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Distributed construction of minimum Connected Dominating Set in wireless sensor network using two-hop information

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ABSTRACT

In a Wireless Sensor Network (WSN), neither there is any fixed infrastructure nor any centralized control. Therefore, for efficient routing, some of the nodes are selected to form a virtual backbone. Minimum Connected Dominating Set (MCDS) can be used as a virtual backbone. However, MCDS construction is an *NP-Hard* problem. In this paper, we propose a novel distributed greedy approximation algorithm for CDS construction which reduces the CDS size effectively. The proposed method constructs the CDSs of smaller sizes with lower construction cost in comparison to existing CDS construction algorithms for both uniform and random distribution of nodes. The performance ratio of the proposed algorithm, which is the best at the current moment, is $(4.8+\ln 5)|\mathrm{opt}|+1.2$, where $|\mathrm{opt}|$ is the size of an optimal CDS of the network. Its time complexity is $O(D)$, where D is the diameter of the network. Its message complexity is $O(nR)$ which is linear, where n is the network size and R is the maximum between number of rounds needed to construct the PDS and number of rounds needed to interconnect the PDS nodes. Our simulation shows that ours is the most size optimal distributed CDS construction algorithm.

1. Introduction

A Wireless Sensor Network (WSN) is formed by the wireless links of the sensor nodes deployed in an area. The sensor nodes are spatially distributed to monitor physical or environmental conditions such as temperature, pressure, sound etc. and send their data to the base station cooperatively. Generally, WSNs are used in monitoring of patients, environment, industry, food, agriculture etc. It is also used in earth sensing, search and rescue, disaster control [1] etc. Each node of a WSN has typically several parts: a radio transceiver, a microcontroller, a battery. The network may contain only static nodes, only mobile nodes or a mixture of both depending on the application. Each node of the network helps in routing by forwarding data of other nodes and which node will forward the data is decided dynamically based on the state of the network. WSN is ad-hoc because it does not depend on any existing infrastructure such as router in wired network. In WSN, nodes can communicate efficiently through the use of a virtual backbone. A virtual backbone is a connected subset of nodes deployed in the entire network which helps in routing. A pair of nodes in the network can communicate each other through the backbone nodes. As there is no fixed infrastructure and centralized control in a WSN, a Connected Dominating Set (CDS) can work as a virtual backbone for efficient routing and connectivity [2].

A Dominating Set (DS) of a network is formed by any subset of nodes of the entire network such that, each node either belong to the subset or neighbour of some element of that subset. If the nodes of a DS are connected, then they form a CDS. The CDS is responsible for transmitting messages from any node to any other node. A source node which does not belong to the CDS, sends its message to the destination node by first sending it to one of its neighbouring CDS nodes. If the destination node belongs to the CDS, it gets the message directly, otherwise it gets the message from one of its neighbours which belongs to the CDS. During routing, a CDS node forwards the message to its CDS neighbours only. So, these CDS nodes only maintain the routing information. Therefore, reduction of CDS size can save the storage space and also makes the routing easier and faster. Also by using a smaller sized CDS as virtual backbone the total energy consumption of the network can be reduced, if the non-CDS nodes switch off their radio when they don't have any data to send. Therefore, construction of Minimum Connected Dominating Set (MCDS) of the network is desirable. However, MCDS construction is an NP-complete problem [3]. For this reason researchers are interested for polynomial time approximation algorithms for CDS construction. As there is no centralized management in WSN, distributed algorithms can be useful

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for finding the MCDS. Energy is vital in WSN because the nodes can't be recharged. Therefore, the distributed approximation algorithms should construct smaller CDSs with low computation and communication costs. The quality of CDS is measured by its performance ratio, which is the ratio of the size of the constructed CDS (by the proposed algorithm) to the size of MCDS. The construction cost is also measured by the overall message and time complexities. To extend the lifetime of the network, in spite of relying on a single CDS, the network should switch between disjoint CDSs [4,5]. Therefore, to switch between CDSs quickly the computation time of CDS construction algorithm should be small enough. In this article, our focus is on constructing size optimal CDS as a virtual backbone of the WSN.

We can construct a CDS either in centralized or distributed manner. Although centralized algorithms provide more accurate information than distributed algorithms, they suffer from scalability problem and hence not feasible for large size WSNs. In centralized algorithms, the reliability of the information accumulated at a centralized processor is low because of the losses involved in multihop transmission. Distributed algorithms are difficult to design. They require only local information exchange between neighbouring nodes. For any WSN in which the average number of hops from any node to central processor is greater than the number of iterations required to perform a task, distributed algorithms are more energy efficient than centralized algorithms [6]. In this paper, we propose a new distributed degree-based greedy approximation algorithm which we name as **D**istributed **C**onstruction of **M**inimum **C**onnected **D**ominating **S**et (DCMCDS) to construct smaller CDSs.

The proposed scheme DCMCDS works in three phases and constructs the CDS using 2-hop information only. In the first phase, it constructs Maximal Independent Set (MIS) in a distributed manner. The MIS is designated as a Pseudo Dominating Set (PDS) because some of the elements may be omitted in the final dominating set. In the second phase, the algorithm constructs a Steiner Tree by adding some more nodes to the PDS, which are needed to interconnect the PDS nodes. In the last phase, the algorithm drops some of the selected PDS nodes to reduce the CDS size further without any loss in coverage or connectivity. Simulation results show that DCMCDS is better than existing CDS construction algorithms in terms of CDS size and construction costs. The performance ratio of the proposed algorithm, which is the best at the current moment, is $(4.8 + \ln 5)|opt| + 1.2$, where $|opt|$ is the size of an optimal CDS of the network. Its time complexity is $O(D)$, where D is the diameter of the network. It has a linear message complexity of $O(nR)$, where n is the network size and R is the maximum between number of rounds needed to construct the PDS and number of rounds needed to interconnect the PDS nodes.

The remaining of the article is organized as follows. In Section 2, we provide some basic definitions which we use in the entire paper. Section 3, provides a review of the works on CDS construction. In the next section (Section 4), we discuss the motivation behind our work and our major contributions. In Section 5, we discuss the centralized version of our proposed scheme in brief. Section 6 discusses the distributed CDS construction algorithm in detail. The analysis of our proposed distributed algorithm is discussed in Section 7. Supporting simulation results are given in Section 8. Finally we presented the conclusion in Section 9.

2. Background

In this section, we discuss some of the fundamental concepts that are useful to understand our work.

Definition 2.1 (DOMINATING SET)**.** In graph theory, a dominating set (DS) for a graph $G(V, E)$ is a subset $V'\subseteq V$ such that for each node $v \in V - V'$, $Adj[v]\bigcap V' \neq \phi$, where $Adj[v]$ denotes set of adjacent nodes of v. The nodes in the dominating set, V' are called **dominators**.

Definition 2.2 (CONNECTED DOMINATING SET)**.** A dominating set which forms a connected subgraph is a Connected Dominating Set (CDS). So, a CDS of a graph is a set of vertices with the following properties:

1. Every vertex of the graph is either belongs to the CDS or is adjacent to atleast one vertex of the CDS.
2. We can reach from any node in the CDS to any other node in CDS by a path which stays entirely within CDS.

The nodes which does not belongs to the CDS are called as **dominatees**.

Definition 2.3 (INDEPENDENT SET)**.** In a graph, a set of vertices in which none of two are adjacent, is called as an independent set or stable set.

Definition 2.4 (MAXIMAL INDEPENDENT SET)**.** An independent set to which by adding any vertex outside the independent set disturbs the property of independent set is called as Maximal Independent Set (MIS) or maximal stable set. In other words, a maximal independent set cannot be a sub set of any other independent set.

Definition 2.5 (UNIT DISK GRAPH)**.** A Unit Disk Graph (UDG) is the intersection of unit disks (of unit radii) in the Euclidean plane. The centre of each disks is a node. So the disk represent the communication range of the node which is same for all nodes. Two nodes are connected by an edge if the Eucledian distance between the two nodes is less than one unit.

Definition 2.6 (STEINER TREE)**.** In a graph $G = (V, E)$, for a given subset of vertices $I\subseteq V$, a Steiner Tree is a tree which interconnects the nodes in I using a set of nodes (known as Steiner nodes) not in I.

3. Related work

For connectivity and coverage in wireless network, CDS can be used as virtual backbone. In 1987, Ephermides first proposed this idea [7]. Since then the research on CDS has never been interrupted. Many researchers proposed different algorithms to construct the CDS. The CDS construction approaches found in the literature can be broadly classified as centralized, distributed and localized algorithms.

In a centralized CDS construction algorithm, the topology information of the entire network is needed at a particular node where the CDS construction algorithm runs. Guha and co-workers [2,8] first proposed two polynomial time centralized algorithms in 1998 . The approximation ratio and time complexities of both these algorithms were $O(\ln \Delta)$ and $O(n^2)$ respectively, where Δ is the maximum node degree and n is the network size. Later on in 2005, Adjih et al. [9] proposed a localized algorithm for CDS construction which was based on multipoint relays (MPR).

In WSN getting the entire topology information at one node is not easy. Therefore, distributed algorithms are very useful for CDS construction. In 1999, Wu and Li [10] proposed the first distributed CDS construction algorithm and Alzoubi et al. [11] reported its approximation ratio as $O(n)$. Later on Stojmenovic et al. [12] and Das et al. [2] proposed different distributed algorithms of approximation ratio $O(n)$ and $O(\log n)$ respectively. However, the time and message complexities of these algorithms are quite high.

Most of the distributed CDS construction algorithms first construct the MIS and then connect these MIS nodes to form a CDS. In 2002, for a UDG, Wan et al. [13] proposed a two phase distributed leader initiated CDS construction algorithm of performance ratio