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Semi-asynchronous and distributed weighted connected dominating set algorithms for wireless sensor networks

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ABSTRACT

Energy-efficient backbone construction is one of the most important objective in a wireless sensor network (WSN) and to construct a more robust backbone, weighted connected dominating sets can be used where the energy of the nodes are directly related to their weights. In this study, we propose algorithms for this purpose and classify our algorithms as weighted dominating set algorithms and weighted Steiner tree algorithms where these algorithms are used together to construct a weighted connected dominating set (WCDS). We provide fully distributed algorithms with semi-asynchronous versions. We show the design of the algorithms, analyze their proof of correctness, time, message and space complexities and provide the simulation results in ns2 environment. We show that the approximation ratio of our algorithms is $3\ln(S)$ where S is the total weight of optimum solution. To the best of our knowledge, our algorithms are the first fully distributed and semi-asynchronous WCDS algorithms with $3\ln(S)$ approximation ratio. We compare our proposed algorithms with the related work and show that our algorithms select backbone with lower cost and less number of nodes.

1. Introduction

WSNs do not have any fixed infrastructure and consist of sensor nodes that perform sensing and communicating tasks. Habitat monitoring, health care, environmental control, military surveillance and target tracking are example application areas of WSNs [1–3]. Backbone formation to construct a robust communication structure is a significant research area in WSNs. Backbones are provided in WSNs in order to decrease the number of messages and total time spent for routing the sensed data to the sink. By clustering the network and backbone formation, an energy-efficient topology is constructed which makes routing and data aggregation tasks easier. In clustering schemes, each node is classified as either cluster head or cluster member. Cluster members are ordinary nodes whereas cluster heads perform various task on behalf of the members of the clusters.

A WSN can be modeled as a graph $G(V, E)$ where V is the set of vertices (nodes of WSN) and E is the set of edges (communication links between the nodes). A connected dominating set is a subset S of a graph G such that S forms a dominating set and is connected. CDSs have many advantages in network applications such as ease of broadcasting and constructing virtual backbones [4]. Due to this fact, CDSs have been extensively studied by researchers [5–7,4,8–10]. Existing CDS algorithms generally aim at minimizing the number of backbone nodes without considering other issues, on the other hand energy-efficient cluster head selection is very important for sensor networks. In the weighted connected dominating set (WCDS) construction problem, the total weight of the set is aimed to be minimized. When the node weights are related to their energy then WCDS becomes a robust backbone architecture. To the best of our knowledge, although central WCDS is studied by researchers [11–14], there are few work on distributed WCDS construction [15–18].

In this study, we propose WCDS algorithms for energy-efficient backbone formation for sensor networks. For WCDS construction, we firstly design a weighted dominating set algorithm then we provide a weighted Steiner tree algorithm to connect dominators. Our proposed algorithms are semi-asynchronous and fully distributed in nature making them suitable for large scale applications in sensor networks. We use β synchronizer independent from the timer events.

The rest of this paper is organized as follows. In Section 2, the network model, backbone formation problem and distributed algorithm model with the synchronizers are described and the related work is surveyed in Section 3. The proposed algorithms are described and analyzed in Section 4 and Section 5. The results of performance tests of the proposed algorithms are presented in Section 6. The performance evaluation of a sensor network application is analyzed in Section 7 and conclusions are given in Section 8.

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2. Background

2.1. Network Model

The following assumptions are made about the network [19]:

- Each node has distinct node_id.
- The nodes are stationary.
- Links between nodes are symmetric. Thus if there is a link from u to v, there exists a reverse link from v to u.
- Nodes do not know their positions and they are not equipped with a position tracker like a GPS receiver.
- Each node knows its neighbors and its own energy.

Based on these assumptions, the network may be modeled as a node weighted undirected graph $G_w(V_w, E)$ where V_w is the set of vertices (nodes) with weights (costs), E is the set of the edges. A node's weight (w) is set as $1/e$ where e is its energy. An example weighted undirected graph model is depicted in Fig. 1 where ids are written inside nodes, weights and energies (in Joules) are placed near to nodes.

2.2. Backbone Formation Problem

Clustering is a basic method to group similar objects from a whole set of objects. In networks, clustering is performed to simply partition the whole network into subnetworks to ease communication tasks. Backbone formation is the construction of the virtual path of cluster heads to provide the relaying of sensed data to the sink. Backbone formation objectives for sensor networks can be listed as follows:

1. Nodes may initiate the backbone formation operation at any time locally. Distributed time synchronization can be a costly operation for battery powered sensor nodes. Hence, these operations should be distributed and asynchronous.
2. The cluster heads are the servers of their cluster members. They collect sensed data from their members to process, aggregate, filter and route this data to the sink. A cluster head may consume its energy very fast, thus selection of cluster heads with high energy is crucial.
3. 3 The backbone formation algorithms should be independent from the underlying protocols as much as possible to interface to various MAC and physical layer standards such as in [20–24].
4. 4 The algorithms should be efficient in terms of time, message and space complexity to provide low energy consumptions of sensor networks.

2.3. Distributed Algorithm Models and Synchronizers

In a distributed algorithm each device starts in an initial state $S_i \in S$, and changes its state from S_i to S_j and may output an $O_n \in O$ after receiving an input $I_k \in I$ according to defined state transition procedures. An input can be an interval event such as a timer interrupt; it can be an external event such as a neighbor's failure or message receiving. The operation is divided into rounds in synchronous communication where each operation step is executed in a round. To be independent from the timer events, synchronizers may be used to design semi-asynchronous algorithms for sensor networks [25]. One of the most practical synchronizers that is suitable for sensor network algorithm design is the β synchronizer. To maintain a β synchronizer, firstly, a rooted tree should be constructed. Each node should know its children and parent in this tree. When a node completes its operation and receives *OK* from children, it sends *OK* message to its parent. Since a sensor network has a natural root node, the sink, the implementation of this synchronizer for sensor networks is straightforward [26].

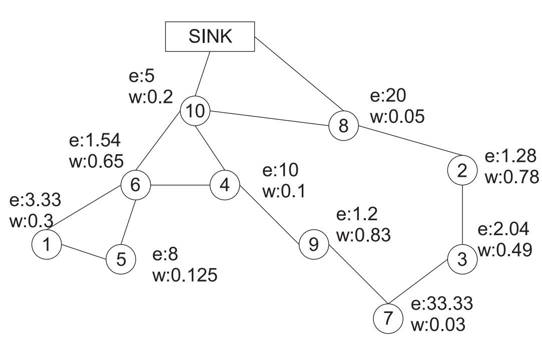

Fig. 1. Network Model.

3. Related work

A two-phased CDS algorithm is proposed by Wu [8], in which initially each vertex marks itself as dominator due to some predefined rules by exchanging neighbor lists. Dai [9] and Cokuslu [10] added extra heuristics to Wu's algorithm to reduce the size of the connected dominating set. Besides, there are many studies on CDS construction [27,5–7,28,29,4,8–10] where the $O(\log(\Delta))$ approximation ratio (Δ is the maximum node degree) can be achieved in $O(\log^2(\Delta))$ rounds [28]. All of these algorithms do not use node weights, they focus on the minimization of the number of dominators. Thus they are out of our concern.

Chvatal proposed a central weighted set cover based dominating set algorithm (CENTSET) with *lnS* approximation ratio where *S* is the minimum weight of the dominating set [30]. In each round, the dominator with the minimum weight ratio is chosen and it is covered with its neighbors. The algorithm stops when all nodes are covered. The weight ratio of the node n with cost c_n is calculated as $c_n/\,\Gamma_u$ where Γ_u is the weight of uncovered neighbor nodes. In [31,5], the authors proposed the distributed synchronous weighted dominating set algorithm (SSET) which is the distributed version of the CENTSET. In SSET, each node finds the weight of its two hop neighbors (2-hop span), then a node enters dominating set if it has the smallest weight ratio among its 2-hop span. Chatterjee proposed a weighted maximal independent set based dominating set algorithm for ad hoc networks [15]. In this algorithm, a node enters the dominating set if it has the smallest weight ratio among dominatee neighbors. After this state change, the dominator node informs its neighbors about its state where the dominatee neighbors check their neighbor's weight until all nodes are covered. Bao proposed an algorithm in which a node becomes a dominator if it has the smallest weight ratio among its one-hop neighbors or it has the smallest weight ratio among one of its two-hop neighbors excluding one-hop neighbors [16]. Chatterjee and Bao's algorithms may produce weighted dominating sets with very high costs as shown in [17]. To further decrease the weight of the dominating set, Wang proposed a two phased weighted CDS algorithm where the first phase constructs dominating set [17]. In this phase, nodes first construct a MIS similar to [15], then each node runs the CENTSET on its 2-hop span and becomes dominatee if a node with its neighbors are covered by a smaller cost than its cost. The algorithm has an approximation ratio of $\min(18\log(\Delta), 4\,\delta + 1)$ for unit disk graphs where δ is the maximum ratio of costs of two adjacent wireless nodes. This approximation ratio can be high for general graphs. Our proposed weighted dominating set algorithm is a fully distributed, improved and semi-asynchronous version of SSET which aims to solve backbone formation problem in sensor networks as explained in Section 4.

In the second phase of the Wang's algorithm, node weighted minimum spanning tree (MST) algorithm is executed to connect the dominators. The approximation ratio of the second phase is 10 for the unit disk graphs but may be high for general weighted graphs as shown in Section 4.2 since weight ratio of a connector is static during the execution of the algorithm. Our algorithms update the weight ratio of the candidate connectors in each round to further decrease the total weight of the selected connectors by simplifying the rules in Klein's