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Round-table negotiation for fast restoration of connectivity in partitioned wireless sensor networks

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ABSTRACT

This paper addresses the problem of restoration of connectivity in wireless sensor networks after multiple simultaneous node failures. Such failures of multiple nodes may split the network into several clusters. These clusters are unaware of their own size, surviving nodes and links as well as size and location of other survivor clusters. A distributed and autonomous approach of reconnecting disjoint clusters in a short time is proposed, in which each survivor cluster undergoes a self-discovery process where it compiles information of connected survivors and then sends a negotiator to participate in a round table negotiation and decision-making process. All such negotiators exchange information and decide upon reconnection paths between clusters through known dead node locations and then assign nodes to be deployed on those paths, using available nodes. The negotiators then return to their respective clusters, convey the decision and the reconnection process is carried out. Analytical results of the self-discovery process have been obtained and simulation results on a large network are presented to illustrate the process. It is shown through a detailed comparison with existing methods that the proposed approach achieves reconnection in significantly lower time and compares favorably with respect to other performance metrics as well.

1. Introduction

Wireless Sensor Networks (WSNs) consist of a group of nodes, with their locations spread over a large geographical area, connected through a network of wireless links, and designed to perform tasks such as gathering and communication of information. These nodes could themselves be capable of mobility and could be placed on mobile platforms like Unmanned Air Vehicles (UAVs) or robots. WSNs have a wide range of applications in search and rescue, monitoring and surveillance in war zones, disaster affected areas, agriculture, industries and more. Use of these systems has increased in recent times as they can operate without any direct and real time human control and in environments where deployment of manpower is not feasible. For the group to operate effectively, constant and complete coordination and communication is essential, which is done over auto-established links only with neighbors within a certain communication range. If some incident, such as an explosion in a war zone or some natural calamity causes loss of multiple nodes, the network may split into different disjoint clusters with no inter-cluster communication. This halts their operation and thus connectivity between those clusters needs to be restored using available resources.

1.1. Motivational example

As shown in Fig. 1(a), nodes are physically distributed over the desired area and the network is completely connected. The green background denotes connectivity, although the connections themselves are not shown. Each node is equipped with GPS, which keeps record of its current and previous locations. Each node checks for presence of its 1-hop neighbors through periodic messages, called heartbeat messages. Subsequently, the area shaded in gray is affected by the blast (see Fig. 1(b)), that is, the nodes in that area are destroyed, causing loss of connectivity as the network gets fragmented. Clusters of surviving nodes are formed where intra-cluster connectivity exists but inter-cluster connections are lost, as shown in Fig. 1(b). This is detected by absence of periodic messages between the nodes in the network. After the event, the individual clusters are unaware of their own size and the size and location of other surviving clusters as connections between them have been destroyed. For the network to start functioning again, even with reduced capability, the first requirement is to establish connectivity between clusters. The restoration process needs to take care of various constraints, based on the environment and capabil-

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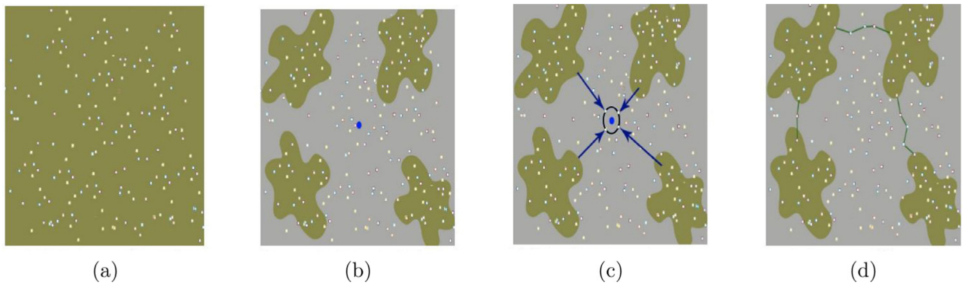

Fig. 1. Illustration of the proposed approach (a) Connected WSN (b) Partitioned WSN with clusters (c) Round table negotiation (Proposed approach) (d) Reconnected network.

ities of nodes. Identification of those clusters is a problem in itself as the nodes do not have information of other surviving nodes in the cluster and a list of such nodes in each cluster has to be created. Once identified, the objective is to restore inter-cluster connectivity with minimal changes in intra-cluster connections.

1.2. Related work

Connectivity restoration in partitioned WSN has been a topic of research with various researchers. Collectively, this body of research has exploited the central idea of node mobility [1–25], placement of additional relays [26] and advanced control methods like optimal control and game theory [26–28]. The approaches based on node mobility can be further categorized into use of only stationary relays [1–21] and a mix of stationary relays and mobile data collectors (MDCs, which continuously travel along their defined routes to connect clusters and collect data) [22–25].

Apart from the heuristics followed for connectivity restoration, these approaches can also be classified on the basis of objectives. The major groups thus obtained are minimization of (i) deployed node count [1–20,26–28], (ii) total travel distance [1,3,14–18,22–28], (iii) largest individual tour length [3,14,22–26], (iv) average tour length [4,24], (v) energy consumed [21], (vi) hop count [4–7], (vii) number of messages [9,15,16], and maximization of (i) coverage [8], (ii) average node degree [2,5,7,20].

In [1–21], nodes from the survivor segments are used as stationary relay nodes, placed at points defined on reconnection paths between the segments. These points are defined using different techniques, for example, incremental optimization based Delaunay triangulation (IO-DT) [1], Steiner points [2,4], geometry of the deployment area and the survivor segments [3–7], Fermat points [12,13], and various other heuristics. The approach used in Joshi et al. [1] and Lee et al. [2] deploy cascaded nodes from survivor segments toward the center. In [1], the deployed node count is optimized using incremental optimization based delaunay triangulation (IO-DT) and in [2] Steiner minimum tree is used. In [3] and [5], the shape of the deployment area is exploited and the geometric shapes are defined. Stationary relays from segments are federated along those shapes to restore connectivity. Lalouani et al. [4] present an approach which identifies the border nodes for each segment and forms their convex hull. Full Steiner trees (FSTs) are defined for each subset of boundary nodes based on straight skeleton, which are then concatenated so as to form minimum cost MST and relays are federated along it. In Lee et al. [6], relays are placed on a defined convex hull and then repeated steinerization is done for optimization. Lee et al. [7] establish a cut-vertex free topology which is tolerant to a single node failure by providing 2-vertex disjoint paths between every pair of partitions. It forms 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. Hwang et al. [8] choose leader nodes closest to the center, define the smallest convex hull using n nodes and the center, and place nodes on and in the convex hull to reconnect. This approach intends to form 2-connected topology, that is, each partition is connected to two other partitions to enhance fault tolerance. Sreejith et al. [9] propose an idea where a mobile node explores every undiscovered area of the map and based on this discovery data, a suitable topology is calculated to connect partitions using minimum number of nodes. In [10], redundancy of robots is exploited to restore connectivity. The robots either move on a defined grid or intend to connect to islands (formed partitions). Thomeczek et al. [11] consider the restrictions in node mobility due to obstacles, persistent dangers over damaged locations, and constrained nature of nodes. So, a mission-aware healing algorithm is defined to achieve connectivity restoration. Ranga et al. [12,13] use fermat points using a trio of segments toward the center of the area to define the location of relay nodes to be deployed. The key idea is to deploy the relays toward the centroid of the triangle instead of finding the Steiner points separately. Shen et al. [14] present an approach which uses a mobile robot to collect information of survivor clusters and identify border nodes. Shortest distance between border nodes are calculated and new optimal location for restoration nodes are calculated, which are federated to restore connectivity. Chouikhi et al. [15] propose two centralized approaches (proactive and reactive) which target the reorganization of the network in the vicinity of the failed nodes to restore the connectivity and hence ensure an optimal channel allocation. In Akkaya et al. [16], underlying sensors detect sub-networks and pick one actor from each segment which knows the ID and location of the others. Two (closest) actors in separated sub-networks are chosen and made to move toward each other in a cascaded fashion (if necessary) until a communication link is established. Abbasi et al. [17] proposed relocation of least number of nodes and reduced the traveled distance and message complexity utilizing existing path discovery activities in the network in order to know the structure of the topology. In ul-Hasan et al. [18], cognitive radio based relays move in the area and try to establish connection among various segments of the damaged network. The objective is to restore connectivity quickly with small number of possible relay nodes. Wang et al. [19] propose a centralized algorithm to restore connectivity using a small number of relay nodes. They propose a 'restore' algorithm to find the shortest distance between two clusters and reconnect, and a 'reinforce' algorithm to strengthen connectivity within or between clusters. Senel et al. [20] present three novel heuristics, namely, Optimized Triangle Selection based on Minimum Spanning Tree Triangulation (OTS-MST), IO-DT, and a hybrid approach involving both. The OTS-MST heuristic considers triangles that have two MST edges and picks the subset of these triangles which provides the highest reduction in the total number of required RNs as compared to a solution that is based on steinerized MST edges. IO-DT calculates the Delaunay triangulation of terminals and iterates over the formed triangles. In each iteration, the algorithm steinerizes a triangle as part of the final topology if selecting such a triangle reduces the