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An adaptive, energy-aware and distributed fault-tolerant topology-control algorithm for heterogeneous wireless sensor networks

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ABSTRACT

This paper introduces an adaptive, energy-aware and distributed fault-tolerant topology-control algorithm, namely the Adaptive Disjoint Path Vector (ADPV) algorithm, for heterogeneous wireless sensor networks. In this heterogeneous model, we have resource-rich supernodes as well as ordinary sensor nodes that are supposed to be connected to the supernodes. Unlike the static alternative Disjoint Path Vector (DPV) algorithm, the focus of ADPV is to secure supernode connectivity in the presence of node failures, and ADPV achieves this goal by dynamically adjusting the sensor nodes' transmission powers. The ADPV algorithm involves two phases: a single initialization phase, which occurs at the beginning, and restoration phases, which are invoked each time the network's supernode connectivity is broken. Restoration phases utilize alternative routes that are computed at the initialization phase by the help of a novel optimization based on the well-known set-packing problem. Through extensive simulations, we demonstrate that ADPV is superior in preserving supernode connectivity. In particular, ADPV achieves this goal up to a failure of 95% of the sensor nodes; while the performance of DPV is limited to 5%. In turn, by our adaptive algorithm, we obtain a two-fold increase in supernode-connected lifetimes compared to DPV algorithm.

1. Introduction

Wireless sensor networks (WSNs) are typically composed of large numbers of tiny sensor nodes that are capable of sensing, processing and transmitting data over wireless channels. Such networks can be used in numerous fields, such as battlefield surveillance [1–3], environmental monitoring [4–6] and traffic control [7–9]. Sensor nodes collaborate in a distributed, autonomous and self-organized manner to accomplish a certain task, usually in an environment with no infrastructure.

Sensor nodes in WSNs should be low-cost and should have small form-factor. This restricts sensor nodes in many ways as they have limited energy, short transmission range, relatively slow CPU and small memory. These limitations bring out many challenges unique to WSNs, such as very low power consumption. Since sensor nodes are battery powered and these batteries are usually not rechargeable, coming up with solutions that reduce energy consumption and prolong network lifetime are very important. Numerous studies address this problem [10–13] in literature. According to Li and Mohapatra [14], 90% of a sensor network's energy is still available after first node

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dies. Despite this substantial amount of remaining energy, the existence of highly-loaded and bottleneck nodes cause early network demise. There are numerous studies that address balancing energy consumption among nodes to ensure that all nodes will run out of energy at about the same time [15]. Low-energy Adaptive Clustering Hierarchy (LEACH) [16] is a well-known early study that uses dynamic transmission ranges to better balance the load and prolong network lifetime. There are also some recent studies which re-establish lost connectivity by adjusting transmission ranges. CoRAD [17] and RESP [32] can be listed as some of those studies. With the recent developments in the hardware of WSNs, dynamic transmission range assignment has become even more effective [18].

Fault-tolerance is another critical issue in WSNs. Due to the error-prone nature of wireless communication, links may fail, packets can get corrupted or congestion may occur [19,20]. There are also factors that cause long-term faults in sensor nodes, such as energy depletion, hardware failure, link breaks, malicious attacks. Multi-hop communication multiplies the chances of faulty incidents for a packet stream traveling from a source to a destination. Therefore, fault-tolerance methods, including fault-tolerant topology control, are essential for improving WSN reliability as well as network lifetime.

As stated by Liu et al. [21], most existing works on fault-tolerant topology-control aim to obtain k-vertex connectivity between any two sensor nodes, where the topology is guaranteed to remain connected until the failure of the kth sensor node.

In this study, the focus is on two-tiered heterogeneous WSNs, where the network consists of two different types of nodes: resource-rich supernodes and simple sensor nodes with limited battery power. In this network model, sensor nodes are connected to the set of supernodes via multi-hop paths. To reflect this asymmetry, [22] proposes k-vertex supernode connectivity, where each sensor is connected to at least one supernode by k vertex-disjoint paths. In such topologies, the sensor nodes remain connected to the supernodes as long as at most $k-1$ sensor nodes fail.

Most studies on fault-tolerance propose static solutions, that is, they do not adapt the topology to the changing network conditions. Bagci et al. [23] propose a static algorithm called the Disjoint Path Vector (DPV) to optimize total transmission power for a given k-vertex supernode-connected network. That study does not consider residual battery energy and disregards the unbalanced load distribution on sensor nodes. As a result, k-vertex supernode connectivity is achieved but may not be preserved for a sufficient amount of time.

In this study, we propose a novel adaptive and distributed topology-control algorithm, Adaptive Disjoint Path Vector (ADPV), which efficiently constructs a k-vertex supernode-connected network topology and adapts the topology to node failures, which in turn increases network lifetime. The contribution is two-fold. First, the residual battery power levels of individual sensor nodes are considered to prolong k-vertex supernode connectivity. Second, an adaptive solution is proposed to restore, if necessary, k-vertex supernode connectivity after a node failure.

The remainder of the paper is organized as follows: Section 2 gives some background information and discusses the related studies. In Section 3, we present our proposed adaptive topology-control solution. The results for simulation experiments are presented in Section 4. Finally, Section 5 concludes the paper.

2. Related work

In this section, we give a brief overview of some of the prominent recent work addressing fault-tolerance, connectivity restoration and heterogeneity in WSNs. We also give a brief overview of the DPV algorithm [23].

Fault-tolerance techniques can be categorized into four [24]: prevention, detection, isolation, and recovery. *Prevention* attains network connectivity and establishes redundant links/nodes when necessary. *Detection* monitors traffic and sends alerts when any indication of fault happens, such as a decrease in packet delivery rate, which would imply a packet loss, interruption, or delay. *Isolation* diagnoses and identifies the alert. As for *recovery*, after detecting and identifying the fault, the system should be able to recover in either a centralized or distributed manner. Note that due to the nature of WSNs it is essential for the recovery scheme to be a distributed method.

The replication and redundancy of components prone to failure is the most commonly used method for fault prevention and recovery [21]. For instance, if some nodes have problems and fail to sense the environment, the redundant nodes in the vicinity can still provide data. Keeping redundant links or multiple paths also provides fault-tolerance when some communication links are broken due to node failures or communication errors.

2.1. Connectivity restoration in WSNs

There are three approaches to connectivity restoration in WSNs: mobile node relocation, relay node placement and topology-control via transmission range adjustment. In the first approach, as the nodes are mobile, the main idea is to reposition the existing alive nodes to restore connectivity. One example of this method is PADRA, developed by Akkaya et al. [25]. In this approach, each node chooses one of its neighbors to be the failure handler, which will start recovery if the node dies. The restoration process only occurs if the entire network gets disconnected, in which case the closest node that can take the dead node's place is relocated to that position.

In the relay node placement approach [26–31], the objective is to place a minimum number of relay nodes in a region where sensor nodes are randomly deployed so that the resulting network topology is fault-tolerant.

These first two approaches, that is, mobile node relocation and relay node placement, may not be practical in real-world scenarios because sensor nodes are often deployed in remote and inhospitable regions with harsh environments that render manual node placement or relocation infeasible. Note that due to the dynamic nature of WSNs, node placement and/or relocation must be repeated periodically. In addition, these approaches require overall