Journal of Network and Computer Applications 36 (2013) 1372–1386

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

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

Constructing rings overlay for robust data collection in wireless sensor networks ☆

Hai Van Luu *, Xueyan Tang

School of Computer Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 21 April 2012
Received in revised form
11 January 2013
Accepted 18 February 2013
Available online 4 March 2013

Keywords:
Sensor network
Data collection
Rings overlay
Robustness

ABSTRACT

This paper investigates the construction of rings overlay in wireless sensor networks and presents an enhanced relay scheme for improving the robustness of data collection through the rings overlay. Rings overlay is a class of multi-path routing structure that exploits the broadcast nature of wireless communication to cope with communication failures. In constructing the rings overlay, we propose a distributed approach to allow sensor nodes to benefit from multi-path routing as much as possible. Our proposed approach only requires sensor nodes to have local neighborhood information. In our enhanced relay scheme, sensor nodes in the ring next to the base station benefit from multi-path routing without having to transmit their data multiple times. Experimental results show that compared with a baseline greedy construction approach and the original relay scheme, the proposed techniques of overlay construction and relay enhancement significantly improve the robustness and accuracy of sensor data collection through the rings overlay.

1. Introduction

Multi-path routing is an important approach for robust data collection against communication failures in wireless sensor networks (Ganesan et al., 2001; Ye et al., 2005; Nath et al., 2004; Considine et al., 2004). *Rings overlay* (Nath et al., 2004; Considine et al., 2004) is a class of multi-path routing structure that exploits the broadcast nature of wireless communication. A rings overlay conceptually organizes sensor nodes into a set of rings around the base station with increasing hop counts to it. For each node, all of its neighbors in the next inner ring are known as its parents. Sensor data are collected through level-by-level propagation from the outermost ring to the base station. By exploiting the broadcast nature of wireless communication, the rings overlay enables sensor data transportation through multiple interleaving paths from sensor nodes to the base station. Thus, the data are successfully transported as long as any one propagation path is failure-free. For example, Fig. 1 shows a rings overlay consisting of three rings R_1, R_2 and R_3. To collect data, node f in ring R_3 first broadcasts its data to its parents d and g in ring R_2. Then, nodes d and g aggregate their data with the data received from f, and broadcast to their parents in ring R_1. Meanwhile, nodes a and c in ring R_2 also broadcast their data to their parents in ring R_1. Finally, the nodes in ring R_1 aggregate their data with the data received from their children, and broadcast to the base station s.

A rings overlay normally does not benefit all sensor nodes in the network. First, a casually constructed rings overlay may leave some nodes connected to the base station through a single propagation path only. In Fig. 1, for instance, node a has only one propagation path $a \rightarrow e \rightarrow s$ to the base station. Second, each node in the ring next to the base station (e.g., nodes b, e, h and i in ring R_1 of Fig. 1) inherently has only one single-hop propagation path to the base station. All the above nodes do not enjoy the benefit of multi-path routing. The data acquired by these nodes remain to be transported by single-path routing that is highly susceptible to communication failures. The robustness of data collection through the rings overlay would be severely limited when there are a significant number of such nodes.

To enhance the robustness of sensor data collection through the rings overlay, we propose and investigate two techniques in this paper. First, we develop a new approach for constructing the rings overlay to prevent sensor nodes from having only few propagation paths to the base station. The objective is to assign sensor nodes to appropriate rings to let them benefit from multi-path routing as much as possible. The proposed construction approach is fully distributed and only requires sensor nodes to have local neighborhood information. Then, we present an enhanced scheme for relaying data to the base station from the sensor nodes in the ring next to the base station. The goal is to improve the resilience of these nodes to communication failures

☆ An earlier version of this work is presented at IEEE WCNC'2010 conference [13].

* Corresponding author. Tel.: +65 8224 9482; fax: +65 6792 6559.
E-mail addresses: lu0002@e.ntu.edu.sg (H.V. Luu), asxytang@ntu.edu.sg (X. Tang).

1084-8045/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.jnca.2013.02.033

in data collection without requiring them to transmit their data multiple times. A wide range of experiments are conducted to evaluate the proposed techniques. Experimental results show that compared with a baseline greedy construction approach and the original relay scheme, the proposed techniques of overlay construction and relay enhancement substantially improve the robustness and accuracy of sensor data collection through the rings overlay.

This paper significantly extends preliminary reports (Luu and Tang, 2010a,b) and enhances the performance evaluation. The remainder of this paper is organized as follows. Section 2 summarizes the related work and introduces how data are collected and aggregated through the rings overlay as preliminaries. Section 3 presents the proposed approach for constructing the rings overlay. The enhanced relay scheme for data collection is elaborated in Section 4. The experimental evaluation is described in Section 5. Finally, Section 6 concludes the paper.

2. Related work and preliminaries

A widely used approach for collecting data from sensor nodes is to construct a routing tree rooted at the base station (Madden et al., 2002; Buragohain et al., 2005; Shrivastava et al., 2004; Tang and Xu 2008a,b; Wu et al., 2007; Yao and Gehrke, 2002). Each intermediate node in the tree is responsible for aggregating the locally acquired data with the data received from its children and forwarding the aggregated data to its parent. However, tree-based routing structures are highly susceptible to communication failures because each failure results in the loss of data acquired by sensor nodes in an entire subtree (Nath et al., 2004).

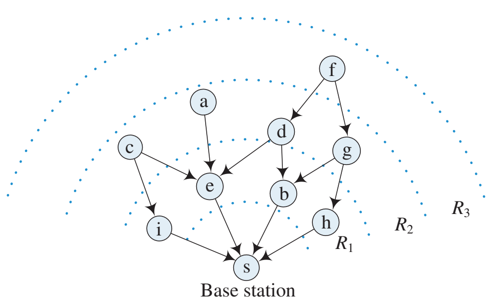

Fig. 1. An example rings overlay.

One possible approach to overcome communication failures in wireless sensor data collection is to use traditional reliable link-layer transport protocols (Kim et al., 2004). Nevertheless, this approach requires additional acknowledgment messages to be transmitted together with each data transmission. Moreover, when a data packet is lost, it has to be retransmitted together with its associated acknowledgments. This process is usually repeated multiple times until the data packet is successfully received or a time-out occurs. As a result, reliable transport protocols would incur significant time overhead for collecting sensor data.

Another approach to address the high loss rate in wireless sensor data collection is to use multi-path routing. One method to perform multi-path routing between two sensor nodes is to create a mesh from a source node to a sink node (Ye et al., 2005). Alternatively, multiple node-disjoint or interleaving paths may be set up between the source and the sink (Ganesan et al., 2001). In addition, there are opportunistic routing methods that try to find a good path from a source node to a sink node on the fly by letting the nodes communicate to elect the best node at each hop to forward a message towards the sink (Biswas and Morris, 2005). These approaches have focused on transporting data from one source node to one sink node. To improve the robustness of data collection over the entire network, the rings overlay (Nath et al., 2004; Considine et al., 2004) exploits the broadcast nature of wireless communication to send data along as many paths as possible from sensor nodes to the base station.

In the rings overlay, sensor nodes are organized into a set of rings R_1, R_2, … around the base station. They are loosely time-synchronized to propagate data level-by-level (Nath et al., 2004). Specifically, the nodes in each ring R_i listen to the transmissions of their children in ring R_{i+1}, aggregate their locally acquired data with the data received from their children, and then broadcast the aggregated data to their parents in ring R_{i-1}. This propagation and aggregation process continues until the base station receives the aggregated data from the nodes in ring R_1. As shown in Fig. 2, a round of data collection proceeds in M time frames if the rings overlay has M rings $R_1, R_2, \ldots, R_M$. Each node turns on its radio for two frames: one frame for sending data to its parents and one frame for receiving data from its children. The length of the time frame is determined a priori based on the density of deployment so that all nodes get enough time to broadcast their data once (Nath et al., 2004). A simple time synchronization protocol similar to that used by TinyDB (Madden et al., 2005; Ganeriwal et al., 2003) can be employed to let sensor nodes agree on a global time base that allows them to wake up and transmit or receive data

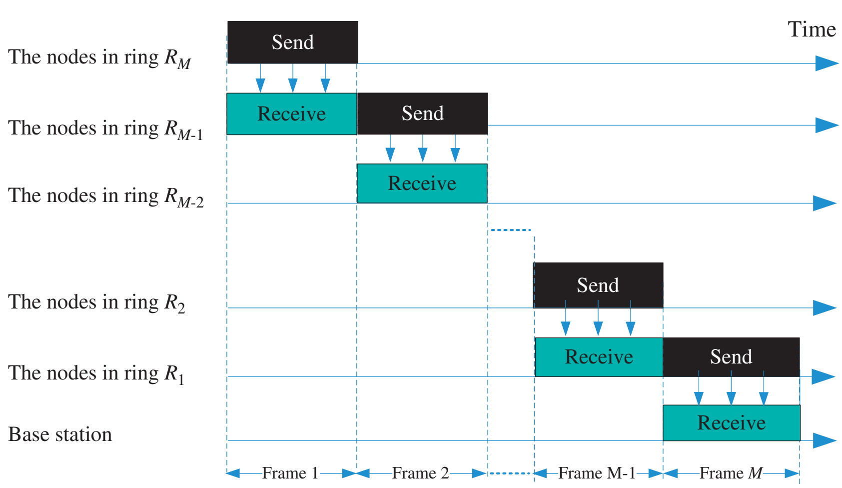

Fig. 2. Sending and receiving schedules of sensor nodes in data collection through rings overlay.