proposed scheme achieves near-optimality in various network configurations.

1. Introduction

Wireless sensor networks (WSNs) are used for various applications, such as target tracking, habitat monitoring, structure monitoring, and wireless surveillance. Typically, a WSN operates for a pre-determined duration, which we refer to as the target lifetime. Generally, the lifetime of a wireless sensor network (WSN) is defined as the duration until any sensor node dies due to battery exhaustion.[1] Since the sensor nodes are powered by batteries, the lifetime of a WSN is constrained by its battery power. Because manual battery replacement is cumbersome or often infeasible, WSNs must use their energy sparingly so as to ensure a long lifetime.

Wireless communication is one of the most energy-consuming operations. If route selection is not properly done to balance the traffic load, the batteries of some sensor nodes may be quickly depleted. There exists a large body of research work on energy-efficient routing for WSNs, focusing on lifetime maximization. Some previous works are summarized below.

Energy-efficient routing for WSNs has been first considered in [16,22,26]. The common idea behind these works is to use the most energy-efficient paths. Although the per-path energy consumption can be minimized in this way, the lifetime of the network is not necessarily maximized. Since the selected paths are in constant use, the energy of the nodes on these paths is quickly exhausted, and 'dead' nodes can create coverage holes and network

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[1] The network lifetime may be defined as the time for which a certain level of coverage is [2].

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partitions. To deal with this shortcoming, new routing schemes that aim at maximizing the network lifetime have been devised. In [8], a Linear Programming (LP) model and a heuristic algorithm are proposed. The key idea of this work is to maximize the network lifetime by balancing the traffic load so that the energy is evenly consumed. Other works have adopted a similar approach [21,23]. In [13], a LP model that considers the energy consumption not only for data transmission and reception but also for sensing and channel-listening is presented. Recently, in [15,28], Mixed Integer Linear Programming (MILP) models for network lifetime maximization are used to take into account such factors as sink locations and sensor-to-sink data flows.

The routing metrics for energy-efficient routing have also been studied. In [5], a routing metric is proposed, which accounts for both the remaining energy and the energy consumption rate of a sensor node. In [19], two metrics are used for route selection, which are the amount of expected energy consumption and the probability of the delivery latency exceeding a given threshold. An energy-efficient geographic routing algorithm, proposed in [24], considers the unstable link condition instead of assuming the ideal link condition. The feasibility of real-time accurate monitoring of energy consumption is demonstrated in [37].

In contrast to the schemes described so far which use single static paths, a scheme that utilizes multiple sub-optimal routes is proposed in [25]. This scheme chooses a set of sub-optimal routes to the destination and alternates between them by constantly monitoring the remaining energy levels of the nodes on the paths in use. Similar schemes that attempt to avoid the continuous use of minimum-cost paths have been studied in [9,20,27].

A hybrid architecture which combines WSN with wireless mesh network to achieve energy efficiency is proposed in [36]. Sensor nodes use their resources only for sensing, while mesh routers perform secure data aggregation and forwarding. In [38], a more advanced hybrid architecture is proposed to incorporate secure aggregation and localization features. The data aggregation technique may be combined with routing. The sensor data may contain redundant information due to spatial–temporal correlation, which is commonly observed in densely-deployed WSNs. Since the amount of data to be transmitted or received is directly related to the energy consumption of sensor nodes, it is desirable to reduce the amount of traffic by eliminating the transmission and reception of redundant information through data aggregation at intermediate nodes. Several schemes have been proposed for extending the network lifetime by jointly optimizing routing and data aggregation [1,10,17]. Energy-efficient routing has been studied for participatory sensing environments (i.e., node mobility) [6]. The schemes proposed in [7,14,30] consider the energy-efficient data delivery from static sensor nodes to mobile sinks. The schemes proposed in [3,11,18,29] consider a scenario in which the mobility of some sensor nodes can be controlled.

Congestion control issue of WSNs has been studied in the context of sensing rate adjustment. In [32], the authors proposed a scheme to detect congestion by monitoring traffic load and to perform congestion control by regulating source sensing rates. Each node first monitors the past and present channel loading conditions and buffer occupancy to detect congestion. When congestion is detected, the node broadcasts suppression messages. Nodes that receive suppression messages reduce their sending rates. In [33], a similar congestion control scheme, which locally monitors and controls congestion by sensing rate adjustment, is proposed. In this scheme, each cluster head monitors the network status to infer congestion level and regulates sensing rates of sensor nodes it governs. In [34], the authors proposed a routing scheme that discovers the congestion zones and determines routing based on the priority of the data and the location of congestion zone. In essence, only high priority packets are routed in the congestion zone and low priority packets are de-toured to avoid the congestion zone. In [35], a congestion control protocol which adopts a swarm intelligence paradigm inspired by the collective behavior of bird flocks is proposed. The scheme guides packets to form flocks and moves them toward the sink while tries to avoid congested regions.

These existing works on congestion control in WSN target at the event-driven applications. To deal with the uncertainty of traffic generation patterns by event-driven applications, they commonly take a reactive approach. They first detect the congested nodes or regions by monitoring link status or buffer occupancies. Then they reduce source sensing rate to reduce the traffic load or change the routing path to avoid congested area.

In this paper, we deal with the problem of satisfying a given ‘target’ lifetime. To our best knowledge, this paper is the first work to tackle this problem. We assume that sensor nodes and sink nodes are static. The use of data aggregation technique is orthogonal to our work (i.e., it may be applied to our scheme to further extend the network lifetime). Because energy consumption depends on traffic volume, the target lifetime cannot be guaranteed through energy-efficient routing alone. We take an approach that jointly optimizes the sensing rate (i.e., controlling the sensor-traffic generation) and route selection. We target at WSNs for periodic monitoring, where the sensing rate can be controlled. One example is the environmental-monitoring WSNs, in which each sensor node periodically monitors its surrounding area, and the sensing data is sent to the sink node. Since the traffic generation pattern is predictable, congestion detection is not necessary for our scheme. In contrast to the existing reactive congestion control schemes described earlier, we proactively determine the sensing rates and routing paths. More important difference between the proposed scheme and the existing works on congestion control is the objective itself. The objective of our scheme is to satisfy the given target lifetime. To this end we find joint optimal solution of routing and sensing rate adjustment. In other words, congestion avoidance itself is not the objective of the proposed scheme. We would like to emphasize that congestion avoidance is related to the issue of lifetime maximization, but congestion avoidance does not guarantee target lifetime satisfaction.

We prove that satisfying the target lifetime while maximizing the sensing rate is a NP-hard problem. For computationally inexpensive solution, our scheme is based on a simple Linear Programming (LP) model and clever