Ad Hoc Networks 11 (2013) 1150–1164

Contents lists available at SciVerse ScienceDirect

Ad Hoc Networks

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

Opportunistic data collection for disconnected wireless sensor networks by mobile mules

Yu-Chee Tseng *, Fang-Jing Wu, Wan-Ting Lai

Department of Computer Science, National Chiao Tung University, Hsinchu 30010, Taiwan

A R T I C L E   I N F O

Article history:
Received 17 November 2011
Received in revised form 28 December 2012
Accepted 2 January 2013
Available online 11 January 2013

Keywords:
Delay-tolerant networks
Distributed computing
Distributed storage
Mules
Protocols
Wireless communications
Wireless sensor networks

A B S T R A C T

This paper considers a field with a number of isolated wireless sensor networks served by some mobile mules and base stations (BSs). Sensing data needs to be carried by mobile mules to BSs via *opportunistic contact* between them. Also, such contact may not be frequent. Thus there are four types of communications in this environment: (i) inter-node communications within a WSN, (ii) opportunistic WSN-to-mule communications, (iii) opportunistic mule-to-mule communications, and (iv) opportunistic mule-to-BS communications. In such disconnected WSNs, since sensors' memory spaces are limited and data collection from isolated WSNs to mules and then to BSs relies on opportunistic communications in the sense that contact between these entities is occasional, *storing* and *collecting* higher-priority data is necessary. Therefore, there are two critical issues to be addressed: the *data storage management* in each isolated WSN and *opportunistic data collection* between these entities. We address the storage management problem by modeling the limited memory spaces of a WSN's sensor nodes as a distributed storage system. Assuming that there is a sink in the WSN that will be visited by *mobile mules* occasionally, we address three issues: (i) how to buffer sensory data to reduce data loss due to a shortage of storage spaces, (ii) if dropping of data is inevitable, how to avoid higher-priority data from being dropped, and (iii) how to manage the data nearby the sink to facilitate the downloading jobs of mules when the downloading time is unpredictable. We propose a *Distributed Storage Management* (*DSM*) strategy based on a novel shuffling mechanism similar to heap sort. It allows nodes to exchange sensory data with neighbors efficiently in a distributed manner. For the opportunistic data collection problem, based on a utility model, we then develop an *Opportunistic Data Exchange* (*ODE*) strategy to guide two mules to exchange data that would lead to a higher reward. To the best of our knowledge, this is the first work addressing distributed storage strategy for isolated WSNs with opportunistic communications using mobile mules. We conduct extensive simulations to investigate the merit of DSM and ODE. The simulation results indicate that the level of data importance collected by our DSM is very close to a global optimization and our ODE could facilitate delivery of important data to BSs through mules. We also implement these strategies in a real sensor platform, which demonstrates that the simple and lightweight protocols can achieve our goals.

1. Introduction

Wireless sensor networks (WSNs) have gained much attention recently [1–3]. A WSN is composed of a large number of nodes, each of which has multiple onboard sensors to collect environment data. Nodes can communicate with each other through their wireless interfaces. WSNs have many applications such as military safety, health care, environmental monitoring, surveillance systems, and social networks [4–8].

We are interested in the data collection issue for *disconnected* WSNs [9] that are separated into multiple isolated groups and do not have network connectivity to outside

* Corresponding author. Tel.: +886 3 513 1218; fax: +886 3 572 4176.
E-mail address: yctseng@cs.nctu.edu.tw (Y.-C. Tseng).

1570-8705/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.adhoc.2013.01.001

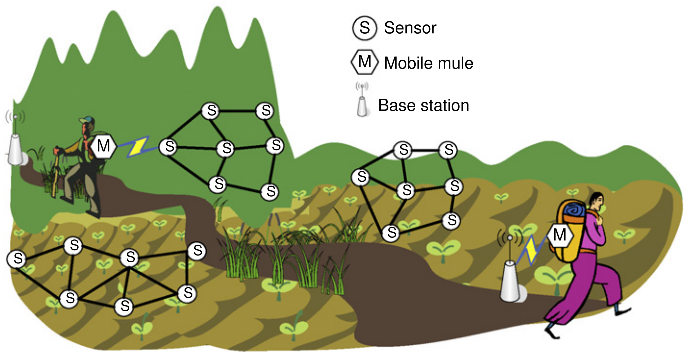

Fig. 1. A scenario of data collection for disconnected WSNs by mobile mules through opportunistic communications.

world. It is thus necessary to dispatch some *mobile mules* [10] to visit them from time to time and carry their sensory data back. WSNs may become isolated due to many reasons, such as physical constraints, cost considerations, and node failure owing to destructive events. In particular, our work is motivated by some recent work [11–14]. In [11], wireless sensors are used for in situ tracking of debris flows in wild mountain areas which are hard to reach by vehicles or human. Collecting data from such isolated WSNs thus may rely on rangers or hikers (when they reach those areas) in an opportunistic way to relay the sensing data back, as shown in Fig. 1. In the YushanNet Project [14] designed for YuShan National Park, Taiwan, hikers are used as opportunistic vehicles to relay sensing data back to outside world [13]. In [12], data collection, storage, and retrieval strategies for underwater WSNs are studied to monitor undersea oil fields. In all of these applications, it is hard to collect real-time information from those WSNs. So mobile mules, which could be animals, hikers, ships, or vehicles, are adopted in an opportunistic way to help collect and carry sensing data back.

In this paper, we consider a network scenario with three components: (i) some static but disconnected WSNs, (ii) some mobile mules with uncontrollable mobility, and (iii) some static base stations (BSs) accessible by mules. By "uncontrollable mobility", we mean that mules have their own designated routes or destinations that are not under control of our system (such as hikers, taxis, buses, and animals). Therefore, communications must rely on opportunistic contact between these entities. There are four types of communications in our system: (i) inter-node communications within a WSN, (ii) opportunistic WSN-to-mule communications, (iii) opportunistic mule-to-mule communications, and (iv) opportunistic mule-to-BS communications. Opportunistic communications happen when two entities have direct contact. We assume that each BS has connectivity to the external world, so our goal is to deliver sensing data to BSs.

The aforementioned networking scenarios raise several challenges to *storage management* and *opportunistic communications*. In disconnected WSNs, since sensors' memory spaces are limited and data collection from isolated WSNs to mules and then to BSs relies on opportunistic communications in the sense that contact between these entities is occasional, storing and collecting higher-priority data (e.g., the freshest and the most urgent data) is necessary. Two critical issues namely, the *data storage management* in each isolated WSN and *opportunistic data collection* between these entities, need to be addressed. For storage management, since an isolated WSN may not be visited by mules frequently, how to buffer more important data in the limited storage of a WSN is an important issue. The memory spaces of an isolated WSN can be regarded as a distributed storage system. The node that is more frequently visited by mules will be identified as the sink of a WSN. We then address three storage management issues: (i) how to buffer sensory data to reduce data loss due to a shortage of storage, (ii) if dropping of data is inevitable, how to avoid more important data from being dropped, and (iii) how to manage the data nearby the sink to facilitate the downloading jobs of mules. Note that (iii) is to facilitate opportunistic WSN-to-mule communications because the WSN-mule contacting time is unpredictable. For opportunistic communications, we assume that mobile mules have unlimited storage spaces, but the frequency and intervals of WSN-to-mule, mule-to-mule, and mule-to-BS contact are not under the control of our system. Therefore, the data exchange policy needs to be addressed when two entities have contact. Since a piece of sensing data needs to be carried from a sensor node to a sink, from a sink to a mule, from a mule to perhaps multiple mules, and from a mule to a BS, we regard its successful delivery to a BS as a reward and our goal is to accumulate more rewards at shorter time.

To respond to these challenges, we propose a *Distributed Storage Management* (*DSM*) strategy for data buffering in an isolated WSN and an *Opportunistic Data Exchange* (*ODE*) strategy for the occasional contact between two mules. DSM is designed based on a novel shuffling mechanism similar to heap sort [15] to keep data with higher priorities closer to the sink. However, unlike heap sort, which is based on a tree structure, DSM uses a mesh-like structure to facilitate data exchanges.[1] On the other hand, ODE

[1] Note that heap sort must be conducted in a complete binary tree. Insertion begins at a leaf and moves up toward the root, while deletion begins by removing the root element, moving the rightmost leaf element to the root, and then adjusting the heap. These operations are basically centralized operations and cannot be applied directly to a real distributed WSN environment.