Optimization of Transmission Range for a Fault Tolerant Wireless Sensor Network

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Abstract. Applications of wireless sensor network face many censorious issues, fault tolerance being a prominent one. The problem of missing communication link(s), sensor node(s) and data is unavoidable in such networks. Fault tolerance is important for reliable delivery of data in WSN applications. This ensures the system's availability for use in case of any interruption or occurrence of fault, thus enhancing the availability and reliability. Current work introduces the fault-tolerance behavior of a dynamically generated system of wireless sensor network that comprises of super-nodes and sensor nodes having k - vertex disjoint paths. As the parameters involved in the process of determination of fault-tolerance of a network change, the capacity of the network to tolerate the fault changes accordingly. This paper proposes an algorithm that evaluates the fault tolerance of randomly generated networks based on k - vertex disjoint path connectivity and also evaluates the results.

Keywords: Wireless sensor network · Fault tolerance · Sensor node Topology control · k - vertex-disjoint paths

1 Introduction

Wireless Sensor Network (WSN) can be visualized as a collection of numerous tiny sensors having the capability to sense, process as well as transmit data through wireless links. Sensor nodes generally co-operate traitorously in an autonomous and distributed manner in order to carry out a specific function, generally in a setup that has inadequate or no proper framework (or infrastructure) [1,2]. Fault tolerance and power efficiency are desired features in WSNs with the aim of achieving network functionality efficiently in case of alterations in energy levels, failures in hardware, errors in communication links, malicious attacks, detrimental environmental conditions, or events having a very high probability of occurrence in WSNs [3,4].

Adjusting the communication range of the nodes and/or choosing only specific nodes of the network to control the neighbor set of nodes that would be involved in transmitting the messages is known as topology control [5]. Approaches for topology control can be broadly grouped into two main categories, namely, heterogeneous and homogeneous [6]. When all the sensor nodes

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used have equivalent transmission ranges, it is referred to as a homogeneous approach while in heterogeneous approach, all the sensor nodes used can have different transmission ranges [1].

In this paper, we have considered an algorithm to achieve fault resilient topology control for heterogeneous WSNs, consisting of super-nodes and sensor nodes. The super-nodes have more power reserves and better capabilities in terms of processing and storage capacities. The super-nodes may process the data from the sensor nodes before forwarding it [7,8,12–14]. Links between the super-nodes are considered to possess longer scope and greater data rates; however, due to their high cost, super-nodes are lesser in number. Super-nodes could also possess certain distinctive capabilities such as acting counter to an event or a specific condition.

A WSN is considered to be k-vertex super-node connected if by removing any $k-1$ sensor nodes, the network is not being partitioned [7]. With the aim of minimizing the allocated transmission range and power of each sensor node and also maintaining k - vertex disjoint paths from each sensor node to the set of super-nodes, topology control can be modeled as a communication range allotment task for all the sensor nodes in the network such that there are a minimum of k - vertex disjoint paths from each sensor node to the set of super-nodes in the network.

The rest of this paper is organized as follows: In Sect. 2, the related work is detailed. Section 3 describes the proposed algorithm. Section 4 discusses the results of simulations and Sect. 5 concludes the paper.

2 Related Work

A noteworthy work about fault tolerance and topology control in heterogeneous wireless sensor networks for a two-layered architecture of the network under consideration has been put forth by Cardei et al. [7], taking both into consideration, the k - connectivity as well as the energy efficiency of the network. The focus is on k - degree Anycast Topology Control (k - ATC) problem, that intents to conform the communication scope of the sensor nodes in order to accomplish k - vertex super-node connectivity while curtailing the maximum communication capacity of the nodes. An acquisitive centralized algorithm known as Global Anycast Topology Control (GATC), in addition to a distributed algorithm termed as Distributed Anycast Topology Control (DATC), that yields k - vertex super-node connectivity through incremental regulation of the communication scope of the sensor nodes in the network has been proposed.

In [1], to attain fault-tolerant topologies, the aim is to ensure the existence of at least k - pairwise vertex disjoint paths from any of the sensor nodes to the super-node. A scale-free topology is useful for a WSN's performance, from the facets of both network strength as well as energy efficiency [9]. The Barabasi-Albert (BA) model depicts that in larger WSNs, a significantly small quantity of sensor nodes possess a high degree while a large quantity of nodes possesses a low degree [10]. In [11], the Adaptive Disjoint Path Vector (ADPV) algorithm is performed in two stages: the beginning one being a single initialization phase followed by the restoration phases. It is of great importance to have fault tolerance in the routing paths that originate from the sensor nodes to go up till the super-nodes and gateway nodes, which are considered to be additionally equipped in terms of power than the sensor nodes [4].

We aim at minimizing the transmission range and the cumulative transmission power of the sensor nodes which are used in the network for a heterogeneous topology whereas these papers consider flat homogeneous topographies. Also, we aim at providing a path between every sensor node to the super-node while they focus on the existence of path in between any pair of sensor nodes. The methodologies used in papers [12] and [13] do not consider k - connectivity between the sensor nodes and super-node and hence do not provide fault tolerance when k - 1 node failures may occur. The methods in [14] do consider the issue of k - connectivity but they do not contemplate the energy efficiency in the resultant topographies.

3 Proposed Algorithm

We initially assume that all the inter-node links are present. Algorithm 1 shows the proposed algorithm. The distance between a pair of nodes is taken as the weight of the edge between them. The initial phase is of edge weight updations in the matrix D wherein those edges whose weights are not within the threshold values' range are eliminated and those edges which satisfy this condition are retained. The next stage is the formation of k vertex disjoint paths on the new formed graph after elimination of edges having weights greater than the threshold value. We start by updating the distance matrix D to form minimum weighted paths between any given pair of nodes. This is done so that the obtained vertex disjoint paths will be formed on minimum inter-node distances.

Next, for all the sensor nodes, with the sensor node under consideration as the source s and the super-node as the destination t, we aim to form at least k vertex disjoint paths. Using Dijkstra's algorithm, we look for a path such that the length of the path is minimized by choosing the minimum weighted edges of the nodes in the path. From the obtained set of vertices, which denotes the shortest path from node s to t, note the maximum and the minimum inter-node distances in the path and delete the super-node. This forms the first path for that particular node. If the shortest path obtained was a direct edge between the node and the super-node, the compressed set of vertices in the path will be empty. Else these nodes are to be deleted from the original graph and we proceed by incrementing the k value. This is repeated until the incremented k value matches the k value provided. Among the k paths discovered for a particular sensor node, the paths are not assigned in the same sequence as they are formed. We arrange all the formed paths in the ascending order of the maximum range of the paths. Among these, the path with the least maximum range is assigned as the path for $k = 1$. Amongst the remaining unassigned paths, the next one with the lowest maximum transmission range is allocated as the path for $k = 2$ and the same pattern is followed for the rest of the k values. This process is then repeated for all sensor nodes to obtain k vertex disjoint paths from each sensor node to the super-node.

Algorithm 1

Input: G, N, k, t
Output: path from node to supernode
Algorithm:

```
for i = 1 to N do
    for j = 1 to N do
        if D_{i,j} ≤ t and D_{i,j} ≠ 0 then
            retain edge between i and j
        else
            delete edge between i and j
        end if
    end for
end for
for S_i = 1 to N − 1 do
    G_new = G
    x = 1
    while x ≤ k do
        find path from S_i to supernode (algorithm 2)
        form the set S_i_path_x by deleting supernode from the set denoting path from node S_i
to supernode
        if S_i_path_x == NULL then
            delete edge between S_i and supernode
        else
            delete nodes that occur in S_i_path_x from G_new
        end if
        x = x + 1
    end while
    form a set by sorting the paths as per their maximum range in ascending order
    for K = 1 to k do
        assign the path having least maximum range as path for K and eliminate it from the set
        return S_i_path_K
    end for
end for
end
```

Theorem 1. *For any vertex $v \in G$, we can compute the shortest distance $D_{v,u} \forall u \in V$ by successively considering the shortest distance in between each pair of intermediate vertices.*

Proof. We prove the above theorem by induction on l where l is the length of the path i.e. the number of edges from v to u.

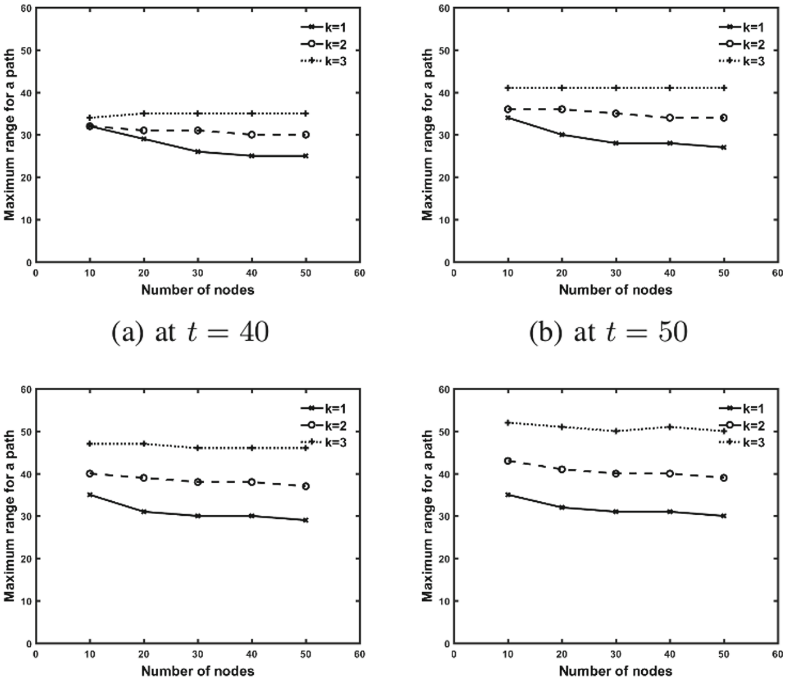
Basis step: $l = 0$. This implies that the set S consisting of the vertices in the path contains only the start vertex v and $D_{v,v} = 0$ is minimum, is true.

Hypothesis: Assume the shortest distance between v and u to be $D_{v,u}$ for a path of length l.

Induction step: We assume that for some k, $l = k - 1$ such that there are k vertices in set S and let w be some vertex such that $w \notin S$ and $D_{v,w}$ is the smallest. One can update $S = S \cup \{w\}$. Using the induction hypothesis, one can claim that for any path to w emerging from S will have minimum distance as $D_{v,w}$. One can say that a path through any vertex $\notin S$ that later reaches w has length at the very least $D_{v,w}$ which is the minimum distance to reach to w from v. Now we know that by adding w to S, path to w from v has shortest length, we can similarly obtain a shortest path from w to u. Thus we can extend this induction hypothesis for $l + 1$ and so on.

4 Results and Discussion

We consider a $100\,\mathrm{m} \times 100\,\mathrm{m}$ region and vary the number of nodes from 10 to 50 for different values of k. The results are reported as an average of 100 instances. Instead of assuring the connectivity between any pair of nodes amongst the sensor nodes, we aim at providing the communication path from each sensor node to the super-node in the network. A threshold is set as the maximum transmission range possible for the nodes.



(a) at $t = 40$

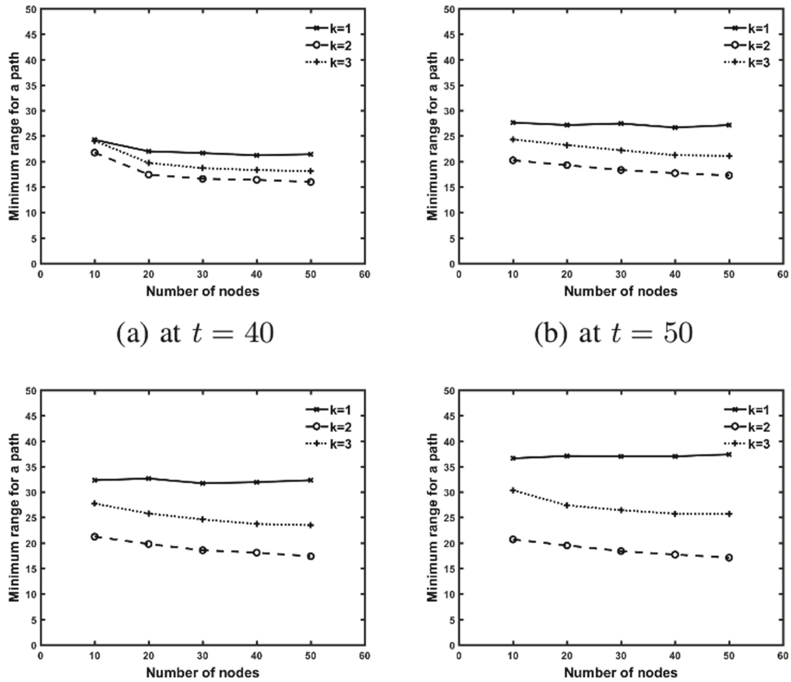
(b) at $t = 50$

(c) at $t = 60$

(d) at $t = 70$

Fig. 1. Number of nodes vs maximum range in a path

Checking k - connectivity for each node in the graph formed ensures that any case of failure of any $k-1$ sensor nodes in WSN does not partition the network thus providing a fault-tolerant topology. Figure 1 shows the number of nodes against the maximum range in a path, which is the maximum distance between any pair of nodes in the path, for the k values $1, 2, 3$ and threshold values $40, 50, 60$ and 70 respectively. As we can see from the figure, for a fixed value of k, as the number of nodes increases, the maximum inter-node distance decreases for the given value of threshold. Also, when the number of nodes and the k value are kept constant and the threshold value is varied, the maximum range in a path increases with increase in threshold value. When the number of nodes is kept constant and k is varied, the maximum distance between any pair of nodes is found to be increasing for the given threshold value with increasing k. From these results, we could conclude that as the network grows more denser, the maximum distance between any pair of nodes in the paths, obtained to form a k vertex disjoint graph, decreases and increases with increasing k values.



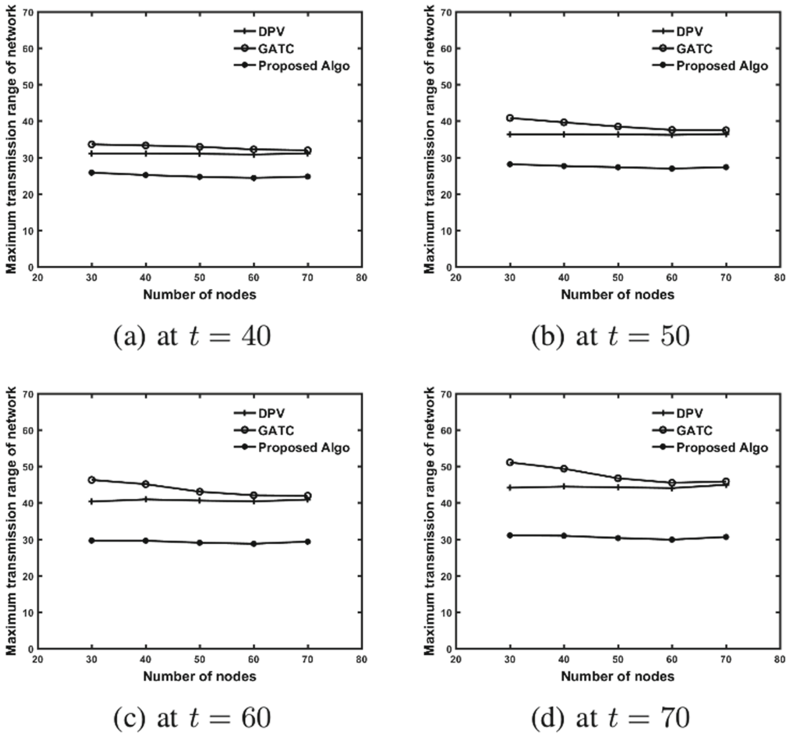
(a) at $t = 40$ (b) at $t = 50$

(c) at $t = 60$ (d) at $t = 70$

Fig. 2. Number of nodes vs minimum range in a path

Figure 2 shows the number of nodes against the minimum range in a path which is the smallest distance between any pair of nodes in the path obtained. From these figures, we can claim that the minimum distance between any pair of nodes in the resulting path decreases as the number of sensor nodes increases for a given value of k and for given number of nodes, with increasing value of k the minimum distance in the path decreases.

Figure 3 shows the number of nodes against the maximum transmission range of the network. This is based on the assumption that the number of nodes in the network vary from 30 to 70. The results obtained by using the proposed algorithm are compared to the results obtained with the GATC algorithm and the DPV algorithm. As we can see from the plots, the DPV algorithm provides a reduced maximum transmission range as compared to the GATC approach and we are able to provide better results than the DPV approach by being able to further reduce the maximum transmission ranges for the topologies obtained. Thus, our approach provides a better topology in terms of average path length as well as the reduced maximum transmission range and also reduces the average power consumed by the network for the randomly generated topologies.



(a) at $t = 40$ (b) at $t = 50$

(c) at $t = 60$ (d) at $t = 70$

Fig. 3. Number of nodes vs maximum transmission range of the network

5 Conclusion and Future Work

In this paper, a fault tolerant topology was formed by minimizing the transmission range with the threshold values under consideration using the k - connectivity property of graphs. The obtained topology could be used to increase connectivity, reduce average path length and also to increase the network lifetime. The approach, being localized and distributed, can be used for large networks for real time applications. A comparison with the existing methods was carried out and the results obtained showed that the proposed approach yielded better results than the existing ones while maintaining the property of k - connectivity as well as providing a fault tolerant topology for the network. This model can be extended to form energy efficient weighted fault tolerant network topologies.

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