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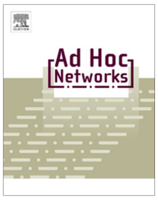

Stability-based and energy-efficient distributed data gathering algorithms for wireless mobile sensor networks

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ABSTRACT

The high-level contributions of this paper are the design and development of two distributed spanning tree-based data gathering algorithms for wireless mobile sensor networks and their exhaustive simulation study to investigate a complex stability-delay-throughput vs. node-network lifetime-coverage loss tradeoff that has been hitherto not explored in the literature. The topology of the mobile sensor networks changes dynamically with time due to random movement of the sensor nodes. Our first data gathering algorithm is stability-oriented and it is based on the idea of finding a maximum spanning tree on a network graph whose edge weights are predicted link expiration times (LETs). Referred to as the LET-DG tree, the data gathering tree has been observed to be more stable in the presence of node mobility, as well as incur a significantly lower delay per round of data gathering (due to the shorter height of the tree with more leaf nodes) and larger throughput per tree. However, stability-based data gathering coupled with more leaf nodes has been observed to result in unfair use of certain nodes (the intermediate nodes spend more energy compared to leaf nodes), triggering premature node failures eventually leading to network failure (disconnection of the network of live nodes). As an alternative, we propose an algorithm to determine a minimum-distance spanning tree (MST) based data gathering tree that is more energy-efficient and prolongs the node and network lifetimes as well as inflicts a lower coverage loss on the underlying network at any time instant, all of these at the cost frequent tree reconfigurations. The MST-DG trees also incur a significantly longer delay per round, due to their larger height and fewer leaf nodes.

1. Introduction

A wireless sensor network comprises of several smart sensor nodes that can gather data about the surrounding environment as well as process them before propagating to a control center called the sink, from which the end user typically operates to administer the network and access the nodes. Wireless sensor networks have been considered to give unprecedented levels of access to real-time information about the physical world, and the benefits of deploying such networks are widely seen these days. However, in almost all cases, the sensor networks are statically deployed and evaluated, wherein the mobility of the sensor nodes, the users and the monitored phenomenon are all totally ignored. Wireless mobile sensor networks (WMSNs) are the next logical evolutionary step for sensor networks in which mobility needs to be handled in all its forms. A motivating example could be a network of environmental monitoring sensors, mounted on vehicles, used to monitor pollution levels in a city. In this example, all the entities involved (i.e. the sensors, the users, and the sensed phenomenon as well) are moving. Likewise, one can conceptualize many such real-time scenarios to deploy

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sensor networks in which one or more of the participating entities move.

Like their static counterparts, the mobile sensor nodes are likely to be constrained with limited battery charge, memory and processing capability as well as operate under a limited transmission range. Two sensor nodes that are outside the transmission range of each other cannot communicate directly. The bandwidth of a WMSN is also expected to be as constrained as that of a static sensor network. Due to all of the above resource and operating constraints, it will not be a viable solution to require every sensor node to directly transmit their data to the sink over a longer distance. Also, if several signals are transmitted at the same time over a longer distance, it could lead to lots of interference and collisions. Thus, there is a need for employing energy-efficient data gathering algorithms that can effectively combine the data collected at these sensor nodes and send only the aggregated data (that is a representative of the entire network) to the sink.

Tree-based data gathering is considered to be the most energy-efficient [23] in terms of the number of link transmissions; however, almost all of the tree-based data gathering algorithms have been proposed for static sensor networks without taking the mobility of the sensor nodes into consideration. In the presence of node mobility, the network topology changes dynamically with time – leading to frequent tree reconfigurations. Thus, mobility brings in an extra dimension of constraint to a WMSN and we need algorithms that can determine stable long-living data gathering trees that do not require frequent reconfigurations. To the best of our knowledge, we have not come across any work on stable data gathering trees for mobile sensor networks.

In this research, we propose two distributed spanning tree-based data gathering algorithms for WMSNs. One of these data gathering algorithms is based on the notion of link expiration time (LET) that is predicted according to a model used for the highly successful Flow-Oriented Routing Protocol (FORP) [13], a stable unicast routing protocol for mobile ad hoc networks. The LET-DG tree is a rooted directed spanning tree determined in a distributed fashion on a network graph comprising of links whose weights are the predicted expiration time. As observed from the simulation results, the LET-DG algorithm discovers long-living stable trees that exist for a longer time. However, the drawback of using stable trees is that they tend to overuse certain nodes (especially the intermediate nodes of the data gathering tree) and lead to their premature failure. As sensor networks are often deployed with higher density, one or more node failures do not immediately bring the network to a halt. The live sensor nodes (the nodes that still have a positive available energy) maintain the coverage and connectivity of the underlying network for a longer time. Nevertheless, the unfairness of node usage persists with stable data gathering trees. As an alternative, we propose a second data gathering algorithm that is based on a distributed implementation of the minimum-distance spanning tree (MST) algorithm run on a network graph comprising of links whose weights are the Euclidean distance between the constituent end nodes. The MST-DG trees have been observed to yield a much longer node and network lifetimes as well as a lower fraction of coverage loss at any time instant (implying a higher coverage loss time), all at the cost of frequent tree reconfigurations. Another drawback observed with the MST-DG trees is that they are relatively taller (larger height) with fewer child nodes per intermediate node as well as fewer leaf nodes, compared to the LET-DG trees, and as a result, we observe the MST-DG trees to incur a much larger delay per round of data gathering compared to the LET-DG trees.

The rest of the paper is organized as follows: Section 2 presents a literature review for data gathering in mobile sensor networks. Section 3 presents the system model, including the models for the link expiration time and energy consumption, as well as states the assumptions. Section 4 describes the proposed algorithm to determine the LET-DG trees in a distributed fashion. Section 5 presents a variation of the LET-DG algorithm to determine minimum-distance based MST-DG trees. Section 6 presents an exhaustive simulation-based comparison of the LET-DG and MST-DG trees with respect to performance metrics such as the tree lifetime; delay per round of data gathering; throughput per data gathering tree; the node and network lifetimes (due to disconnection) along with a distribution of the probability of node failures; and the coverage loss time along with a probability distribution of the coverage loss. Section 7 concludes the paper and outlines ideas of future research. Owing to the larger tree lifetime and lower delay per round of data gathering, we also observe a relatively larger throughput per LET-DG tree.

Note that most of the performance comparison studies in the sensor network literature stop their simulations with the first node failure. In this paper, we continue beyond the first node failure and keep track of the time and distribution of the subsequent node failures as well as simultaneously gather data to analyze the loss of coverage inflicted on the network due to node failures and obtain the distribution of the coverage loss time vis-à-vis the fraction of loss of coverage suffered. Throughout the paper, the terms ‘data aggregation’ and ‘data gathering’, ‘edge’ and ‘link’ are used interchangeably. They mean the same.

2. Literature review

Most of the work on data gathering algorithms for WMSNs is focused around the use of clusters wherein researchers have tried to extend the classical LEACH (Low Energy Adaptive Clustering Hierarchy) [3] algorithm for dynamically changing network topologies. Variants of LEACH for WMSNs that have been proposed in the literature include those that take into consideration the available energy level [12] and the mobility-level [2] of the nodes to decide on the choice of cluster heads; stability of the links between a regular node and its cluster head [4]; as well as set up a panel of cluster heads to facilitate cluster reconfiguration in the presence of node mobility [1]. In another related work [26], the authors assume the network to comprise of a mix of static and mobile nodes: A cluster is evolved within the neighborhood of every static node, with the static node as the cluster head; a mobile