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Connectivity restoration in a partitioned wireless sensor network with assured fault tolerance

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ABSTRACT

Wireless sensor network (WSN) applications, especially those serving in inhospitable environments such as battlefield reconnaissance, are susceptible to large-scale damage which usually causes simultaneous failure of multiple collocated sensors and gets the network divided into disjoint partitions. In order to prevent the WSN from being inoperative, restoring the overall network connectivity is crucial. Furthermore, it may be desirable to make the repaired network topology resilient to future single node failures caused by aftermath. In this paper, we present an effective strategy for achieving such recovery goal by establishing a bi-connected inter-partition topology while minimizing the maximum path length between pairs for partitions and deploying the least count of relay nodes (RNs). Finding the optimal number and position of RNs is NP-hard and we thus pursue heuristics. The proposed Connectivity Restoration with Assured Fault Tolerance (CRAFT) algorithm strives to form the largest inner simple cycle or backbone polygon (BP) around the center of the damaged area where no partition lies inside. RNs are then deployed to connect each outer partition to the BP through two non-overlapping paths. We analyze the properties of CRAFT mathematically and validate its performance through extensive simulation experiments. The validation results show that CRAFT yields highly connected topologies with short inter-partition paths while employing fewer RNs than competing schemes.

1. Introduction

In recent years, numerous applications have fueled interest in WSNs, especially those serving in harsh environments [1]. In a hostile application setup, such as coast and border surveillance, search-and-rescue and battlefield reconnaissance, the unattended operation of miniaturized sensors would decrease the cost of the application and avoid the risk to human life. 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 [2]. Upon deployment, the sensor nodes are expected to stay reachable to each other in order to coordinate their actions while performing a task, and to forward their readings to in situ users. Therefore, the inter-sensor connectivity has a significant impact on the effectiveness of WSNs and should be sustained all the time.

Meanwhile, a sensor is susceptible to failure due to the small form factor and limited onboard energy supply. Moreover, a WSN deployed in a harsh environment is susceptible to partitioning due to: (i) a failure of a single node caused by battery depletion, malfunction of external hazard, if the faulty node is a cut vertex, or (ii) simultaneous failure of multiple collocated nodes. The former can be mitigated by provisioning bi-connectivity so that the network does not get partitioned. The latter is handled by relay node placement to re-establish a connected

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inter-partition topology after the failure takes place, as in the case of our proposed CRAFT approach. Mitigating the simultaneous failure of multiple collocated nodes through resource provisioning would require massive resources that will most probably involve nodes outside the area of deployment due to susceptibility to damage. Thus, it is not cost effective to guard the network against such type of failure. Therefore, CRAFT reacts to simultaneous node failure and provisions resources to tolerate only a single node failure in the recovered network topology since it could be more possible due to aftermath or unexploded bombs, etc., in addition to contemporary causes of failure such as exhaustion of the onboard energy supply and electronic breakdown. In addition, the probability of a single node failure is higher than that of multiple collocated nodes failure, bi-connecting the partitions helps to reduce the probability of network re-partitioning after recovery. Fig. 1(a) shows an articulation, where the area covered by dark circles represent the extent of the damage, after which the surviving sensor nodes are grouped into seven disjoint partitioned WSNs due to the loss of connectivity. Restoring inter-partition connectivity would be crucial so that the WSN becomes functional again. A similar scenario arises when multiple autonomous WSN segments are required to collaborate to achieve a common task as seen in Fig. 1(b). Forming a bi-connected inter-segment topology, i.e., establishing two vertex-disjoint paths among every pair of segments would boost the application robustness and balance the inter-segment traffic in a network.

We shall use the term federation to refer establishing connectivity in both scenarios, i.e., repairing a damaged WSN or linking multiple independent WSN segments. Federating multiple WSN partitions while forming a bi-connected topology is an under-researched problem. When the network nodes are not mobile, the topology cannot be autonomously reconfigured and relays nodes (RNs) need to be deployed to achieve the federation goal. Naturally the RN count opts to be minimized in order to cope with resource scarcity or just to cut the federation overhead. Therefore, the federation problem is fundamentally how to establish a 2-vertex connected inter-partition topology where no cut-vertex exists by deploying the least RN count. Such RN placement optimization problem can be mapped to forming Steiner Tree with minimum Steiner points and Bounded Edge-Length, which is proven to be an NP-hard problem by Lin and Xue [3]. In order to address such complexity this paper presents CRAFT, a polynomial-time Connected Restoration algorithm in a partitioned WSN with Assured Fault Tolerance. In addition to the 2-vertex connectivity, CRAFT also opts to: (i) reduce the maximum path length between pairs of segments in order to help in bounding the inter-partition data latency, and (ii) boost the average node degree in order to further provide route alternatives and enable load balancing.

CRAFT strives to identify an inner ring formed by exploiting the Steiner Point (SPs) which connect outer partitions with the fewest relays based on which non-ring partitions are bi-connected by exploiting the found SPs to the ring. The rationale is that a ring is a bi-connected topology that involves the fewest edges among the partitions. Given that CRAFT opts to employ the fewest relays, finding the least-cost cycle, ring, in a graph is NP hard and thus heuristics are pursued. CRAFT operates in two phases. In the first phase, CRAFT forms the *largest inner simple cycle,* referred to as *backbone polygon* (*BP*), which does not contain any partition. CRAFT opts to find the *BP* by creating an inward growing topology from the outmost partitions. This is done in rounds. The first round forms the convex hull of all partitions and identifies an SP of every three adjacent partitions on the convex hull. The set of partitions and SPs will be collectively referred to as terminals. In each of the subsequent rounds CRAFT identifies *border terminals* (*BTs*) in the set *S* of unprocessed SPs and P_i's, i.e., were not considered in any of the previous rounds, by computing the convex hull of all elements in *S*. Then, the newly found SPs, each of which connects a group of three adjacent *BTs*

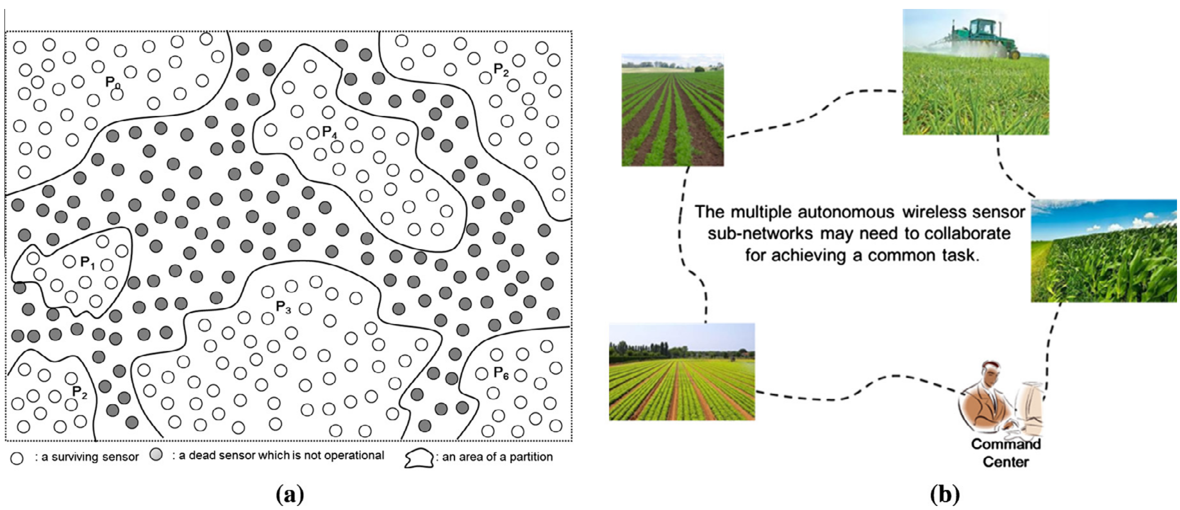

Fig. 1. Illustration of two scenarios which require inter-partition connectivity in WSNs, (a) the dark circles represent dead sensors in the damaged area; the surviving (light) sensors are split into seven disjoint partitions. (b) Four standalone WSNs are to be federated in order to achieve a common task, e.g., set pressure of water sprinklers.