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Multi-objective hierarchical algorithms for restoring Wireless Sensor Network connectivity in known environments

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ABSTRACT

A Wireless Sensor Network can become partitioned due to node failure, requiring the deployment of additional relay nodes in order to restore network connectivity. This introduces an optimisation problem involving a tradeoff between the number of additional nodes that are required and the costs of moving through the sensor field for the purpose of node placement. This tradeoff is application-dependent, influenced for example by the relative urgency of network restoration. We propose a family of algorithms based on hierarchical objectives including complete algorithms and heuristics which integrate network design with path planning, recognising the impact of obstacles on mobility and communication. We conduct an empirical evaluation of the algorithms on random connectivity and mobility graphs, showing their relative performance in terms of node and path costs, and assessing their execution speeds. Finally, we examine how the relative importance of the two objectives influences the choice of algorithm. In summary, the algorithms which prioritise the node cost tend to find graphs with fewer nodes, while the algorithm which prioritise the cost of moving find slightly larger solutions but with cheaper mobility costs. The heuristic algorithms are close to the optimal algorithms in node cost, and higher in mobility costs. For fast moving agents, the node algorithms are preferred for total restoration time, and for slow agents, the path algorithms are preferred.

1. Introduction

Wireless Sensor Networks (WSNs) consist of multiple sensing and relay nodes organised into a cooperative network which communicate with each other using radios, exchanging information, making joint decisions on network and sensing configurations, and transmitting their data over multiple hops to one or more sink nodes. The sink nodes have access to the wider world and are more powerful than sensor and relay nodes in terms of memory, power, computation, etc. Many sensor nodes with limited resources are deployed in the vicinity of the phenomenon of interest along with a small number of sink nodes which gather and process data. Sensors play dual roles: generating data and relaying data from other sensors to a sink.

Wireless Sensor Networks have been used widely in industry, science, transportation, civil infrastructure, and security. Many applications expose WSNs to danger such as direct attack in a battlefield or accidental damage from wildlife and weather, and collapsed buildings. In addition, sensor nodes have limited power sources, and thus they can fail due to depleted batteries. Network connectivity can be significantly degraded upon the loss of just a few nodes. The loss may partition the network, in which groups of nodes may only be able to communicate with each other, with no route to the wider network. This leads to a longer delay in the messages or a network that no longer functions due to many nodes being disconnected.

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Therefore, to overcome sensor node failure and to restore network connectivity, network repair should be initiated, where we must place new nodes in the environment to restore connectivity to the sink for all sub-partitions. It is this issue that we consider in this paper.

There are four main subtasks in the problem: (i) determining what damage has occurred (i.e. which nodes have failed and what radio links have been blocked); (ii) determining what changes, if any, have happened to the accessibility of the environment (i.e. what positions can be reached, and what routes are possible between those positions); (iii) deciding on the positions for the new radio nodes; and (iv) planning a route through the environment to place those nodes. The problem thus involves both exploration and optimisation, and depending on circumstances may require the placement of nodes before the changes to connectivity and accessibility have been fully mapped. In this paper, we consider the simpler problem in which we assume the exploration tasks have already been completed, and so our aim is to optimise our use of resources in the static fully observed problem. We assume possible locations for new radio nodes are limited to a finite set of positions where a node can be securely placed and which can be accessed. Physically moving around the environment may be expensive in energy use, may take significant time, or may expose the agent placing the nodes to danger, and thus solutions which allow cheaper path plans are also preferred. Depending on the application, either one of the two objectives may be more important: placing expensive nodes in, for example, agricultural pollution monitoring favours solutions with fewer nodes, while restoring connectivity during disaster response favours solutions that can be deployed quickly even if they require more nodes. Thus the network repair problem is multi-objective.

In general, WSN applications require the minimum number of deployed nodes not only to reduce the node cost but also to reduce the maintenance cost. Some of these applications might require a quick recovery, e.g. intrusion detection, or air pollution monitoring (which monitors the concentration of dangerous gases), etc. One specific application where the joint optimisation of connectivity restoration and route planning could be pursued is the intrusion detection where a deployed WSN may be destroyed by intruders or by accidents and new nodes need to be positioned quickly to restore the system. Another application could be firefighters search and rescue in a building, where a deployed WSN was wiped out by a fire. However, information for evacuation such as fire spreading and locations of survivors in the building need to be collected quickly. In these scenarios, the joint optimisation can be pursued to minimise the cost of new positioning nodes and also the time to repair the network. Our contribution is the novel problem of simultaneous network connectivity restoration with constrained route planning, in the presence of obstacles, and the development and analysis of a family of hierarchical algorithms including complete algorithms and heuristic algorithms. We assume a known connectivity graph which includes all possible new node locations and existing nodes, and where the edges indicate that two positions could communicate with each other. We also assume a mobility graph over the same set of positions, but where the edges represent a possible motion path between two positions.

We first consider hierarchical objectives, and propose two complete algorithms (Optimal Node Algorithm (N-OPT) and Optimal Path Algorithm (P-OPT)). We then study an algorithm for finding the Pareto set, which contains all non-dominated solutions – that is, solutions that improve on all other solutions on at least one of the objectives. Because the runtimes of the complete algorithms are not very efficient (long runtimes), we propose two heuristic algorithms which prioritise the different objectives: Shortest Cheapest Path algorithm (SCP) prioritises node cost and Integrated Path algorithm (IP) prioritises mobility cost. We evaluate our proposed algorithms on randomly generated graphs, varying the number of terminals and the graph density, comparing the node cost and mobility cost for each algorithm. We also assess the total time for restoration, incorporating CPU time, movement time and installation time, for different speeds of agent. We have found that the SCP algorithm tends to find graphs with fewer nodes, while the IP algorithm finds slightly larger solutions but with cheaper mobility costs. The SCP algorithm is significantly faster, particularly on dense graphs. Both SCP and IP are close to N-OPT in node cost (approximately one extra node for SCP, and two extra nodes for IP compared to N-OPT), and higher in mobility costs than P-OPT (approximately between 16% and 22% for SCP, and between 10% and 13% for IP). In addition, SCP and IP are close to the Pareto frontier in node cost but quite far from the Pareto frontier in mobility cost. We have also found that the capacity of an agent impacts the choice of heuristics. For fast moving agents, the SCP algorithm is faster in total restoration time, and for slow speed moving agent, the IP algorithm will be faster.

In the remainder of the paper, we discuss research background and some related work, then we introduce the network repair problem, followed by details of the proposed algorithms. We then describe the experiments and results, and finish with the conclusions.

2. Background and related work

The wireless communication network and the mobility problem can be represented as graphs. An undirected graph G is a pair (V, E), where V is a set of vertices, and E is a set of edges $E = \{\{x, y\} : x \in V, y \in V\}$. We can augment a graph with a cost function, which is normally either a vertex-weight $w : V \rightarrow N$ assigning a weight to each vertex, or an edge-weight $c : E \rightarrow R$ assigning a weight to each edge. The vertex-weight of G is then $\Sigma_{v \in V} w(v)$, while the edge-weight of G is $\Sigma_{e \in E} c(e)$. A subgraph S of G is a graph $S = (V', E')$, where $V' \subseteq V$ and $E' \subseteq E$. A path P from vertex x_0 to x_n in a graph G is a sequence of oriented edges $\langle (x_0, x_1), (x_1, x_2), \ldots, (x_{n-1}, x_n) \rangle$, where $\{x_{i-1}, x_i\} \in E$, for each i from 1 to n. The edge weight of a path P is $\Sigma_{e \in P} c(e)$. A circuit is a path in which $x_n = x_0$. A cycle is a circuit in which $x_0 (= x_n)$ is the only vertex that appears twice. A connected graph is one in which there is a path between every pair of vertices. A graph is said to be k-connected if it remains connected whenever fewer than k vertices are removed. Given