Activated Swarm Fault Tolerance in Wireless Sensor Networks under Massive Correlated Failure

ZHAOFENG LI\textsuperscript{1,2,3} AND YICHUAN JIANG\textsuperscript{1,3*}

\textsuperscript{1}Key Laboratory of Computer Network and Information Integration of State Education Ministry, School of Computer Science and Engineering, Southeast University, Nanjing 211189, China
\textsuperscript{2}Research Center for Learning Science, Southeast University, Nanjing 210096, China
\textsuperscript{3}Key Laboratory of System Control and Information Processing, Ministry of Education, Shanghai, 200240, China
E-mail: lizhaofeng@live.cn, yjiang@seu.edu.cn

Received: April 30, 2011. Accepted: June 28, 2011.

The massive correlated failure is an intractable issue in random distributed wireless sensor networks (WSNs); thus it is very important to design an effective fault tolerance method. To handle this problem, we propose an activated swarm fault tolerance (ASFT) method and its extension e-ASFT to repair the interrupted multi-hop transmission link. The principles of our proposed method are labour division and collaboration, where different nodes play different roles and cooperate on transmitting replacement link task in the activated swarm area. The mathematical process of ASFT is described in the fashion with graph theory. The simulation results show that ASFT and e-ASFT can achieve high success ratio under massive correlated failure.

\textbf{Keywords:} Fault tolerance; swarm; wireless sensor networks; massive correlated failure.

1 INTRODUCTION

In order to handle fault happened in wireless sensor networks (WSNs), various kinds of tolerance approaches have been proposed: coverage and connectivity research [1-3], relay node replacement research [4-5] and swarm intelligence based fault tolerance research [6]. The key of fault tolerance research is to enable the smooth communication, thus the tolerance in this

*Corresponding author: Yichuan Jiang
The paper aims to repair the interrupted multi-hop transmission link. The WSNs is shown in Figure 1.a, and the transmission link is shown in Figure 1.b. However, the massive correlated failure brings new challenge to the function of the wireless sensor networks. The tolerance under massive correlated failures is an important problem in wireless sensor networks, and it has crucial practical significance and need in the application of WSNs. Massive failure has been deeply researched in many traditional systems and networks [7, 8], while little attention has been paid in wireless sensor networks. In the real world, this kind of failure can be caused by bomb explosion or landslide. In this paper, it is shown in Figure 1.c.

Most related works focus on the single independent failure and tolerate it by virtue of the centralized model [9] or complex algorithms [4, 5]. In this paper, we propose an activated swarm fault tolerance (ASFT) method and its extension e-ASFT to repair the interrupted multi-hop transmission link under massive correlated failure. The proposed method is based on swarm intelligence which is a hot topic in the artificial intelligence area [10, 11]. There are lots of analogies between the sensor node and social insect: deficient individual ability, limited communication range and awareness of local information. Swarm members make simple (but wise) decision, and as a whole, they can achieve a complicated task. In [10], the authors mention the labour division and collaboration are universal in many species of social insects. The activated swarm is a new notion in wireless sensor networks, which is a temporary organization of sensor nodes who have perceived the failure of nodes. The formulation of activated swarm is the foundation and preparation of labour division and collaboration; and we utilize the two swarm intelligence concepts in the design of the proposed method. All the tolerance processes are executed in the swarm area without the supervision of centralized nodes. The difference between ASFT and e-ASFT is the different sizes of the activated swarm areas. The principal element of ASFT is that different sensor nodes play different roles but cooperate with each other on transmitting replacement link task within the activated swarm area.

The rest of this paper is organised as follows. Section II describes the preliminaries and models of our work. The mechanisms of ASFT and e-ASFT
are given in section III. Section IV is the mathematical description of ASFT. The simulation and analyses of ASFT and e-ASFT are presented in section V. Section VI is the related work. Finally, the conclusion and future work are described in section VII.

2 PRELIMINARIES AND MODELS

2.1 Network Model
In this paper, the wireless sensor networks are homogeneous and sensors are static and isotropic, where the communication and sensing ranges are represented by the same disks. All the sensors are distributed randomly. Each sensor node in the networks has a unique identifier, which is for the awareness of adjacent sensors (local information). Every sensor stores the unique identifiers of its neighbours in neighbour table (denoted by NT). The invalidation of sensor node can be perceived by its adjacent nodes simultaneously. We use neighbour table to perceive the fault and simply discuss it in the following sections.

2.2 Establishment of Transmission Link
We also assume that data can be transmitted between any two sensor nodes through directional multi-hop, and the starting node only knows the identification of the destination node. The starting node wants to transmit data to the destination node through a steady transmission link, but at first the link is unknown. The sequential unique identifiers of multi-hop constitute a simple data structure named as link table (denoted by LT). The link table is stored in every node of multi-hop transmission link. With the reference to [6], the process of establishing data transmission link is broadcasting establishment task forward and ensuring the link backward. The starting node broadcasts a forward establishment task to discover a route to the destination node. The task is delivered in the networks, and the prefix of the task is the unique identifiers of the starting and destination node. The rest part of establishment task is the items of intermediate nodes. According to the prefix of a task, sensor node can distinguish different tasks and performed tasks. Sensor node adds its own unique identifier into the items of intermediate nodes, and then broadcasts the performed task forward. In order to avoid data overflow caused by the repeated transmission of the same task, every node performs the same task only once. The destination node selects a shortest task route from the received task, and then transmits the link data backward to the starting node through intermediate nodes. The multi-hop nodes of the transmission link store the link table, and after that the data is transmitted through the transmission link. Those sensors who are not contained in the transmission link do not store the link table.
3 MECHANISMS OF ASFT

The labour division and collaboration are the principles of ASFT. The activated swarm forms when massive correlated failure occurs, and disappears when the failure is tolerated. The mechanisms of ASFT are expressed below.

1. Perceiving the failure.
2. Activated swarm forms.
3. Marking swarm nodes as direct observer and identifying their statuses.
4. Labour division and transmitting replacement link task.
5. Tolerating successfully or setting up a new transmission link.

ASFT consists of the above five phases. We describe the structures of NT, LT, activated swarm and each phase in the following subsections.

3.1 Structures of NT and LT

To make the presentation of NT and LT more transparent, some basic abbreviations and structures need to be mentioned. The symbol $S_i$ represents a sensor node and $l_i$ represents for the location of $S_i$, while the number $i$ is the unique identifier of the sensor node. The sensor node $S_j$ that matches the inequality $|l_i - l_j| \leq r_i$ is the entries of neighbour table of $S_i$ (NT$_i$), where $r_i$ is the communication rage of $S_i$.

Link table contains the items of the identifications of the starting node, the destination node and the intermediate nodes. It denotes as LT$_{ij}$, where $i$ represents for the starting node $S_i$ and $j$ represents for the destination node $S_j$, and it is only stored in the member of LT$_{ij}$.

Specific structures of NT and LT are described in Table 1 and Table 2, citing $S_b$ in Figure 2 as the example.

Neighbour table maintained in every sensor is used for perceiving fault. We assume that every sensor informs the neighbour nodes of its effectiveness by broadcasting a specific message in the end of every working cycle. Com-

<table>
<thead>
<tr>
<th>HOST NODE</th>
<th>NEIGHBOUR NODES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_b$</td>
<td>$S_a$</td>
</tr>
<tr>
<td></td>
<td>$S_c$</td>
</tr>
<tr>
<td></td>
<td>$S_d$</td>
</tr>
<tr>
<td></td>
<td>$S_e$</td>
</tr>
<tr>
<td></td>
<td>$S_f$</td>
</tr>
</tbody>
</table>

TABLE 1
Neighbour Table.

<table>
<thead>
<tr>
<th>STARTING NODE</th>
<th>DESTINATION NODE</th>
<th>INTERMEDIATE NODES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_i$</td>
<td>$S_j$</td>
<td>$S_a$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$S_b$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$S_c$</td>
</tr>
</tbody>
</table>

TABLE 2
Link Table.
paring the received messages with the maintained neighbour table, sensor node can perceive the defunct nodes and meanwhile updates the neighbour table. The link table stored in multi-hop nodes is the important criterion for the division of labour. The sequence of intermediate nodes in the link table is the same as the transmission link.

3.2 The Characteristic of Failure
Bomb explosion, landslide, etc. can lead to massive correlated failure in wireless sensor networks. This kind of failure is a messy problem, because it can cause blind spot in the networks. The number of defunct sensor nodes is huge. The damage area is limited, but the function of networks in this area is completely destroyed; the original data of target and event in the damaged area is lost. However, this failure should not influence the operation of the entire networks especially the data transmission. In Figure 3(a), the centric circle represents the massive correlated failure.

3.3 The Characteristic of Activated Swarm
The most notable characteristic of activated swarm is that, beside the basic functional behaviour in networks, the member of the activated swarm takes the extra and simple actions which are ignored by outlanders according to the swarm. The activated swarm is composed of all the sensor nodes who perceive the failure. The activated swarm forms when massive correlated failure occurs, and dismisses when the failure is tolerated. The structure of activated swarm is not centralized. There are no cluster heads or dominant nodes which are used to arrange the information transmission and working states of other nodes in the activated swarm. In this sense, activated swarm is a flexible organization. It is the foundation and preparation of the following tolerance steps. For example in Figure 3(a), the annulus that surrounds the massive correlated failure area is the activated swarm area. In general, activated swarm restricts the tolerance information and process in the swarm area. Swarm
members are similar to each other: geographically, they surround the failure area and approach to each other; physically, they perceive the failure within a very short time interval and may constitute a new topology to repair the interrupted link.

3.4 Marking Swarm Nodes and Identifying Their Statuses
The process of marking swarm nodes is in parallel with the formulation of the activated swarm. In order to constitute activated swarm and avoid overflow of tolerance information, the sensor nodes who perceive the failure mark themselves as direct observer. In this way, swarm members can distinguish between staff and non-staff of the activated swarm. Non-staff ignores the tolerance information generated in the activated swarm and does not participate in the fault tolerance process.
The identifying status is the preparation step of labour division and transmission of replacement link task. There is only one criterion of identifying status: link table. This process is accomplished in each direct observer respectively. There are three kinds of statuses.

1. Upstream node. The upstream is a relative position in the transmission link. Because of the unidirectivity of transmission link as we assumed before, the data transmission is nonreversing. If the sensor node stores a link table and its next node is defunct, it is upstream node. In the next step of ASFT, it undertakes foremost action.

2. Downstream node. The downstream is also a relative position. If the sensor node stores a link table and its upriver node is defunct, it is downstream node. In ASFT, downstream node undertakes lesser action, waiting for the replacement link task from the upstream node.

3. Spectator node. Spectator nodes are potential nodes to repair the interrupted transmission link. If the sensor node does not store link table or its next and upriver nodes are still available, it is spectator node. Spectator nodes take the rest actions of fault tolerance.

3.5 Labour Division and Transmitting Replacement Link Task

After the identifying of statuses, the activated swarm accomplishes the labour division. At first, upstream node transmits a replacement link task to its adjacent nodes. This process is shown in Figure 3(b). Figure 4 is the partial view of Figure 3. Taking Figure 4 as instance, the structure of replacement link task transmitted by upstream node is given in Table 3.

The replacement link task is similar to the task of establishing a new transmission link. But the prefix of the replacement link task is the original transmission link (denoted by OTL) instead of the identification of the starting and destination nodes. The massive correlated failure may destroy more than one sensor node of the transmission link simultaneously, so in Table 3, the ‘‘spectator

![FIGURE 4](image-url)
The partial view of massive correlated failure.
nodes” and “downstream node” are blank. The upstream node does not know the identification of the downstream node. The OTL can lead the flooding information to the downstream node, and it is also useful to distinguish the different replacement link tasks as shown in Figure 3(b). The task can only be delivered in the swarm, and the symbol of direct observer aims to impose restrictions on the transmission scale of the replacement link task.

The spectator node delivers the task, and meanwhile adds its own unique identifier into the “spectator nodes” column. The same replacement link task is transmitted by a spectator node only once. This restriction is the same as the establishment of a transmission link.

At last, if the downstream node receives the task, it transmits the alternative nodes of the defunct nodes backward to the upstream node through the “spectator nodes” contained in the task. Meanwhile, the original transmission link is updated in every node and the activated swarm is dismissed. This process is shown in Figure 4(c).

If the upstream node does not receive the ensuring information from downstream node, it means the fault tolerance fails. The upstream node sends a notification of interrupted link to the starting node, and then the starting node establishes a new transmission link connected to the destination node. The original link is deleted and the swarm disappears as well.

3.6 Overview of e-ASFT

The e-ASFT is the extension of ASFT. In e-ASFT, the activated swarm area is expanded, which consists of direct observer and indirect observer. In e-ASFT, after marking themselves as direct observer, these sensor nodes broadcast the notification of failure to adjacent areas. Indirect observer is the neighbour of direct observer and it marks itself by the information received from the direct observer. They constitute an annulus surrounding the direct observer area and meanwhile participate in transmitting replacement link task. In e-ASFT, all the indirect observers are spectator nodes. More sensor nodes participate in the process of fault tolerance, therefore the consumption increases as well.

4 MATHEMATICAL DESCRIPTION

The essential thought of mechanism of ASFT is finding the alternative nodes in the activated swarm to replace defunct sensors by transmitting replacement
link task. In this section, we will utilize graph theory to describe the mathematical process of ASFT, shown in Figure 5 to Figure 10.

In Figure 5, the step 1 is the preparation work. Node a identifies its status as upstream node, and gets ready for transmitting replacement link task in step 2. In step 2, all the nodes in rank 2 receive the replacement link task. It is the first time that they are “explored”, so nodes in rank 2 accept the replacement link task. Meanwhile, they are marked as “explored” in Figure 6.

In step 4, the nodes in rank 2 transmit the processed replacement link task to the adjacent areas. Clearly, some of the “explored” nodes can receive the replacement link task repeatedly, for example the rank 1 node and the rank 2 nodes. As shown in Figure 7, those nodes have been explored by the same task (the same OTL), so they ignore the received replacement link tasks.

The nodes whose level is lower than rank 2 may be firstly “explored” by multiple replacement link tasks, for example node $c_2$, $c_3$, and $c_4$ in Figure 7. Although the processed multiple replacement link tasks are different, they are
all the derivative of the original task transmitted by the upstream node. Node $c_2$, $c_3$, and $c_4$ have to select one processed task respectively. In this paper, the selection is random. The result is shown in Figure 8.

The transmission of replacement link task continues until the downstream node receives the task, shown in Figure 9. The downstream node also randomly selects a processed task, and ensures the replacement link backward to the upstream node through the “spectator nodes” contained in the accepted task.

The mathematical process of ASFT and e-ASFT is similar to the breadth-first-search. The great difference is that this process is accomplished by transmitting replacement link task between distributed nodes not by executing algorithm in centralized node.

5 SIMULATION AND ANALYSIS

We design the platform with java in eclipse, comprising SWT plug to accomplish visualization. We begin our experiments in such a virtual environment: all the sensor nodes are distributed randomly in an $800 \times 600$ rectangle; the sensor networks are homogeneous; the sensing range and the communication range are 100 with an abstracted circle. We try to present the relationship between the success ratio of ASFT and the density of sensor nodes in the networks and then give the comparison between ASFT and e-ASFT. During the simulation, we use the total number of sensor nodes in the networks to represent the density of the sensors. The abscissa is from 50 to 300 and the step number is 50. To simply describe the characteristics of the randomly distributed networks, we calculate the maximum, the minimum and the average number of neighbours of sensor nodes and show it in Figure 11.

The comparison of ASFT and e-ASFT is illustrated in Figure 12. In this experiment, the area of the massive correlated failure is a fixed circle whose diameter is 200. At first, we calculate all the truly connected data transmission links, and neglect those isolated sensor nodes who cannot communicate with
FIGURE 9
Downstream node receives the replacement link task.

FIGURE 10
The last step of ASFT: ensuring back to upstream node.

FIGURE 11
The number of neighbours in different sensor networks.
other sensors. Secondly, we use the fixed-size massive correlated failure destroys every part of those transmission links except the starting and destination nodes. Meanwhile, we record the success ratio of ASFT and e-ASFT.

From Figure 12, we find that the success ratio of e-ASFT is larger than ASFT and as the number of sensor nodes in the networks increases, the success ratio of ASFT and e-ASFT increase as well. That is because the more sensor nodes participate in transmitting replacement link task, the higher the success ratio is. The activated swarm area of e-ASFT is larger than ASFT, because e-ASFT contains the indirect observer. When the number of sensors in the networks is 300, the success ratio of ASFT and e-ASFT are nearly 100%.

In the last set of experiments, we make the further comparison between the ASFT and e-ASFT. We fix the number of sensor nodes in the networks into 300 and gradually increase the damage percentage of coverage. The coverage size is a circle with diameter 200. When the damage percentage is zero, only one sensor in the transmission link is destroyed. When the damage percentage is 100% the size of massive correlated failure is similar to the experiments in Figure 12 and it at least destroys three sensor nodes in the transmission link simultaneously. The record of success ratio is shown in Figure 13.

Figure 14 is the communication consumption comparison of ASFT and e-ASFT. The indicator of communication consumption is the communication times in the process of ASFT and e-ASFT. We calculate all the communication times during the experiments. It is clearly that the communication consumption of e-ASFT is larger than ASFT, because the activated swarm area of e-ASFT is larger and more spectator nodes participate in the process of transmitting replacement link task.

From these experiments, we can make the conclusion that ASFT and e-ASFT can address massive correlated failure effectively. The success ratio of e-ASFT is larger than ASFT, but the consumption is also larger. The above
results show that ASFT and e-ASFT can achieve high success ratio under massive correlated failure.

6 RELATED WORK

6.1 Connectivity and Coverage Research
One approach to achieve fault-tolerance is to investigate the connectivity and coverage problems of wireless sensor networks. In [1], Bai et al. propose a
“Diamond” pattern, which can be viewed as a series of different evolving patterns. Depending on the different ratio of communication rage (denoted by $r_c$) and sensing rage (denoted by $r_s$) of sensors, the Diamond pattern can be depicted as the well-known triangle lattice pattern or the “Square” pattern. It has been proved that the Diamond pattern is asymptotically optimal to achieve four-connectivity and full coverage for WSNs when $r_c/r_s > \sqrt{2}$. This kind of work is originated and provides insights on how optimal patterns evolve and how to search for them, for example in [2].

Ammari and Das [3] describe a new measure of fault tolerance, called conditional fault-tolerance, for a class of wireless sensor networks, named k-covered wireless sensor networks (kCWSN), using the concept of forbidden faulty set which means a simultaneous failure of all the neighbours of any node is prohibited. All the fault tolerance works on this area are fundamental of other researches.

6.2 Relay Node Replacement Research
Relay node replacement which is to deploy a small number of additional relay nodes to provide k vertex-disjoint paths between every paired functional device has been proposed and wildly researched. All these works require exhaustive algorithms to guarantee this problem [4, 5]. In [4], the algorithm is built on approximation algorithms. The interesting variable on this paper is to change the goal from vertex k-connectivity which is the traditional research area to partial k-connectivity who can provide the k vertex-disjoint paths between every pair of original sensors. In [5], the authors construct a fault tolerance backbone network using additional relay nodes. This network also needs approximation algorithms to achieve 2-connected of the induced communication graph with smallest number of additional nodes.

6.3 Swarm Intelligence Fault Tolerance
The ideology of swarm intelligent is also used by Sundaram Rajagopalan and Chien-Chung Shen [6] to design a unicast routing protocol for hybrid ad hoc networks. Although it is not in wireless sensor networks, great inspiration can be gained from it. A special packet called ant is used to travel in the networks. Based on it, the starting node can establish a transmission route to the destination node and others nodes in the networks can update the routing table. With the help of ant’s travelling and routing tables maintained by every node, data transmission and fault tolerance can be achieved. This protocol can perform well in ad hoc networks, but is not suitable in sensor networks, because the consumption of transporting ants and holding a routing table is too huge for each sensor node.

6.4 Centralized Model Research
In [9], the authors proposed a new fault tolerance method in three dimensional based on the centralized model. The method divides the network into different
clusters and set up sentry nodes to arrange the working states of sensor nodes in every cluster. There are active and inactive working states. If some node becomes defunct, the sentry node awakes the inactive node to replace the defunct node. The method has good performance if the failure is single and independent. However, the massive correlated failure can destroy many sensors including the sentry nodes, and in this case, the centralized model is not available.

7 CONCLUSION AND FUTURE WORK

This paper has described an activated swarm fault tolerance method (ASFT) and its extension (e-ASFT) in random distributed wireless sensor networks. Fault tolerance in this paper aims to improve the life-time of the multi-hop transmission link in the networks in spite of the interruption caused by the massive correlated failure. To meet this goal, we introduce the notion called activated swarm and design the mechanism of ASFT. We present the mathematical process of ASFT and also investigate the relationship between the success ratio and the density of sensor nodes. Meanwhile we make the comparison between ASFT and e-ASFT. The results show that ASFT and e-ASFT can achieve high success ratio under massive correlated failure. Our future work consists of deeper study in fault tolerance with this new method considering the consumption and the competition between different swarms. In fact, labour division and collaboration can be widely used in wireless sensor networks, not only on fault tolerance, but also on data fusion, environmental awareness, and so on. The characteristics of WSNs have many analogies with ant colonies: deficient individual ability, limited communication range and awareness of adjacent area; but as a whole, global optimization can be achieved.

ACKNOWLEDGEMENT

This research was supported by the National Natural Science Foundation of China (No.61170164, No.60803060), the Specialized Research Fund for the Doctoral Program of Higher Education of State Education Ministry of China (No.20090092110048), and the Foundation of Key Laboratory of System Control and Information Processing, Ministry of Education, P.R. China (No. SCIP2011006).

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