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Optimized bi-connected federation of multiple sensor network segments

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ABSTRACT

Wireless sensor networks (WSNs) serving in hostile environments are susceptible to simultaneous failure of multiple collocated nodes that cause the network to split into distinct segments. Restoring connectivity would be needed to resume full WSN operation. Similar scenario is encountered when autonomous WSNs have to collaborate for achieving a common task. Proactively provisioning spare connections would be also desirable to prevent possible partitioning caused by a single node failure in the federated topology. In this paper, we present an optimized strategy for establishing 2-vertex distinct paths between every pair of segments or individual WSNs while minimizing the number of the deployed relay nodes (RNs) and increasing the efficiency of the resulting bi-connected topology in terms of average node degree. The proposed Optimized Bi-Connected federation of multiple sensor network segments (OBiC) algorithm strives to form a single simple cycle which visits every segment exactly once. The least number of relays are populated along the steinerized edges of the formed bi-connected topology by the cycle and thus 2-vertex inter-segment disjoint paths are guaranteed. We analyze the properties of OBiC mathematically and validate its performance through extensive simulation experiments. The validation results show that OBiC yields highly-connected topologies with short inter-segment paths while employing fewer RNs than competing schemes.

1. Introduction

WSNs have attracted growing interest in recent years due to their numerous applications, especially those serving in harsh environments [1]. In a hostile application setup, such as coast and border surveillance, search-and-rescue and battlefield reconnaissance, employing a WSN that operates unattended would decrease the cost of the application and avoid the risk to human life. Since a sensor node is typically miniaturized and constrained in its energy, computation and communication resources, a large set of sensors are deployed to ensure area coverage and increase the fidelity of the collected data [2]. 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. Such a failure may be limited to a single node that is caused by battery depletion, or due to malfunction or external hazard. If the faulty node is critical, i.e., serve as a cut-vertex in the WSN topology, the network may get partitioned into disjoint segments [5]. Such partitioning can be avoided by provisioning bi-connectivity at the time of network setup. Moreover, WSNs operating in a harsh environment

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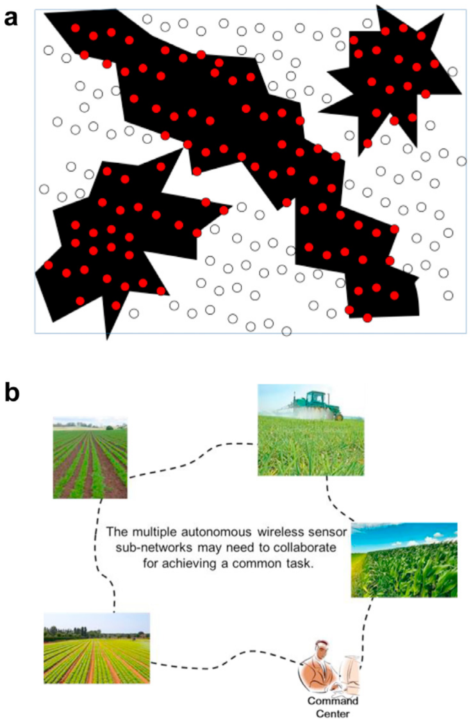

Fig. 1. Illustration of two scenarios which require inter-segment connectivity in WSNs, (a) a partitioned WSN due to multiple failure of collocated sensors (b) standalone WSNs are to be federated in order to achieve a common task, e.g., set pressure of water sprinklers.

may suffer from a major damage that results in simultaneous failure of multiple collocated nodes causing the network to split into disjoint segments. For example in a battlefield, parts of the deployment area may be attacked by explosives and some nodes get destroyed. Fig. 1-(a) shows an articulation, where the dark circles represent the damaged nodes and the surviving sensor nodes, denoted by light circles, are grouped into seven disjoint partitioned WSNs due to the loss of connectivity. This type of failure is handled by relay node placement to re-establish a connected inter-segment topology after the failure takes place. Mitigating the simultaneous failure of multiple collocated nodes through resource provisioning at the time of network setup 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.

The focus on this paper is on recovery from the simultaneous failure of multiple collocated nodes with an additional objective of tolerating future single node failures in the recovered network topology. The rationale for such an objective is that shortly after the recovery a node may be damaged due to aftermath or unexploded bombs, etc. In addition, the probability of a single node failure is generally higher than that of multiple collocated nodes, due to causes such as exhaustion of the onboard energy supply and electronic breakdown, as mentioned above. Bi-connecting the formed inter-segment topology will help in reducing the probability of network re-partitioning after recovery. In addition to WSN partitioning caused by node failure, another scenario is considered in the paper where 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 the network.

We shall use the term *federation* to refer to establishing connectivity in both scenarios, i.e., repairing a damaged WSN or linking multiple independent WSN segments. Federating multiple WSN segments 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 relay nodes (RNs) need to be deployed to achieve the fedeartion goal. Naturally the RN count opts to be minimized in order to reduce the federation overhead. Therefore, *the federation problem tackled in the paper is fundamentally how to establish a 2-vertex connected inter-segment topology 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 OBiC, a polynomial-time Optimized Bi-Connected federation of multiple sensor network segments. In addition to the 2-vertex connectivity, OBiC also opts to boost the average node degree in order to further provide route alternatives and enable load balancing.

In order to meet the bi-connectivity goal with the least cost, OBiC strives to form a single simple cycle of all segments which is a Hamiltonian cycle. A Hamiltonian cycle of a graph allows no repetition of vertices (segments) other than the repetition of the starting and ending one. Finding a Hamiltonian cycle is a known NP-Hard problem [4]. Therefore, OBiC pursues a heuristic approach that is composed of three phases. During the first phase, OBiC constructs a digraph $dG=(dV, dE)$ where each segment is connected to the nearest neighbor inward toward the center of the area and also linked to at least one outer segment. For identifying the inter-segment inward edges, OBiC groups segments as tiered border terminals found by a nested set of convex hulls of the segments. Based on the found *dG*, in the 2nd phase OBiC strives to identify a concave hull of the segments, denoted by *Cave*. Then OBiC opts to bi-connect the segments inside *Cave* using the found inward edges in *dE*, which results in more distorted concave hull with its size minimized. Throughout the minimization of *Cave*, OBiC eventually forms a Hamiltonian cycle, represented as an undirected graph $G_{2c} = (V_{2c}, E_{2c})$. During the 3rd phase, OBiC optimizes the identified G_{2c} by reducing the total length of the circumference and finally populates the least count of RNs on each edge $e \in E_{2c}$ to connect the two end segments of *e*.

The rest of the paper is organized as follows. Related work is covered in Section 2. The problem is formally defined and the considered system model is described in Section 3. The details of OBiC are provided in Section 4. The validation results are presented in Section 5. The paper is finally concluded in Section 6.