A distributed approach using redundancy for wireless sensor networks reconfiguration

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Abstract **- In this paper, we are interested in the fault-tolerant approach in the wireless sensor networks (WSN) based on reconfiguration. Indeed, we propose an approach of monitoring of a WSN by distributed reconfiguration which relies on the concept of redundancy. This allows the node sensors to be organized in groups where each node will have a quite precise role. It also makes it possible to manage the redundancy which will consist in leaving active only certain member nodes. The other redundant member nodes go into sleep mode and will be awaked using an operation of reconfiguration if the active nodes fail. A node can be also a data source measurement (called simple node) or a gateway node, may be used in several groups at the same time, and whose main role is to provide the communication function. The preliminary results of implementation and simulation of this approach showed that this distributed structure is suitable to ensure simultaneously the fault-tolerance property and to improve the performance of the network.**

Keywords — **monitoring, redundancy, wireless sensor network, reconfiguration, distributed approaches, simulation.**

I. INTRODUCTION

The technology of wireless sensor networks has aroused a considerable interest these last years thanks to its immense potential of applications in several domains such as environment control, house automation and the military applications. The researches in this field are diversified considering that sensor nodes forming the network communicate between them by radio and without pre-established infrastructure but have limited resources in terms of calculation, storage, band-width and energy.

A WSN is a special type of Ad hoc networks containing several sensor nodes which are able to collect data and to transmit it using a multi-jump routing protocol to the collection point, called Sink node (see figure 1). Each node gets his energy from an individual battery that consumption due to the communication and data processing must be optimized. The important density of sensor nodes implies the existence of redundant nodes.
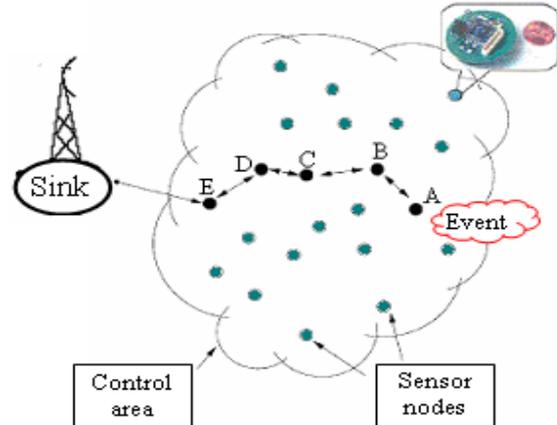

Figure 1.   A wireless sensor network architecture

Generally, the breakdowns in a WSN can be caused by the mobility or the exhaustion of the nodes energy. These breakdowns must be detected and solved in an acceptable time without affecting quality of service. Several monitoring approaches (detection and management of breakdowns) known as centralized were proposed by integrating a monitoring module in a distant station of supervision. The deployment of a big number of sensor nodes in the same network makes these approaches slow and costal in term of energy. Indeed, the network becomes overloaded by the control and reconfiguration messages exchanged between nodes and the station of supervision.

A considerable number of works are directed towards the routing protocols. Other works were interested by the WSN Clustering to design hierarchical protocols of routing [1]. Statistical studies on the research types are in [9], [10] and [11]. Recent works on the WSN are directed towards the energy saving, monitoring, quality of service and data security. According to the literature, there is a few number of works on the monitoring field. We can mention for example:

Congduc Pham in [2] is interested by the transport protocols for sensor networks which must identify and solve the congestions and manage the breakdowns of a certain number of sensors to guarantee the reliability of the transmission.

The author of [3] proposes an approach to supervise a WSN. It is based on the graph theory to guarantee the maximum covering by using a bipartite graph and the maximum convexity by using detection of the critical nodes in the network.

Andreas Meier and Al propose in their recent article [4] an algorithm for the failure control in nodes. This control is ensured by using of observant nodes which can announce to the Sink of the useful information when a problem is detected. Sink makes the appropriate decision to reconfigure the network.

R.Kacimi proposes in [15] an energy efficient protocol based on a virtual ring construction between nodes. This ring uses a grouped wake up for detect eventual faults.

We note that these works propose centralized approaches where the task of monitoring is ensured by the Sink. This centralization of the operations of diagnosis and reconfiguration in only one module (Sink in general) presents major disadvantages:

- Overload of the monitoring module by control treatments.
- Overload of all the nodes of network by the control and reconfiguration messages, which increases considerably energy consumption especially in the case of large scales networks. So WSN life time is reduced.
- The failure detection can be delayed because of transmission times.
- The failure of the monitoring module paralyzes the operation of the entire network.

These observations let us thinking to exploit sensors nodes capacities for treatment to develop a decentralized monitoring approach for a WSN.

In this context, we propose a solution based on the reconfiguration of a WSN in the case of failure (the fault-tolerance) with taking certain factors of optimization. This solution is based on the property of the material redundancy coupled with some properties of the graph theory. Indeed, it is about a distributed strategy making sensor nodes contribute to breakdowns detection and reconfiguration in order to maintain the network convex and ensure the total zone covering. In other words, the network is seen as a distributed system where the nodes have the responsibility of locally detect of defects and to reconfigure the failing part without passing by the node of collection (Sink).

In our approach, the WSN is divided into Clusters which we call groups. Each group is represented by a sensor node having the role of coordinator. This one ensures the communication of the group of nodes which it represents with other groups and to manage the redundancy of the nodes members of his group. A member can ensure the interconnection between the other adjacent groups, in this case we say that it has the role of gateway (or node of connection). A member can have also a simple role charged to capture physical metrics of the environment such as the temperature. In this last case, the node is called simple member.

This paper will be organized as follows. Section 2 presents a general overview of WSN monitoring. The third section presents some existing work on the distributed approaches for monitoring of this class of networks. Section 4 exposes our proposed solution of monitoring. Finally, the preliminary results of simulation of this contribution and the future prospects will be presented in the last section.

II. WSN MONITORING

The monitoring of a wireless sensor network consists to detect all types of breakdowns and defects, then to find remedies for their consequences. This must be made in real time. The origin of these defects can be physical or logical which affects the design process, the manufacture and even the operation of producing devices. The defects in a WSN can involve errors and failures affecting the normal behaviour of the system, which presents a risk of deviation, disconnection or bad collection of information.

The diagnosis plays a very important part in any system, it is a tool of monitoring and reliability. It is based on tests applied on all or part of the system in order to having always an operational unit. For a WSN, the objective of the diagnosis is to have a network which ensures its tasks with an optimal manner.

The nature and the missions of a WSN require operations of detection and reconfiguration in real time and by an automatic module (without human intervention), i.e. it must be equipped by a mechanism of test and reaction to the defects which is integrated in the network. This principle calls terms of auto-organization or auto-reconfiguration. The online tests make it possible to reconfigure the network in a limited time in the event of failure detection. Figure 2 summarizes the important phases for WSN monitoring.
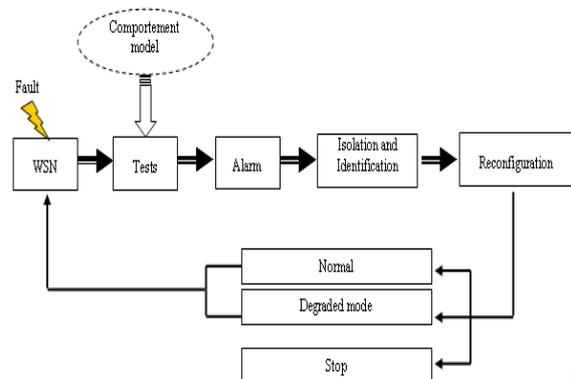

Figure 2.   Monitoring of a WSN

III.   EXISTING WORKS

In this section, we present certain works developed in the domain of WSN monitoring using the distributed approach.

MWAC Protocol (Multi Wireless Agent Communication) described in [5] proposes a method that integrates multi agent system on a WSN. The agent is a program implemented on each node, it is responsible of self organization and reconfiguration using role attribution algorithm and a messages protocol. This approach does not treat the redundancy for reconfiguration.

In [6], Barrenetxea designed a simple and decentralized algorithm to transmit the data of a single source to a single destination. For that, he reformulated the routing problem to the random paths constraints on graphs, then, he derived distributed algorithms to find the local parameters for random steps which will induce a certain property of decentralization in the network. The principal characteristic of this formulation is that nodes will be able to transmit messages between a source and a destination by all the possible paths, without a preliminary recognition of the paths and their state in each node. The author considers also the practical aspects of the multiple coding descriptions techniques in large scale sensor networks, where the number of available paths between a source and a destination is important.

The author of [7] proposes a distributed algorithm for topology control and self-organization based on a local knowledge to construct a virtual backbone on ad hoc networks and wireless sensor networks. He considers that the nodes can be in one of the following states: isolated, active, dominant or dominated. So, he obtains a clustering method in the network where each cluster is dominated by a cluster head.

Colette Johnen and Al [8] propose an approach called DMAC (Distributed and Mobility-Adaptive Clustering algorithm). It is an algorithm of self-organization which resembles that proposed in [7] for the partition of the nodes into dominant and dominated, but using other metrics like the nodes weight (the number of neighbours). The authors formulate the problem with logical rules and predicates and some properties of graph theory. A recent work proposed in [12] consists in using an alternative of SNMP (Simple Network Management Protocol) reduced for the WSN.

IV. PROPOSAL OF A DISTRIBUTED APPROACH FOR WSN RECONFIGURATION

After several library searches, we noted that the majority of existing works on the WSN monitoring use a centralized aspect to implement faults detection and reconfiguration. There are a few number of works based on decentralized or distributed approach and they are recently investigated, this offers new future prospects of interesting researches.

As contribution in this domain, we propose in this paper a distributed (or decentralized) approach for the WSN monitoring. This approach is based on distributed algorithms implemented at sensor nodes level. Nodes will be able to detect and reconfigure locally failing situations in order to ensure the network convexity and area covering with optimal characteristics.

A. Network organization

The wireless sensor network is deployed according to an unspecified topology and which can be dynamic, i.e. the nodes can move and we can add new nodes. The network is composed of N identical nodes having a GPS circuits to identify their positions. The main task of sensors is the data collection. For our case, we use scalar data (physical sizes like the temperature, pressure,…) in a given field. Collected information is transmitted to a treatment station called Sink.

Our network organization consists in dividing it into groups (zones or clusters) using a distributed algorithm of roles assignment which is implemented on each node. The same algorithm is used for the network reorganization in case of topology change due to failures or nodes mobility.

Each group contains a set of nodes. Each node has a role according to the affected roles of its neighbours. Inside a group, a node can play one of the following roles:

Coordinator (or cluster head) is elected to ensure the communication of the group with the outside which can be another group through its coordinator or Sink.

Gateway is an intermediate node between several coordinators. It must belong to the intersection zone of several groups. We note that a coordinator can never be adjacent to another coordinator node.

Simple (or ordinary) which captures required data and communicate it to the Sink via its coordinator.

The algorithm used here is inspired by the protocols CGSR [14], DMAC [8] and work of [5]. It is noted that we re-used the same roles, the difference is that we adapted the messages exchange to our approach which is interested in the redundancy and the fault-tolerance that details are given in below. The general principle of the algorithm of roles assignment is defined by the pseudo code shown in figure 3.

The network is deployed according to a deployment strategy (random, matrix or linear). When the Sink is initialized, each node begins its operation with the neighbourhood detection by exchanging messages, and then it runs the roles assignment algorithm. The role change can involve the change of some neighbours role, this principle is illustrated in figure 4.

```
Algorithm: Role assignment for a node
1:      Begin
        // Notation:  C: Coordinator, G: Gateway, S: Simple
2:    | IF NbNeighbours ≠ 0 THEN
3:    |   IF NbNeigboors = 0 THEN
4:    |         Role = C;
5:    |   ELSE
6:    |     IF (Nb_C_Neighbours =1) AND (Role ≠ C)
      THEN
7:    |           Role = S;
          ELSE // There is many Coordinators in my
neighborhood
8:              IF Role = C  THEN
          ProcedureElectionCoordinator();
                ELSE // Not a coordinator, be a Gateway
                  Role = G;
9:        ELSE   // There is no neighbour, so no role
10:         Role = NOROLE
```
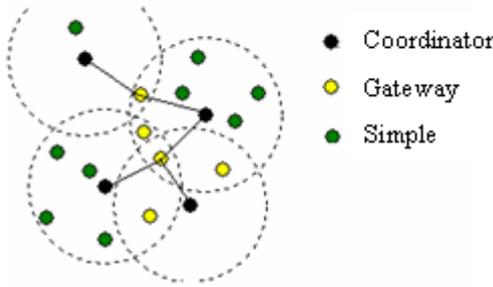

Figure 4.   Role assignment Illustration

B. Exchanged messages

As the proposed approach has a distributed process, each sensor node is assumed to detect its neighbours to ensure the network convexity in addition to an optimal path in the direction of the Sink. So, the node diffuses the Hello message containing its identifier and the number of hops towards the Sink (HC: Hop Count).

Any node receiving the Hello message, answers by the HelloRep message and updates its neighbourhood table. The HelloRep message transmits the role, adjacent groups, the position and the HC of its sender. All the nodes receiving the HelloRep message (including the node source of the request), update their neighbourhood tables and execute the roles assignment algorithm. In the case of role change (as for a node newly introduced), it diffuses in its neighbourhood the Changerole message containing the new assigned role to inform its neighbours. It is noticed here that the nodes profit from the information flow (like here the neighbourhood) without to have required it for some nodes.

The gateway nodes contain a list of adjacent coordinators nodes, consequently they can provide information on all the adjacent groups. when a coordinator receives the HelloRep message of a gateway node, it updates his knowledge on the adjacent groups (table of the adjacent groups), since the HelloRep message contains the identifiers of the coordinators who are reachable through this gateway.

Two or several coordinator nodes can enter in conflict, for example these coordinators become neighbours because of the mobility. This conflict can be solved by evaluating a score function for each coordinator (we can use the energy level like function score) to choose the best. This operation is ensured using the ResconfliRep message containing the identifier and the score of the coordinator who detects the conflict. The other coordinator receiving this message has to take one of the two decisions: to stay coordinator if its score is the best or to leave its role and becomes simple node. In this case, it diffuses the Changerole message in its neighbourhood.

C. Redundancy management

In order to optimize the energy consumption by nodes using our proposed protocol and by consequence extend the network lifetime, any coordinator manages the redundancy of the other member nodes of his group. He must ensure a maximum connectivity with a minimum of gateway nodes, and a maximum covering of area with a minimum of simple nodes.

A node (of all roles) is declared as redundant one if and only if there exists an other neighbour having the same role which can ensure the tasks of the node candidate to be redundant. These tasks depend on the role played by the node:

1. If the role is gateway (see figure 5), the gateways of the same group which remain active, must ensure the interconnection between their coordinator and the coordinators of the adjacent groups. So, a gateway node $L1$ is declared redundant if there exists in its group at least another gateway node $L2$ where the set of accessible adjacent groups through $L1$ is included or equal in the set of accessible adjacent groups through the $L2$ node. We can formulate this problem as follows:

Let:
- G_i a group of nodes having C_i as coordinator.
- L_j a gateway node in the G_i group.
- $Grp(L_j)$ the set of adjacent groups accessible by C_i through the gateway L_j.
- The predicate $Redundant(L_j)$ being True when the L_j node is declared redundant. So, we have:

$$Redondant(L1) / L1 \in G_i \Rightarrow \exists L2 \in G_i / Grp(L1)$$
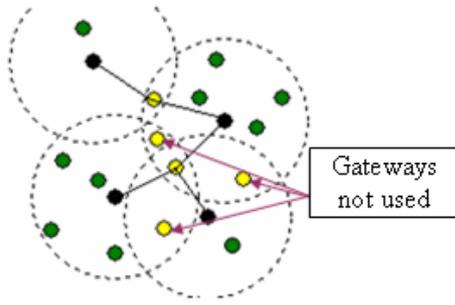$$\subseteq$$
$$Grp(L2).$$

Figure 5.   Gateway nodes redundancy

2.   If the role is simple node (see figure 6), the neighbours of the same group witch remain active must ensure the maximum covering of the controlled area by this group, including the regions covered by the redundant simple nodes. By the same manner as the gateway nodes, a simple node *S1* is declared redundant if there exists in its group at least another simple node *S2* where distance between *S2* and the coordinator is greater or equal to that between *S1* and the coordinator. Inorder to facilitate the implementation of this approach, we propose to introduce a property used to construct a Gabriel graph [13]. Then, we can say the *S1* node is declared as redundant if it is positioned in the circle traced between *S2* and to the coordinator. We can formulate this problem as following:

$$Redondant(S1) / S1 \in G_i \Rightarrow \exists S2 \in G_i \ et \ S1 \in Circle(S2,R_i)$$

Where *circle(S2, Ri)* means the set of points limited by the circle traced between *S2* and *Ri.*

Covered area by the redundant node

Redundant simple node

Gabriel propriety is used
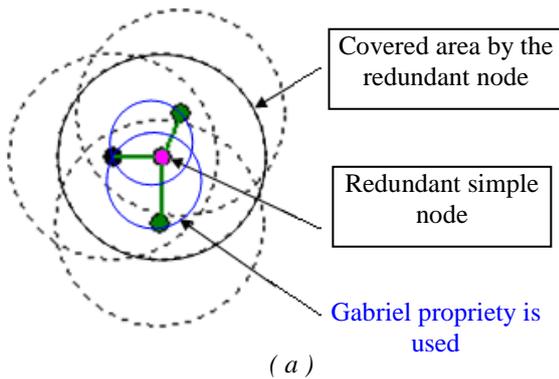
(a)
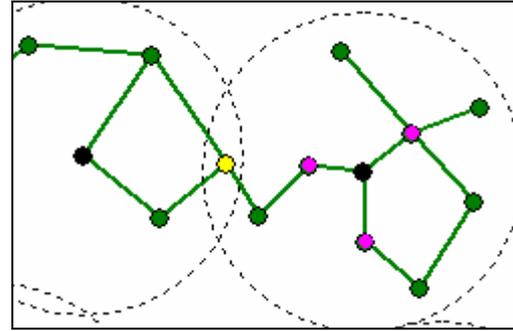
(b)

Figure 6.   Simple nodes redundancy

(a) Principle
(b) illustrative example

Only the coordinator is able to change the state of a member node in his group, it uses the ChangeState message carrying the new state to be taken (NS for New State) to sleep an active node (NS=SLEEP) or awake a slept node (NS=ACTIVE).

D. Breakdowns detection mechanism

Let us recall that our contribution is concentrated on the fault-tolerance by exploiting the phenomenon of the redundancy. So, the previously defined protocol is enriched by mechanisms to detect breakdowns and to reconfigure the network if necessary as well as the nodes redundancy management. Our contribution consists to introduce these mechanisms to have a fault-tolerant network. It is required to have continuously a convex network and maximum covered. These mechanisms take account the optimization of the messages exchange and the energy consumption.

To have a coherent network, nodes use a mutual control (the neighbors control each other). If a problem arrives, the reconfiguration will be necessary. For that, the nodes of each group exchange Hello messages periodically to detect the good performance as following:

1.   The coordinator of each group diffuses periodically the Hello message to active nodes of his group.

2.   Any active node receiving the Hello message from its coordinator, answers by the HelloRep message.

3.   A node which does not answer after a Hello message is declared failing by the coordinator, that can be due to node mobility or breakdown. In this way, the coordinator awakes all his slept neighbours and launches the roles assignment procedure for a reconfiguration.

4.   If a node (which is not coordinator) detects the failure of its coordinator, it diffuses the ChangeState message with a value NS equal to ACTIVE in its neighbourhood. Any node of the same group which receives this message wake up (if it is in sleep state) then, executes the roles

assignment algorithm. The new elected coordinator will take the relay.

N.B

By measurement of optimization and to reduce the number of the Hello messages exchanged inside a group and by consequence in the entire network, a node declares the failure of its coordinator if it does not receive the Hello message from this last for one period threshold defined, only the coordinators diffuse the Hello message. The hello frequency is a network parameter which depends on the application domain.

V. SIMULATION AND PRELIMINARY RESULTS

To check the good performance and to get some preliminary results of our approach proposed in this paper, we implemented the solutions and algorithms discussed in as a simulator using the Builder C++ version 6. It is an application which shows in detail the functionalities of this protocol (messages exchange, roles change, redundancy,…) . The user has the possibility to producing situations requiring a reconfiguration (displacement, deletion, addition of nodes, etc). It also makes it possible to extract and represent graphically the data produced by the various experiments such as the progression of energy. For that, we tested the approach on networks of sizes varying between 20 and 1000 nodes (20, 30,…, 90 and then 100.200,…, 1000). Each network is deployed by randomly.

We illustrate in figures 7 and 8 some results of simulation by using a WSN of 30 nodes with a ray of transmission of 80 meters deployed on a space of deployment of 400 X.400 meters:
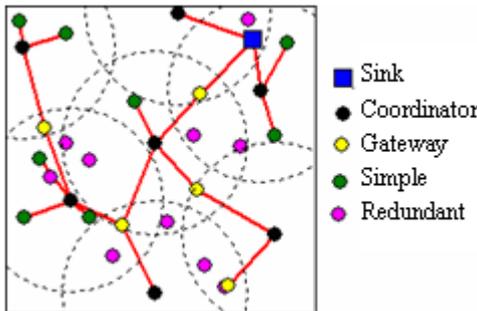

Figure 7.   Results of our redundancy principe applied on a WSN of 30 nodes
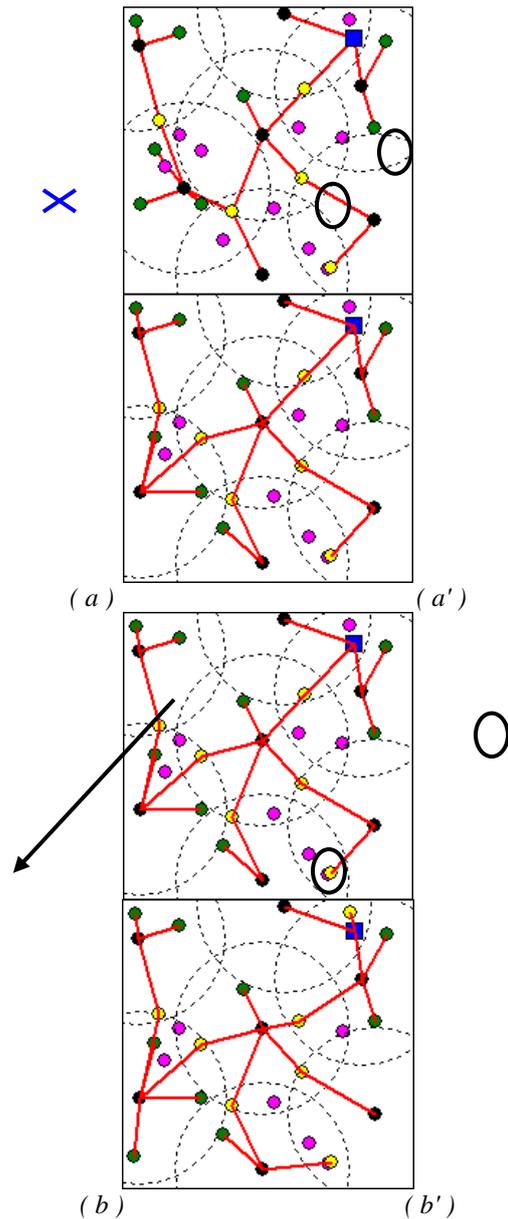

(a)   (a')

(b)   (b')

Figure 8.   Some breakdowns scenarios and their reconfiguration

Figure 8 shows adequate reconfigurations of the WSN after failure due to (a): deletion of the coordinator shown by X, and (a') its reconfiguration by election of a new coordinator, some changes (role and state) of neighbours are shown by circles in the figure. (b): displacement of a gateway node shown by the pointer and (b') its reconfiguration by waking up of another gateway node shown by the circle (the moved node changes role and becomes simple).

Coordinator nodes consume more energy because messages exchange with all the other active members and necessary operations for reconfiguration in case of defect. We trace the energy consumption graph of a coordinator in both cases (with and without redundancy):
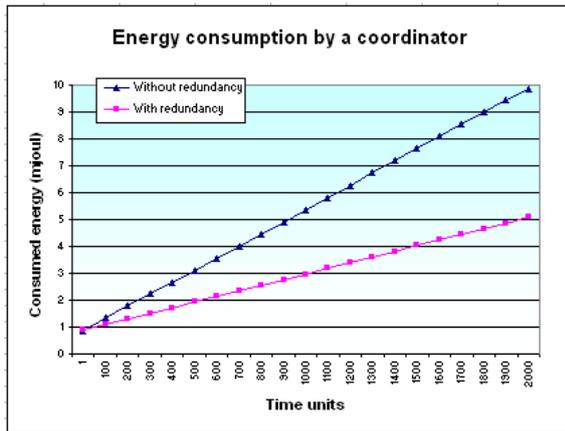
Figure 9.   Energy consomption by a coordinator

We see in figure 9 the influence of the redundancy on the energy consumption of a coordinator. Indeed, the nodes in sleep mode allow their coordinator to save his energy by avoiding the communication with them. So, the distributed aspect of our solution makes the control treatment to be local (redundancy, breakdowns detection and reconfiguration) without crossing the entire network to arrive at Sink.

The use of redundancy allows the network to save its energy and by consequence extend its life time. The following graph of figure 10 shows the life time extension for a WSN when using redundancy.
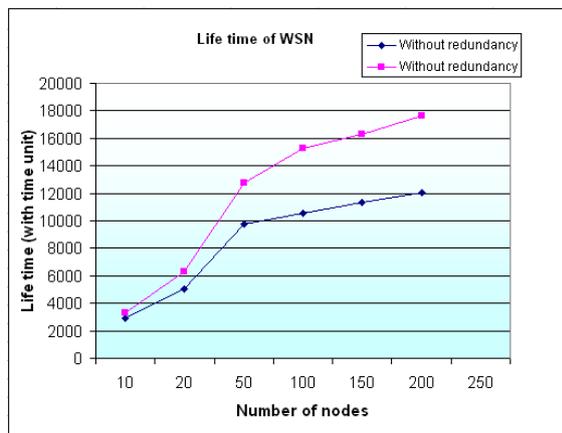

Figure 10. Life time variation

VI.   CONCLUSION AND PROSPECTS

In this article, we proposed a distributed approach for WSN monitoring in order to extend its lifetime by optimizing the energy consumption and using the redundancy of nodes. The preliminary results obtained are encouraging. The performances of our approach can be reinforced by a comparison with centralized solutions and the existing distributed approaches. As future prospects, we propose the optimization of several aspects in our approach such as the election procedure of the coordinators to ensure an optimal distribution of tasks, the breakdowns detection mechanism by eliminating the periodic hello messages or at least minimizing their frequency, and the redundancy

management to have a reconfigurable network in the failure event. Finally, we wish to use a robust simulator like NS2 or Omnet++ to validate our results.

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