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Adjustable convergecast tree protocol for wireless sensor networks ☆

Tzung-Shi Chen [a,*], Hua-Wen Tsai [b], Chih-Ping Chu [c]

[a] Department of Computer Science and Information Engineering, National University of Tainan, Tainan 700, Taiwan
[b] Department of Computer Information and Network Engineering, Lunghwa University of Science and Technology, Taoyuan 300, Taiwan
[c] Department of Computer Science and Information Engineering, National Cheng Kung University, Tainan 701, Taiwan

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ABSTRACT

For data-collection applications in sensor networks, it is important to ensure base station receives a complete picture about the monitored area. Convergecast is an important communication pattern commonly used to collect continuous data. The prior broadcast trees are not suitable for convergecast, because convergecast is a reverse broadcast process. We point out the load-balancing problem in the current design of sensor networks. A non-load-balancing tree makes some nodes consume energy faster than others. It is important to design a distributed load-balancing solution due to the lack of global knowledge about the network topology. This paper presents a novel convergecast tree protocol and a distributed adjustment algorithm to attain load balancing and to extend network lifetime. The tree protocol constructs an approximate load-balancing convergecast tree. Additionally, the adjustment algorithm dynamically adjusts tree structure to avoid breaking tree link. The tree adjustment only needs localized information and operations at the sensors. Moreover, the tree adjustment is controlled by a sensor's grandparent to avoid loop problem. This study performs extensive simulations, demonstrating that the proposed protocols can effectively increase convergecast throughput.

1. Introduction

Advance in micro-electronics industry and wireless technology have lead to the development of low-power, low-cost, multifunctional sensor nodes in recent years. A wireless sensor consists of a small processor, memory, power, sense and transceiver units. A wireless sensor network is composed of hundreds even thousands of sensors to monitor physiological change, and the presence of various chemical or biological materials in the environment [3]. Sensor networks can be deployed for areas a user wants to monitor, even in inaccessible environments. An external device (sink or base station) is deployed to collect data from sensor networks.

Data collection is one of the predominant applications of sensor networks. Although some applications may only query aggregate information such as the maximum/minimum/mean/medium/average of certain measurements, other applications are interested in macroscopic imaging of certain features of the monitored field, which carries much more information than simple aggregation [6]. Such location-specific information is often crucial in habitat monitoring, seismic structure response, ecosystem evaluation, traffic density monitoring, and natural disaster monitoring. Due to limited transmission range, sensors far away from the base stations deliver their data through multi-hop communication. To design an efficient communication to collect data is important. Additionally, sensor nodes are equipped with battery typically. To change or recharge battery is a difficult mission, because the sensor network may be deployed in inaccessible environments. To design an efficient communication protocol in sensor network is a challenge. Fully utilizing node energy is an important issue for sensor networks.

Flooding is a simple approach to transmit data, but it is not suitable for data collection. In flooding, all nodes need send data to their neighbors if they receive new data, regardless of whether the neighbors have already received the data from another node. However, flooding has two primary problems. First, the implosion problem occurs when multiple copies of data are sent to a node. Obviously, implosion is increased quickly following the number of node is increased [18]. The second problem is redundant forwarding. A node wastes energy to forward and receive the same data. Some studies proposed different solutions to decrease implosion and redundant forwarding [1,2,7,15,17,19,22].

For increasing communication efficiency, some studies proposed clustering solutions for sensor networks [10–13,20,21,23]. Clustering enables network scalability to a large number of sensors and extends network lifetime. A node acts gateway to communicate with nodes that are nearby in a clustering. Gateway is also

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* Corresponding author. Tel./fax: +886 6 2606123.
E-mail addresses: chents@mail.nutn.edu.tw (T.-S. Chen), HWTsai@mail.lhu.edu.tw (H.-W. Tsai), chucp@csie.ncku.edu.tw (C.-P. Chu).

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responsible for communicating with different clusters. The clustering methods try to balance the communication cost and load between gateways. Other studies proposed building tree routing in sensor networks to minimize energy consumption and to extend network lifetime [4,5,26]. Tree structure is suitable for data collection, because it is easy to maintain tree routing; each node only needs to know its parent. But these proposed tree-based protocols are designed for broadcasting. A reverse broadcast communication pattern *convergecast* is discussed in [9,16,29]. Convergecast is designed for collecting macroscopic imaging of certain features of the monitored field. A set of nodes or all nodes send their data to a base station periodically. Compression or partial-aggregation techniques can be applied to decrease traffic volume. The base station can obtain original data by decoding, and then collects the complete information from sensor networks. In a convergecast tree, the sensors near the base station have a lot of grandchildren, so they have to bear more forwarding load than nodes far away from the base station. The proposed broadcast trees are not suitable for convergecast, because they construct trees with non-leaf nodes as few as possible. If these broadcast trees are utilized to perform convergecast, some non-leaf nodes will consume energy faster than other non-leaf nodes. This is because that these non-leaf nodes must relay more data if they have more children and grandchildren than others. The tree is finally partitioned into several subtrees, because some nodes died. The children of dead node become orphaned nodes, and cannot forward data to the base station. To solve unbalancing energy consumption problems, authors of [8,11,14] proposed load-balancing solutions for sensor networks.

The prior works did not consider the load-balancing solution for convergecast tree to extend network efficiency. This study proposes a novel adjustable convergecast tree (ACT) protocol that dynamically adjusts tree structure. ACT constructs a load-balancing convergecast tree to collect periodical data from a sensor network. A load-balancing tree can reduce the possibility that some nodes bear more forwarding loads than others. This study also proposed a distributed adjustment algorithm to readjust the aging nodes' children. An aging node requests its parent readjust its children before energy is exhausted. Additionally, the adjustment process only needs localized information. The dynamic tree prolongs tree lifetime and enhances convergecast performance.

The remainder of this paper is organized as follows. Related work is discussed in Section 2. Section 3 introduces the preliminary study. Section 4 presents the adjustable convergecast tree protocol in detail. The proposed protocol is compared with other protocols. Simulation results are addressed in Section 5. Finally, conclusions are presented in Section 6.

2. Related work

This section discusses existing tree structures for sensor networks. Boukerche et al. [4] proposed an energy-aware distributed heuristic for a special rooted broadcast tree that facilitates data-centric routing in wireless sensor networks. The selection of non-leaf nodes is based on node residual power. The selection algorithm is executed in rounds to distribute the work among the nodes and demand fair energy consumption for all nodes. A round encompasses initialization and data-transmission phase. During the initialization phase, the non-leaf nodes are reselected based on node residual power to form a new tree. In data-transmission phase, all nodes transmit data to a sink. Each round ends at the end of data-transmission phase, and then the next round begins. If a node battery has run down, it becomes a dead node and it cannot forward its children's data to sink again. The children of dead node become orphan nodes. In this approach, the orphan nodes can reconnect to tree structure in the initialization phase of a round. But the initialization phase has to consume additional energy to avoid producing orphan nodes. Furthermore, this approach cannot dynamically readjust tree structure during the data-transmission phase.

Because previously proposed tree structure cannot be readjusted dynamically, Yang et al. [26] proposed an approach (DQEB) for dynamic query-tree that can dynamically readjust tree structure. Additionally, their approach also minimizes broadcast cost by utilizing the minimum number of nodes to broadcast messages. They proposed an algorithm to identify "aging" non-leaf nodes. Once a non-leaf node is identified as is an aging node, this node attempts to find a new parent node for its children. First, the aging node queries its children about their parent candidates. The aging node's children find out their parent candidates from their neighbors, and reply parent candidate information to the aging node. Next, the aging node chooses one of the parent candidates as the new parent node, and instructs its children to connect with their new parent, respectively. If all original children of aging node become other nodes' children, the aging node becomes a leaf node. This approach prevents the formation of a disconnected tree.

The function of sensor is to collect environmental data for a user. Thus, convergecast is a crucial communication pattern for sensor networks. However, convergecast communication pattern is the opposite of the broadcast communication pattern. If a broadcast tree is utilized to collect complete data, some non-leaf nodes close to the root will die faster than others. It is because that the broadcast tree is constructed with as few non-leaf nodes as possible. Using broadcast tree to perform convergecast, the nodes close to the root must relay many packets to the root if they have a lot of grandchildren. These nodes bear heavy transmission loads. Finally, the tree will soon be partitioned into several subtrees.

Annamalai et al. [3,25] proposed a heuristic algorithm to construct a collision-free convergecast tree with schedules assigned. Their scheme is capable of code allocation in cases in which multiple codes are available to minimize the total duration required for convergecasting. Thepvilojanapong et al. [24] proposed a hierarchy-based anycast routing (HAR) protocol for collecting data over multi-hop, wireless sensor networks. The HAR constructs a hierarchical tree by locating its child nodes, which discovers their own child nodes in turn. HAR avoids flooding and periodic updating route information; however, the tree will be reconstructed when nodes fail or when adding new nodes. Every node maintains a parent candidate table to avoid becoming an orphan node. When a node detects that it lost the connection with its parent, the node immediately chooses an appropriate parent from its parent candidate table, and then connects with the new parent. If no candidate exists in the node's parent candidate table, the orphan node performs the joining process again. The worst case is the orphan node has not received any response from other nodes during the joining process. In this situation, the orphan attempts to reverse the relationship between it and its children. The orphaned node queries its children whether they have parent candidates. If one child has parent candidates, the orphan node chooses this child as its new parent. Next, the selected child chooses a new parent from its parent candidate table, and connects with the new parent. However, this approach consumes energy quickly; especially the network is partitioned into several subnetworks.

Yan et al. [28] proposed a routing mechanism to achieve load balance through constructing a dynamic load-balancing tree (DLBT) in wireless sensor networks. The DLBT structure is a tree-like topology, and every node has a level value which represents the number of hops to the root node. Each node may have more than one upstreaming node as the parent candidates and each candidate has a probability to be chosen as the parent node. The probability is related to the traffic load of each candidate and is also a