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A trade-off between energy and delay in data dissemination for wireless sensor networks using transmission range slicing

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Abstract

Data dissemination is an essential function in *wireless sensor networks* (WSNs). A WSN consists of a large number of unattended sensors with limited storage, battery power, computation, and communication capabilities, where battery power (or *energy*) is the most crucial resource for sensor nodes. Because delay time is also a critical metric for certain applications, data dissemination between *source sensors* (or simply *sources*) and a *sink* (or *central gathering point*) should be done in an energy-efficient and timely manner. In this paper, we present an approach that characterizes a trade-off between energy and *source-to-sink delay* (or simply *delay*). Specifically, we decompose the transmission range of sensors into *concentric circular bands* (*CCBs*) based on a *minimum transmission distance* between any pair of sensors. Our decomposition strategy provides a classification of these *CCBs* that helps a sensor express its *degree of interest* (*DoI*) in minimizing two conflicting metrics, namely energy consumption and delay. We also propose a data dissemination protocol that exploits the above-mentioned decomposition to meet the specific requirements of a sensing application in terms of energy and delay. We prove that the use of sensors nodes, which lie on or closely to the shortest path between a source and a sink, as proxy forwarders in data dissemination from sources to a sink, helps simultaneously minimize energy consumption and delay. Also, we compute theoretical lower and upper bounds on these two metrics. Our simulation results are found to be consistent with our theoretical results, and show that the first *CCB* minimizes energy consumption; the last *CCB* minimizes delay; and the middle *CCBs* trade-off energy consumption with delay in data dissemination in WSNs.
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Keywords: Wireless sensor networks; Data dissemination; Slicing; Energy; Delay

1. Introduction

A wireless sensor network (WSN) is composed of a large number of sensor nodes that communicate with each other possibly through multi-hop wireless links despite the absence of any fixed administration or established infrastructure. They also collaborate to collect data during monitoring an environment and disseminate them to a central gathering point, called the *sink* (or *base station*). Sensor networking technology, however, faces a critical problem due to the limited energy, storage, sensing, communication, and computation capabilities of sensors. Because data dissemination is a vital function in WSNs, optimized protocols should be designed to guarantee an efficient operation of the network by extending its lifetime and providing the sink with sensed data in a timely manner for further analysis and processing. Therefore, it is necessary to minimize the energy consumption and delay when disseminating data packets collected by sources towards the sink.

Battery power (or *energy*) is the most crucial resource for sensors, and particularly in certain environments, such as battlefields, where replacing or recharging batteries is difficult or even impossible. In addition, some sensing applications require fast response-time, which imposes some bounds on delay. On the one hand, the energy consumption is dominated by the transmission energy E_{tx}, which is

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proportional to the distance d between transmitter and receiver, i.e., $E_{tx} \propto d^{\alpha}$, where $2 \leqslant \alpha \leqslant 4$ is the path loss exponent. Hence, minimizing the energy consumption could be done by minimizing the distance d. On the other hand, delay is proportional to the number of forwarders on the dissemination path between a source and the sink. Therefore, in order to minimize delay, it is necessary to minimize the number of forwarders, which in turn could be achieved by maximizing the distance between consecutive forwarders. Thus, finding a trade-off between energy consumption and delay seems to be very appealing as they represent two conflicting metrics.

This paper presents a study of the trade-off between energy consumption and delay based on the idea of decomposing the transmission range of sensors into *concentric circular bands* (*CCBs*) when building dissemination paths between sources and the sink. A dissemination path is a set of segments forming a chain of *proxy forwarders*. This decomposition is based on a *minimum transmission distance* between any pair of proxy forwarders which we computed analytically. Because sensors are densely and uniformly distributed in a sensor field, every *CCB* contains a subset of sensors as potential proxy forwarders. Our proposed data dissemination protocol trades off energy consumption with delay using a classification of the obtained *CCBs*. This classification enables a sensor to specify its *degree of interest* (*DoI*) in energy consumption and delay. The main contributions of this paper can be summarized as follows:

(i) We propose a novel data dissemination protocol that trades off energy consumption with delay at different levels by decomposing the transmission range of sensors into *CCBs* and classifying them. These levels could favor minimizing energy consumption or delay, or trade-off between them. We also provide extensive simulations that help sensing application designers gain more insight on how to trade-off energy consumption with delay.
(ii) We prove that the selection of sources as proxy forwarders which lie on or closely to the shortest path between source and sink yields minimum energy consumption and delay.
(iii) We compute lower and upper bounds on energy consumption and delay based on the above-mentioned transmission range decomposition approach.

The remainder of this paper is organized as follows. Section 2 reviews a sample of energy-efficient data dissemination protocols for WSNs. Section 3 discusses our proposed protocol which trades off energy consumption with delay. Theoretical and simulation results are presented in Section 4. Simulation results are presented in Section 5. Section 6 concludes the paper.

2. Related work

This section describes a sample of data dissemination protocols for WSNs that trade-off energy with delay.

Yang and Vaidya [20] proposed a wakeup scheme, called Pipelined Tone Wakeup (PTW), which achieves a balance between energy saving and end-to-end delay. The PTW scheme is based on an asynchronous wakeup pipeline that overlaps the wakeup procedures with the packet transmissions. It uses wakeup tones which allow a large value of duty cycle ratio without causing a large wakeup delay at each hop. The use of wakeup tones helps achieve energy saving by hiding most of the wakeup delay. Miller et al. [14] studied the trade-off between energy, latency and reliability. Specifically, they presented a probabilistic broadcast scheme, called Probability-Based Broadcast Forwarding (PBBF), which minimizes energy usage and optimizes latency and reliability. The PBBF protocol was designed for WSN applications using broadcast mechanism in disseminating sensor data, instructions, and code updates. This broadcast scheme could be added to energy-conserving MAC protocols using a sleep mode. To achieve a certain level of reliability, which is defined by an application and corresponds to the fraction of sensors receiving a broadcast, the energy and latency were found to be inversely proportional. Zorzi and Rao [22] proposed a transmission technique for WSNs, called Geographic Random Forwarding (GeRaF) and based on geographic routing, where each node is supposed to be aware of its location and that of a sink. In this forwarding technique the relay node is decided only after the transmission has started. In fact, multiple listening nodes in the coverage area of the sending node might receive the packet, which will yield packet duplication. To solve this problem, a scheme for contention among receivers should exist. A multi-hop performance of this transmission scheme regarding the average number of hop to reach a sink, and the average number of available neighbors is provided. Moreover, Zorzi and Rao [23] gave a detailed description of their MAC protocol and an evaluation of the latency and energy performance. Bandyppadhyay and Coyle [3] proposed a transmission scheduling scheme using a collision-free protocol for gathering sensor data. They also studied many trade-offs between energy usage, sensor density, temporal and spatial sampling rates. He et al. [7] presented a stateless routing protocol for real-time communication in sensor networks, called SPEED, which provides real-time unicast, real-time area-multicast, and real-time area-anycast services. Sensor nodes are supposed to be location-aware and maintain location information about their neighbors to make localized forwarding decisions. SPEED maintains a uniform delivery speed across a sensor network in order to meet the requirement of real-time applications such as disaster and emergency surveillance. The SPEED protocol assumes that end-to-end delay is proportional to the distance between source and destination, which helps sensor nodes estimate the end-to-end packet delay based on the speed of the packet and the distance to the sink. Sohrabi et al. [17] proposed a sequential assignment routing (SAR) protocol which is used by sensor nodes to select a path among multiple ones to the sink node. Multiple paths