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ECCRA: An energy-efficient coverage and connectivity preserving routing algorithm under border effects in wireless sensor networks

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ABSTRACT

Wireless sensor networks can be used to monitor the interested region using multi-hop communication. Coverage is a primary metric to evaluate the monitoring capacity. Connectivity also should be guaranteed so that the sink node can receive all sensed data for future processing. In this paper, combining these two problems, we study the connected, coverage problem given a specific network coverage ratio under border effects. We consider the scenario where the sensor nodes are distributed in a circle-shaped region uniformly. We first derive the network coverage provided by N sensor nodes by the mathematical formulae exactly. The lower bound of the network connectivity probability is also derived. Since sensor nodes are equipped with energy-limited batteries, energy conservation in such networks is of paramount importance to prolong the network lifetime. Accordingly, we then propose a location-independent, energy-efficient routing algorithm ECCRA which achieves the required network coverage and sensor connectivity simultaneously. The extensive simulation results demonstrate that our algorithm is correct and effective.

1. Introduction

With the development of very-large-scale integration (VLSI), micro-electro-mechanism system (MEMS) and wireless networking technology, wireless sensor networks attract more attention in recent years. A wireless sensor network is composed of numerous tiny sensor nodes. These nodes have processing and communication capacities, which can collect surrounding information and then transmit report data to a sink node/base station [1]. Then the sink node aggregates/analyzes the report data received and decides whether there is an unusual or exceptional event occurrence in the deployed region. However, some inevitable practical factors hinder the wireless sensor networks to be used ubiquitously. For example, the battery power carried by a sensor node is limited, which prevents the sensor node from executing complex instructions or algorithms. For many applications, the desired lifetime of a sensor network is of order of a few years. It may be infeasible or undesirable to recharge batteries in sensor nodes once a wireless sensor network is deployed. Hence, energy efficiency is a paramount design consideration for all wireless sensor networks.

There are two main approaches for energy conservation. The first is to design the energy-efficient protocols throughout all stack layers. For example, in the MAC layer protocol, power consumption can be reduced by decreasing the wake-up time of a transmitter or by employing a smart scheduling of slots to avoid signal collision and data retransmission [2]. In the routing layer protocol, a clustering algorithm, called Low Energy Adaptive Clustering Hierarchy (LEACH) [3], utilizes a randomized rotation of a local cluster-head (CH) to evenly distribute the energy load among nodes in the network. It also uses localized coordination to enable scalability and robustness for dynamic networks and incorporates data fusion into the routing protocols to achieve energy conservation. Younis et al. presented an algorithm called HEED that periodically selects cluster-heads based on the node's residual energy and a secondary parameter, such as node proximity to its neighbors or node degree [4]. Bandyopadhyay et al. proposed a distributed clustering algorithm where the communication between the node and its CH is organized in a multi-hop manner [5]. Using the results of stochastic geometry, the authors formulate a network energy dissipation function and derive the probability p of becoming a CH that minimizes energy dissipation. The value of H, the maximal number of hops from a node to its CH, is also calculated in [5]. Furthermore, Jin et al. proposed an energy-efficient multi-level clustering algorithm EEMC and derived the optimal number of levels asymptotically to minimize the network energy consumption [6]. The second is to minimize the number of active sensor nodes or schedule the status (i.e., active, idle or sleeping) of the sensor nodes

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while preserving some network properties (e.g., network coverage [7–9], network connectivity [10–12], or both [13–16]).

Compared with the above literatures, we study the coverage and connectivity problems under border effects in wireless sensor networks. Then, by integrating the routing issue, we propose a location-independent, energy-efficient routing algorithm ECCRA. The main contributions are listed as follows:

(1) Given N nodes, we calculate the coverage ratio a network may provide.
(2) Given N nodes, we calculate the lower bound of the connectivity probability a network may provide.
(3) We design ECCRA algorithm to preserve the specific network coverage ratio and network connectivity probability simultaneously. At any moment, each active node is able to maintain a minimal hop count routing path to the sink node, which reduces the data transmission latency. Furthermore, this algorithm can dynamically schedule the nodes to achieve the different network coverage ratio and network connectivity probability requirement.

The rest of the paper is organized as follows. Section 2 surveys the related work. Notations, assumptions and some definitions are provided in Section 3. Section 4 analyzes the network coverage and the network connectivity probability given N nodes. Some useful theorems are also presented in this section. Section 5 proposes an energy-efficient coverage and connectivity preserving routing algorithm ECCRA. In Section 6, the simulation results are shown to validate our analysis and compare our algorithm with others. Section 7 concludes the paper and points out the future research directions.

2. Related work

Coverage is an important metric to measure the quality of service (QOS) of the network, which has been extensively investigated [17].

Ye et al. developed a probing based algorithm PEAS to conserve energy [7]. This algorithm does not require any node to maintain knowledge of the states of the neighbor nodes and it distributes node wake-ups randomly over time. When a sleeping node wakes up, it detects whether any active node is present within a certain probing range by broadcasting a probing message and waiting for a reply. If no reply is received within a time period, it starts working until it fails or depletes all its energy. In this solution, the application specified probing range indirectly determines the degree of coverage. However, this probing based approach has no guarantee of adequate network coverage.

Tian et al. proposed a sponsored area algorithm which aims at providing full coverage by its off-duty eligibility rules [8]. A node can turn itself off as long as its active neighbor nodes can cover all of its sensing area. In addition, a back-off based self-scheduling scheme was presented to avoid generating possible blind points of coverage when several neighbor nodes try to fall asleep simultaneously. This rule underestimates the area already covered because the node only considers the sponsored area provided by the nodes that locate in its sensing area, therefore much extra energy is consumed.

In one of the earliest work related to sensor network coverage, Slijepcevic et al. introduced a centralized heuristic that selects mutually exclusive subsets of sensor nodes [9], due to the NP-hardness of the concerned problem. The members of each of those subsets together completely cover a geographical area. As only one subset needs to be active at any time, their technique results in energy savings while preserving the network coverage. However, the authors only presented a centralized algorithm which does not extend easily to a distributed algorithm. Furthermore, the input of their algorithm is the set of fields, while finding such a field partition is time-consuming and difficult in practice, where a field is a set of points that are covered by the same set of sensor nodes.

In [13], the authors proposed the notion of a connected node cover, defined as the node set that can fully cover the queried area and constitute a connected communication graph at the same time. The authors also demonstrated that the calculation of the smallest connected node cover is NP-hard, and they proposed both centralized and distributed approximated algorithms to solve it and provided the performance bounds as well. However, the method of [13] requires that each individual sensor node be aware of its precise location to check its local coverage redundancy. In some special applications, it is expensive or infeasible to acquire the location information.

Zhang et al. have proved if the radio range r_t is at least twice as large as the sensing range r_s (i.e., $r_t \geqslant 2r_s$), the network coverage implies network connectivity [14]. That is, as long as the set of active nodes completely covers the monitored region, the network is connected. To minimize the number of active nodes for energy conserving purpose, the overlap of sensing disks of active nodes should be minimized. The model they put forward is that in the ideal case, the center points of the three closest nodes should form an equilateral triangle with side length $\sqrt{3}r_s$. Based on these results, the authors proposed a distributed, localized algorithm, called Optimal Geographical Density Control (OGDC). Furthermore, combined with SPAN algorithm [12], Wang et al. proposed Coverage Configuration Protocol (CCP) to maintain the network coverage and the network connectivity simultaneously when $r_t < 2r_s$ [15]. It is noted that although [14] and [15] showed with an assumption of $r_t \geqslant 2r_s$ that if a set of nodes covers a given region completely, then the communication graph induced by the nodes is connected, this property, however, is no longer held if it is partial rather than full covered. Moreover, the active nodes are elected by the message exchange and the location information, which introduces the high algorithm overhead and the long algorithm delay in the large-scale networks. Comparably, our algorithm can determine the active nodes quickly and each active node can find a connected minimal hop count routing path via less message exchange.

Compared with the above negotiation-based [7,8] or location-based [9,13–15] coverage algorithms, Liu et al. [16] provided a solution to the joint scheduling problem under the constraints of both network coverage and network connectivity without the availability of location information, which is closest to our paper. They proposed a randomized scheduling algorithm and presented the analytical results to illustrate the relationship among achievable network coverage ratio, event detection probability, event detection delay, energy saving, and node density. Simulation results demonstrate that such a random scheduling method can achieve user-specified coverage quality with guaranteed network connectivity. In fact, their results could be better convinced if border effects are considered.

3. Preliminaries

3.1. Notations

The symbols are listed in Table 1.

3.2. Assumptions

(1) The sensor nodes, including the sink node, are uniformly distributed in a circle-shaped region with radius R.