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Centralized connectivity restoration in multichannel wireless sensor networks

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ABSTRACT

Wireless sensor networks (WSNs) are widely used in various domains. In general, the applications, in which the WSN is deployed, require that this network presents a minimum degree of reliability, effectiveness and robustness. However, the specificity of the nodes deployed in this kind of networks makes them prone to failures. One of the important problems caused by a sensor node failure is the loss of the network connectivity, which means that some network parts become isolated and hence, the nodes cannot reach the sink. In addition to the initial nodes' deployment that ensures the connectivity, other connectivity restoration mechanisms must be integrated to overcome the problem of WSN partition after a node failure. In this paper, we propose two centralized approaches for the connectivity restoration in a multichannel WSN. The first approach Preventive Failure Recovery (PFR) performs just before the partition of the network while the second approach Rotating Nodes based Failure Recovery approach (RNFR) is a reactive approach that intervenes after the failure occurrence. The main task of these two approaches targets the reorganization of the network in the failed nodes' vicinity to restore the connectivity and hence ensure an optimal channel allocation as for the initial configuration. We prove the performance of the two proposed approaches by evaluating them through simulation and comparing them to each other and to another existing approach.

1. Introduction

In the recent years, wireless sensor networks (WSNs) (Akyildiz et al., 2002) have been widely deployed in different domains going from simple data collection to critical system monitoring and control. More and more researchers have dedicated their work to improve the reliability, robustness and efficiency of the WSNs regarding the requirements of different applications. However, the characteristics of sensor nodes (limited CPU, memory, battery, wireless communications, etc.) and the harsh environments, in which they are deployed, drastically decrease the reliability of WSNs and even lead to the failure of fulfilling their expected mission. On one hand, a node failure, due to energy depletion or any physical damage, may partition the network into disjoint parts; where some of these parts get disconnected from the sink. On the other hand, the interferences between senor 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 largely discussed in literature. One of the common techniques used to handle such a problem is the use of multichannel communications. Since the integration of multichannel radios in wireless sensor devices, many interesting studies have been dedicated to optimally exploit the benefits of multichannel communications in such networks (Wu et al., 2008; Chowdhury et al., 2009; Incel et al., 2011; Zhou et al., 2006; Kim et al., 2008; Yang and Yi, 2010). The proposed mechanisms help to minimize the collision/retransmission ratio, and then the energy consumption. However, the probability of node failure remains high. Thus any node may fail due to energy depletion or physical damage. In many applications, the WSNs are deployed in unreachable or dangerous environments (where the replacement of a failed node or of its battery is not easy and even unfeasible). The problem becomes even more critical when the failed node is an articulation node (cut-vertex). This node is a particular node whose failure split the network in two/several disconnected parts. To overcome this problem, the WSN can use a rearrangement technique to restore the network connectivity. Many researches have suggested the network reorganization to restore the network connectivity (Younis and Waknis, 2010; Lee and Younis, 2010;

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Tamboli and Younis, 2009; Younis et al., 2008; Abbasi et al., 2013; Lee et al., 2015; Essam et al., 2015; Imran et al., 2012; Haider et al., 2015; Mi et al., 2015; Ranga et al., 2014, 2015a,b, 2016). However, the proposed algorithms did not consider the use of multichannel communications to reduce the interference ratio in the network. Indeed, the failure recovery in a multichannel context requires the consideration of some additional parameters and processing tasks. For instance, a channel reallocation process, minimizing the interferences between the nodes, is generally needed to deal with the network topology changes. Our main idea is to propose an approach for the connectivity restoration while respecting the multichannel context. We aim to relocate some nodes around the failed articulation node with the minimum impact on the network initial topology and configuration. This impact is given in terms of the number of relocated nodes, the total traveled distance, the interference ratio and the number of nodes assigned to different channels after the failure recovery.

In this paper, we propose a centralized solution related to one of the most challenging issues in WSN: the restoration of the network connectivity after an articulation node failure while considering the multichannel allocation. Therefore, we propose novel fault tolerance techniques that aim to relocate sensors to restore the connectivity and perform channel reallocation in the network. We first formulate the problem as a multi-objective optimization problem. Then, we propose some heuristics to solve it in a realistic way. As we opt for a centralized processing, the sink is the only node responsible of the whole recovery procedure from the nodes' reorganization to the channel reallocation after the connectivity restoration. The conceived solution uses some graph theory heuristics such as graph coloring (Brelaz, 1979) heuristics for channel (re)allocation and *Steiner Points* (Wang and Li, 2002) heuristic to rearrange the nodes around the articulation node zone. The centralization of the processing avoids the need of coordination between the nodes. However, a new problem arises: How the sink can communicate the recovery information to the isolated partitions of the network after the failure of the articulation node? In a previous work (Chouikhi et al., 2014), we detailed all the recovery steps as they are performed by the sink. We did not present how the recovery information is delivered to the nodes involved in the recovery process. In this paper, we propose two alternatives of the centralized solution presented in Chouikhi et al. (2014): a preventive alternative *Preventive Failure Recovery* (PFR) and a reactive alternative *Rotating Nodes based Failure Recovery* (RNFR) (Chouikhi et al., 2015a). In PFR the whole procedure is triggered just before the failure of the articulation node and then the sink communicates the information to the whole network through this node which is still functional. However, RNFR intervenes after the failure occurrence, which means that the WSN is already partitioned into disjoint segments when the fault recovery process is triggered. We propose that the sink selects a set of nodes (called ID_set), from the failed node's 1-hop neighbors, to communicate the recovery information to each concerned node. The selected nodes move in cascade to reach all the disconnected network parts.

The rest of this paper is organized as follows: Section 2 overviews the existing works related to the topic of connectivity restoration in WSNs. In this section, we present the most interesting and recent researches dedicated to the problem of connectivity loss after the failure of a single or multiple nodes. In Section 3, we formulate the problem of an articulation node failure recovery in a multichannel context as a Multi-objective Optimization Problem (MOP). We present our first approach Preventive Failure Recovery (PFR) in Section 4 with a detailed description of all the heuristics used to solve the problem of connectivity loss in a multichannel context. Section 5 is dedicated to Rotating Nodes based Failure Recovery approach (RNFR). In particular, in this section, we focus on the nodes' rotation technique used by RNFR to disseminate the recovery information to all the network segments. Section 6 evaluates the performance of PFR and RNFR. The two proposed approaches are compared to an exact solving solution as well as to an existing connectivity restoration solution. Section 7 concludes the paper and highlights on our future work.

2. Related work and contributions

2.1. Related work

The connectivity is one of the most crucial requirements in WSNs. In the literature, many interesting works have been dedicated to ensure, improve or restore connectivity in this type of networks (Chouikhi et al., 2015b). The solutions proposed in the literature can be classified into two main classes: preventive solutions and curative solutions. The preventive solutions aim to prevent the connectivity loss by avoiding the failure of nodes or giving an alternative way to handle the transmission of the information to the sink in the case of a node's failure. Generally, these solutions are based on *energy consumption management* (multichannel communications, sensor activity/sleeping schedule, etc.), *deployment strategies* (redundant nodes, relay nodes, etc.) and *multi-path routing* techniques. The curative class includes all the solutions triggered after a failure occurrence. These solutions use different techniques to resume the correct network functioning. The main techniques used are *new nodes' deployment* and *network reorganization*. These techniques are commonly used to improve or to restore the network connectivity to prevent or recover from the network partition. Network reorganization techniques are based on the existing nodes' redeployment, which means that some nodes are relocated in some new locations to improve or restore the connectivity. It thus assumes that some or all nodes are movable (Younis and Waknis, 2010; Lee and Younis, 2010; Tamboli and Younis, 2009; Younis et al., 2008). These techniques can be also used in coverage improvement.

Many proposed mechanisms use node reorganization technique to enhance the WSN reliability. Younis and Waknis (2010) 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. The algorithm presented in Tamboli and Younis (2009) replaces the failed node by neighbors one by one. Each node moves back and forth to the failed location for a period of time. In Younis et al. (2008), the authors proposed the RIM (Recovery through Inward Motion) approach which performs a local recovery around the failed node. The main idea of RIM is to move the neighbors in the direction of the failed node until they can reach each other. If at any time a node becomes disconnected of one of its neighbors because of its relocation, the disconnected node follows this neighbor to get reconnected to it again. The relocation procedure is triggered recursively to avoid any node disconnection. Nevertheless RIM restores the connectivity, it was proved to be very costly in dense networks in terms of the relocated nodes' number and the traveled distance. In fact, when we increase the network density, the number of a node's u neighbors increases and when this node moves to a new location, it becomes unreachable for many of its neighbors. The latter must move too, to reconnect to u again, and so on. This leads to more relocated nodes which travel more distance when the network becomes denser. In Mi et al. (2015), the approach CSDS (a Critical Sensor Determination and Substitution) was proposed for mobile sensor networks. The strategy used by this approach allows the identification of critical nodes and the selection of a backup sensor for each critical node. The selection of the best candidates to be backup nodes is based on criticality, hop-count and Euclidean distances of their neighbors. The main advantage of CSDS is that only one node will be relocated in the case of an articulation node failure.

The LeDiR (Least-Disruptive topology Repair) algorithm proposed in Abbasi et al. (2013) for wireless sensor–actor networks (WSAN) restores the connectivity between actors (nodes designed to take some actions collaboratively to achieve predefined application tasks). The main idea of this algorithm is relocating the minimum number of nodes without extending the length of the shortest inter-actor path. In LeDiR, the recovery process is restricted to the neighbors belonging to the smallest disjoint network segment after the WSAN segmentation. Imran et al. (2012) proposed DCR (Distributed partitioning detection and Connectivity Restoration algorithm) that detects the critical nodes in WSANs and selects a backup non-critical node for each one based on *Guardian nomination* principle. An extended version, named RAM, of DCR has been proposed to deal with multi-node failures. In Ranga et al. (2014), the authors proposed DPCRA (Distributed Prioritized Connectivity Restoration Algorithm) which identifies the articulation nodes in a proactive way and elects some Failure Handlers (FHs). The latter detects the partition of the network after an articulation node failure and the first designed FH triggers the failure recovery process. If this FH is unable to start the connectivity restoration process within a permissible reaction time, the next designed FH starts the recovery process. Moreover, DPCRA adopts a cascaded relocation to handle the connectivity restoration. Haider et al. (2015) proposed the RACE (Restore Actor Connected Coverage) algorithm that recovers from the failure of critical and non-critical actors. If the failed actor is non-critical, its neighbors move to cover the actor's bereaved sensors (uncovered sensors after the actor failure). In the case of a critical actor failure, its neighbors independently determine the best candidate to replace the failed actor. This selection is based on the candidate criticality (to avoid a cascaded relocation) and the impact on the number of uncovered sensors. The non-critical actor, which covers the small number of sensors uncovered by other actors, will be preferred to substitute the failed actor. In Ranga et al. (2015a), the authors proposed an energy efficient approach. The latter exploits two point crossover genetic algorithm to heal a partitioned WSAN after a backbone actor failure and uses sensor nodes as bridging routers.

In addition to the mechanisms proposed above for the recovery from a single articulation node failure, many interesting algorithms discussed the connectivity restoration after the simultaneous nodes' failures. The algorithm DORMS (Distributed algorithm for Optimized Relay node placement using Minimum Steiner tree), proposed in Lee and Younis (2010), uses *Steiner Trees* to reconnect the WSN after the failure of multiple nodes. DORMS moves mobile relay nodes towards the center of the damaged zone to form a bridge between the different disconnected parts of the network. In Lee et al. (2015), the authors discussed the problem of simultaneous failures of multiple sensors that leads to the partition of the WSN into disjoints segments. They proposed an approach, called CRAFT (Connectivity Restoration with Assured Fault Tolerance), which establishes a bi-connected inter-partition topology by deploying a minimal number of relay nodes. It tries to form the largest backbone empty polygon around the center of the failed zone which means that no partition exists inside this polygon. Then, the algorithm determines two disjoint paths for each partition to connect it to the backbone polygon. These paths are formed by the deployed relay nodes. Another algorithm, called RIR (Recovery algorithm with Increased Robustness), proposed in Essam et al. (2015), targets the failure of multiple critical nodes. RIR replaces the failed nodes with non-critical healthy nodes having the highest residual energy in order to maintain the network connectivity as longer as possible. Moreover, to minimize the distance traveled by the substituting nodes, RIR considers the problem of failure recovery as a Minimum Cost Flow (MCF) problem. The failed nodes are considered as the destinations in the MCF model while the healthy nodes are considered as source nodes. The MCF model determines the solution generating the minimal cost, where the cost function denotes the total traveled distance. In Ranga et al. (2015b), the approach Restore Relay Lost Connectivity using zero Gradient Based Point (RRLC-GBP) that recover from a large scale failure. This solution determines a point at which the gradient of disjoint sub-networks becomes zero inside the convex hull polygon. Then, some relay nodes are deployed towards this point to reconnect the disjoint parts of the WSN.

All the mentioned algorithms recover node failures and offer some techniques to restore the connectivity in WSNs. These solutions use a single channel for the data transmission. However, in a multichannel context, which is commonly used to avoid interferences in WSNs, the approaches presented above cannot be applied directly. Indeed, they require some mechanisms for channel management after the failure if we want to integrate them in multichannel networks. The consideration of multichannel context when conceiving an algorithm for connectivity restoration will considerably simplify and favor the application of such an algorithm in multichannel WSNs. We investigated the problem of fault recovery for WSNs in a multichannel context in Chouikhi et al. (2014). We proposed a centralized solution that tries to reorganize a minimum set of nodes in the failed node vicinity to restore the network connectivity. We gave also some mechanisms for the initial allocation and the reallocation of the available channels in the network. As the proposed solution is centralized, we were interested only to the description of the heuristics that are performed by the sink to recover from the failure. In Chouikhi et al. (2015a), we extended our work and propose Rotating Nodes based Failure Recovery approach (RNFR) that use a node rotation based technique to disseminate the recovery information in the whole network.

2.2. Contributions

In this paper, we focus on the centralized fault tolerance solutions in WSNs using multichannel communications. Our contributions can be summarized as follows:

- First, we formulate the problem of the network connectivity restoration in a multichannel context as a Multi-objective Optimization Problem (MOP). This formulation allows us minimizing the impact of failure recovery on the WSN configuration in terms of topology and initial channel assignment while restoring the connectivity.
- Then, we propose a centralized preventive approach, named Preventive Failure Recovery (PFR), for the recovery from an articulation node failure which is triggered when the energy level in the articulation node falls below a predefined threshold. PFR is executed by the sink just before the articulation node failure and uses some heuristics from graph theory to perform a localized recovery around the failed node. These heuristics rearrange some neighbors to reconnect the disjoints partitions of the WSN and then reallocate the channels. Once the recovery decision was taken by the sink, the latter communicates this decision to the whole network through the articulation node which is still functional before its fails.
- As a second approach, we propose the centralized curative approach Rotating Nodes based failure Recovery (RNFR). This approach uses the same heuristics used by PFR for the connectivity restoration and the channel reallocation. However, RNFR performs after the occurrence of the articulation node failure leading to the network partition. It can be applied for all type of failures (energy depletion, physical damage, node crash, etc.). We suggest a node rotation strategy to deliver the recovery data to each isolated partition in the WSN. According to this strategy, the sink elects a set of nodes, from the 1-hop neighbors of the failed node, to disseminate the restoration information to all the disjoint network segments.
- We evaluate the performance of the two proposed approaches by simulation. Moreover, we compare them to an exact solving method for the multi-objective optimization problem and to an existing approach RIM (Younis et al., 2008).

The two approaches PFR and RNFR as well as the heuristics used will be described in detail in Sections 4 and 5.

3. Problem formulation

In this section, we focus on the formulation of the connectivity restoration problem in a multichannel WSN. The multichannel communication is used to reduce the interference ratio between the sensor nodes. Thus, the initial channel allocation must minimize the number of interferences between the nodes. Besides, if an articulation node fails in the network, its recovery must restore the connectivity while minimizing the interferences in the network (optimal channel allocation).

We use graph theory to formulate our problem. Thus, we consider the problem of channel allocation/reallocation as a graph coloring problem and the problem of connectivity restoration as a sub-graph connection problem. For the latter, we will exploit a technique based on Steiner Points (SPs) (Wang and Li, 2002) used to reconnect sub-graphs with a minimum cost.

We consider the problem of recovery from an articulation node failure as a nodes' relocation and channel reallocation problem with the main objectives: (i) to minimize the number of relocated nodes, (ii) to minimize the total distance traveled by the relocated nodes, (iii) to reduce the interference ratio, and (iv) to minimize the number of nodes changing their channels after the failure recovery. Our problem will be formulated as a Multi-objective Optimization Problem (MOP) (Sections 3.3 and 3.4). The four objectives, mentioned above, will be represented by four objective functions: f_1 (Eq. (3)), f_2 (Eq. (6)), f_3 (Eq. (11)) and f_4 (Eq. (15)) respectively.

3.1. Assumptions

In this work, we use the following assumptions:

- We consider a network of a fixed number **N** of sensor nodes deployed using a uniform distribution. Each sensor can move within the network area with a fixed speed v to recover from an articulation node failure.
- All the sensor nodes have the same communication and sensing ranges R_c and r_s and an initial energy level.
- All the nodes operate in the multichannel context. We consider that at each time the multichannel network configuration is quasi-optimal.
- The studied WSN is used for periodic data gathering.
- A single articulation node fails at the same time.
- No other node fails during the recovery process.

3.2. Network model

We model the WSN as a colored graph $G = (V, E)$. The set of vertices V represents the sensor nodes ($|V| = n$) and the set of edges E represents the interference links between the nodes. Each available channel i is represented by a different color. We define M as the set of colors (channels) ($|M| = m$). An edge e, $(u, v) \in E$, exists if and only if the two nodes interfere (i.e. the distance between nodes u and w $d(u, w) \le 2R_c$, with R_c the communication range). We assume that all the sensors are movable and then they can move from their initial positions.

3.3. Channel allocation problem

Considering the limited number of available channels for the WSN, the optimal channel allocation is the allocation that reduces the number of interfering nodes assigned the same channel. Thus, we formulate the channel allocation problem as a graph vertices coloring problem with limited number of colors. Then, we try to minimize the number of adjacent vertices colored with the same color. To this end, we define the function $c(v) = j$ representing that the vertex v is colored by the color j. The vector $s = (V_1, V_2, \ldots, V_m)$ represents the decision vector that minimizes the number of adjacent vertices colored with the same color and V_j is the set of vertices colored by the color j.

To minimize the number of conflicts (number of conflicting nodes), we define the binary function $\delta_j(v)$ for the vertex $v \in V_j$ as:

$$\delta_j(v) = \begin{cases} 1 & \text{if } \exists\, u \in V_j | (v, u) \in E \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

The number of conflicts over a color j is determined by:

$$\Delta_j = \sum_{v \in V_j} \delta_j(v). \tag{2}$$

Thus, we define f_1, the objective function that aims to minimize the number of adjacent vertices colored with the same color as:

$$f_1(s) = \sum_{j=1}^{m} \Delta_j \tag{3}$$

Therefore, the optimization problem is:

$$\text{minimize } f_1(s) \tag{4}$$

$$\text{subject to:} 1 \le c(v) \le m, \quad \forall\, v \in V \tag{5}$$

The constraint (5) ensures the coloring of all the vertices.

Considering the objective function f_1 for an optimal channel allocation in the network, we guarantee that whatever is the deployment of the sensor nodes in the network (initial deployment and partial redeployment to recover a failure), the channels are assigned in such a way as to minimize the interferences in the network.

3.4. Failure recovery problem

After an occurrence of an articulation node failure, we aim to restore the connectivity while restricting the recovery process around the failure zone. The connectivity restoration is performed through the relocation of some nodes. However, we must restrict the impact of the relocation process around the failure vicinity.

We use an algorithm based on Steiner Points (SPs) (Wang and Li, 2002) to determine the new locations of the relocated nodes. In addition, to reduce the impact of the failure recovery on the whole WSN, a minimal set of SPs must be elected to restore the connectivity. Then we use only the 1-hop and 2-hop neighbors of the failed node to replace these SPs. Thus, the connectivity must be restored while:

- minimizing the number of relocated nodes to recover the failure of the articulation node (the number of SPs occupied by nodes);
- minimizing the total distance traveled by the relocated nodes.

In addition, we consider the multichannel context, which means that the failure recovery must also:

- minimize the number of interfering nodes;
- minimize the number of nodes assigned new channels after the connectivity restoration.

Therefore, the problem of failure recovery in multichannel WSN can be defined as a multi-objective optimization problem with four objectives to achieve. To formulate our problem, we introduce the following notations:

- $SPset$: the set of all determined SPs around the failed node ($|SPset| = k$).
- $H_1(AP_f) = \{v \in V | d(v, AP_f) < R_c\}$: the set of 1-hop neighbors of the failed node.
- $H_2(AP_f) = \{v \in V | R_c < d(v, AP_f) < 2R_c\}$: the set of 2-hop neighbors of the failed node.
- $G' = (V', E'_I)$: The colored graph representing the multichannel WSN after the failure recovery and defined in the same way as

$G = (V, E)$ (Section 3.2).

- $s' = (V'_0, V'_1, V'_2, \ldots, V'_m)$: representing the solution vector of the multi-objective optimization problem after the failure recovery compared to $s = (V_0, V_1, V_2, \ldots, V_m)$ the solution vector before the failure.
- $c_s(v)$: the function that gives the color of a vertex v in the solution s.
- $V'_j = \{v \in V' | c_{s'}(v) = j\}$: the set of vertices of G' colored with the color j.
- V'_0: the set of uncolored vertices denoting the locations unoccupied by sensor nodes (SPs or old positions of relocated nodes).
- Initially, $V_0 = SPset$.

Each objective i, $i = 1, \ldots, 4$, described above can be defined by an objective function f_i to be optimized. If we consider the first objective that consists in minimizing the number of adjacent vertices colored by the same color, this objective can be achieved by minimizing the function f_1 (Eq. (3)) defined in Section 3.3.

The second objective function f_2 is defined in the same way as f_1:

$$f_2(s') = \sum_{j=1}^{m} \Gamma_j \tag{6}$$

with

$$\Gamma_j = \sum_{v \in V'_j} \gamma_j(v) \tag{7}$$

and $\gamma_j(v)$ gives if the vertex is recolored or not:

$$\gamma_j(v) = \begin{cases} 1 & \text{if} \quad v \in V'_j \wedge c_{s'}(v) \neq c_s(v) \\ 0 & \text{otherwise.} \end{cases} \tag{8}$$

In the same way, to find the set of SPs elected to be used by the replacing nodes in the WSN, we define:

$$\varphi_j(v) = \begin{cases} 1 & \text{if} \quad v \in SPset \cap V'_j \wedge j \neq 0 \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

$$\Phi_j = \sum_{v \in V'_j} \varphi_j(v) \tag{10}$$

$$f_3(s') = \sum_{j=1}^{m} \Phi_j \tag{11}$$

To formulate the last objective f_4, we define:

$$d_{SP_i}(u) = \begin{cases} 1 & \text{if } u \text{ replace } SP_i \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

and

$$D(SP_i) = \sum_{u \in H_1 \cup H_2} d_{SP_i}(u) dist(SP_i, u) \tag{13}$$

with

$$dist(SP_i, u) = \sqrt{(x_{SP_i} - x_u)^2 + (y_{SP_i} - y_u)^2} \tag{14}$$

where (x_{SP_i}, y_{SP_i}) and (x_u, y_u) represent the coordinates of the Steiner Point SP_i and the node u.

The function f_4 that represents the total traveled distance can be written as:

$$f_4(s') = \sum_{SP_i \in SPset} D(x). \tag{15}$$

Therefore, our multi-objective optimization problem becomes:

$$\text{minimize } f(s') \tag{16}$$

with $f(s') = [f_1(s'), f_2(s'), f_3(s'), f_4(s')]^T$,

Subject to:

$$G' \text{ is connected} \tag{17}$$

$$c_{s'}(v) \in M, \quad \forall\, v \in V' \backslash V'_0 \tag{18}$$

$$|V'_0| = |SPset| \tag{19}$$

Constraint (17) ensures that the network becomes connected after the failure recovery process, while (18) guarantees that each node is assigned a channel from the available channels.

Many methods are proposed in the literature to give the exact solutions of multi-objective optimization problems. Unfortunately, these methods cannot be applied in the WSN context due to their exponential execution time and their complexity (NP-complete). Thus, we opt for heuristics to find a solution to our optimization problem while respecting the WSN characteristics. In the following sections, we will propose two connectivity restoration approaches for multichannel context based on heuristics: a preventive approach *Preventive Failure Recovery* (PFR) and a curative approach *Rotating Nodes based Failure Recovery* (RNFR).

4. Preventive Failure Recovery approach

To find a feasible solution of our multi-objective optimization problem in an acceptable time, we will decompose the initial problem into sub-problems so that every sub-problem is associated with one or several objectives to optimize. Moreover, we solve the sub-problems sequentially in such a way as the output of a sub-problem becomes the input for the following one.

Therefore, our *Preventive Failure Recovery* approach (PFR), which gives a solution of the multi-objective problem, executes in three main steps as follows:

1. First, find an optimal network configuration which minimizes the number of adjacent neighbors in the graph G using the same channel. This will be fulfilled by using two graph coloring heuristics.
2. Then, after a failure occurrence, we should determine the minimal set of nodes, given by an SP algorithm, that will be used to replace the failed node and hence to restore the WSN connectivity. The nodes of this set must be chosen in such a way as to minimize the total traveled distance.
3. Finally, once the connectivity restoration finished, we proceed to the channel reallocation around the failed node while minimizing the number of interfering nodes and the number of nodes assigned new channels.

4.1. Initial channel allocation

The problem of channel allocation can be represented as a problem of graph coloring with m colors. A number of heuristics have been proposed to solve such a problem.

4.1.1. Heuristics of graph coloring

The graph coloring heuristics can be classified into three main classes: constructive algorithms, local search algorithms and evolutionary algorithms. In the first class of heuristics, the nodes are colored one by one until an optimal solution is obtained (e.g. *glutton algorithm* and *DSATUR*). The local search algorithms start from an initial colored graph and try to improve the solution iteratively until reaching an optimal configuration or a maximum iteration number (e.g. *simulated annealing* and *Tabucol*, Hertz and Werra, 1987). The last class includes mechanisms that use a set of individuals adapting themselves individually and cooperating by an information exchange (e.g. *genetic algorithms* and *ant system algorithms*).

In a small network context, local search heuristics are very efficient. However, as the number of nodes increases, it becomes difficult to obtain an optimal solution in a timely manner. To improve the local search algorithms performance, many researches propose to combine them with a constructive algorithm to reduce the graph size before applying the local search method. The constructive heuristic colors the maximum number of vertices with no conflicts called *stable color classes*, and then the local search heuristic colors the remaining nodes.

In our work, we opt for a hybrid coloring strategy that combines a constructive heuristic with a local search heuristic.

4.1.2. Hybrid graph coloring strategy

As our solution is centralized, the initial channel allocation (graph coloring) is performed by the sink which can obtain a global view of the whole network. This centralized processing will improve the coloring process.

The constructive heuristic exploits the neighborhood information collected by the sink to construct the stable classes. The heuristic is described in Algorithm 1.

Algorithm 1. Constructive coloring heuristic.

Initialization:
- According to the number of neighbors of each node (neighborhood degree), the sink puts all nodes in a list L starting with the node having the highest neighborhood degree.
- $C = \{C_1, \ldots, C_m\} = \emptyset$ the set of colored nodes, in which class C_j includes the nodes colored by j.
- *STOP = false*

While *STOP = false*

1. Take the first node v in L, color it with the available color j with the smallest ID, put v in the C_j and remove it from L.
2. Move to the next node, if it is not a neighbor of any $u \in C_j$, color it with j, remove it from L and add it to the C_j. Otherwise, move to the next node. Repeat this process until the end of the list L.
3. If $L = \emptyset$ or no more color is available, then *STOP = true*.
4. Go to 1.

This algorithm reduces the number of uncolored nodes, which increases the efficiency of the local search heuristic. To color the remaining nodes, we propose a heuristic based on *Tabucol* algorithm (Hertz and Werra, 1987),which is proved to provide good results.

Tabucol starts from an initial solution s and iteratively moves a vertex v from C_i to C_j to obtain a new solution s'. The move *(v, i)* becomes *tabu* which means that v cannot be colored by the color i for t iterations (t is a parameter). The move can be removed from the *tabu list TL* according to the *aspiration* function *Asp*. Initially, $Asp[z] = z - 1$; z represents the number of conflicts in a solution s. Then, every time a solution s' such as $f(s') \leq Asp[f(s)]$ is generated, we put $Asp[f(s)] = f(s') - 1$; *f(s)* denotes the number of adjacent vertices in the same color class. If the move giving s' is tabu, we remove its tabu status and consider it as possible. The choice of the aspiration function avoids the algorithm to go back to a solution visited yet. The number of iterations can be limited either by a predefined maximum computation time or by a maximum number of consecutive iterations that do not improve the best obtained solution without enhancing of the optimal solution. The steps of the local search heuristic are described in Algorithm 2.

Algorithm 2. Tabucol based heuristic.

Initialization:
- $s = \{C_0, C_1, \ldots, C_m\}$, $C_0 = L$; /* C_0 the set of uncolored vertices*/
- $TL = \emptyset$; /* the tabu list*/
- $s^* = s$; /*s^* is the current optimal solution*/
- Initialize *Asp* and *max_itr*;
- *STOP = false*, *itr* = 1;

While *STOP = false* **and** $itr < max_itr$

1. Generate $N'(s)$ of p (parameter) solutions chosen from $N(s) = \{s' | s'$ is obtained from s by moving a node from C_0 to C_i, $i = 1 \ldots m$, with no tabu move except if $f(s') \leq Asp[f(s)]\}$;
2. $s' = \mathrm{argmin}_{s'' \in N'(s)} f(s'')$, (the solution with the minimum number of conflicts);
3. If $f(s') < f(s^*)$, $s^* = s'$. if $f(s^*) = 0$, *STOP = true*;
4. $s = s'$;
5. Update *TL*
   - Put the new move *(v, 0)* in *TL*
   - If $|TL| > t$, remove the old move from *TL*
   - Update *Asp*; $itr = itr + 1$.
   - Go to 1.

In Algorithm 2, the parameter *max_itr* (representing the maximal number of iterations) as well as the *tabu list* size influence the algorithm execution time and the quality of the obtained solution.

Once the channel allocation ends, the sink informs every sensor node which channel is to be used. Thus, the nodes switch their radios to their assigned channels and can receive data from other nodes. The nodes assigned the same channel that use CSMA to access the channel. The data will be transmitted from the sensor nodes to the sink using the assigned channels until a failure occurrence.

4.2. Preventive failure detection

PFR focuses on the failure of an articulation node caused by energy depletion. Then, when a node detects that its energy level falls under a predefined threshold, it sends a *failure_report* to the sink. The sink considers the node sending this message as a failed node and immediately triggers the recovery procedure the *failure_report* sending node is an articulation node. As we are in a centralized context, the sink performs the connectivity restoration and channel reallocation mechanisms as described in the following sections.

4.3. Connectivity restoration

The heuristics proposed in this section aim to restore the connectivity by relocating a minimal set of sensor nodes while minimizing the total traveled distance. Then, we propose to use the failed node's 1-hop neighbors (and may be some 2-hop neighbors) to reconnect the isolated network segments. In addition, we use the Steiner Points (SPs) (Wang and Li, 2002) to determine the new locations of the replacing nodes.

We first form a polygon with all the failed node's 2-hop neighbors as vertices. The heuristic of SPs determination performs as follows:

1. For each two nodes i and j of the polygon, a triangle Δ_{ij} is formed with the failed articulation node n_f as its third vertex.
2. For each Δ_{ij}, the SP is the point inside Δ_{ij} that minimizes the distance $d = dist(SP, i) + dist(SP, j) + dist(SP, n_f)$. To find this SP, the proposed approach use the approximation algorithm *k-LCA* (Robins and Zelikovsky, 2005), with k set to 3.
3. Among all the determined SPs, we remove the SPs covering less than two vertices of the polygon (i.e. $\forall\ i$ vertex $dist(i, SP) > R_c$) and the redundant SPs (covering vertices covered by other SPs). The remaining SPs are put in $SPset_{min}$.
4. If some vertices of the polygon (2-hop neighbors) remain uncovered by the SPs, we form a new polygon with these vertices and the SPs of $SPset_{min}$. We apply the steps 1–3 to find the new SPs.
5. The process is repeated until all 2-hop neighbors are covered by the SPs.

Once the minimum set of Steiner Points $SPset_{min}$ (giving the new positions of the replacing nodes) determined, we move to the second step of connectivity restoration process that selects the set of sensor nodes that will occupy the SPs. In this step, we use another heuristic to elect the nodes to be relocated in such a way as to minimize the total traveled distance the number of conflicting links. According to the number of determined SPs, two cases can take place:

- **Case 1**: $|SPset_{min}| \le |H_1(n_f)|$: each SP will be occupied by a 1-hop neighbor. The election of replacing nodes uses the following heuristic that executes in five steps:
  1. Determine the node $v_1 \in H_1(n_f)$ and the Steiner Point $SP_1 \in SPset_{min}$ that gives the value:

$$d(SP_1, v_1) = \max_{SP_i \in SPset_{min}} \left(\min_{v_j \in H_1(n_f)} dist(SP_i, v_j) \right) \tag{20}$$

  2. Add the couple (v_1, SP_1) to the set of replacing nodes $Rset$.
  3. Remove v_1 from the list of nodes that are eligible for the replacement of Steiner Points and SP_1 from $SPset_{min}$.
  4. Repeat the steps 1–3 to the remaining set $H_1(n_f)\setminus v_1$.
  5. Repeat all the steps until $SPset_{min} = \emptyset$.
- **Case 2**: $|SPset_{min}| > |H_1(n_f)|$: All the failed node's 1-hop neighbors as well as some 2-hop neighbors will move to the locations of the SPs. We proceed in the same way as the first case except that we include 2-hop neighbors. We verify in every step that the number of relocated 2-hop neighbors remains lower than $|SPset_{min}| - |H_1(n_f)|$. The 2-hop nodes will be replaced in cascade using the DARA algorithm (Abbasi et al., 2009).

Fig. 1 depicts the steps of the network organization, where the green nodes represent the 1-hop neighbors, the blue nodes represent the 2-hop neighbors and the gray nodes represent the empty locations earlier occupied by the replacing nodes before their relocation.

4.4. Channel reallocation

After the progress of the failure recovery procedure described in Section 4.3, the optimal channel allocation is no more respected. Indeed, the relocation of the replacing nodes leads to a new network topology with the appearance of new interfering links and the disappearance of some ones. A channel reallocation becomes a necessity to maintain an optimal channel allocation in the WSN. Then, we propose a recoloring heuristic based on the algorithm *Tabucol* (Hertz and Werra, 1987).

Let f_0 be the number of conflicts (number of interfering nodes) before the nodes relocation, the procedure of node re-coloring performs as follows:

- Re-color the relocated nodes one by one and calculate the number of conflicts each time:
  1. If this number is less or equal to f_0, stop.
  2. Else move to the next node.
- If the number of conflicts remains greater than f_0 we re-color the relocated nodes' 1-hop neighbors one by one and we calculate the number of conflicts each time:
  1. If this number is less or equal to f_0, stop.
  2. Else move to the next node.
- Repeat the process until the maximum number of iterations is reached.

The re-coloring process is described in details in Algorithm 3, where *TL* is the tabu list including the tabu moves, *r(s)* denotes the number of re-colored nodes in the current solution s and s^* represents the optimal coloring solution.

Algorithm 3. Re-coloring heuristic.

Initialization:
- $s = \{C_1, \ldots, C_m\}$;
- According to conflict degree, the reorganized nodes, except the nodes whose degree is 0, are sorted in a list L starting with the highest degree.
- Initialize *max_itr*
- $itr = 1$, $c(s) = 0$;

while $STOP = false$ **and** $itr < maxitr$ **do**
  Generate $N'(s)$ of m solutions chosen from $N(s) = \{s' | s'$ is obtained from s by moving the first node v in L from C_i to C_j, $j = 1, \ldots, i-1, i+1, \ldots, m\}$;
  $s' = \mathrm{argmin}_{s'' \in N'(s)}[(f(s''), r(s''))]$;
  if $f(s') < f_0$ **then**
    Break;
  end if
  if $f(s') \le f(s^*)$ **then**
    $s^* = s'$;
  else
    Add the neighbor $u \in C_i \setminus TL$ of v with the highest conflict degree at the end of L;
    $s = s'$; $r(s) = r(s) + 1$;
    Remove v from L and update the tabu list TL;
    $itr = itr + 1$;
  end if
end while

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 Δ is the maximum number of neighbors in the network and the number n_m is the number of relocated nodes. Such a choice allows the heuristic finding an acceptable solution where all 1-hop neighbors are recolored at least once.

At this stage, the multi-objective optimization problem is solved and the decision concerning the recovery process is taken by the sink. However, the nodes are still unaware of the recovery information as the recovery process is only performed by the sink. PFR proposes that the recovery decision is enclosed in a *recovery* message and sent from the sink to the articulation node. As the latter is still functional, it communicates the recovery message to all the network segments.

The PFR preventive strategy allows relocating all participating nodes before the failure of the articulation node, which easily solves the problem of isolated segments without any additional processing. However, this solution is not suitable for the failures caused by a factor other than the energy depletion.

In the following section, we propose a curative approach that will involve all types of failure as it is triggered after the WSN partitioning.

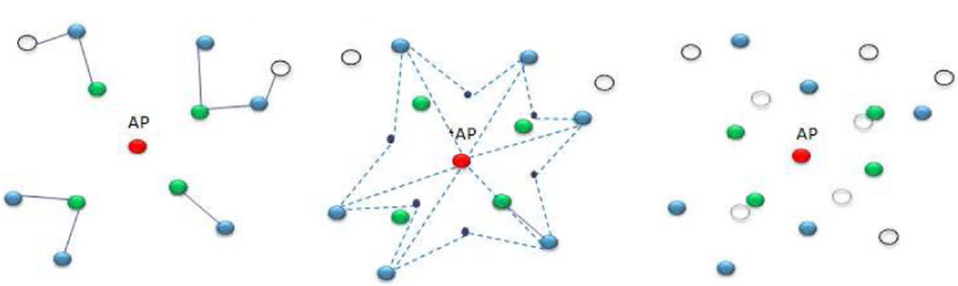


Fig. 1. The WSN reorganization after the failure. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

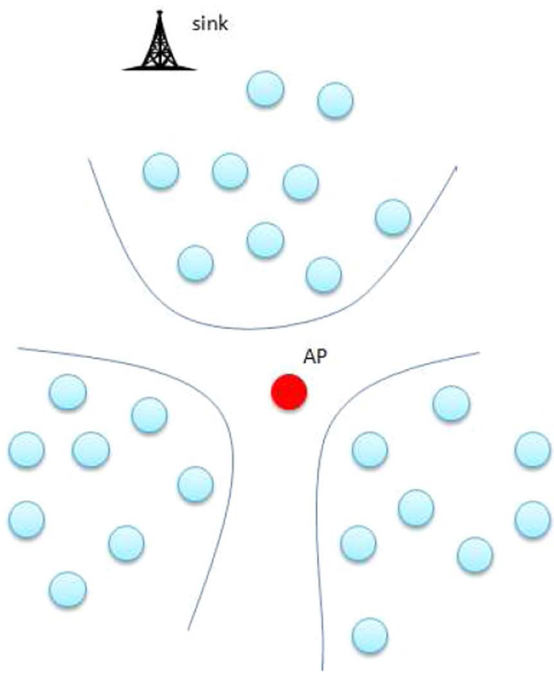


Fig. 2. Example of a WSN partition.

As the only node which connects the different segments of the network is the articulation node that we discuss its failure, the question that arises is: how the sink can communicate the information to all the WSN nodes? In the next section, we consider the problem of network division into isolated segments where the sink cannot reach the nodes belonging to a segment other than its segment as depicted in Fig. 2. We propose a curative solution RNFR (Rotating Nodes based Failure Recovery) based on the recovery information delivery by some rotating sensor nodes.

5. Rotating Nodes based Failure Recovery approach

The initialization phase is still the same as in PFR. In this phase, the neighborhood tables are built, the set of articulation nodes is determined and the initial channel allocation is done. In the normal functioning, the nodes collect information in their sensing areas and send the data to the sink periodically through multi-hop routing. This functioning is disturbed by the failure of any articulation node that leads to network partitioning.

5.1. Node failure detection

The first difference between PFR and RNFR is the failure detection of an articulation node. In PFR, the articulation node proclaims its failure when its residual energy falls under a predefined threshold. However, in RNFR, the failure of an articulation node is detected by its 1-hop neighbors. Indeed, periodically, the sink updates the routes and each node verifies if its neighbors are still alive by consulting its neighborhood table built during route construction. When a node v misses the *update* message from one of its neighbors u, v sends a series of *heartbeat* packets. If u does not answer, v deduces the failure of u and sends a *failure_report* message to the sink to inform it of the node's u failure. Once the sink receives the *failure_report* message, it checks if the failed node is an articulation node or not. If it is the case, it triggers the recovery procedure which uses the same algorithms and techniques as PFR (described in Sections 4.3 and 4.4).

Unlike PFR, a new problem arises here: upon the failure of the articulation node, the network is divided in two or several segments that can no more communicate with each other. At that time, how can the nodes belonging to the isolated segments receive the recovery information from the sink? As a solution, we propose to rotate some particular nodes – hence forth called border nodes – in such a way that the information generated by the sink can reach every segment in the network.

5.2. Rotation of border nodes

As PFR, RNFR will imply the 1-hop and 2-hop neighbors of the failed articulation node. These nodes may belong to one or more disconnected segments. This configuration may render these nodes unaware of the recovery information sent by the sink. We propose a new strategy to deliver the recovery information in the whole network. The idea is to select some nodes (border nodes) from each segment that will be in charge of disseminating the recovery information from one segment to another.

To propagate the recovery information from one segment to the next one, the sink elects in each segment i two particular 1-hop neighbors of the failed node n_f. These nodes are elected in such a way as the node *Left Border* LB_i (respectively *Right Border* RB_i) represents the left most border node of the segment i (respectively the right most) (*cf.* Fig. 3(a)). As the recovery information cannot reach all the border nodes because of the network partitioning, these nodes will rotate in cascade while delivering the information to the nodes belonging to the same segment as well as the next segments (as we will detail below). All the border nodes LB_i and RB_i form the $BNset$.

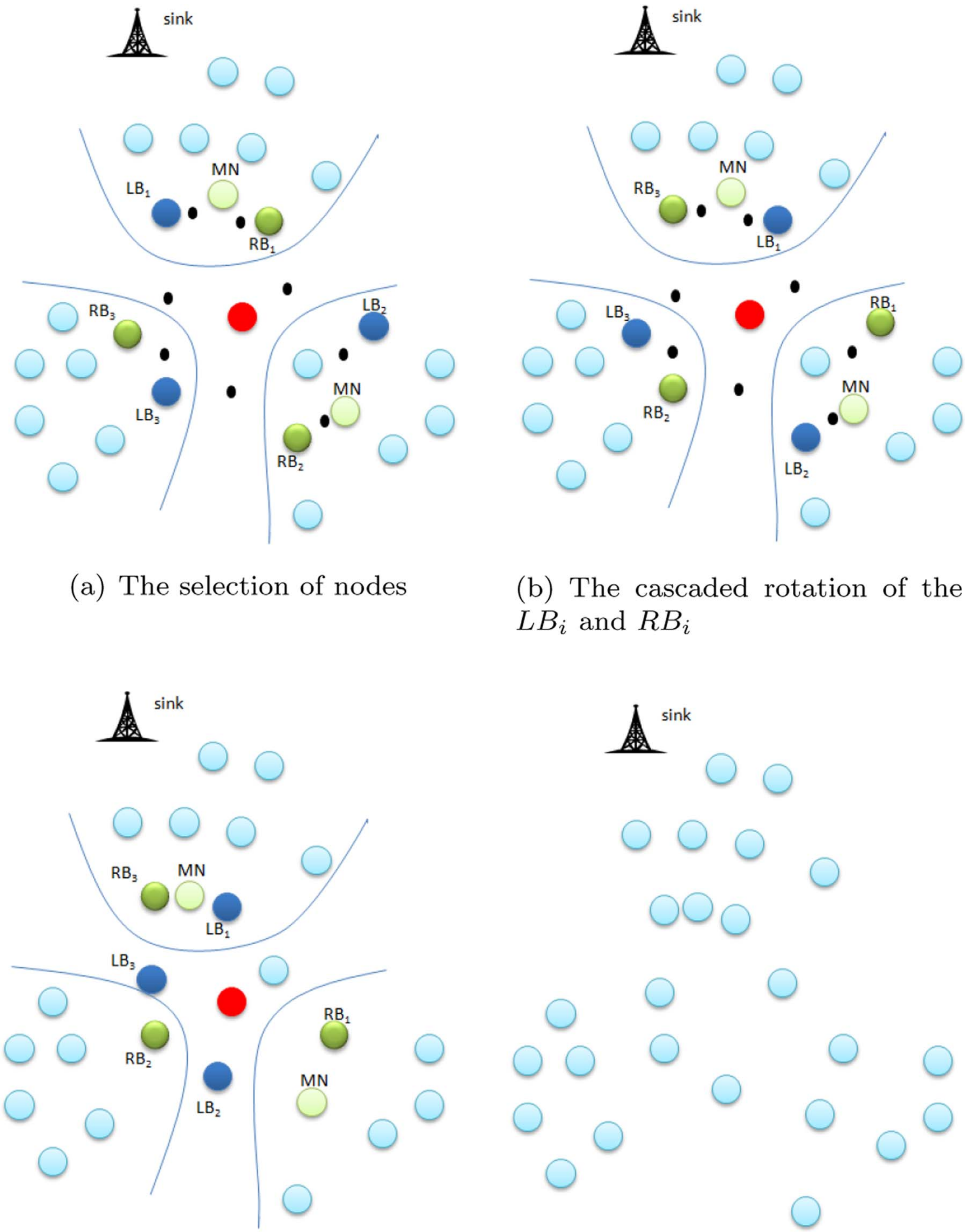
If in a segment i some 2-hop neighbors ($\in H_2(n_f)$ are covered neither by LB_i nor by RB_i, the sink elects a minimal number of nodes (called MN_i set) from the 1-hop neighbors ($\in H_1(n_f)$ to cover the uncovered 2-hop neighbors. We also define $MNset = \bigcup_i MN_i$ and $IDset = BNset \cup MNset$.

Once $IDset$ is formed, the transmission procedure of the recovery information towards the different isolated segments of the network executes as follows:

- The sink sends the $IDset$ and the recovery data to LB_1 of the primary segment (the segment of the sink).
- LB_1 moves to the RB_1 position and transmits, while moving, the information to the MN_1 nodes.
- Each node of MN_1 transmits the information received from LB_1 to the nodes belonging to $H_2(n_f)$.
- When RB_1 receives the recovery information, it moves to the next segment and delivers the message to LB_2.
- The process is repeated until the RB_{ns} of the last segment ns reaches the position of LB_1 of the primary segment.
- Once all the nodes of $BNset$ delivered the recovery information to all the segments and reached their final positions, the nodes participating in the failure recovery ($recoveryset$) (the set of nodes designed to be moved to the selected SPs, *cf.* Section 4.3) move to their new positions.Algorithm 4 sums up the nodes' rotation process.

Algorithm 4. Node rotation algorithm.

if $nodeid = sink$ **then**
  i = 1;
  select(*ID_set*);
  send(*recovery_information*, *ID_set*, LB_1);
end if
while $i \le L$ (number of network segments) **do**
  if $nodeid = LB_i$ **then**
    move_to(RB_i);
  else if $nodeid = RB_i$ **then**
    move_to(LB_{i+1});
    broadcast(*recovery_information*, *ID_set*);
  else if $nodeid \in MNset$ and $\exists\ v \in H_1(nodeid)$



(a) The selection of nodes

(b) The cascaded rotation of the LB_i and RB_i

(c) The relocation of the participating nodes

(d) The WSN topology after the recovery

Fig. 3. The node rotation-based recovery.

```
then
   send (recovery_information, v);
else
   drop (recovery_information, ID_set)
end if
if nodeid ∈ recoveryset then
    move_to(SP);
  end if
  i = i + 1;
end while
```

Fig. 3 shows the steps of the nodes' rotation and relocation mechanisms to deliver the recovery information and to restore the network connectivity. Fig. 3(d) represents the new WSN topology after the network reorganization and the nodes' relocation.

To optimize the rotation process, any node participating in the connectivity restoration moves to its new location as soon as it receives the recovery information. If a rotating node u will occupy a SP, it moves towards the next rotating node v until reaching a distance equal to R_c from v. Then, u transmits the recovery data to v and moves to the SP position. Moreover, if the rotating node participates in the recovery process, it moves to the SP location immediately after its successor received the recovery information. Consequently, before the end of the rotation process, the majority of nodes concerned by the replacement reach their final positions. In addition, if the first border node LB_1 is involved in the failure recovery procedure, the last rotating node RB_{ns} directly moves towards the position expected to be occupied by LB_1. This optimization impacts the total traveled distance as well as the total recovery time.

It is to mention that the whole recovery process depends on the node mobility. As we said in the previous sections, we assume that all the nodes are movable, while it is not the case in many networks. However, our solution is still applicable for WSNs with partial nodes' mobility. In this case, in the SPs' replacement and in the cascaded rotation we only use the movable nodes (whatever the number of hops towards the failed node is).

6. Performance evaluation

In this section, the two proposed approaches PFR and RNFR are evaluated through simulation and compared to an exact solving using the Min–Max method (Coello et al., 2007). We also compare our solutions to RIM (*Recovery through Inward Motion*) approach (Younis et al., 2008).

6.1. Simulation settings

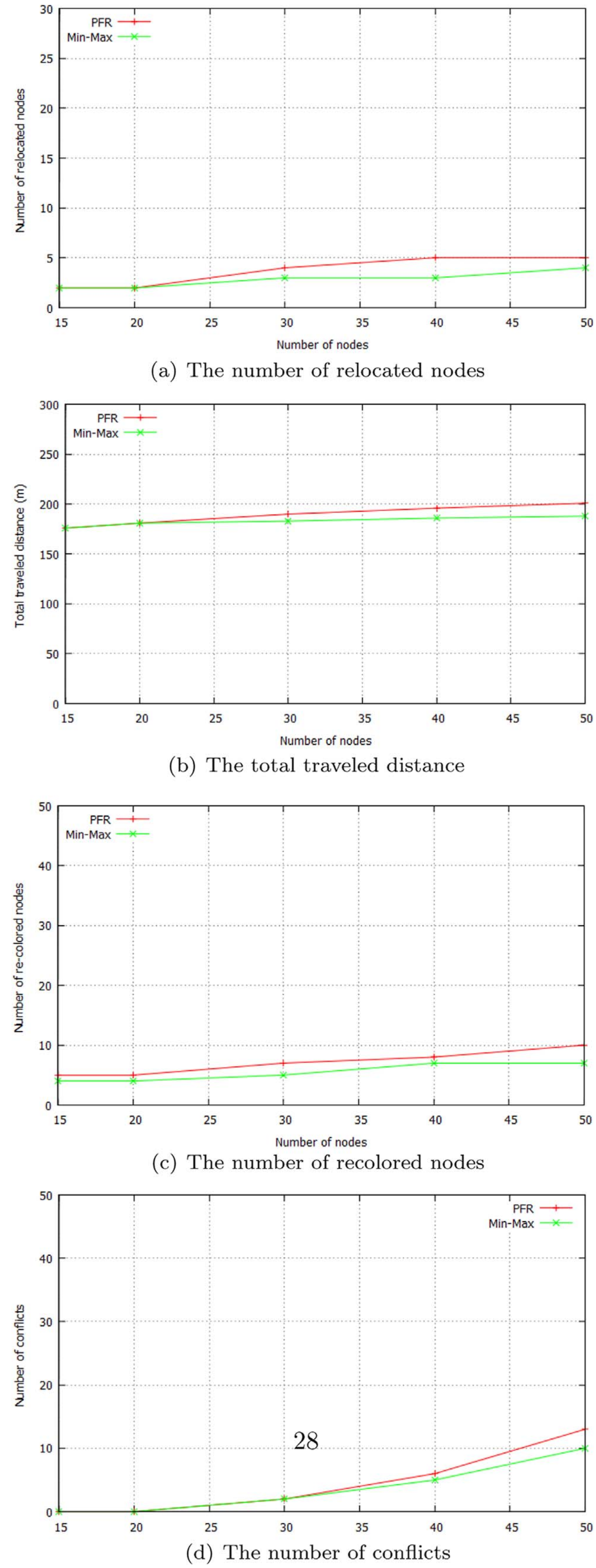
For all the simulation scenarios, we use the parameters summarized in Table 1 where the nodes are scattered in the area and the approaches execute after a number of randomly chosen nodes' failure.

We evaluate the performance of the proposed approaches using several metrics described as follows:

1. *The number of conflicts*: reports the number of interfering nodes using the same channel.
2. *The number of re-colored nodes*: reports the number of nodes assigned a new channel after the failure recovery.
3. *The number of relocated nodes*: indicates the number of relocated nodes caused by the connectivity restoration process and the rotation process.
4. *The total traveled distance*: this metric denotes the distance traveled by all the moved nodes to recover from the failure.
5. *The restoration time*: denotes the total time of the recovery process from the detection time to the end of the reorganization process.
6. *The number of control messages*: this number impacts the use of the

Table 1
Simulation parameters.

Parameter	Value
Environment	Omnet++, MATLAB
Area size	1000 m × 1000 m
Number of sensors	[15,250]
Network topology	Uniform distribution
MAC protocol	Unslotted 801.15.4
Number of channels	4
Communication range R_c	100 m
Sensing range r_s	50 m
Number of runs	≥ 30
Speed	1.5 m/s



(a) The number of relocated nodes

(b) The total traveled distance

(c) The number of recolored nodes

(d) The number of conflicts

Fig. 4. Comparison of the proposed solution to the Min–Max method.

bandwidth and the consumed energy during the restoration of the network connectivity.

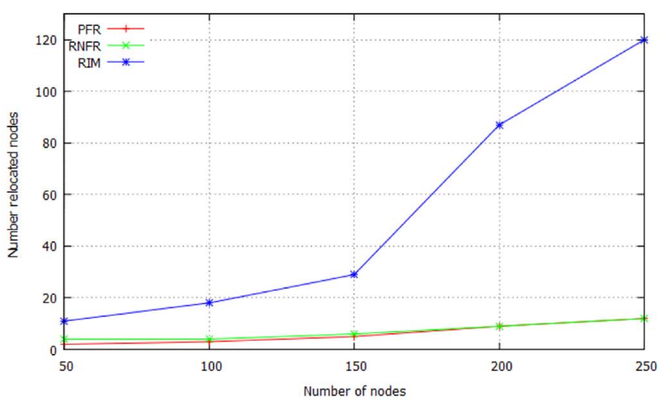
6.2. Results

Fig. 4 shows the performance of the PFR approach compared to an exact solving of the presented multi-objective optimization problem using Min–Max method. This figure depicts that our proposed heuristics give a near optimal results, in particular in small WSNs. For instance, PFR generates the same number of relocated nodes as the Min–Max method in a WSN with 20 nodes, as well as the optimum number of conflicts in WSNs with 15 and 20 and 30 nodes. The results deviate slowly from the optimum when increasing the number of nodes.

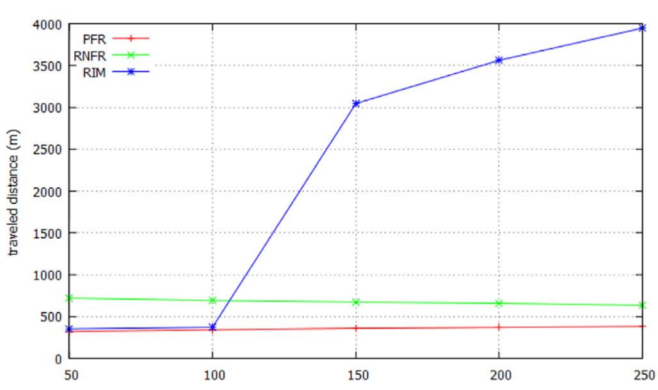
Fig. 4(a) shows that the number of relocated nodes increases with the number of nodes in the network. This result is due to the fact that the number of 2-hop neighbors used to find new locations for the relocated nodes increases with the network density. As a consequence, the total traveled distance becomes more important too as depicted in Fig. 4(b). However, the average distance traveled by each node decreases from 88 m in a WSN with 15 nodes to 40.2 m in a WSN with 50 nodes. We also notice that the percentage of relocated nodes, regarding the total number of nodes, remains quasi-unchanged (between 10% and 13%).

Figs. 4(c) and (d) depict that even if more nodes change their channels, the number of conflicts increases with the total number of nodes in the network. This result is explained by the fact that more nodes may interfere with each other when the network density becomes more important.

In Fig. 5, we compare the performance of our two proposed approaches PFR and RNFR to the performance of RIM approach in terms of the number of relocated nodes and the total traveled distance.

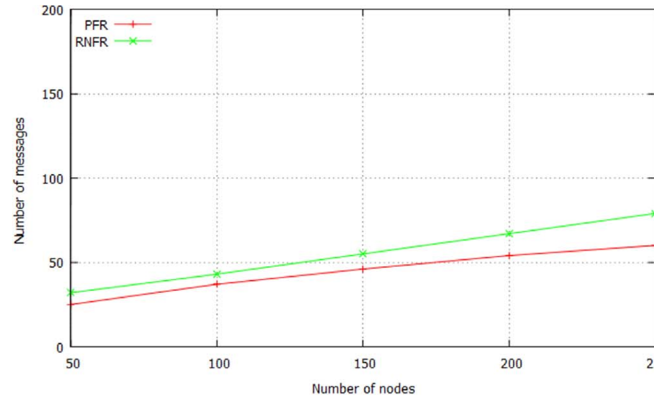


(a) The number of relocated nodes

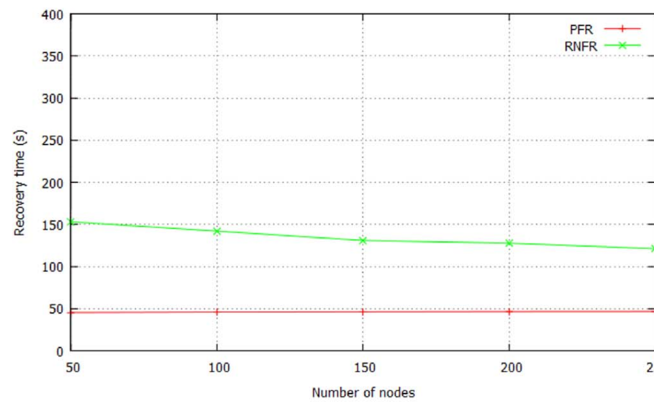


(b) The total traveled distance

Fig. 5. Comparison of PFR, RNFR, and RIM approaches.



(a) The number of control messages



(b) The total recovery time

Fig. 6. Comparison of PFR and RNFR in terms of time and number of messages.

As shown in Fig. 5(a), PFR and RNFR outperform RIM in terms of number of nodes involved in the relocation process. It is clear that the two approaches restrict the recovery process around the failed node. RIM involves more nodes in the relocation process where the replacing nodes are relocated in a cascaded movement towards the failed articulation node especially in dense networks. The PFR approach also outperforms RNFR which needs to relocate more nodes. These additional nodes correspond to the rotating nodes used to communicate the recovery information from one segment to another. However, the two approaches engage the same number of relocated nodes in dense networks as all the rotating nodes are participating in the connectivity restoration process. The same behavior is obtained in Fig. 5(b) representing the total traveled distance for the three approaches. This behavior proves the scalability of the approaches PFR and RNFR as a direct result of the localized relocation mechanism used to partially reorganize the WSN in the failed node vicinity.

Fig. 6 compares PFR and RNFR in terms of the number of control messages and the total recovery time. The obtained results show that RNFR generates more messages than PFR. The difference between the two approaches is due to the need of cooperation between the nodes, in RNFR, for the failure detection and the recovery information delivery to all the network segments. This difference becomes more important with the increasing network size. For instance, RNFR generates 32 messages in a WSN with 50 nodes and 79 in a network with 250 nodes. These values respectively decreases to 25 and 60 when PFR is used.

Fig. 6(b) illustrates the time taken by the WSN to resume its normal functioning. We assume that the nodes move with a speed equal to 1.5 m/s (Caldeira et al., 2015). We notice that RNFR requires more time to converge. This additional time is due to the rotation process used in this approach. This is expected as some nodes must rotate in cascade before the replacing nodes move to occupy the SPs, which is not the case for PFR where the replacing nodes move directly to their final positions. Moreover, in RNFR, as the number of rotating nodes and their traveled distance decrease, the recovery time becomes less important when the number of nodes increases.

From the above performance evaluation, we conclude that PFR outperforms RNFR for all the metrics. However, PFR can be used only as in the case of an energy depletion failure. For all the other failure scenarios, RNFR must be used.

7. Conclusion

In this paper, we focused on the connectivity restoration in multi-channel WSNs. We proposed two centralized solutions for the failure recovery of an articulation node. The two proposed approaches use a WSN reorganization technique to restore the network connectivity caused by the articulation node failure with respect to the multichannel context. Therefore, we turn to the graph theory, in particular the graph coloring and the Steiner tree problems, to conceive an efficient solution adapted to the described above context. We proposed two approaches using centralized heuristics to solve each sub-problem. The first approach *Preventive Failure Recovery* (PFR) performs just before the failure of the articulation node. Thus, the latter could deliver the recovery information to the whole network just before it becomes nonfunctional. The second approach *Rotating Nodes based Failure Recovery* (RNFR) is curative and is applied after the effective failure of the articulation node which leads to the network partitioning. The evaluation showed that both PFR and RNFR provide accurate results as the exact solving method Min–Max. Moreover, they outperform the existing approach RIM in terms of the number of relocated nodes and the total traveled distance. We notice that PFR performance is a bit better than RNFR performance due to the rotation cost introduced by this latter. In addition, the proposed approaches are proven to be scalable. This scalability is achieved by the use of a localized recovery mechanism that restrict the partial network reorganization around the failed node. As a future step, we will focus on the distribution of the recovery process to reduce the overhead induced by the centralized solutions.

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