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An energy-efficient topology construction algorithm for wireless sensor networks

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ABSTRACT

Topology management schemes have emerged as promising approaches for prolonging the lifetime of the wireless sensor networks (WSNs). The connected dominating set (CDS) concept has also emerged as the most popular method for energy-efficient topology control in WSNs. A sparse CDS-based network topology is highly susceptible to partitioning, while a dense CDS leads to excessive energy consumption due to overlapped sensing areas. Therefore, finding an optimal-size CDS with which a good trade-off between the network lifetime and network coverage can be made is a crucial problem in CDS-based topology control. In this paper, a degree-constrained minimum-weight version of the CDS problem, seeking for the load-balanced network topology with the maximum energy, is presented to model the energy-efficient topology control problem in WSNs. A learning automata-based heuristic is proposed for finding a near optimal solution to the proxy equivalent degree-constrained minimum-weight CDS problem in WSN. A strong theorem in presented to show the convergence of the proposed algorithm. Superiority of the proposed topology control algorithm over the prominent existing methods is shown through the simulation experiments in terms of the number of active nodes (network topology size), control message overhead, residual energy level, and network lifetime.

1. Introduction

Topology control is a promising approach to achieve energy conservation and to extend the lifetime of the wireless sensor network without degrading the important network performance such as coverage, connectivity, and throughput [1,2]. Energy conservation remains the primary concern of the topology control protocols. Generally, the topology control process is composed of two main phases: topology construction and topology maintenance. Topology construction aims at building a topology to connect the network nodes based on a desired topological property. Construction of a dense network topology leads to excessive energy consumption due to overlapped sensing areas, while a very sparse network topology is highly vulnerable to partitioning. Therefore, creation of an optimal, reduced, and connected network topology is of great importance in sensor networking. Topology maintenance tries to preserve the connectivity and coverage of the network by recreating or restoring the network topology [2]. The topology maintenance mechanisms are classified in [4] as static, dynamic and hybrid approaches. They can be further classified based on the energy and time triggering techniques [4].

Energy-efficient topology control approaches proposed for wireless sensor network are classified in four different groups [3]: power-adjustment approach, power-mode approach, clustering approach, and hybrid approach. The power-adjustment approach [5–11] is the most common form of the topology control in which each sensor node dynamically adjusts the transmission range of its radio to

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minimize the power consumption during transmission. In this approach, the adjacent sensor nodes tries to find the appropriate (minimum possible) transmission range to keep the network connected. The power-mode approach [12–14] is based on the amount of energy consumption of a sensor node in its four possible operating modes: transmission, reception, sleep, and idle modes. Obviously, the energy consumption during the transmission and reception modes is significantly higher than that in the idle mode. Besides, continuous listening to the packets not addressed to the idle node dissipates the sensor power as compared to the sleep mode. Therefore, the idea behind the power-mode approach is to turn off the radio of the redundant idle nodes (not participating in transmitting and receiving) to move to the sleep mode for more energy conservation. The idea of the cluster-based topology control approaches [15,16] is to construct a network topology with a hierarchical structure that is more scalable and easier to manage. In this approach, the network is partitioned into clusters, each having a cluster-head and several cluster-members. In each cluster, only the cluster-heads are responsible for handling the communication requirements of the cluster. The other nodes can be activated when it is required. This significantly reduces the energy consumption by minimizing the number of active nodes. The hybrid approaches [17,18] aims at achieving a higher energy conservation level and a longer network lifetime through combining the clustering, power-adjustment, and power-mode approaches.

The connected dominating set (CDS) principle has recently emerged as a promising approach to construct and maintain an energy-efficient network topology in WSN [1–3,19–25]. In this approach, a virtual communication backbone covering the entire network is formed by keeping the CDS nodes activated and turning off the redundant non-CDS sensor nodes. The CDS of a WSN is constructed in such a way that each node in the WSN is either a member of the CDS or is a neighbor of one of the nodes in the CDS. A host of solutions have been presented to solve the CDS problem in literature. To name just a few, Li et al. [26] and Alzoubi et al. [27] proposed MIS (maximal independent set)-based greedy algorithms to solve the CDS problem. Dai and Wu [28] and Butenko et al. [29] presented prune-based heuristics to find the CDS of the network graph. Ma et al. [21] formalized the energy-efficient topology construction problem to the minimal CDS problem. They also proposed three CDS-based localized algorithms for topology control in WSNs. First, a self-pruning algorithm providing the shortest path from every node to the sink in the generated topology, second an ordinal-pruning algorithm to significantly reduce the number of coordinators, and finally a layered-pruning algorithm as a trade off between the first two pruning algorithms. Qureshi et al. [23] proposed a reliable and energy-efficient CDS-based topology construction and maintenance protocol called Poly for WSNs. In the proposed method, a polygonal network backbone is formed by turning-off the unnecessary nodes while keeping the topology connected and network covered. The authors showed the superiority of Poly over the three other CDS-based topology control protocols presented in [16,30,31]. Bin-Othman et al. [24] models the energy-efficient topology construction problem with the minimum weighted CDS problem in which the residual energy of each sensor is defined as its weight. A CDS-based hierarchical topology construction mechanism called α-minimum-routing-cost connected dominating set (α-MOC-CDS) is defined and discussed in [39] to achieve efficient broadcasting and routing in wireless sensor networks. α-MOC-CDS has a special constraint such that for any pair of nodes, there is at least one path on which all intermediate nodes belong to α-MOC-CDS and the number of intermediate nodes on the path is smaller than α times of that on the shortest path in the original network. Therefore, α-MOC-CDS avoids the number of routing hops becomes. It is shown that the α-MOC-CDS is an NP-hard problem in a general graph. A heuristic localized algorithm is proposed to construct α-MOC-CDS in polynomial time. Simulation results show a trade-off between the CDS size and routing cost. In [40], it is shown that, under general graph model, there is no polynomial-time constant approximation for α-MOC-CDS unless $P = NP$ when $\alpha \geqslant 2$. In this reference, a polynomial-time constant-approximation algorithm called GOC-MCDS-C is proposed. The proposed algorithm is composed of two stages. In the first stage, GOC-MCDS-C constructs the MIS of the graph. The MIS nodes are connected in the second stage. Under unit disk graph model, GOC-MCDS-C produces the connected dominating sets smaller than $148 \cdot opt_{MCDS} + 208$, where opt_{MCDS} denotes the minimum size connected dominating set.

Wightman and Labrador [31] presented a CDS-based algorithm called A3 to the topology construction in WSNs. A3 estimates the distance between the sensors on the basis of the strength of the received signal. A3 generally is made of three main phases, neighborhood discovery phase, children selection phase, and second opportunity phase. A3 gives the higher priority to the most energetic child nodes that are farther from the parent node. A3 uses four messages: hello message, parent recognition message, children recognition message, and sleeping message. A3lite as an extension of A3 was also proposed in [31]. A3lite uses only hello and parent recognition messages. The major problem with A3Lite is that sending a sleep message to all nodes that are dominated by the other nodes may cause some points of the area remain uncovered. Two other extensions of A3, named as A3Cov and A3CovLite, were presented by Wightman and Labrador in [2]. *A3Cov* checks to see if an unconnected node is sensing-covered by another active node. If so, it is moved directly to the sleeping mode. Else, the node must stay awake for a time period. If it receives a sensing coverage message before the timeout expires, it goes to the sleeping mode. Otherwise, it must remain active. A3CovLite [2] is a combination of A3Lite that reduces the message complexity of A3 and A3Cov that solves the coverage problem of A3. An energy-efficient topology control algorithm called A1 was proposed by Rizvi et al. [1] for WSNs. A1 is very similar to A3 and uses the signal strength and residual energy criteria to select the dominators. However, it is a one-phase algorithm and only uses the hello message to construct the backbone. The starting node discovers its neighbors, and the neighbors of the initiator node discover their neighbors sequentially. This process continues until the complete topology is constructed.