On Construction of Fault-Tolerant Virtual Backbones in Heterogeneous Wireless Sensor Networks

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1 INTRODUCTION

As critical support of the Internet of Things (IoT), Wireless Sensor Networks (WSNs) consist of many distributively deployed wireless sensor nodes that enable the IoT to sense and control the environment without physical backbone infrastructure. In WSNs, the Virtual Backbone (VB) is widely adopted to alleviate the broadcast storm problem. [3]. Instead of the whole network, transmission messages between sender nodes and sink nodes forward only through the nodes in the VB. Constructing VB based on *Connected Dominating Set* (CDS) has been studied extensively in recent years. However, CDS can not serve as a virtual backbone well in heterogeneous WSNs. Due to the difference in functionality or communication capability, the wireless sensors in a heterogeneous WSN may not have a uniform transmission range. Therefore, a *Strongly Connected Dominating and Absorbent Set* (SCDAS) is constructed to be treated as VB in heterogeneous WSNs. Let $D = (V(D), E(D))$ be a directed graph, and let $S \subseteq V(D)$ be a subset of D. If every node $u \in V(D) \backslash S$ has at least one incoming and one outgoing neighbor in S and $D[S]$ is connected, where $D[S]$ is the subgraph of D induced by S, then S is called as an SCDAS of D.

The sensor failures caused by part damage or energy depletion in WSNs are inevitable. In order to improve the reliability of VB, Dai and Wu [1] firstly suggested constructing a *k-Connected m-Dominating Set* ((k, m)-CDS) in WSNs. A (k, m)-CDS S is a subset of D such that every node not in S has at least m neighbors in S and $D[S]$ is k-connected. Most recent studies focused on finding an approximation algorithm for constructing a (k, m)-CDS in the corresponding WSNs [2, 6]. However, their work is all based on homogeneous WSNs, in which all sensors have the same transmission range. Therefore, in this poster, we study the problem of constructing the fault-tolerant virtual backbones in heterogeneous WSNs and propose a novel algorithm for constructing the (k, m)-SCDAS. We also conduct several experiments to investigate the effectiveness of the proposed algorithm by comparing the existing methods. Experimental results show that the proposed algorithm outperforms the others.

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2 ALGORITHM DESIGN

In this section, the main idea of our algorithm for constructing fault-tolerant virtual backbones in heterogeneous WSNs is presented. This algorithm forms the (k, m)-SCDAS in heterogeneous WSNs based on the recursion strategy. At the beginning of the algorithm, an existing algorithm is called to construct a rigorous $(1, m)$-SCDAS in the graph. Then, the algorithm recursively makes an $(i - 1, m)$-SCDAS S to be an (i, m)-SCDAS. Before describing the detail of the algorithm, we first introduce some important definitions below.

Definition 2.1. Given an interger k and a directed graph D, a node set $I \subseteq V(D)$ with at least k nodes is a *k-inseparable* set of D if, for each pair of nodes $x, y \in I$, there exist at least k node-disjoint directed path from x to y in D. A *k-block* B is a maximal k-inseparable set of D.

Definition 2.2. Let $C \subseteq V(D)$ be a subset of D. Given an integer k and a node $r \in V(D)$, D is *$(C, r)k$-unilaterally connected* if, for each node $t \in C$, there exists at least k node-disjoint directed path from r to t in D.

In short, an i-block is a set in which the connectivity of nodes between each other is higher than that of other nodes. Now, suppose that S is an $(i - 1, m)$-SCDAS of D such that $S_0 \subseteq S$ and $D[S]$ is not i-strongly connected yet. At first, we shall find an i-block of $D[S]$ and denote it as B. Let $U \subseteq V(D) \backslash S$ as an augmentation subset of S. In the following, some extra nodes will be added into U till $D[S \cup U]$ is i-strongly connected.

If $D[S]$ is not i-strongly connected, there must exist some nodes $r \in S \backslash I$ such that $D[S \cup U]$ or $D^r[S \cup U]$ are not $(B, r)i$-unilaterally connected. For convenience, we call these nodes as *scatter nodes*. The main idea of our scheme is to decrease the number of scatter nodes to zero by adding some extra nodes into U and finally make S to be an (i, m)-SCDAS. To this end, we need to find a so-called *desired* T-path of $D[S \cup U]$ or $D^r[S \cup U]$. A desired T-path P has three properties: i) P starts from a scatter node r. ii) P has at most two internal nodes. iii) When we add all of the internal nodes of P into U, $D[S \cup U]$ (or $D^r[S \cup U]$) is $(B, r)i$-unilaterally connected. By property iii), at most $2|S|$ desired T-paths that need to be found out to make $D[S \cup U]$ i-strongly connected. In this process, at most $4|S|$ nodes are added into U according to property ii).

The pseudo code of the proposed algorithm is presented in Algorithm 1. Due to the space constraint, the detail for constructing the i-block and the desired T-path are omitted. To sum up, by repeating

Algorithm 1: Constructing a (k, m)-SCDAS in the DG

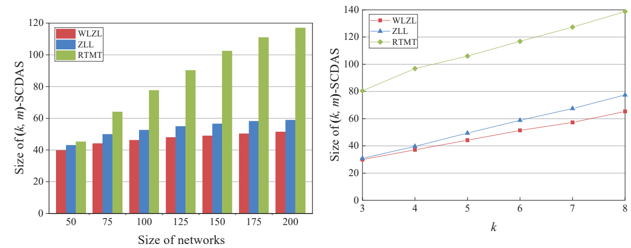
Input: Two positive integers k,m with $m \geq k$ and a k-strongly connected directed graph D.
Output: A $(k$,$m)$-SCDAS S.
Find a rigorous $(1$,$m)$-SCDAS S_0;
$D \leftarrow S_0$;
$D^r \leftarrow$ reverse all edges of D;
for $i = 2$ **to** k **do**
  $U \leftarrow \emptyset$;
  Find an i-block B of $D[S]$;
  while *$D[S \cup U]$ is not i-strongly connected* **do**
    if *there is a node $r \notin B$ such that $D[S \cup U]$ is not (B, r)i-unilaterally connected* **then**
      Find a desired T-path in D;
      Add the internal nodes of T-path into U;
    else
      Find a desired T-path in D^r;
      Add the internal nodes of T-path into U;
    end
  end
  $S \leftarrow S \cup U$;
end

the process above, we can recursively make an $(i-1, m)$-SCDAS S to be (i, m)-SCDAS for each $i \in \{2, 3, \cdots, k\}$. On the other hand, the size of S expand at most five times for each i. So, the constructed (k, m)-SCDAS has a bounded size of $5^{k-1}|S_0|$, where S_0 is a rigorous $(1, m)$-SCDAS constructed initially.

3 EXPERIMENTAL RESULTS

In this section, we present simulations conducted to analyze the performance of our algorithm, which is abbreviated WLZL below. Plenty of simulated heterogeneous WSNs are generated by randomly deploying sensor nodes in a square area of 1000×1000 units uniformly with a transmission range within $[r_{min}, r_{max}]$, where $r_{min} = 300$ and $r_{max} = 450$. Each set of experiments is run in different candidate networks 100 times. Two algorithms proposed in [5] and [4] are chosen to be comparison algorithms and abbreviated as ZLL and RTMT, respectively.

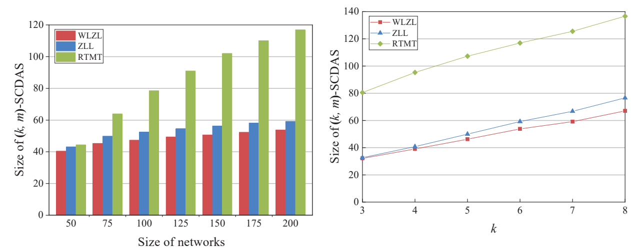
Fig. 1 shows the average size of (k, m)-SCDAS output by three algorithms in the case that $k = m$. Fig. 1(a) is the result of varying varying network sizes ranging from 50 to 200 with a fixed k of 6. The average size of SCDAS generated by three algorithms increases with the size of networks. It is reasonable since a larger network needs more dominators. We can observe that our proposed algorithm produces the smallest average size of (k, m)-SCDAS among the three algorithms. Fig. 1(b) shows the comparison result with respect to varying values of k in networks of 200 nodes. We can see that WZLZ has a better result in all settings of the value of k, and the gap widens with the growth of k. The average size of (k, m)-SCDAS generated by WZLZ has about 16% fewer nodes than that generated by ZLL when $k = 8$. It can be known that our algorithm has a much better performance when the value of k is large. The comparison results for the case that $k < m$ are reported in Fig. 2. For



(a) Comparison of generating $(6, 6)$-SCDAS.

(b) Comparison of generating (k, k)-SCDAS in networks of 200 nodes.

Figure 1: Comparison of generating (k, k)-SCDAS.



(a) Comparison of generating $(6, 7)$-SCDAS.

(b) Comparison of generating (k, m)-SCDAS in networks of 200 nodes.

Figure 2: Comparison of generating (k, m)-SCDAS.

convenience, we set $m = k+1$. In this case, the size of (k, m)-SCDAS is slightly larger than the case when $k = m$. However, WZLZ is still the best performing algorithm under all settings of the parameter. These results all show the advantage of the proposed algorithm under various conditions.

4 CONCLUSION

In this poster, we propose a novel algorithm for constructing the (k, m)-SCDAS in heterogeneous WSNs. Comparative experimental results show the better effectiveness of the proposed algorithm than the other existing algorithms. In the future, we will further investigate the performance of the algorithm under different settings of parameters.

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