Future Generation Computer Systems 28 (2012) 780–790

Contents lists available at SciVerse ScienceDirect

Future Generation Computer Systems

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

A distributed energy-efficient clustering algorithm with improved coverage in wireless sensor networks☆

Zhixin Liu [a,*], Qingchao Zheng [a], Liang Xue [a], Xinping Guan [a,b]

[a] Center for Networking Control and Bioinformatics, Institute of Electrical Engineering, Yanshan University, Qinhuangdao, 066004, China
[b] Institute of Electronic, Information, and Electrical Engineering, Shanghai Jiaotong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 24 June 2010
Received in revised form
24 March 2011
Accepted 28 April 2011
Available online 25 May 2011

Keywords:
Wireless sensor networks
Clustering
ID assignment
Coverage
Network lifetime

ABSTRACT

Coverage preservation, unique ID assignment and extension of network lifetime are important features for wireless sensor networks. Grouping sensor nodes into clusters is an effective way to improve the network performance. By analyzing communication energy consumption of the clusters and the impact of node failures on coverage with different densities, we propose a DEECIC (Distributed Energy-Efficient Clustering with Improved Coverage) algorithm. DEECIC aims at clustering with the least number of cluster heads to cover the whole network and assigning a unique ID to each node based on local information. In addition, DEECIC periodically updates cluster heads according to the joint information of nodes' residual energy and distribution. The algorithm requires neither time synchronization nor knowledge of a node's geographic location. Simulation results show that the proposed algorithm can prolong the network lifetime and improve network coverage effectively.

1. Introduction

The past few years have witnessed increased popularity use of wireless sensor networks (WSNs) in applications such as pollution monitoring, critical infrastructure surveillance, disaster management and battlefield reconnaissance. Such a network typically consists of hundreds to tens of thousands of low-cost sensor nodes, deployed randomly in the area of interest in a relatively uncontrolled manner. Due to probably harsh working environments, sensor nodes are usually left unattended in sensing regions and make individual decisions to perform sensing tasks, and construct network topology and routing policy, which makes it difficult or impossible to re-charge or replace their batteries. Therefore, designing energy-efficient algorithms becomes important for extending the lifetime of nodes, maximizing network coverage, and enhancing robustness against node failures [1,2].

Grouping sensor nodes into clusters has been widely pursued by the research community over the last few years. It leads to the appearance of a great number of task-specific clustering protocols [3–5]. With clustering, the nodes organize themselves into local clusters, with one node acting as the cluster head. All non-cluster-head nodes transmit information to their cluster heads, while the cluster head nodes aggregate the received information and forward it to the remote base station. Since some neighboring nodes within one cluster coverage may detect the same event or phenomena simultaneously, local data aggregation at the cluster heads can significantly reduce the total amount of data to the base station, thus saving energy and bandwidth resources [6]. Moreover, clustering can stabilize the network topology at the level of nodes, enhance the scalability of the network, and reduce interference among the sensor nodes [7].

Coverage is also one of the most important design goals in many applications of WSNs [8]. A good coverage should minimize the overlap among the ranges of the clusters and cover all the sensors deployed within the monitored region [9]. Minimum overlap among clusters is also desirable for energy efficiency because it reduces the number of cluster heads in the network, and improves the efficiency of algorithms (such as data aggregation and routing) executed at the cluster heads. In WSNs, how to efficiently use the energy of the nodes while achieving better coverage performance is a challenging problem.

In this paper, we propose DEECIC (Distributed Energy-Efficient Clustering with Improved Coverage), a distributed clustering algorithm that considers both energy and topological features of the sensor network. DEECIC offers a feasible and efficient solution to handle large-scale networks with their enhancements to better assign unique IDs to sensor nodes, reducing communication

☆ This work was supported in part by National Basic Research Program of China (973 Program, No. 2010CB731800), the National Science Fund of China under Grant No. 60804030, 60974123 and the Educational Foundation of Hebei Province of China under Grant No. 2008147.

* Corresponding author.
E-mail addresses: lzxauto@ysu.edu.cn (Z. Liu), zhengzheng1987@126.com (Q. Zheng).

0167-739X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.future.2011.04.019

expense and improve network coverage. Independent of time synchronization and without node location information, DEECIC achieves good distribution of cluster heads within the network. DEECIC is also fast and locally scalable: since sensor nodes are energy-constrained, frequently receiving data from common nodes and forwarding them to the base station will consume a large amount of energy on cluster heads, DEECIC can achieve re-clustering within constant time and in a local manner.

The rest of the paper is organized as follows. Section 2 describes the network model and formulates the problem that we address. Section 3 summarizes previous work. Section 4 presents the DEECIC protocol in detail and analyzes its properties. Section 5 shows the effectiveness of DEECIC protocol via simulations, and compares it to other clustering techniques. Finally, Section 6 gives the concluding remarks and directions for future work.

2. Network model and problem statement

2.1. Network model

Different architectures and design goals/constraints have been considered in various applications of WSNs. The following lists some relevant architecture parameters and constraints in our clustering algorithm.

2.1.1. Node deployment and capability

- The sensor nodes are scattered randomly in a region of interest and all the nodes are not mobile.
- Nodes are left unattended after deployment.
- Nodes are location-unaware, i.e. no GPS or other location-aware mechanism is available.
- All nodes are isomorphic (have similar capabilities such as processing, communication and broadcasting power level), and at the beginning they have no globally unique IDs.

Network-wide unique IDs are beneficial for administrative tasks, such as configuration and monitoring of individual nodes. This is also regarded as a good way in many clustering algorithms [10,11]. However, the pre-existence of network-wide global IDs is not realistic in large WSNs, because it requires hard-coding the IDs on nodes prior to deployment. This is costly when a network contains hundreds to tens of thousands of nodes.

2.1.2. Clustering attributes

- DEECIC does not require a strict time synchronization mechanism. The node in the network makes decisions independently according to its own schedule.
- Clustering is completely distributed. Each node only interacts with a small set of sensor nodes within its transmission range. Conventional centralized algorithms often need to operate with information associated with each node. An error in communication or a loss of a critical node could potentially cause a serious algorithm failure since some commands, data or parameters are usually of higher importance in a centralized algorithm. In terms of scalability, robustness and fault-tolerance, localized algorithms often perform better than centralized algorithms because they reduce the amount of central coordination and enable nodes to act independently and simultaneously in a network.
- Regardless of network size, DEECIC produces a clustering of nodes within a fixed constant time.

2.2. Clustering objectives

Our clustering scheme in sensor networks is directed by two fundamental requirements: energy conservation and coverage preservation. This is a different interpretation of clustering compared to previous works which only consider maximum energy saving or maximum coverage. In many cases, for example in a forest monitoring application, it is often required that information from each part of the monitored area be provided at any moment to monitor a fire. However, the loss of a few nodes deployed in a dense area does not generate significant impact on network coverage compared to loss of nodes in a sparse area. Since deterministic placement of sensor nodes may be impossible, it is required for the network to integrate these requirements in a coherent manner to achieve clustering within the network.

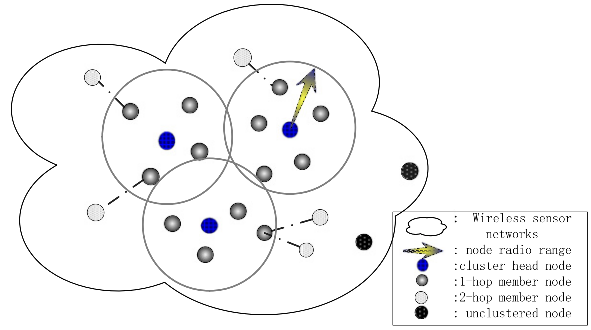

Fig. 1. The clustering model of DEECIC.

In this paper, we take a unique look at the cluster head election problem, specifically concentrating on the residual energy and topological properties of the nodes. Let $\mathbb{CH}$ be the set of all cluster heads in the network. Our goal is to select the least number of elements of $\mathbb{CH}$ such that each node in the network belongs to a cluster. This can provide good coverage performance of the entire monitored area. Since utilizing the least clusters to provide the best coverage of the network is an NP-Hard problem, which requires a centralized solution with the location information of the deployed sensor nodes, one goal of our work is to provide a heuristic approach to solve this problem. In our work, each node can relay its data within 2 hops to the cluster head (the details are discussed in Section 4), and assign its unique ID based on local information. In every round, the nodes need to self-organize and coordinate in order to select the optimal cluster head in each cluster. Apart from this, the nodes that are important to network coverage task have a smaller chance to be cluster heads.

A node in DEECIC can have four possible states: cluster head, 1-hop member node (an immediate neighbor of a cluster head), 2-hop member node (an immediate neighbor of a 1-hop member node) and unclustered node (not a member of any cluster). Fig. 1 depicts the clustering model of DEECIC.

3. Related works

In this section, we summarize the related works regarding ID assignment, coverage and clustering, and distinguish our approaches from the works presented in the literature.

3.1. ID assignment

Several protocols have been proposed recently for ID assignment in WSNs [10,12–14]. In [12], the authors propose an algorithm that assigns globally unique IDs. Unlike our approach, it uses a tree structure to compute the size of the network. Then unique IDs are assigned using the minimum number of bytes. However, this protocol has to use not only temporary ID and final ID but also information of sub-tree size, which results in high communication cost. In most of the ID assignment protocols in WSNs, IDs are locally unique within 2 hops in order to distinguish neighbors of sensors. The approach proposed in [13] utilizes a proactive conflict