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Randomized fault-tolerant virtual backbone tree to improve the lifetime of wireless sensor networks ☆

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ABSTRACT

Backbone nodes are effective for routing in wireless networks because they reduce the energy consumption in sensor nodes. Packet delivery only occurs through the backbone nodes, which depletes the energy in the backbone drastically. Several backbone construction algorithms, including energy-aware virtual backbone tree, virtual backbone tree algorithm for minimal energy consumption and multihop cluster-based stable backbone tree, fail to form a complete backbone when converting important nodes, such as a cut vertex tree node to a non-backbone node. Thus we propose a fault-tolerant virtual backbone tree (FTVBT) algorithm that addresses all of these conflicts and we give theoretical derivations of the bounds for the probability that a sensor node can connect with the backbone. Furthermore, randomized FTVBT improves FTVBT by redistributing non-tree nodes randomly among all the eligible tree nodes based on their fitness values, thereby decreasing the rapid depletion of energy in a particular node and increasing the network lifetime. We performed simulations in NS2 and analyzed the experimental results.

1. Introduction

At present, wireless sensor networks (WSN) are major research topics in the areas of computer science and telecommunications. Wireless sensors are deployed in a region that needs to be monitored. Large numbers of sensors are deployed randomly, which are low power, low cost, memory/computationally-constrained devices that form a network. These devices transmit the sensing data back to a sink. Some emerging applications of WSNs include environmental monitoring, industrial control, healthcare, military uses, area surveillance and natural habitat monitoring. The sensor nodes consume energy during events such as sensing, computation and communication. From a traditional perspective, the energy consumption by WSNs is dominated by communication rather than by sensing and computation. In most cases, the computational energy cost is insignificant compared with the communication cost [1,2]. The sensing cost can also be assumed to be negligible in some networks.

Numerous solutions have been proposed for network life management based on deployment optimization (coverage, connectivity), topology control, energy efficient routing, clustering, data aggregation, mobile sinks/relay nodes and backbone approaches [3–7]. In this study, we propose a multihop routing protocol that performs better than single hop routing. In single hop routing, the energy consumption can be reduced in only a few nodes. Thus, single hop transmission is not suitable

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in situations where the sink node is not reachable. In these situations, multihop routing protocols are preferred but they require adequate resources to transmit data to the sink, which increases the communication overheads and costs. Addressing these issues by routing through a backbone can reduce the communication overheads and the overall energy consumption of WSNs.

In this study, we attempt to increase the lifetime of sensor networks by constructing a virtual backbone tree. Several virtual backbone algorithms have been proposed previously such as energy-aware virtual backbone tree (EVBT), multihop cluster-based stable backbone tree and a virtual backbone tree algorithm for minimal energy consumption (ViTAMin). Constructing the backbone involves selecting tree nodes and each sensor node (non-tree node) is associated with at least one tree node. The tree nodes are selected based on their energy, upstream distance from the parent tree node and the angle between the node and its parent. Mobile sink nodes are considered in the present study. We propose a novel backbone construction and reconstruction algorithm and we explain how the N-of-N lifetime is maintained. Even if only one sensor node exists in a region, the backbone will be maintained by virtual backbones and the mobile sink.

Section 2 provides a brief overview of related research and the challenges involved in the formation of a backbone. An overview of the proposed fault-tolerant virtual backbone tree (FTVBT) is provided in Section 3, which also includes the algorithms for backbone construction, reconstruction, the randomized fault-tolerant backbone formation approach, and a discussion of the network lifetime. The simulation results and an evaluation of FTVBT are presented in Section 4. Finally, Section 5 gives our conclusion and some directions for future research.

2. Related work

The network lifetime is an important issue when evaluating sensor networks [8,9]. In previous studies, the network lifetime has been defined in various ways, such as the mean expiration time, the time when a specific fraction of nodes remains alive in the network and the time when the first loss of reporting occurs. Thus, the definition of the network lifetime is context-dependent and it can be specified in different ways for various scenarios [10]. In our scenario, we define the network lifetime as the time when backbone trees cannot be formed that cover the entire network such that every node can communicate with the sink node.

Many energy-efficient routing algorithms have been proposed to improve the lifetime of WSNs. Recently, two attractive categories of routing methods have been investigated: cluster and virtual backbone-based routing methods. Cluster-based protocols [11–13] use a hop limit-based model where the sink is within the hop limit of a cluster member that transfers the data directly to the sink node. The current solution used for clustering requires maintenance to reorganize the clusters due to mobility and node failures. To better organize the sensor nodes, different algorithms [14,15] have been used to set up a virtual backbone among the active nodes. A set of active nodes forms a backbone to perform certain tasks and they provide services to the nodes that are not involved in the backbone. Backbones reduce the operational costs involved in the communication between the sink and other sensor nodes, thereby decreasing the overall energy consumption of each packet and increasing the WSN lifetime.

Virtual backbones provide an infrastructure for efficient communication with the sink node. Nodes are selected as tree nodes (black) and non-tree nodes (blue). All of the communication between a particular sensor node and the sink node occurs via the tree nodes. Various strategies can be used to select the tree nodes. In EVBT [16], the sink node transmits a broadcast request (BCR) packet to all of the nodes in its sensing range. The nodes that receive this packet compute its fitness factor and time delay (t_d). The nodes then wait until t_d has expired. If a node receives another BCR request during this interval, the node becomes a non-tree node and it selects the nearest tree node as its parent; otherwise, the node becomes a backbone tree node and a branch of the virtual backbone. Selecting the nearest tree node as part of the backbone for the upstream link does not involve many computations, but it is not the shortest route to the sink. The main aim is to reduce the energy usage and to enhance the persistence of the network. ViTAMin [17] finds the shortest path to the sink for each tree node by adding a distance parameter to track the existing BCR packet, which is referred to as an extended BCR (EBCR) packet. The modified EVBT (m-EVBT) [18] reduces the total energy consumption by utilizing the distance between nodes and energy consumption information to identify upstream connections. Like ViTAMin, the energy consumption information is passed via an EVBT construction request (ECR) packet. EVBT can be built without using a time delay [19]. Only nodes with energy greater than the threshold are considered for selection as tree nodes. A node with a degree of one is always a non-tree node. Distributed Breadth First Search are run and if a vertex is not reached, it is joined to the virtual backbone. The virtual backbone is constructed and maintained with the minimal number of tree nodes. The network lifetime can be increased by controlling the mobility in the sink using a centralized and dynamic scheme [20–22].

2.1. Issues and challenges

In EVBT, ViTAMin and m-EVBT, the time delay is computed based on the node's fitness factor when an ECR or EBCR packet is received. If an EBCR or ECR packet is received before t_d expires, the node becomes a sensor node. Fig. 1 shows how this mechanism can lead to failure during the formation of a backbone. Node N3 has the ability to become a backbone node but it becomes a non-backbone node because it also receives an ECR packet from N2 before t_d expires. Thus, because N3 becomes a non-tree node, the virtual backbone cannot be constructed further.