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Survey Paper

Topology management techniques for tolerating node failures in wireless sensor networks: A survey

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ABSTRACT

In wireless sensor networks (WSNs) nodes often operate unattended in a collaborative manner to perform some tasks. In many applications, the network is deployed in harsh environments such as battlefield where the nodes are susceptible to damage. In addition, nodes may fail due to energy depletion and breakdown in the onboard electronics. The failure of nodes may leave some areas uncovered and degrade the fidelity of the collected data. However, the most serious consequence is when the network gets partitioned into disjoint segments. Losing network connectivity has a very negative effect on the applications since it prevents data exchange and hinders coordination among some nodes. Therefore, restoring the overall network connectivity is very crucial. Given the resource-constrained setup, the recovery should impose the least overhead and performance impact. This paper focuses on network topology management techniques for tolerating/handling node failures in WSNs. Two broad categories based on reactive and proactive methods have been identified for classifying the existing techniques. Considering these categories, a thorough analysis and comparison of all the recent works have been provided. Finally, the paper is concluded by outlining open issues that warrant additional research.

1. Introduction

The growing interest in applications of wireless sensor networks (WSNs) has motivated a lot of research work in recent years [1–4]. For some of these applications, such as space exploration, coastal and border protection, combat field reconnaissance and search and rescue, it is envisioned that a set of mobile sensor nodes will be employed to collaboratively monitor an area of interest and track certain events or phenomena. By getting these sensors to operate unattended in harsh environments, it would be possible to avoid the risk to human life and decrease the cost of the application.

Since a sensor node is typically constrained in its energy, computation and communication resources, a large set of sensors are involved to ensure area coverage and increase the fidelity of the collected data. Upon their deployment, nodes are expected to stay reachable to each other and form a network. Network connectivity enables nodes to coordinate their action while performing a task, and to forward their readings to in situ users or a base-station (BS) that serves as a gateway to remote command centers [5,6]. In fact, in many setups, such as a disaster management application, nodes need to collaborate with each other in order to effectively search for survivors, assess damage and identify safe escape paths. To enable such interactions, nodes need to stay reachable to each other and route data to the BS). Therefore, the inter-sensor

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connectivity as well as the sensor-BS connectivity have a significant impact on the effectiveness of WSNs and should be sustained all the time.

However, a sudden failure of a node can cause a disruption to the network operation. A node may fail due to an external damage inflicted by the inhospitable surroundings or simply because of hardware malfunction. The loss of a node can break communication paths in the network and make some of its neighbors unreachable. Moreover, WSNs operating in a harsh environment may suffer from large scale damage which partitions the network into disjoint segments. For example in a battle field, parts of the deployment area may be attacked by explosives, and thus a set of sensor nodes in the vicinity would be destroyed and the surviving nodes are split into disjoint partitions (segments). Restoring inter-segment connectivity would be crucial so that the WSN becomes operational again.

In this paper, we first highlight the challenges that node failures introduce to the operation of WSNs and provide taxonomy of recovery techniques that are geared for restoring the network connectivity. We categorize fault-tolerance techniques proposed in the literature according to the pursued recovery methodology into proactive and reactive techniques. Further classification is done within each category based on the system assumptions, required network state, metrics and objectives for the recovery process, etc. Under each category, we discuss several algorithms and highlight their strengths and weaknesses. Finally, we enumerate open research issues that are yet to be investigated by the research community. To the best of our knowledge, this paper is the first to survey contemporary connectivity-centric fault-tolerance schemes for WSNs, and sheds light on several practical issues for application designers. It will also be a good resource for newcomers to this research area.

Since the process of providing fault-tolerance is in general a form of topology management (i.e., often leads to changes in the network topology parameters), we start in Section 2 with an overview of contemporary techniques and objective of topology management in WSNs. The rest of the paper is organized as follows. In Section 3, we describe our categorization of the existing approaches. The remaining sections follow this categorization. Section 4 discusses techniques for tolerating a single node failure or a sequence of independent and non-simultaneous failures affecting non-collocated nodes. Recovery from simultaneous failure of multiple nodes is covered in Section 5. Section 6 enumerates open issues and outlines possible future research directions. Finally, Section 7 concludes the paper.

2. Topology management techniques in WSNs

Networks require monitoring and maintenance whether they are wired or wireless. The service which provides these tasks is called network management. Network management includes five functional areas as identified by the International Organization of Standardization (ISO): configuration management, fault management, security management, performance management and accounting management [1,5,7]. The unique requirements and constraints of wireless networks such as WSNs have inspired a new functional area, namely topology management. This term is sometimes used interchangeably with topology control and refers to the management of parameters such as degree of connectivity of the network, transmission power, state, or role of the nodes, etc. By modifying these parameters, one can change the topology of the network. Note that this stage naturally follows the creation of an initial topology.

The primary objective of the topology management techniques in WSNs is to achieve sustainable coverage while maintaining network connectivity and conserving energy. For example, these techniques are employed to track the status of communication links among the nodes, to conserve energy by switching off some of the nodes without degrading network coverage and connectivity, to support hierarchical task assignment for data aggregation, to balance the load on existing nodes and links, or to provide scalability by minimizing medium access collision and limiting overhead. Topology management in WSNs can be done through deterministic node placement or performed autonomously after random deployment given the limited human intervention [8]. Existing topology management techniques/algorithms for WSNs can be classified into the following five categories:

- **Node Discovery:** Detecting the nodes and their locations is an essential function in a WSN not only after the initial deployment but also for integrating newly added nodes. The scope of node discovery is subject to certain trade-offs based on the application goals. For instance, for large networks, resource savings in terms of energy and bandwidth can be achieved by not sharing some of the topology details that are deemed unnecessary for certain parts of the network [9].
- **Sleep Cycle Management:** To conserve energy and extend the network lifetime, some of the redundant nodes in a WSN can be turned off. In addition to the energy savings, this technique causes the number of transmitted messages to decline, which lowers signal interference and the failed transmission attempts. Determining the sleep schedule while sustaining full area coverage and strong network connectivity is a popular topology management optimization that has received quite an attention from the research community [10–13].
- **Clustering:** To achieve scalability and energy efficiency, nodes of a WSN may be grouped to form a hierarchical topology. In this way, nodes can send their readings to a cluster-head which in turn aggregates and forwards the data to the sink node after eliminating redundant data [14]. Although the failure of the cluster-head often requires re-clustering, some approaches have provisioned the topology adjustment by associating primary and backup cluster-heads for each sensor node [15–17].
- **Power Control:** The transmission range reflects the maximum distance at which a receiver can be from a sender. The longer the range is, the higher the power consumption would be. Many of the advanced radios allow programmable transmission power so that a node