Computers and Electrical Engineering 000 (2016) 1–22

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng

Distributed connectivity restoration in networks of movable sensor nodes☆

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ARTICLE INFO

Article history:
Received 8 April 2016
Revised 17 October 2016
Accepted 17 October 2016
Available online xxx

Keywords:
Wireless sensor network
Restoring connectivity
Fault tolerance
Node failure
Topology repair

ABSTRACT

In wireless sensor networks, hostile deployment terrains make resource constrained sensor nodes vulnerable to failures. Sometimes, even a single node failure can partition a network into many disjoint segments and can fail the application mission completely. Since, in most scenarios manual intervention is not possible and hence network must have self-healing capability by detecting and recovering faults at its own. In this paper, a distributed connectivity restoration (DCR) scheme is proposed which on node failure(s) reconstructs the network topology by using cascaded node movements enabling self-healing capability in the network. The DCR is based on partial network information including topological overhead associated with each node. The selection of befitting nodes to be relocated during cascaded movement is done strategically by using partial network information such that the relocation and message overheads are reduced. Ns-2 based simulation experiments are performed to evaluate the performance of the proposed scheme and is compared with other baseline approaches.

1. Introduction

Nodes of a Wireless Sensor Network (WSN) are small, inexpensive devices typically constrained in computation, communication and energy resources. These nodes are deployed in large numbers mostly in hostile environments. After deployment, sensor nodes (interchangeably written as nodes) form a connected network and stay reachable to each other during whole network's lifetime. The connectivity enables the nodes to coordinate their actions and transmit their sampled information to the sink node or base station [1]. In fact, in many applications, such as disaster management, sensor nodes need to coordinate their actions in order to detect damage, search survivors and identify safe paths to escape from affected regions. In order to coordinate such actions, nodes need to be connected to each other as well as to base station during network operation.

Sensor nodes are expected to operate autonomously in unattended and hostile environments where they are deployed randomly. Thus, it is common for sensor nodes to become faulty during their deployment. Also, failures may occur due to various other reasons including battery exhaustion, radio interference, de-synchronization, or dislocation [2]. The failure of node(s) may cause the coverage and connectivity losses. Sometime, failure of a single node can fragment the network into many disjoint unreachable segments (i.e. network may partition into various parts). Therefore, in presence of these frequent failures, providing adequate coverage and connectivity throughout the lifetime of the network is a challenging task

☆ Reviews processed and recommended for publication to the Editor-in-Chief by Guest Editor Dr. R. Varatharajan.

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http://dx.doi.org/10.1016/j.compeleceng.2016.10.014
0045-7906/

in WSNs. However, in this work, the main focus is on network connectivity rather than coverage as the problem of coverage has already been extensively studied in [3]. Nonetheless, the presented scheme avoids coverage hole to be left uncovered within the region of interest (RoI) except boundary of the region.

One solution for restoring the connectivity of the network is re-deployment of nodes in place of failed nodes, but due to inaccessibility of environment, manual redeployment of failed nodes is not possible [2,4]. Therefore, WSN should have self-healing capability for automatically coping with such failures. On the other hand, sensor nodes are resource constrained devices, operating in distributed fashion and hence, the recovery procedure should be energy and communication efficient capable of coping with distributed system challenges. Many approaches have been proposed in recent past for recovering network from node failures and topological vulnerabilities. Most of these approaches exploit nodes' mobility and use neighboring nodes to replace the failed nodes [4,5] recursively i.e. using cascaded movement. For example, a node s_f fails, then one of its neighboring node say s_a is moved to the position of s_f and thus leaves the position of s_a vacant. Further, the hole created due to movement of s_a is now handled in same way by moving one of its neighboring node say s_{aa} to its position. This cascaded node movement is continued till a node is reached whose relocation does not create any topology breakdown. The last relocated node is called a leaf node. The nodes that move to fill the vacant positions in the relocation process are called the failure handlers (FHs).

The performance of these connectivity restoration schemes is measured in terms of total number of messages exchanged, numbers of nodes moved and total distance traveled by them in order to recover network connectivity. The total distance and number of nodes moved directly depends on FH selection criteria. After failure of a node, the communication between its neighboring nodes may be interrupted fully or partially. Therefore, nodes need to have some partial knowledge of network's topology for efficiently coordinating the recovery process. The contemporary schemes utilize this information in different ways to restore inflicted links with minimal topology changes. The performance of a scheme depends on the contents, size (in number of hops) and correctness of this partial information and also on the way in which the information is utilized [4]. But, collecting, storing and updating this large amount of information regarding network topology require lots of message exchanges amongst nodes. Therefore, there is a tradeoff between relocation and communication overhead which needs to be managed carefully while designing connectivity restoration schemes for resource constrained networks such as WSNs.

This work presents a distributed connectivity restoration (DCR) scheme which relies on local view of nodes. However, the DCR opts cascaded relocation of nodes based on partial information, but unlike other schemes, in DCR, nodes individually find suitable FH before every relocation such that successive selection and relocation of FHs result in movement of minimum number of nodes. In order to minimize nodes' movements, each node collects and maintains the information of minimum distant leaf node from it through a distributed procedure. The nodes utilize this information to select suitable nodes as FHs at each step during relocation process and this process finally halts at the leaf node nearest to the failed node. Hence, the DCR always reconstruct the topology by moving least number of nodes. The DCR collects and utilizes local information in a better way as compared to contemporary schemes and outperform other schemes in almost every scenario. In order to ensure efficient recovery of successive node failures, the changes in network topology are updated strategically after every recovery process by exploiting minimal communication amongst nodes that too only in the vicinity of repositioned nodes. Additionally, the DCR avoids the unnecessary overheads of assessing the impact of a node failure in terms of network connectivity i.e. on every failure of a node the scheme does not check whether it is a cut-vertex or not. The scheme is entirely distributed enabling self-healing capability of the network to cope with frequent failures. The performance in terms of communication overhead, number of nodes moved and the distance traveled by moving nodes is analyzed numerically and through simulation experiments. In order to validate performance, the scheme is also compared with some existing approaches.

The rest of the paper is organized as follows. In next section, a brief summary of related work is given. Section 3 elaborates system model, major assumptions and problem formulation. In Section 4, the DCR is explained. The Section 5 gives performance evaluation followed by conclusion in Section 6.

2. Related work

In recent years, many topology management schemes have been proposed to control inter-node connectivity after failure of one or multiple nodes in a WSN. These schemes are either proactive or reactive [4–7]. The proactive schemes rely on tolerating failures rather than recovering from them. While in reactive schemes, to mitigate failures the scheme strives dynamically after the occurrence of failures. Two variants of proactive approaches are available in literature. In first, the network topology is designed in such a way that network can tolerate failures without degrading desired coverage and connectivity [8–11]. In second variant, some sensor nodes are strategically augmented in network topology for tolerating failures [12,13]. In case of reactive schemes, mainly three variants are reported in literature. In first category, some mobile sensor/actor nodes are repositioned to restore the desired network connectivity level [14–20]. In second category, some sensor/relay nodes are re-deployed strategically in the RoI in order to recover network from connectivity and coverage losses [21–23]. While in third category, some mobile relay nodes are deployed in the network, which tour disjoint blocks of nodes and carry data among them.

Please cite this article as: K.P. Sharma, T.P. Sharma, Distributed connectivity restoration in networks of movable sensor nodes, Computers and Electrical Engineering (2016), http://dx.doi.org/10.1016/j.compeleceng.2016.10.014