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Restoring connectivity in a resource constrained WSN

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A B S T R A C T

Wireless Sensor Networks (WSNs) in applications like battlefield surveillance or environmental monitoring are usually deployed in inhospitable environments, in which their constituent nodes are susceptible to an increased risk of failure due to hazardous operating conditions or adversary attacks. In these scenarios it is possible for multiple nodes to fail at the same time and partition the WSN into disjoint segments. Such loss of connectivity may cause service disruptions and render the WSN useless. Given the critical role a WSN plays and the fact that deployment of additional nodes may be infeasible, the WSN must have the ability to self-heal and restore connectivity by utilizing surviving resources. In this paper we present a distributed *Resource Constrained Recovery* (RCR) approach that reconnects a network partitioned into disjoint segments by strategically repositioning nodes to act as relays. In case the number of surviving relocatable nodes are insufficient to form a stable inter-segment topology, some of them are employed as mobile data collectors with optimized tours to reduce data latency. The performance of RCR is validated through mathematical analysis and simulation.

1. Introduction

Due to their cost advantage, ease of use, rapid deployment and round the clock operation, the use of Wireless Sensor Networks (WSN) is increasingly prevalent in applications designed to operate in harsh environments like battlefields, border surveillance, rain forests etc. In these applications, the WSN is setup in an ad-hoc manner, with sensor nodes being deployed aerially in the area of interest, and once on the ground coordinating with one another to form an interconnected network to carry out application specific tasks. In such setup and operation scenarios nodes have an increased risk of failure due to the harsh environmental conditions or due to enemy action. For example, bombing or missile strikes in a battlefield or a forest fire could render a large collection of nodes inoperable and partition the network into disjoint segments. Given the unattended operation and the infeasibility of timely deployment of additional nodes, the WSN must be able to recover from collocated node failures autonomously in order to restore connectivity and resume its service.

Multiple strategies have been pursued to tolerate multi node failures in WSNs (Younis et al., 2014). Published schemes can be classified broadly into proactive and reactive strategies. Proactive strategies involve careful node-placement wherein node positions are determined prior to network deployment and then leveraged to provision redundancy by forming a k-connected topology (Han et al., 2007; Li and Hou, 2004; Wang et al., 2003) or using redundant nodes as backups (Chen et al., 2001; Wang et al., 2005). Although a proactive strategy can lower the risk of network partitioning, it does not provide sufficient mitigation in ad-hoc network formation scenarios since the node positions cannot be accurately determined at time of deployment and a large scale failure may damage some nodes and all their backups.

Reactive strategies on the other hand are based on reconfiguring the network topology after failure. Basically, an inter-segment topology is formed in order to reestablish connectivity amongst disjoint segments. Reactive strategies can be broken down into two main classes, namely, centralized and distributed, based on the amount of information available during the recovery process. A centralized approach assumes the knowledge of the entire network state, which is exploited to find an optimal recovery solution. The recovery basically boils down to a node placement problem for which there are a number of published heuristics (Cheng et al., 2008; Lloyd and Xue, 2007; Senel and Younis, 2011; Senel and Younis, 2012). Meanwhile, distributed approaches rely on local state information and try to reconnect the network by either having representative nodes from the segments meet at a common point (Joshi and Younis, 2012; Lee and Younis, 2010; Joshi and Younis, 2013) or exploiting the shape of the network topology before failure to determine the recovery paths (Joshi and Younis, 2014; Joshi and Younis, 2015). Although centralized approaches yield optimized solutions, they require

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external resources, i.e., aerial support from satellites, aircrafts or UAVs to collect and disseminate global network state information on demand. Such external support may not be available at all times or be feasible due to budgetary constraints. Therefore, distributed approaches are deemed more practical for ad-hoc formed WSNs.

1.1. Contribution

In this paper we study the connectivity restoration problem under resource availability constraints. The problem is motivated by the fact that after a catastrophic failure the surviving segments may not have enough mobile nodes that can serve as relay nodes (RNs) and form a stable inter-segment topology. Basically, most distributed recovery approaches found in the literature, e.g., (Lee and Younis, 2010; Joshi and Younis, 2013; Joshi and Younis, 2014; Joshi and Younis, 2015), are based on the assumption that the surviving segments have sufficient RNs within them and these RNs are available for repositioning without negatively affecting the intra-segment connectivity. This assumption, however, may not hold in practical scenarios where failures randomly take place and a segment may have insufficient RN count to support recovery. To tackle such a challenging recovery problem, we present a novel *R*esource *C*onstrained *R*ecovery (RCR) approach.

RCR aims to reconnect the disjoint segments in a partitioned WSN that has a fixed number 'l' of available RNs that is insufficient for forming a stable inter-segment topology. Therefore, RCR utilizes the available RNs to provide intermittent connectivity amongst the segments. We make the recovery problem even more realistic by restricting the capability of the available RNs. Out of the 'l' RNs available we consider 'l_S' of them to be stationary RNs and 'l_M' to be mobile RNs that can be utilized as mobile data collectors (MDCs). This restriction is due to the fact that some RNs may have low battery life either due to the overhead experienced while participating in the recovery process, or because they may have suffered some damage that impairs their movement. Therefore it is practical for these RNs to be stationary and act as an interface between disjoint segments in order to prolong their lifetime.

Fig. 1 gives a succinct overview of our strategy. Given an ad-hoc WSN, as seen in Fig. 1(a), that suffered a large scale failure due to an external event, the network is partitioned into four disjoint segments as in Fig. 1(b). Our aim is for the disjoint network segments to discover one another and reestablish communication links between them by employing the surviving relay nodes. In the first phase highlighted by Fig. 1(c), segments populate representative RNs towards a common meeting point, the location of which is determined prior to failure and stored within network nodes. If the segment has excess RNs to spare for recovery, they follow the leading RN in a cascaded manner towards the meeting point. Once connected at the center, the RNs exchange information with one another and now know the number of RNs available for recovery and how many of them can be employed as MDCs and stationary RNs. Based on this information exchange, in the second phase the segments are divided into groups whose count is equal to the number of MDCs so that each MDC is assigned a subset of segments to tour. In the segment grouping process, we can utilize some of the stationary RNs as interfaces between various groups to ensure balanced tour loads on the MDCs. In the third and final phase the remaining stationary RNs that are unutilized during the grouping process are employed to shorten the travel path of the largest MDC tours. Fig. 1(d) shows the final reconnected topology.

RCR is validated through simulation experiments. The simulation results show that RCR outperforms competing schemes and produces tours that are not only smaller in total length but they also share the travel load more equitably and thus improve data latency. The rest of the paper is organized as follows. The next section sets RCR apart from existing solutions. Section 3 discusses the system model. Section 4 describes RCR in detail. Section 5 reports the simulation results. Section 6 concludes the paper.

2. Related work

As pointed out in the previous section, proactive strategies that aim to exploit redundancy as a recovery mechanism by forming k-connected topologies do not scale well to handle multi-node failures. In addition, distributed reactive recovery solutions that deal with single node failures e.g., (Das et al., 2007; Akkaya et al., 2010; Senel et al., 2007), cannot be scaled to handle multi-node failures. These solutions require the neighbors of a failed node to collaborate with one another, to either find a replacement for the failed node, or inward movement by all neighbors until connectivity is reestablished. This reliance on neighbors of a failed node does not scale for multi node failures, since in a multi node failure scenario, the scope of failure is unknown, i.e. the nearest healthy node may be many hops away. Surviving nodes will not know in which direction to proceed for recovery unless they store multi-hop information and maintaining a global view of the network state imposes significant messaging and storage overhead.

In the remainder of this section we set RCR apart from published recovery solutions that tackle multi-node failures.

Centralized approaches such as FESTA (Senel and Younis, 2011) and IO-DT (Senel and Younis, 2012) treat recovery as a relay placement problem, which is equivalent to solving for the Steiner Minimum Tree with Minimal Steiner Points (SPs) and Bounded Edge-Length (SMT-MSPBEL) shown to be NP-Hard by Lin and Xue (1999). The solution provides the minimum number and position of RNs that need to be deployed in order to reconnect the network. Although these approaches provide the best possible solution for recovery, they require the entire network state. Hence their use may not be possible in a resource constrained ad-hoc network that does not have access to satellite links or airborne units to provide the entire state. Also these centralized approaches cannot tackle

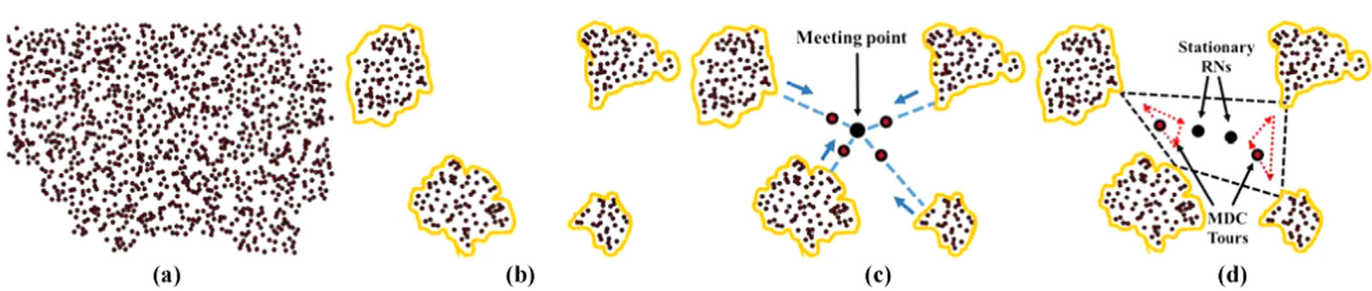

Fig. 1. Overview of RCR. (a) An ad-hoc WSN pre-failure, (b) WSN partitioned into 4 disjoint segments after a catastrophic failure, (c) segments populating RNs towards a common meeting point and discovering one another and (d) two RNs employed as stationary relay nodes to shorten the MDC tours.