Enhancing Reliability in Backbone Assisted Wireless Sensor Networks

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Abstract: The initial route discovery or the final node to node association is an important metric to determine the performance of any routing protocol. While not remarking on the efficiency of the existing routing protocols, we develop a method to construct an initial backbone structure that can be used for communications. Specific to application domains in a wireless sensor network, the quality of service parameters varies. Our approach is based on a backbone structure that takes care of the robustness of the followed routes by employing a hybrid algorithm "Quasi-MST". Also, it guarantees the communication reliability by maintaining an alternate parent list in case of node failures due to energy depletion. We try to analyze the effect of varying ranges and sink positions on the reliability of the network when subject to node failures. We also put forward a more robust mechanism to counter for route failures.

Keywords: Wireless sensor network, reliability, tree based architecture, minimum spanning tree, breadth first search.

1. Introduction

A wireless sensor network is characterized by energy constrains, intermittent mobility, localization problems. Research, till date, mainly, focus on energy efficiency while others require delay management strategies. Reliable data transmissions in sensor networks have attained very little research attention. One main reason is that usually sensor networks do not require reliable data transmission. This is due to the fact that the sensor measurements that are transmitted are often redundant in nature. Hence, loss of a few packets hardly affects the performance of the sensor based system in entirety. However, for real time applications like structural health monitoring [1], and event detection systems [2], the timeliness and the reliability of data transmission becomes important. Therefore, for one way communications (i.e., from the source (individual nodes) to the sink (base station)), a tree based hierarchy is more suitable. For the simplicity of analysis, we assume a sensor network that has a backbone assisted message transmission system. The tree traversal can be implemented through the standard Breadth First search (BFS), Minimum Spanning Tree (MST) and Depth First Search (DFS) methods. Each has its specific advantages and limitations. The network is organized on the basis of “the within communication radii” constraint. The shortest distance between the nodes is taken as a valid edge since this criterion makes our approach similar to most of the existing routing algorithms.

On observing the MST based architecture we see that the path length to the base station increases due to single connections of the edges on the basis of shortest distance. An MST is a method to obtain a minimum cost spanning tree built edge by edge. The next edge to include is chosen according to the criterion that results in a minimum increase in sum of the costs of the edges so far included. It finds a minimum weight set of edges that connects all vertices. Hence the order of the tree increases leading to more number of hops for message transfer and lesser number of distinct routes to the base station. A BFS on the other hand, connects breadth wise. It finds all nodes within one connected component. It
is the shortest path between two nodes ‘\( u \)’ and ‘\( v \)’ (with path length measured by number of edges). It constructs BFS tree from a graph, reducing the network depth and increases the number of distinct paths to the base station. The chances of successful message delivery increases manifold. As the depth of the Breadth First Search is much smaller than the corresponding MST tree, routing via BFS can support more nodes in the same network layer. However, the links connecting the first level nodes to the next level nodes (downlink) or the base station (uplink) become susceptible to early failures due to faster energy depletion and are often termed in literatures as ‘hot spots’.

Our approach adopts a hybrid strategy to incorporate the advantages of a BFS based communication backbone at the first level and following an MST based connection strategy thereafter. This allows more number of available routes to the sink at the first level and restricts the connections to single routes in the levels following, reducing the chances of ‘Hot Spots’. It is obvious that as a BFS based sink rooted tree can have multiple child nodes, a single parent failure may cause a drastic reduction in reliability and more number of orphan nodes. Our approach aims in presenting a trade off against the availability of redundant routes (for better delivery reliability) to the drastic energy depletion (due to redundant transmissions). Through our algorithm, the path length reduces effectively in contrast to a MST based sink rooted tree, thereby decreasing the obligation of multiple forwarding of the same message. Also, the connections are more distributed with a few nodes acting as the centers for aggregation, offering more uniform energy exhaustion.

The node failures are taken care by selecting an optimal parent based on a selectivity criterion from the alternate parent list (APL) that is maintained by each node. Each node maintains a table containing its current parent and its alternate parent. The node selects the alternative route (using APL Algorithm) to communicate in case the current parent fails to communicate or dies due to energy depletion. Literatures on the concept of redundant routes have been used to improve lifetime of the network or reduction in energy consumption for query based network architectures [3-4]. Ref [5] estimates node and link reliabilities assuming a WSN to be a perfect set of K-designated nodes while Ref [6] outlines constraints like connecting link reliability and cost estimates for topology formation. Applications like structural health monitoring require a more deterministic deployment scheme, where MST based backbone is more suitable. Also, an event detection based application usually encounters a one way communication; where an MST performs well as compared to a BFS [7-8]. This criterion forms the basis of our discussion. Besides, there has been no research to the best of our knowledge, on communication and node reliability estimation of a network based on minimum spanning trees. Hence the consequence can be applied for event detection real time applications suited to disaster control systems.

2. System Model

We consider an event driven wireless sensor network having nodes that are aware of their locations with respect to their randomly generated IDs. The initial backbone construction employs a BFS for the first level connections. These connections then proliferate using an MST subsequently. The paths used for forwarding the sensed data depend on the sensors detecting the event, their hop distance and the selectivity of nodes. This decision for transmitting is done on the basis of weights of the communication links.
Reliability computation

Let an event be detected by 'n' nodes at different levels of a tree (of 'k' levels). The communication reliability of an event is dependent on the reliability of the node in terms of activeness of the node that is proportional to the residual energy of the nodes, the reliability of the link that is determined by the commutative probability of the activeness of the leaf parent consecutive pair. For simplicity, we assume that the route failure due to link disruption because of environmental conditions is negligible and hence the link and route reliability converge.

Let \( V \) denote a set of 'n' sensing devices \( \{v_1, v_2, \ldots, v_n\} \) in an event driven wireless sensor network. Let \( T = (V, E) \) denote the network tree that represents the communication edges \( E \) of the nodes in \( V \). The nodes are considered neighbors if they are within communication range. Reliability is now estimated for such a tree based structure.

Definition 1: Given a tree \( T = (V, E) \), an edge \( (u, v) \in E \), and range \( R \) of a node, then a node \( S_j \) will be the child of node \( S_i \) if and only if \( S_j \) is in range of \( S_i \), where \( (S_i, S_j) \in V \).

Reliability of the node (NR) = Probability of activeness of the node = Remaining energy of the node/ initial energy of the node. Since the activeness of a node 'i' does not depend on the activeness of node 'j' the probability is computed as independent events.

Communication probability of events (CR) = Probability of sending of data from the sensed sensor to the base station.

\[
CR = P(A_k).P(A_{k-1}/A_k).P(A_{k-2}/A_{k-1}) \ldots P(A_i/A_{i+1})
\]

Where \( P(A_i) \) is the probability of the activeness of the node at level 'k' and \( P(A_{k-1}/A_k) \) is the conditional probability of activeness of node at level (k-1) subject to the condition that node at the \( k^{th} \) level is active. Since the node activeness is solely dependent on its own residual energy, \( P(A_{k-1}/A_k) \) reduces to \( P(A_{k-1}) \). Hence equation (1) becomes

\[
P(A_k).P(A_{k-1}).P(A_{k-2}) \ldots P(A_i)
\]

At layer 'k' if \( A_k \) is a parent of more than one nodes (say 'm') 'k+1' th layer nodes then

\[
P(A_k) = P(P(A_{k+1}) \cup P(A_{k+2}) \cup \ldots \cup P(A_{k+m}))
\]

Algorithm (HYBRID)

1) Choose the sink vertex 's' and a set \( S = \{s\} \) and \( A = \emptyset \). By looping through the vertices of neighbors discover and add the unexplored neighbors to a data structure to be explored later forming the first Breadth first search level.

2) Find the lightest edge (weight is determined by the Euclidean distance based shortest path) such that one end joins in 's' and the other is in \( V/S \). Add this edge to \( A \) and its other edge to \( S \).

3) If \( V/S = \emptyset \), then stop and output the minimum spanning tree \( \{S, A\} \); otherwise go to step 1.

4) Compute the communication and node reliability of the links involved in the route from the place of event to the sink using equation 1, 2 and 3.

5) In case a connecting node fails, possible routes are computed using alternate parents (selected on the basis of alternate parent list algorithm) from the stored list of parents maintained by each node.

Alternate Parent List Algorithm (APL)

1) Collect and maintain the neighbour set for each node according to definition 1 and Hybrid algorithm. Sort list according to minimum (cost) weights.
2) Choose one among them which is optimal parent for that node (at the time of reconstruction of the tree) under the given constraints: any node, which is in communication range, should not be the parent itself, should not be the child of the node and if any node exist which is in communication range and belongs to the upper level of the tree.

3) For two or more node fulfilling the criteria for optimality choose the one with low cost. Assign alternate parents to all other nodes in the list in the order of least cost.

4) In case the optimal parent fails, compute route through the next parent in the list.

3. Results

We have implemented the algorithm Hybrid (Qsi-MST) and undertook several experiments with various inputs. Given the set of sensors ‘S’ and the tree level denoted by ‘L’, we get the reliability of communication for a minimum spanning tree (Prim’s and BFS based). These results are further compared to the results of the Qsi-MST (Hybrid) algorithm. The different backbones signify different sink rooted tree topologies generated by changing the sink positions. Results are obtained for different communication ranges for different sink positions, different ranges and averaged over a set of 5000 discrete events for 100 nodes.

Figures 1(a) and (b) depict that the total number of successful deliveries in case of the hybrid algorithm is same as the corresponding MST backbone when the communication radius is less (r=20). This is due to the fact that at smaller ranges the probability of neighbors falling in the vicinity of a sink node is less and hence the first level of the algorithm hybrid does not have many neighbors to connect in a greedy manner. Thereafter there is a significant increase in the successful deliveries in case of our approach for larger ranges and nearly equal to or even better than the corresponding BFS. Figures 1(a) and (b) show the performance of our algorithm without the alternate parent allocation and do not take node failures into account.

![Figure 1](image1.png)

(a) For Different Communication Range  
(b) For Different Backbone Structure

**Figure 1**: Successful Deliveries to Sink for Prim’s MST, BFS and Qsi-MST Approach.

Figure 2 depicts the average of the total consumption of energy of parent nodes in the backbone for the three algorithms. The total energy consumption is computed as the sum of energy spent during transmitting, receiving and during the idle wake up of the parent nodes. The ‘hot spots’ are the parents nearer to the sink that aggregate and forward multiple data of their corresponding child nodes. Thus, we show that the problem of ‘hot spots’ is effectively reduced as the average energy consumption is least for parent nodes through algorithm as compared to BFS or MST based backbones. We assume the energy dissipation for each node follows the first order radio energy model.
Figure 2: Energy Consumption of Parent Nodes

The improvement in the communication reliability is done by employing redundant routes via alternate parents for all the three algorithms. Here, we consider node failures and compute reliabilities according to equations (1), (2) and (3). These results present the performance of the backbone structures on application of the Alternate parent algorithm (APL) against node failures. It can be observed that the reliability of an MST and Qsi-MST can be improved, comparable to the reliability achieved by employing a BFS. Tables 1 and 2 give the details of the amount of improvement in the delivery statistics and the communication reliability for the different backbones.

Table 1: Number of Events Successfully Delivered to the Sink

<table>
<thead>
<tr>
<th>Algorithm Based Structure</th>
<th>Backbone 1 Without APL</th>
<th>Backbone 1 With APL</th>
<th>%Improvement</th>
<th>Backbone 2 Without APL</th>
<th>Backbone 2 With APL</th>
<th>%Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFS</td>
<td>4843</td>
<td>4997</td>
<td>3.08</td>
<td>3832</td>
<td>4593</td>
<td>15.22</td>
</tr>
<tr>
<td>MST</td>
<td>2317</td>
<td>4571</td>
<td>45.08</td>
<td>2884</td>
<td>4780</td>
<td>37.92</td>
</tr>
<tr>
<td>Qsi-MST</td>
<td>3042</td>
<td>5000</td>
<td>39.16</td>
<td>3912</td>
<td>4747</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Table 2: Average Communication Reliability for 5000 Events for Different Tree Structures

<table>
<thead>
<tr>
<th>Algorithm Based Structure</th>
<th>Backbone 1 %Rel without APL</th>
<th>Backbone 1 %Rel with APL</th>
<th>%Rel without APL</th>
<th>%Rel with APL</th>
<th>Backbone 2 %Rel without APL</th>
<th>Backbone 2 %Rel with APL</th>
<th>%Rel without APL</th>
<th>%Rel with APL</th>
<th>Backbone 3 %Rel without APL</th>
<th>Backbone 3 %Rel with APL</th>
<th>%Rel without APL</th>
<th>%Rel with APL</th>
<th>Backbone 4 %Rel without APL</th>
<th>Backbone 4 %Rel with APL</th>
<th>%Rel without APL</th>
<th>%Rel with APL</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFS</td>
<td>95.78</td>
<td>95.09</td>
<td>92.14</td>
<td>92.19</td>
<td>93.46</td>
<td>93.86</td>
<td>75.66</td>
<td>96.15</td>
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<td></td>
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</tr>
<tr>
<td>MST</td>
<td>52.28</td>
<td>65.35</td>
<td>55.33</td>
<td>74.38</td>
<td>55.49</td>
<td>86.62</td>
<td>47.19</td>
<td>83.11</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qsi-MST</td>
<td>76.25</td>
<td>88.86</td>
<td>58.67</td>
<td>85.97</td>
<td>83.29</td>
<td>89.03</td>
<td>66.38</td>
<td>90.30</td>
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4. Conclusions

We run into several wireless sensor network applications that essentially require a backbone assisted communication. Usually an MST is employed for such applications. Our objective of reliable communication is not satisfied by using a BFS based backbone as it is optimal for a network that has equal path lengths between the nodes. Also, for real world applications, cost based weighted graphs are adopted (disqualifying the implementation of a BFS) where the performance of our algorithm is elevated. Unlike the BFS strategy there is only one energy intensive node that happens to be the sink or the base station that can be monitored critically against failures or replenished with energy. This article also presents a simple but effective method to improve the reliability of the
conventional BFS and Prim’s tree based communication backbone architectures. We conclude that though BFS based strategy may exhibit higher reliability for certain cases, our algorithm performance presents a better tradeoff by reducing the problem of single point of failure which is the main drawback for tree based backbones. The Alternate parent list (APL) algorithm shows a further improvement to the Qsi-MST based architecture as per the number of successful deliveries or the average communication reliability. The notable feature in our approach (‘Qsi-MST’) as compared to the BFS algorithm or prim’s algorithm is that the complexity is lesser than $O(n^2)$ and depends probabilistically on the number of nodes connecting to the sink node in a greedy manner. Thus, the algorithm suggests a more robust architecture where a tree based communication backbone structure is obligatory.

References

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