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A virtual infrastructure for large-scale wireless sensor networks

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Abstract

The primary goal of a wireless sensor network is to collect useful information from the network. Most wireless sensor networks are assumed that the number of nodes are very large and they should operate with confined resources. Consequently it is important to take a scalable and energy-efficient architecture.

In this paper, we present *Railroad*, a data collection and topology management architecture for large-scale wireless sensor networks. It proactively exploits a virtual infrastructure called *Rail*, which acts as a rendezvous area of the event data and queries. By using Rail, Railroad achieves scalability and energy efficiency under dynamic conditions with multiple mobile observers and targets. We evaluate the communication cost and the hot area message complexity of Railroad and compare them with previous approaches. We evaluate communication cost of Railroad by both an analytic model and simulations.

Keywords: Wireless sensor networks; Data collection; Topology; Railroad

1. Introduction

In large-scale wireless sensor networks (WSNs), sensor nodes are stationary and deployed densely and randomly. The sensor nodes have relatively small memory, restricted computation power, and limited communication capability compared with the traditional high-performance devices [1]. They operate in untethered conditions without any central control. Moreover, they have to work with built-in batteries and cannot be supplied with external power sources. These restrictions severely restrict the freedom of design. They, however, should be overcome for successful operations and thus lots of approaches have been proposed [2,4,6–10]. The desirable features for wireless sensor networks include energy efficiency, self-organization, scalability, and fault-tolerance.

The primary goal of a wireless sensor network is to collect useful information by monitoring phenomena in the network. Having nothing to say, the most important features for *data collection* in WSNs include both energy efficiency and scalability. Nevertheless, it has been one of the most challenging issues up to now.

In this paper, we propose *Railroad*, a data collection and topology management system using *Rail*, the globally unique virtual infrastructure of the system. Railroad exploits the geographic shape of a network and constructs only one Rail in the network. Rail intermediates communication among the nodes, observers, and targets. More details are discussed in Section 3.

One of the basic motivations in Railroad system is to detour query messages around Rail not to transfer them along the shortest path. It stands on the basis of the fact that the scalability of a network is limited by the hotspot region of the network and it is the center of the network in most cases [12]. Another is that a single query packet is smaller than a single data packet and the generation rate of query packets is much smaller than that of data packets (i.e., event messages) in general. Upon detecting an event message, Railroad does not forward the entire event message to another place without any request of a query. It

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rather stores an event summary into Rail. The aforementioned two properties may help to increase network scalability and to reduce the overall energy consumption of the network.

We clarify several terms to eliminate confusion. A *source* is a sensor node which issues an event data, while a *sink* is a node which generates a query message. In addition, many sensor network applications such as target tracking and habitat monitoring need a data collection architecture supporting mobile objects like animals, persons, and vehicles. We use the terms *target* and *observer* for these mobile objects to distinguish them from sources and sinks. A target is an object which generates an event data and forwards it to a source; while an observer is an object which issues a query and delivers it to a sink. For example, a bear (a target) periodically broadcasts its location with a small beacon attached on it; while a zoologist (an observer) with a hand-held computing device observes its life via a sensor network.

The rest of this paper is organized as follows. Several related works are introduced with their strength and weakness in Section 2. In Section 3, basic operations of "Railroad system" are introduced. We propose Railroad system and show how the network constructs Rail, how events and queries are delivered among sources and sinks, and how Railroad system supports mobile observers and targets. In Section 4, we analyze performance of Railroad. We evaluate communication cost and hot region message complexity of Railroad and compare them with other approaches. In Section 5, simulation results are shown to evaluate communication cost and hot region characteristics of Railroad and are compared with the previous works. And finally, we summarize our work in Section 6.

2. Related works

Many data collection/dissemination architectures have been proposed since the advent of wireless sensor networks. Traditional ways include flooding, gossiping, using an external storage, and so forth. Since they usually bring about significant energy consumption or single point of failure due to hotspot problems [1], more structured approaches appeared to solve such the problems.

Directed diffusion [2] introduced the concept of a data-centric routing and data dissemination based on the names described by attribute-value pairs. After a sink broadcasts its interest for a certain type of data, the nodes in an area of interest start setting up the gradients which indicate where the replies should be sent. The matched data are forwarded back to the sink along the gradients. Although directed diffusion struggles against energy-efficiency problem by using several heuristics to achieve optimized paths, the sinks periodically propagate their interests and the flooding messages can bring about network congestion.

A Geographic Hash Table (GHT) [6] based on Greedy Perimeter Stateless Routing (GPSR) algorithm [3] is introduced to implement an efficient and scalable data dissemination for densely deployed wide-area sensor networks. It is cued by Distributed Hash Table algorithms (DHT) such as Pastry [14], Tapestry [17], Chord [16], and CAN [13]. They are targeting completely distributed large-scale networks. However, GHT has a hotspot problem since all the event and the query messages are concentrated on the so-called home nodes. This problem seriously restricts network scalability even though GHT prepared some algorithms such as structured replication and home perimeter replicas.

The main goal of Two-Tier Data Dissemination (TTDD) is to support mobile observers continuously changing their locations [10]. Grid structures are created on the basis of the locations of the source nodes and they support mobility of the observers. Queries and data are transmitted along the grids. It supports mobile observers with the grid structures, however, it is not appropriate where targets also have mobilities. When the targets are mobile, the number of grids rapidly increases and it limits network lifetime.

3. Railroad system

This section introduces basic operations of Railroad system. They are largely divided into three parts: the setup stage to construct Rail, message forwarding with the support of Rail, and the support for mobility issues.

To begin with, we indicate some assumptions for Railroad system. First, the sensor nodes are randomly deployed and there is no centralized authority to control them since it may restrict network scalability. Second, to bring off geographic routing, every node has its location information whether it is based on a physical coordinate system or a virtual coordinate system [5]. Third, all the nodes know the coordinates of the center of the network. It is required to form Rail at the setup stage. Fourth, there are multiple mobile observers and targets which generate queries and events in the network. Fifth, the probability of event generation is uniform over the network.

3.1. Railroad system overview

There are a great number of sensor nodes with multiple mobile observers and targets in the network. There exists one globally unique virtual infrastructure, namely *Rail* where the nodes on Rail are called *rail nodes* to distinguish from the other nodes as shown in Fig. 1. Rail is built up in an area between the network center (O) and the boundary. It acts as a rendezvous area where queries from observers and metadata for event data from target objects join on it and look for if there are corresponding data to the queries. A node on Rail is called a *rail node*.

The Railroad operations are categorized into three main categories; event notification, querying, and data delivery as shown in Fig. 2. Event notification and query forwarding toward Rail are achieved by a depth routing.