Articulation Node Failure Recovery for Multi-channel Wireless Sensor Networks

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Abstract—Wireless sensor networks (WSNs) are one of the most used networks in different domains. However, the particularity of nodes deployed in this type of networks increases the failure probability. To overcome this problem and guarantee the continuity of the network functioning, some solutions must be integrated. These solutions implement fault tolerance mechanisms that recover from a failure and resume the correct functioning of a WSN. In this paper, we propose a centralized curative approach dedicated to restore connectivity in multi-channel WSNs. The use of multichannel communications allows simultaneous data transmission, which decreases the interference ratio between nodes and then decreases data retransmission. The proposed solution targets the failure of a particular node (articulation node) which leads to partitioning the WSN into many segments isolated from each other, and hence the data can’t reach the sink due to connectivity loss. Therefore, the main tasks of our approach are the restoration of the connectivity after an articulation node failure using reorganization, and the reallocation of channels. Moreover, the solution use a node rotation technique to communicate the recovery information to all the disjoint parts of the network. The performance of the proposed solution is evaluated and proved through simulation.

I. INTRODUCTION

As a promising technology, the wireless sensor networks (WSNs) [1] have known a deployment expansion in different domains going from simple data collection to critical system monitoring and control. In these type of applications, data is transmitted from each sensor to the sink using one or multi-hop paths, which assumes that the network is connected. However, the characteristics of sensor node (limited CPU, limited memory, limited battery, wireless communications, etc) and the harsh environment, where they are deployed, negatively affect the reliability of WSNs and even may lead to the failure to fulfill its expected mission. On one hand, a node failure, due to energy depletion or any other problem, may partition the network into disjoint parts disconnected from the sink. On the other hand, the interferences between sensor nodes increase the phenomena of collisions/retransmissions, which demand an extra energy consumption causing the premature failure of some nodes.

The problem of interference ratio minimization has been widely discussed in literature, and the common technique used in such a problem is the multi-channel communication. Since the integration of multi-channel radios in wireless sensor devices, many interesting researches have been dedicated to optimally exploit the benefits of multi-channel communication [2]-[7]. The proposed mechanisms help to minimize the collision/retransmission ratios, and then the energy consumption. However, the probability of node failure is still high. Thus any node may fail due to energy depletion or any other factor. In many applications, the WSNs are deployed in unreachable or dangerous environments. Therefore, a node battery exchange is unfeasible. Moreover, the replacement of a new node instead of the failed node is impossible. The problem become very serious when an articulation node fails and hence, the network is partitioned into isolated segments. To overcome this problem, the WSN need to be reorganized to restore the lost connectivity. The main idea in the network reorganization is to relocate some nodes around the failed node with minimum impact on the network initial topology.

In this paper, we will focus on recovering from one of the most serious failures in WSNs in a multi-channel context. In particular, we discuss the recovery from an articulation node failure and the channel reallocation after the failure when the number of channels is limited, and hence the interferences can’t be avoided but minimized. We formulate the problem as a constrained multi-objective optimization problem; then, we propose a centralized approach to solve it in a near optimal manner. In our centralized solution, the sink is responsible for the whole recovery procedure from failure detection to channel reallocation after the connectivity restoration. The recovery solution presented in the paper uses some graph theory heuristics such as graph coloring [8] heuristics for the channel reallocation and Steiner Points [9] heuristic to rearrange the nodes around the failed node. The centralization of the solution avoid the need of coordination between nodes, but a new problem arises: How the sink can communicate the recovery decision to the isolated parts of the network? As a solution to this problem, we propose to rotate some nodes in such a way to transmit the information to all segments.

The rest of this paper is organized as follows: section II gives a background of fault tolerance in WSNs and overviews the works related with this topic. Section III describes the formulation of the recovery problem. The proposed solution is described in section IV and evaluated in section V. Section VI concludes the paper.
Fault tolerance topic is one of the most topics attracting more and more researchers. The importance of this topic leads to many works dedicated to improve the WSN reliability. The solutions proposed in the literature can be classified into two main classes: preventive solutions and curative solutions. The preventive solutions aim to prevent node and/or network failure. Generally, these solutions are based on energy consumption management (multi-channel communications, sensor activity/sleeping schedule), deployment strategies (redundant nodes) and multi-path routing technique. The curative class includes all the solutions triggered after a failure occurrence. These solutions use different techniques to resume the network functioning. The main techniques used include backup paths, node redeployment and network reorganization. The last technique can be used also to prevent the network failure. To reorganize the network, some nodes are relocated in new locations. This technique performs well in connectivity restoration and coverage improvement.

Many proposed algorithms use the nodes reorganization technique to enhance the WSN reliability. In [10], Younis and al. proposed CRR (Connectivity Restoration through Rearrangement) which recovers from the connectivity loss by moving some nodes to new locations in the failed node vicinity. CRR defines the new locations as the Steiner Points of a Steiner Tree connecting the different network segments. Another algorithm, proposed in [11], uses Steiner Tree to reconnect the WSN after multiple nodes failure. It moves mobile relay nodes to form a bridge between the different parts of the network. The algorithm presented in [12] replaces the failed node by neighbors one by one. Each node moves back and forth to the failed location for a period of time. The algorithm LeDiR (Least-Disruptive topology Repair) proposed in [16] for Wireless sensor-actor networks (WSANs) restores connectivity between actors by relocating the minimal number of nodes without extending the length of shortest path. The authors proposed two versions of LeDiR: the first version is centralized and the second is distributed. In LeDiR, the recovery process is restricted to neighbors belonging to the smallest disjoint network segment after the WSAN partition. All the mentioned algorithms recover from a node failure, but they use a single channel for the data transmission, which increases the interference ratio and then the data retransmissions. The collision/retransmission phenomenon may cause premature failures. In [13], we proposed a solution combining the use of multi-channel communication with the WSN failure recovery. The proposed approach guarantees the connectivity restoration after the WSN partition by relocating some nodes, then reallotates channels while restricting the reallocation process to the nodes belonging to the failed node vicinity.

The most important contribution of our work, besides the definition of failure recovery solution for WSNs in a multi-channel context, is the use of node rotating to communicate the sink decision to all disjoint segments.

The centralized solution proposed in this paper aims to restore the connectivity after an articulation node failure. This failure leads to network partitioning into several disconnected segments as we can see in figure 1 where the black node denotes the failed node. The connectivity restoration is done through the relocation of some nodes. The approach assumes that the WSN is composed by mobile sensor nodes, where each node can move to a new location. Moreover, we assume that the network uses multi-channel communications to transmit data from the sensors to the sink.
The number of interfering links over a node \( v \) is determined by summing the interfering links between this node and all its neighbors:

\[
\Delta(v) = \sum_{u \in V'} \delta(v, u).
\]

And finally, the total number of interfering links over the whole network is defined as:

\[
f_1 = \frac{1}{2} \sum_{v \in V'} \Delta(v).
\]

The coefficient \( \frac{1}{2} \) is added to avoid that each link is considered twice (for each extremity vertex).

In the same way, the function \( \gamma(v) : V' \times V' \mapsto [0, 1] \) indicates if a node is re-colored or not:

\[
\gamma(v) = \begin{cases} 
1 & \text{if } c_{G'}(v) \neq c_G(v) \\
0 & \text{otherwise}
\end{cases}
\]

The total number of re-colored nodes is defined as:

\[
f_2 = \sum_{v \in V'} \gamma(v).
\]

To formulate the third objective, we define the function \( pos_G : V' \mapsto \mathbb{R} \times \mathbb{R} \) as the position function that returns the coordinates of a node. Therefore, to determine if a node is relocated or not, we define \( \varphi(v) \):

\[
\varphi(v) = \begin{cases} 
1 & \text{if } pos_{G'}(v) \neq pos_G(v) \\
0 & \text{otherwise}
\end{cases}
\]

Then, the total number of relocated nodes is determined by:

\[
f_3 = \sum_{v \in V'} \varphi(v).
\]

The last objective in our problem is to minimize the distance traveled by each relocated node. Let \( pos_G(v) = (x, y) \) and \( pos_{G'}(v) = (x', y') \) the positions of the relocated node \( v \) before and after the network reorganization. The distance traveled by this node is:

\[
dist(v) = \sqrt{(x' - x)^2 + (y' - y)^2}
\]

The fourth function is defined as the total distance traveled by all the relocated nodes

\[
f_4 = \sum_{v \in V'} dist(v) \varphi(v)
\]

Therefore, our multi-objective problem becomes:

\[
\begin{align*}
\text{minimize } & f \\
\text{s.t.} & \\
& G' \text{ is connected} \\
& 1 \leq c_{G'}(v) \leq m, \forall v \in V'
\end{align*}
\]

where constraint (1) ensures the connectivity of the WSN, while (2) guarantees that each node is assigned a channel from the available channels.

In the next sections, we will decompose the problem in sub-problems according to its objectives, and we will propose an algorithm to solve each one. Moreover, we solve the sub-problems sequentially by using the output of a sub-problem as an input for the next one.

IV. NODE ROTATION BASED FAULT TOLERANCE APPROACH

In the WSN initialization phase, the sink determines the 1-hop and 2-hop neighborhood tables for each node according to the node location and the communication range. Then, each node is assigned a reception channel using the heuristics proposed in [13]. In the same time, the sink extracts the spanning tree with backup edges from the network to search for all articulation nodes. The information about channel allocation and articulation nodes is communicated to the network nodes to inform each node which channel must be used.

After the initialization phase, the sensor nodes collect data and send them to the sink periodically. Each node receives the data on its assigned channel and transmits it on its parent channel. The process of data transmission needs the synchronization between the receiver and the sender to guarantee that they use the same channel in the same time. Thus, we divide the time into periods, composed each of a set of time slots, where children transmit data at the time slot in which their parent switches to its channel to receive data. Each time period begin with a broadcast slot, in which all the nodes switch to the same channel to exchange the control messages; while the remaining time is dedicated to data collection and transmission.

During the data transmission, a failure can occur due to energy depletion or any other factor (external attack, crash, etc.). Therefore, the sink must take the appropriate act to overcome the failure. The process of the failure recovery is performed in two steps: in the first step, the approach rearranges the nodes around the failed node to reconnect all network segments, and the second step consists of the re-coloring of the reorganized nodes without affecting the whole network. The recovery process will be detailed in the following sections. We relies on graph theory by using sub-graphs connection technique and partial graph recoloring method.
A. Node Failure Detection

The failure of a node is detected by its 1-hop neighbors. During the route construction, each node builds its neighbors table. Periodically, each node checks if its neighbors are still alive by sending a heartbeat messages. When a node misses the heartbeat message from one of its neighbors, it deduces its failure and sends an error-report towards the sink to inform it about the failure. If the failed node is an articulation node, the 1-hop neighbors inform their neighbors that a recovery process will take place. If a recovery is needed, all the 1-hop and 2-hop neighbors switch to a predefined channel. Once the sink receives the error-report message, it checks if the failed node is an articulation node. If it is the case, it triggers the recovery procedure and updates the neighborhood tables and the articulation nodes’ set, otherwise, it only performs the required updates.

B. Nodes relocation

To reorganize the WSN, we move some nodes to new locations. These locations must be chosen in such a way that allows to restore the connectivity. We use the same technique of Steiner Points (SPs) used in [10] to find the new locations and then move some 1-hop and 2-hop neighbors to these locations.

The first step in this heuristic is to find all the Steiner Points. The heuristic will limit the reorganization process to the failed node vicinity (1-hop and 2-hop neighbors). As in [10], to find the Steiner Points we use k-LCA [14], with k set to 3. We first form a polygon with all 2-hop neighbors as vertices. Then we consider the 3-star formed by two adjacent vertices and the failed node. The heuristic considers a vertex as covered if a SP exists within a distance less than the communication range R. We keep only the SPs covering at least two polygon vertices. The SPs covering only one or no polygon vertex, as well as the SPs covering only vertices covered other SPs, are removed. If some 2-hop nodes are still uncovered, we form a new polygon with these nodes and the remaining SPs as vertices. We apply the same SP search technique as for the first polygon. We repeat this process until all 2-hop neighbors are covered. Figure 2 illustrates the the SPs locations (the black points).

Let $H_i(n_f) = \{v \in V | v \in \text{1-hop}(n_f)\}$ and $SP_{set}$ the sets of 1-hop, 2-hop neighbors and SPs of the failed node. After finding the new locations, the second step consists of moving nodes towards these locations. At this stage, two scenarios can take place:

- $|SP_{set}| < |H_i|$; each SP will be occupied by the nearest 1-hop node.
- $|SP_{set}| > |H_i|$; all 1-hop nodes will move to SPs locations, as well as some 2-hop nodes. The moved 2-hop nodes will be replaced using the DARA protocol [15], which keeps the same network topology.

C. Channel reallocation

After deciding which node has to move towards which location, the sink updates the neighborhood tables and the number of interfering links. Then, some nodes will be recolored in such a way that minimizes the number of interfering links without affecting the initial coloration of the network.

We use the well known graph coloring algorithm Tabucol algorithm [17] to recolor. The procedure of nodes re-coloring performs as described in Algorithm 1. As the network is modeled as a graph, the algorithm starts from the initial coloring solution, and try to obtain a better solution in term of number of edges having the two extremities colored by the same color. The technique performs in several iterations, resulting each to a number of conflicting edges, as well as a number of total recolored vertices. The retained color solution is the one which generates the minimal results.

A moderated number of iterations restricts the re-coloring process to the failed node vicinity. We choose this number equal to $\Delta \times n_m$, where $\Delta$ is the maximum number of

Algorithm 1 Re-coloring algorithm

Initialization:

- $s = \{C_1, \ldots, C_m\}$ the color vector;
- According to conflict degree, the reorganized nodes, except nodes whose degree is 0, are sorted in a list $N$ starting with the highest degree;
- Initialize max_itr
- STOP = false, itr = 1, $r(s) = 0$ (number of recolored nodes);

While STOP = false and $itr < \text{max_itr}$

1) $s^* = s$
2) Generate $N'(s)$ of $m$ solutions chosen from $N(s) = \{s' | s' \text{is obtained from } s \text{ by moving the first node in } L \text{ from } C_i \text{ to } C_j, j = 1, \ldots, i-1, i+1, \ldots, m\}$;
3) $s' = \arg\min_{s' \in N'(s)} |f(s', r(s'))|$
4) If $f(s') < f_0$, STOP = true. If $f(s') \leq f(s^*)$, $s^* = s'$; else add the neighbor $u \in C_i \setminus TL$ of $v$ with the highest conflict degree at the end of $L$ and Go to 6;
5) $s = s'$; $r(s) = r(s) + 1$;
6) Remove $v$ from $L$ and update the tabu list $L$
7) $itr = itr + 1$. Go to 2.
neighbors in the network and the number $n_m$ is the number of relocated nodes. Our choice allows the heuristic to find an acceptable solution by re-coloring all 1-hop neighbors at least once and restricts the propagation of re-coloring process.

In this stage, the decision concerning the recovery process is taken, but the nodes are still unaware about the recovery information. The sink is responsible for communicating the information to the network. It selects some particular nodes and moves them in a rotation manner to guarantee that the information reach all isolated segments.

### D. Node Rotation

In our solution, we select a minimal set of nodes and we rotate some of them in a cascade manner to communicate the recovery information to all parts of the WSN. The selected set for the information delivery is defined as $ID\_Set = RN\_Set \cup MN\_Set$, where $RN\_Set$ denotes a set of rotating nodes and $MN\_Set$ a set of members nodes that will participate in information delivery without moving.

The idea is that a Rotating Node (RN) takes the recovery information, moves to the next segment and sends the information to a selected RN belonging to this segment. To minimize the distance traveled by each RN, we use two particular RNs in each segment: Left-Border RN (LB-RN) (dark gray nodes in figure 3(a)) and Right-Border RN (RB-RN) light gray nodes in figure 3(a)). The LB-RN is responsible for transmitting the information to other MNs in the same segment, while the RB-RN is responsible for communication the recovery decision to the next segment. The selection of the MNs is done as follows:

- For each segment, the sink selects the nearest 1-hop neighbor to the left border as the LB-RN and the nearest 1-hop neighbor to the right border as the RB-RN.
- If some 2-hop neighbors participate to the recovery, and they are out of the communication range of LB-RN and RB-RN, some 1-hop neighbors are selected as MNs to guarantee that these nodes can be reached.

After the formation of $ID\_Set$ the recovery process performs as follows:

- The sink sends the $ID\_Set$ and the recovery information to the LB-RN of the first segment (connected to the sink).
- The LB-RN moves to the RB-RN position and transmits the information to other MNs while moving.
- Each node receiving the information checks if it is a MN and if one of its neighbors will participate in the recovery process. If it is the case, the node sends the information to this neighbor, else the message will be discarded.
- When the RB-RN receives the recovery information, it brings it, moves towards the next segment and transmits the message to the LB-RN.
- The process repeats until the RB-RN of the last segment reaches the first segment LB-RN position as shown in figure 3.

To reduce the recovery time, any node participating in the recovery process begins to move since it receives the recovery information. Before the RN rotation ends, the majority of participating nodes reach their new positions. In addition, if the first LB-RN is participating in the recovery, the last RB-RN moves directly towards the position expected to be occupied by this LB-RN. Figure 4 shows the topology of the WSN after the network reorganization. Figure 3(c) shows the relocation of nodes in their new locations determined by the SPs.

![Figure 4. The WSN after the failure recovery](image)

### V. Performance Evaluation

In this section, the proposed solution is evaluated through simulation on Omnet++.

#### A. Simulation Parameters

A WSN is created by deploying the nodes in a 1000m by 1000m area. The number of nodes is varied from 50 to 250 randomly scattered, while the transmission radius is set to 100m. We use the metrics to evaluate the performance of the proposed approach:

1. **Number of interfering links**: reports the number of interfering links causing collisions and retransmission.
2. **Packet delivery ratio**: indicates the percentage of packets successfully received.
3. **Number of re-colored nodes**: reports the number of nodes assigned a new channel after the failure recovery.
4. **Number of relocated nodes**: indicates the influence of the connectivity restoration process on the network topology.
5. **Total traveled distance**: this metric denotes the distances traveled by all moved nodes to recover the failure. In fact, this distance influences the recovery time and energy.

#### B. Results

Figure 5 resumes the results achieved by the multi-channel allocation mechanism used in our solution. Figure 5(a) shows the number of interfering links generated by the use of 2, 3 and 4 channels. As we can see, The use of more channels decreases the number of interfering links considerably. Moreover, figure 5(b) depicts how the interference ratio is still very low (under 13%) even in WSN with a large number of nodes when using 4 channels; while this ratio exceeds (35%) when using 2 channels.
We first evaluate the impact of multichannel communication on the transmission reliability by measuring the packet delivery ratio as depicted in 5(c). We notice that the use of more channel reduces the number of lost packets. Moreover, when the gap between the results obtained by each scenario becomes bigger with the increase of the number of nodes. For example, in a WSN with 50 nodes, the use of 2 and 4 channels generates a packet delivery ratio equal to 92% and 99.6% respectively with a gap of 7.6% between the two results; while this gap increases to reach 25.6 (70.5% and 96.1% respectively) in a WSN using 250 nodes. Therefore, the obtained results show the importance of the use of multi-channel communication in the improvement of data transmission reliability.

After a failure, the network is reorganized and some nodes are relocated and/or re-assigned new channels. Figure 6 shows the impact of the failure recovery on the network in terms of relocated nodes, traveled distance and number of nodes assigned a different channel. We notice that the number of nodes that change their positions increases (6(a)) with the network size while the distance (figure 6(b)) decreases. Theses results are expected as the density of the WSN increases which means that the failure influences more nodes, but in the same time the moving nodes are closer to their new locations, so they travel a shorter distance. Therefore, as figure 6(b), in a small scale network, each relocated node travels an average of 38m; while a node travels only 14m in networks with 250 nodes. The results shown in 6(c) reflect the fact that when the number of neighbors increases, we need to recolor more nodes. Moreover, when the number of channels decreases, we can recolor only a few nodes to minimize the number.
of interfering nodes as we have a number of choices. For instance, if we use 2-channels we recolor only 55 nodes in a WSN with 250 nodes generating 521 interfering links; while with 4 channels we recolor 89 to generate only 230 interfering links. Figure 6(a) depicts also the number of rotating nodes (LB-RNs and RB-RNs). Unlike the number of nodes used for the recovery, the number of rotating nodes used to deliver the recovery information increases. As the density becomes high, the network is partitioned into less isolated parts, and hence few nodes are needed to communicate the information to all the segments.

VI. CONCLUSION

In this paper, we focused on the recovery from an articulation node failure in WSNs. We proposed a centralized solution to recover from the network partition and restore the lost connectivity. Moreover, we consider that the WSN uses a multi-channel communication to minimize the interference ratio. The proposed approach use a WSN reorganization technique to overcome the problem of connectivity loss. We relied on the graph theory, in particular the graph coloring and the Steiner tree problems, to conceive an efficient solution that can improve the WSN performance as well as its fault tolerance property. We first formulated the problem as a constrained multi-objective problem with four objective functions; then we proposed an approach for the node failure recovery. In the proposed solution, the sink is responsible for the WSN reorganization and then the channels re-allocation. The recovery information computed by the sink is communicated to the isolated WSN segments by the use of a rotation technique of some nodes. These nodes are chosen based on their locations, and they are rotated in a cascade. The performance of the presented solution is evaluated by simulation. As a next first step in our work, we will focus on the distribution of the recovery process to reduce the overhead of generated by the node rotation. Then as a second future step, we will extend the solution including hierarchical mechanisms.

REFERENCES