Connectivity Restoration in WSN Using Minimal Topology Changes

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Abstract—In wireless sensor networks, the efficiency mainly depends on the network connectivity among the nodes as well as coverage of the monitoring area. Failure of nodes due to technical faults or power exhaustion may disturb the existing connectivity by partitioning the network. Node replacement mechanisms are used based on the controlled mobility with the handling of node failures. The idea is to identify the critical nodes which cause the network partitioning and to designate the failure handlers for them suddenly after the network deployment of sensor nodes. To increase the network coverage by identifying the coverage holes and move the mobile nodes to a certain distance. The connectivity restoration process is done using the failure handler with identified movement distance. The effectiveness of the proposed approaches will be validated through simulation experiments.

Index Terms— Connectivity, Coverage holes, Failure handling, Minimal Topology changes, Network Coverage, Nodefailure, Relocation process.

1 Introduction

WIRELESS Sensor Networks consist of small sensor sor nodes deployed randomly over an area to monitor the environment or detect intrusion. The connectivity of the network and the coverage provided by the network is very crucial for the effectiveness. Sensor nodes are equipped with detectors for intrusion, sensing the changes in temperature, humidity, chemicals, or any other characteristic of the environment that needs to be monitored. The environment is constantly observed, consolidated, and sent to a monitor or Base Station (BS). Data transmission from the sensors to the BS can be periodic, event-triggered, or in response to a query from the BS. While each sensor node has limited computation capabilities and usually non -rechargeable battery power, the collaboration among thousands of sensors deployed in a region makes sensor networks a powerful system for observation of the environment. Many of the important applications of sensor networks demand autonomous mobility for the sensor nodes. Various types of mobility have been considered for the mobile node [4]. These can be broadly classified as random, predictable or controlled.

In the predictable mobility the mobile element is mounted on a bus like vehicle. The sensor nodes learn when the vehicle comes near them, and wake up accordingly to transfer their data. In the controlled mobility all the sensors can move on demand in addition to their sensing capabilities. This work has been done under the paradigm of controlled mobility.

Connectivity in the network is lost due to network partitioning, where partitioning of network is caused by the failure of a node which is serving as a cut-vertex (i.e., a gateway for multiple nodes). Each node should determine whether it is a cut-vertex or not, in advance. The cut-vertex is determined by cut-vertex determination algorithm. In this algorithm the network graph is converted into depth first spanning tree.

One such cut vertex nodes are identified; each node designates the appropriate neighbor to handle its failure. The designated node picks a node, called dominatee, whose absence does not lead to any partitioning of the network. This is achieved by utilizing the Connected Dominating Set (CDS) of the whole network. The CDS algorithm identifies the dominating elements called dominators (an element of CDS) and dominatees (1-hop away from a dominator). The cut vertex determination and the failure handler detection processes are done initially when a sensor network is deployed.

The failure handling process is a dynamic process which has been held after the failure occurrence. At the time of these processes, the assumption is that only one node fails at a time and no other node fails until the connectivity is restored. The failure handling process is achieved by the movement of every node in the failure handling set to their feasible points determined by the MTC. To avoid the energy loss of a particular node served as failure handler every node in the failure handling set participates in the failure handling process. The migration of set of nodes for reconfiguration of network would cause coverage holes in terms of sensing modalities. These coverage holes have to be minimized to improve the efficiency of the network. To reduce the coverage gaps, the failure handler is placed in the surrounding of the failed node without affecting the connectivity. The technique is named as Minimal Topology Changes (MTC). The location of the nodes in the failure handling set is identified using MTC.

This technique reduces the Total Movement distance of all the Nodes (TMN) and increases the total coverage area.

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2 Related Work

In Wireless Sensor Networks, mobility of a sink may provide an energy efficient way for data Collection. Node mobility has been exploited in wireless networks in order to improve various performance metrics such as network lifetime, throughput, coverage, and connectivity. Two types of mobility were considered in these efforts: inherent and controlled mobility. Inherent mobility can be further classified as random and predictable depending on the travel path. Controlled mobility of the internal nodes within the WSN has mostly been exploited to improve the network lifetime and coverage. In this case, mobile nodes are used as carriers to relay data from sources to the destination [4].

The Dai's algorithm [5] also strives to restore the connectivity when a cut-vertex node fails using cascading movement. But it does not provide a mechanism to detect cut-vertices. As mentioned in [6], the communication range (*Rc*) and sensing range (*Rs*) of each sensor can be controlled or adjusted by itself so that coverage and connectivity can be guaranteed. The main objective of coverage maintenance is to compensate the loss of coverage with minimum expenditure of energy. Dynamic Coverage Maintenance (DCM) schemes exploit the limited mobility of the sensor nodes. The basic vector construction method is keyed in [7]. The connectivity failures are not considered in this work and mobility of the sensor nodes is limited.

In CCAP proposed in [12] the coverage of the actor nodes are maximized with connected interactive topology. But the coverage area reduction due to node failure is not considered. COCOLA [13] deal with the connectivity restoration using mobile nodes. It fixes extra nodes in the network for repositioning of failure nodes. DARA [14] is also deals with restoration of connectivity when a cut-vertex fails.

It does not find the cut-vertex and just assumed that the network details are available in the node itself, which require the knowledge of the whole network topology. The dominators and dominatees are used in CDS formulation. This approach eliminates the concept of information gathering at each node, which may require the knowledge of the whole topology. The key concepts of CDS formation is discussed in [2]. The main advantage of connected dominating set is that it centralizes the whole network into small connected dominating set sub network, so that network topological changes do not affect this sub network. The reduced CDS is determined by pruning the current CDS by the process named marking process [3]. The reduced CDS is efficient than CDS.

Single and Multiple Node Failure handling are given in PADRA and MPADRA algorithms specified in [1]. PADRA achieves optimized recovery of a node failure by preplanning the failure handling process. These algorithms use CDS and cascaded movement idea together in order to restore the failure of cut-vertices. In case of a failure, the closest dominatee determined using CDS will start a cascaded movement toward the location of the failed node. If local DFS is used for finding the cut-vertex, then the PADRA is referred as PADRA+. But in this work the coverage holes are introduced in the network after the cascaded movement for connectivity restoration.

From the literature survey, it is observed that most of the researches are related to either the connectivity maintenance of the network or the initial deployment strategy to improve the coverage. The improvement of the coverage area after any modification in the network has not been discussed largely in the literature. Hence, in this work both the connectivity restoration technique and coverage improvement technique are proposed. The reduction in coverage area due to connectivity restoration is minimized by MTC.

3 Problem Definition

The assumption is that the nodes (i.e., sensors) are randomly deployed in an area of interest and form a connected network. The mobility capability is only exploited whenever needed. The nodes in such networks have a limited energy supply. The radio range, denoted by r, of a node refers to the maximum Euclidean distance that its radio can reach. For all the nodes r is assumed to be constant. The Euclidean distance formula is given by,

$$r = \sum_{i=0} \sum_{j=1} ((x_i - x_j)^2 + (y_i - y_j)^2)^{(1/2)}$$

Where x_i, x_j, y_i and y_j are the x and y position of the nodes on the grid. Sensing range for each node, on the other hand, is assumed to be 2r. The energy of each node is fixed initially. The energy is reduced for a particular node if the energy becomes zero, the node is assumed to be failed. Another assumption is that there is no obstacle on the path of a moving node and the nodes can reach their exact locations by maintaining a constant speed.

- The **M**aximum **M**ovement distance of all **I**ndividual nodes (MMI):
  $\max_{i \in s} M_i$
  The maximum distance moved by an individual node for a particular purpose.
- **T**otal **M**ovement distance of all the **N**odes (TMN):
  $\sum_{i \in s} M_i$
  The Total Movement distance of all the Nodes is the summation of all MMIs.

Where, S denotes the set of nodes in the network and Mi denotes the total movement distance for a particular node.

4 MinimalTopology Changes

4.1 Connected Dominating Set (CDS) Computation

The dominators and the dominatees are calculated by finding Neighbor Node List (NNL), Boundary Node List (BNL) and inner node list (INL). The NNL is determined by transmission range of the nodes. If the distance between two nodes is less than the addition of the radii then they

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are said to be neighbors. Neighbors of every node are stored in appropriate NNL. If a node has only one element in its neighbor node list that node is inserted in BNL. Others are inserted in INL. The calculated dominators are stored in the list CDS. The direct neighbors of dominator nodes are taken as dominatees. In most cases the dominatees are selected as failure handler. In some critical situation, the dominator is taken as a failure handler.

4.2 Cut-vertex Determination Algorithm

A cut vertex is defined as a sensor node whose removal breaks network connectivity. The cut vertices are determined by the cut vertex determination algorithm. The network is represented as a graph. The fig 1.a shows the graph and Fig 1.b shows the spanning tree of graph in Fig 1.a the depth first search is done for the spanning tree of the graph. Edge (v,w) is the path between two nodes v and w. where v is the parent and w is the child in the spanning tree.

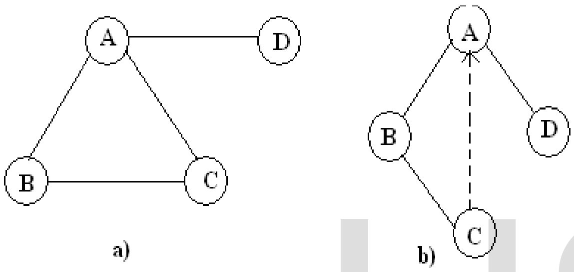

Fig.1 a. Simple graph b. Spanning tree for Fig 1.a.

1. The root (A) of the tree is visited first and marked. Then B is visited from A and marked. where A is v andisw.

2. When the edge (v,w) is considered, if w is unmarked, or, if v is unmarked, the edge is known as tree edge.

The tree edges are denoted as normal lines in Fig 1.b

3. When the edge (v,w) is considered, if w is already marked, and when edge (w,v) is considered, if v is already marked, the edge is known as back edge (i,e) the edge is not a part of the tree. The back edge is denoted as dashed lines in Fig1.b.

4) The cut-vertex is determined by doing the preorder traversal on the depth first spanning tree.

5) The numbers correspond to the order in which a depth search visits the vertices are referred as preorder number (Num(v)) is determined.

6) Then for each vertex v in the depth first spanning tree, the lowest numbered vertex (Low(v)), that is reachable from v by taking zero or more tree edges and then one back edge (in that order) is calculated. Low(v) is minimum of

a. Num(v)
b. Low(w) among all tree edges (v,w)
c. Num(v) among all back edges (w,v)

7) u is an articulation point (cut-vertex) iff u has a child w such that Low(w) >= Num(v) provided u is not a root.

4.3 Recovery Process

The cascaded movement is used from the dominatee to the failed node in order to maintain battery power loss on an individual node. The dotted line shows the direct replacement path. It results in quick energy loss for node F. In the cascaded movement node F replaces node D and node D replaces node A. The TMN can be reduced by fixing the position of the failure handler D in the nearest position of the cut-vertex A, not in the exact position of A. The nearest position is known as 'Minimum Movement Point' shown in Fig 2. It is calculated by the following steps.

a) A position is fixed on the path between the failure handler and the cut-vertex at the distance α metres from the cut-vertex. (α is an integer, 0<α≤10, Initially the maximum value is fixed for α).

b) Then the Failure Handler is moved to the calculated position.

c) The neighbors of the Failure Handler are calculated from the new position.

d) If all neighbors of the cut-vertex are visited by the Failure Handler from the new position then the α value is fixed and the position of the Failure Handler is stored. Otherwise the α value is reduced and the neighbor checking is done until all nodes of the cut-vertex are visited from the new point.

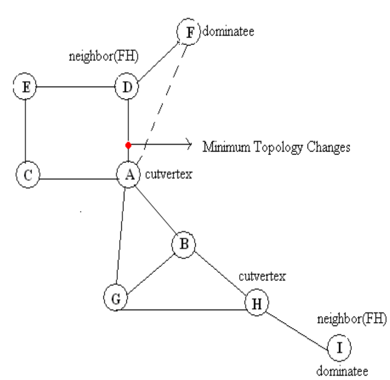

Fig.2 Graph having cut-vertices along with failure handlers

So the connectivity is maintained. In the same way the position of each dominatee is fixed in the surrounding of the next node in the failure handling path without affecting the connectivity.

5 PERFORMANCE EVALUATION

The performance evaluation of MTC algorithms are analysed in this section. The algorithms are evaluated in terms of mobility distance and total coverage area.

5.1 Simulation Setup

The proposed algorithms are simulated using ns-2.34 for different number of nodes that are deployed randomly over 500m × 500m. The number of deployed nodes varies from 10 to 40. In the simulation the TwoRayGround propagation model is taken for Radio Propagation and omni-directional antenna is considered for packet transmission. The IEEE 802.15.4 MAC is considered for the channel access mechanism.

For each sensor node, a fixed amount of 100J reserved energy is assumed. The sensing range of each sensor node is 80m with communication range is twice of the sensing range, i.e. Rc= 2Rs and a homogenous network environment is considered.

6 CONCLUSION AND FUTURE WORK

The cut-vertices and CDS are determined using Cut-vertex Determination Algorithm and CDS algorithm respectively. The dominators and the dominatees are used in the connectivity restoration process. Basically, if a node finds out that it is a cut-vertex, one of its neighbors is delegated to perform failure recovery on behalf of that node. The replacement position is determined within the transmission range of the failed node without affecting the connectivity of the network. The failure recovery is done by determining the failure handling set and replacing the nodes in the failure handling set with the positions calculated using MTC. The movement is shared among the nodes in the failure handling set to avoid the energy loss of the failure handler. The total coverage of the network area is increased up to 5 percent for 40 nodes compare to existing techniques. The total mobility distance of the nodes due to connectivity restoration is reduced by 20m. In future, this problem can be extended to multiple node failure problems for a larger set of nodes.

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