MULTI-ROBOT SENSOR RELOCATION TO ENHANCE CONNECTIVITY IN A WSN

Sahla Masmoudi Mnif and Leila Azouz Saidane

National School of Computer Science, University of Manouba, Manouba, Tunisia

ABSTRACT

Ensuring connectivity in Wireless Sensor Networks (WSN) is a challenging issue, especially in hazardous areas (like battlefield). Many applications of WSN require an important level of connectivity in the network to detect a given event (like detection Intrusion) and forward it to the "sink" node in order to alert users. For these risky areas the deterministic deployment is not usually guaranteed and the network is composed by a set of disconnected Islands. We present in our work two strategies to relocate sensors in order to improve the connectivity using mobile Robots. These two solutions are called Multi-Robot Island-based Relocation (MRIBR) and Multi-Robot Grid-Based Island-based Relocation (MRGIR). Through several simulations, we show that MRGIR outperforms MRIBR. Our study can be used especially to make a trade-off between the number of deployed sensors and the numbers of the used mobile robots, according to the quality needed for the application.

KEYWORDS

Sensor, Wireless Sensor Network, Mobile Robot, Redundant, Connectivity, Relocation

1. INTRODUCTION

Wireless Sensor Network (WSN) applications have been suggested for many applications, especially in risky and hazardous regions. The main objective of these applications is to detect any abnormal event in the area of interest. One relevant application is detection intrusion in a battlefield and coast and border surveillance. We remind that a WSN is composed of a set of small entities called "sensors," each sensor is characterized by a limited energy and is constrained in its computation and communication resources. When a sensor detects a phenomenon, in the given area, the deployed sensors have to communicate together in order to forward this event to the "sink" node. The sink node will alert the user by the detected event. An illustrative application is military applications especially for detection intrusion in battlefield or frontier control. The deployment in these risky areas cannot be assisted by human, and a random deployment is necessary. Random initial deployment leads in most of cases, to a portioned network. In each network partition redundant nodes can appear. However the connectivity must be usually guaranteed to survey correctly the controlled zone. We propose to use mobile robots to enhance the connectivity in the network using redundant nodes. The main role of the mobile robots is to discover the network topology and to connect the disconnected parts of the network simultaneously. In addition, robots must coordinate their movement and cooperate during operation.

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We propose in this work two strategies for redundant sensors relocation using mobile robots in order to improve the connectivity in a wireless sensor network. The main difference between the proposed strategies is the functioning and the movement adopted by mobile robots to achieve their mission.

2. RELATED WORK

In recent years, sensor relocation has been a challenging matter that was studied by many researchers. Several solutions have been proposed to solve the redeployment issue. One relevant solution was to provide motion capability to all sensors. This way, the sensors can move and relocate themselves in order to adjust the topology and achieve the connectivity and/or the coverage. The sensors must synchronize their movement to enhance the network topology. Among the proposed solutions, we mention particularly the cascade motion which is detailed in [2]: instead of moving directly to the target, the sensor nodes adopt a cascade movement which means that the nearest node to the target point will move there, and the location of nearest node is replaced by moving another sensor and so on. Virtual Forces Aspect has been also proposed as a solution for sensor relocation. In this way, deployed sensors communicate together and compute their new locations in order to ensure connectivity and/or coverage. Then these sensors exerce a repulsive or an attractive force to move to their estimated locations. This strategy was studied and presented in [18]. The mobility of nodes is very efficient and improves the network topology, but it requires an important energy consumption which causes the node depletion and decreases the network lifetime. Other solutions consist of the use of fixed sensor nodes and the network is assisted by some ”actors” like mobile robots. Some studies, proposed to use the robot to carry data between disconnected sensors so that robot collects the detected event from nodes and then delivers these information for the other nodes. This approach is presented by [19]. In this way the event is delayed and a latency time is introduced which can be considered as a shortcoming for critical applications.

Another set of related works include algorithms using DATA MULES [14][15], which are wireless devices integrated on mobile entities (animals, vehicles). A DATA MULE is a data collector; it picks up data from nodes and relays it to other nodes. So that, data would not be relayed on long routes and the network lifetime is increased In other proposed solutions, the actors are advanced mobile sensors that exploit the redundant nodes and relocate them to achieve better connectivity and /or coverage trying to preserve the network lifetime as long as possible. In recent years many researches have been interested by sensor relocation to enhance the connectivity in the WSN.

3. PROPOSED SOLUTION

In our work, we consider particularly a WSN over a risky or unreachable region of interest. We suppose that the WSN is containing a large number of static sensors which are deployed in the considered region in a random manner (eg, dropped from an airplane). This deployment leads generally to the partition of the network, so that the connectivity between nodes is not guaranteed. We suppose that the position of the sink node is fixed and known. Each sensor has a communication range noted by r_c and a sensing range noted by r_s.

We note that, all deployed sensors have the same connectivity range and the same sensing range. Upon deployment, the position of each sensor is fixed and known by the use of a localization technique (eg GPS). In our proposed solution, mobile robots are used to relocate redundant nodes in order to enhance the network connectivity and as a consequence the coverage will be improved. A mobile robot is a mobile platform which has a large amount of energy and can be recharged when needed. The robot is also characterized by an important computation capability and has a communication range noted by R_c. Each mobile robot handles a number of fixed sensors that can be used to heal connectivity holes. Each robot knows the frontiers of the controlled area.

After a random deployment over the WSN, the total connectivity between all sensor nodes is not guaranteed. The resulted network is partitioned. When an event is detected, it may be not delivered to the sink node. The formed network is composed by a set of disconnected islands, we call island every set of connected sensor nodes. The Island containing the sink node is called "MainIsland". To ensure the connectivity in the WSN, we should connect islands to the MainIsland. Generally, each Island contains redundant nodes.

3.1. Redundant sensors Identification

To identify redundant nodes, we use hexagonal pavement of the region, sensors belonging to two adjacent cells are able to communicate. A sensor is said to be redundant if its cell (perception zone) is covered by other cells.

3.2. Identification of Island-Head

For each Island in the network, an Island-Head is elected. The main role of the Island-Head is to collect information concerning all sensor nodes belonging to the Island (position of each sensor, position of redundant nodes, number of redundant nodes, and number of deployed nodes…). To elect an Island-Head we define criterion described by this equation

$$f = \frac{1}{2} * \frac{Eres}{E\max} + \frac{1}{2} * \frac{nb_n}{Nb_{nodes}}$$

where E_{res} and E_{max} represent respectively the residual energy and the maximum level of energy for a given node. Nbn and Nbnodes refer to the number of neighbours of a sensor node and the numbers of nodes in a given Island. The node with the highest value of f is elected as an Island-Head. Meaning that, node with the highest amount of energy and having the largest number of one hop neighbours is chosen as an Island-Head. In case of multiple candidates, the node with higher Identity is elected. A backup Island-head is chosen to replace Island-Head in case of its depletion. When the Island-Head is elected, it collects the positions of redundant nodes and these nodes go to the passive mode (sleeping mode) to save energy of the whole network.

In our solution, we propose to use some robots to relocate redundant sensors and connect Islands to the MainIsalnd. For this purpose, used robots should communicate together and synchronise their movements and functions. We propose two strategies for robots to improve the connectivity in WSN. We call the first one "Multi-Robot Island-Based Relocation" and we note it by "MRIBR", in which robots moves is based on Islands. The second strategy is called "Multi-Robot Grid-Based Island-Based Relocation and is noted by "MRGIR", with this strategy, in addition to the island-based model, the controlled area is portioned according to a grid.

4. MULTI-ROBOT ISLAND-BASED RELOCATION

In this solution, we use mobile robots to redeploy sensors in order to improve the connectivity in WSN. Upon random deployment, the islands are formed and the Island-Heads are elected as described in the previous section. We remind that, mobile robots have no idea on the network topology. Nevertheless, each robot is aware by the position of the “sink node”. Robots should communicate to connect islands to the “MainIsland”.

To achieve their goal, each mobile robot can be in one of the three states:

- **Free:** the robot walks in the controlled area with a random manner.
- **Busy:** the robot places and relocates sensors in order to connect an island to the “MainIsland”.
- **Topology Discovery:** Periodically, the robot stops (after a distance of 2* Rc and sends a Hello-Robot Message. Each sensor receiving a ”Hello-Robot”, forwards this message to its ”Island-Head” and the ”Island-Head” replies with ”Island information” message containing all information concerning this island (position of nodes, positions of redundant sensors, sensors identities, number of redundant nodes...).

Each robot starts its work with Topology Discovery state, after sending Hello-Robot message, the robot waits for a given period.

- If the robot does not receive any reply, it continues its walk in a random direction and stays in Topology Discovery state.
- If the robot receives an ”Island-information”,
  - If the encountered Island is the “Mainland”, the robot memorizes all information concerning the “MainIsland” and stays in the Topology Discovery state.
  - If the encountered Island is an ordinary Island, the robot computes the position of the nearest node of the ”sink” and then it calculates the number of needed sensors to connect the island to the “MainIsland”.
  - If this requested number of sensors is available on the robot, the robots changed its state to busy state. It then relocates them (the nodes will be relocated according to hexagonal pavement).
  - If this requested number of sensors is not available on the robot, it continues its walk in a random manner.

To identify a robot we use an Identity number (ID-Robot) which is assigned to each robot to make distinction between all robots. Each robot maintains a sequence number for each visited Island which will be increased after every new visit to an Island.

When a robot places sensors to connect an Island to the “MainIsland”, the robot should verify if the locations of the sensor is still empty by sending “Hello-Robot” Messages.

After connecting a given Island to the “MainIsland”, all sensors belonging to this Island must mark their membership to the “MainIsland”.

When a mobile robot encounters redundant sensor nodes, it picks up these sensors unless its maximum capacity is not reached. We note also that when a mobile robot encounters another one, it can ask the encountered robot, if needed and possible, to give it some redundant nodes.

5. MULTI-ROBOT GRID-BASED ISLAND-BASED RELOCATION

In this solution, we maintain the concept of Islands and our goal is also to connect all the Islands to the “MainIsland”. We propose also to divide the controlled area vertically to zones as described in Figure 1.

Each robot is placed on a zone and knows the frontiers of its zone. Each mobile robot is responsible of its zone and is not allowed to leaves its zone.

The identification of redundant nodes is made in the same manner like in MRIBR technique and the placement of nodes in the controlled area is made according to hexagonal pavement.

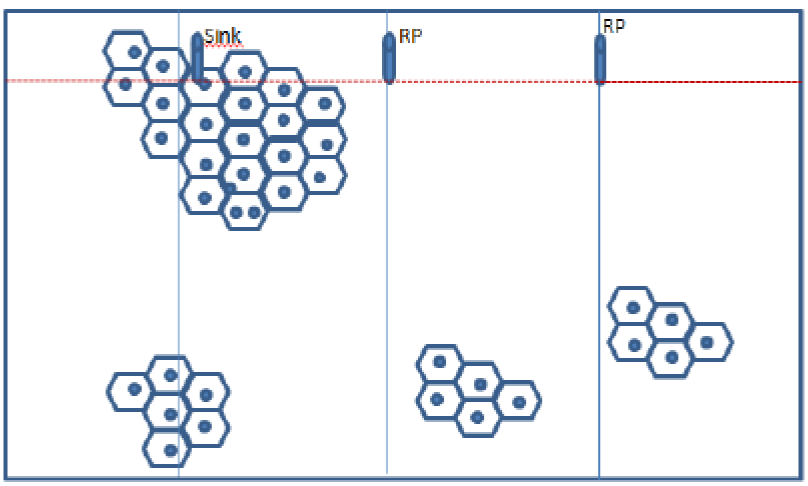

Figure 1: Network Model

When the sink node belongs to only one zone and when the position of the sink node is known by all mobile robots, we define Reference Points (RP) which are fictive points replacing sink node in each zone as described in Figure 1.

Each robot in its zone will function as described in the above section but by replacing the sink node by RP. Hence a mobile robot will discover its zone and tries to connect discovered Islands to RP Points. The mobile robot chooses its nearest RP to connect Islands.

For the intermediate zone the robot should also connect its two RP, if they are not already connected.

Reference Points can be used as points of collect (collection of fixed senors); a mobile robot can place sensors in these points when the robot has a large number of redundant sensors exceeding its needs (greater than a predefined threshold).

6. PERFORMANCE EVALUATION

Our proposed solution is implemented under NS2 simulator using MannaSim packages. Several simulations were established with different scenarios. For all simulations we use a large number of deployed sensors to ensure full connectivity and coverage over the network. The sensors are initially deployed randomly through a square ROI, we set $r_c = r_s = 25$m and $R_c = 60$m. We set the dimension of the Region of Interest to 600*600. The number of deployed sensor nodes is set to 150 sensors in the first time. In a second step, we will vary the number of deployed sensors from 50 to 450 sensors.

To evaluate and compare our proposed strategies MRIBR and MRGIR, we fix a set of metrics like connectivity time, the average travelled distance by a robot and the connectivity rate**.**

6.1. Connectivity Time

We note by CT this criterion. Connectivity Time is defined as the needed time to ensure connectivity in the network. This criterion should be minimized. We present the connectivity Time according to the number of mobile robots as described in figure 3 and then we present this connectivity according to the numbers of sensors as described in Figure 2.

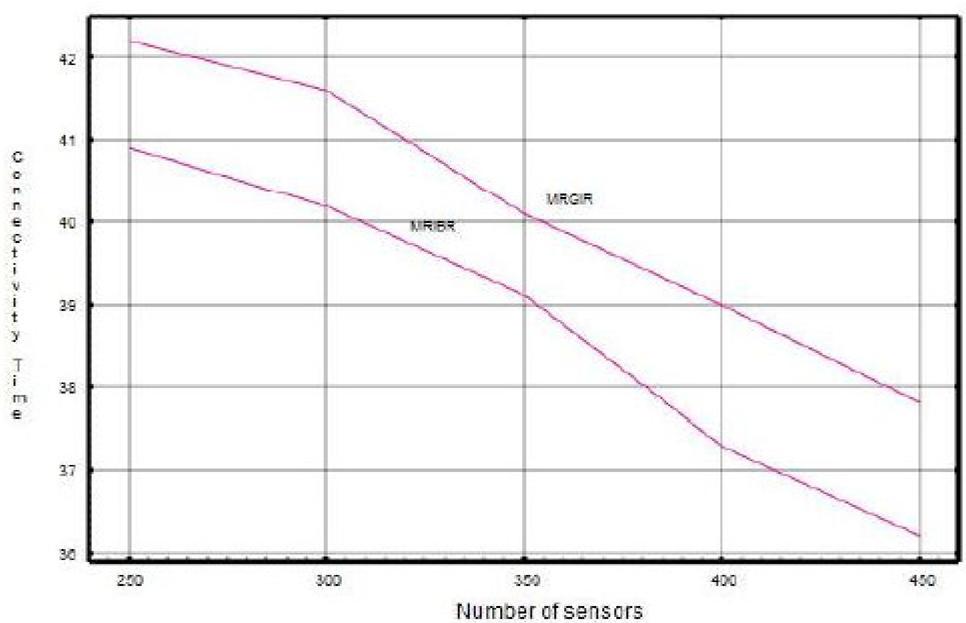

Figure 2: Connectivity Time/Numbers of sensors

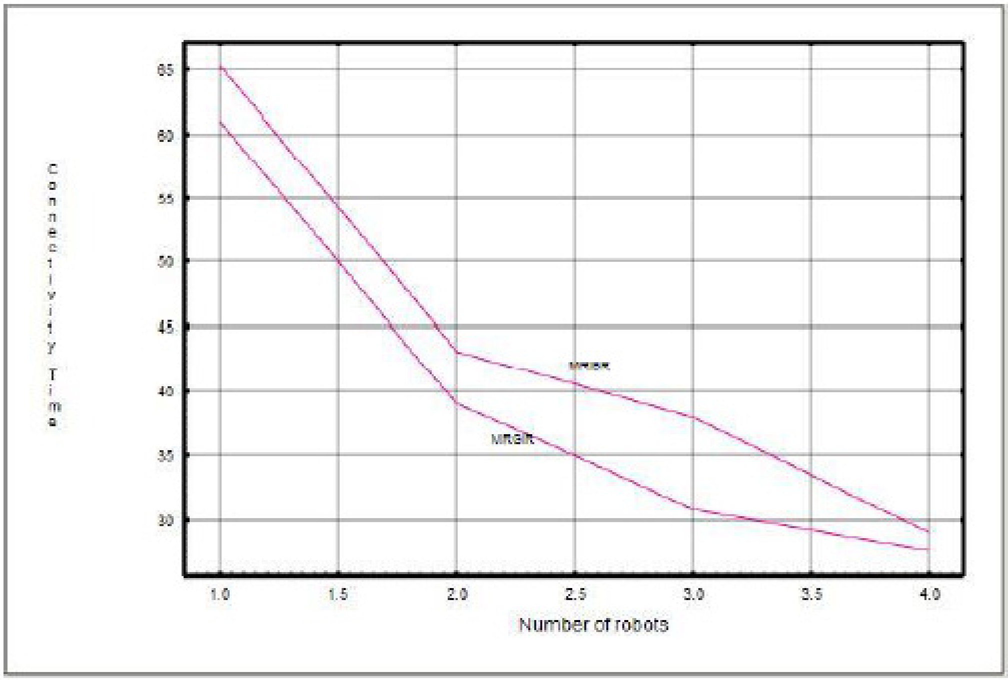

Figure 3: Connectivity Time/Numbers of robots

Figure 2 and figure 3 show that the curves have the same shape. We remark that, the connectivity time decreases when the number of sensors and the number of robots increases. This is explained by when the number of robots increases, the tasks are realized by more than one robot minimizing the total connectivity time. We remark also that from a given number of robots (4 robots in figure 3), the connectivity time starts to stabilize. We remark also that MRGIR outperforms MRIBR in term of connectivity Time.

6.2. Average travelled distance

The Average Travelled Distance is the average distance travelled by a mobile robot after performing the algorithm. It is giving by the following equation

$$\frac{\text{Total Travelled distance by all robots}}{\text{Number of robots}}$$

Figure 4 shows the average travelled distance by a mobile robot according to the number of sensors. We remark that the travelled distance decreases when the number of deployed sensors increases. This can be explained by the fact that the number of holes decreases when the number of deployed sensors increases. Figure 4 shows also that MRGIR outperforms MRIBR.

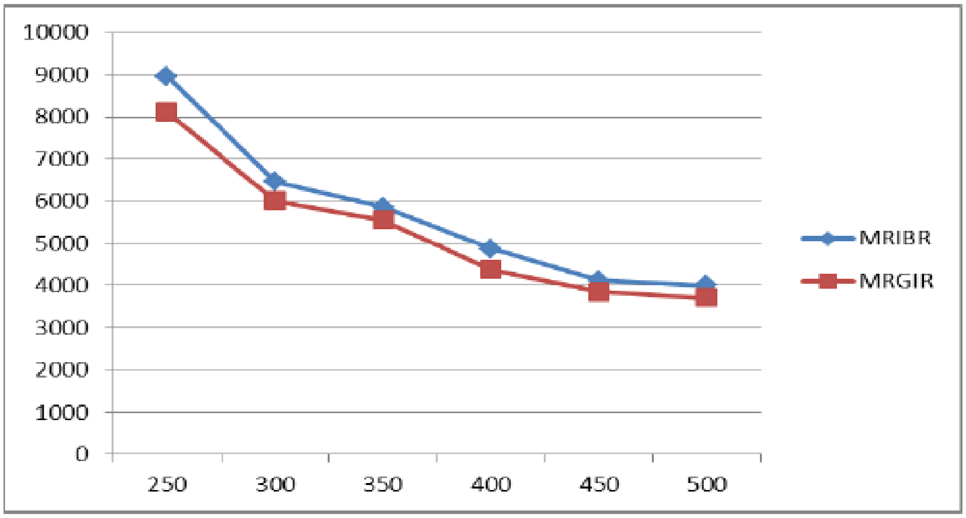

Figure 4 : Average Travelled Distance/Numbers of sensors

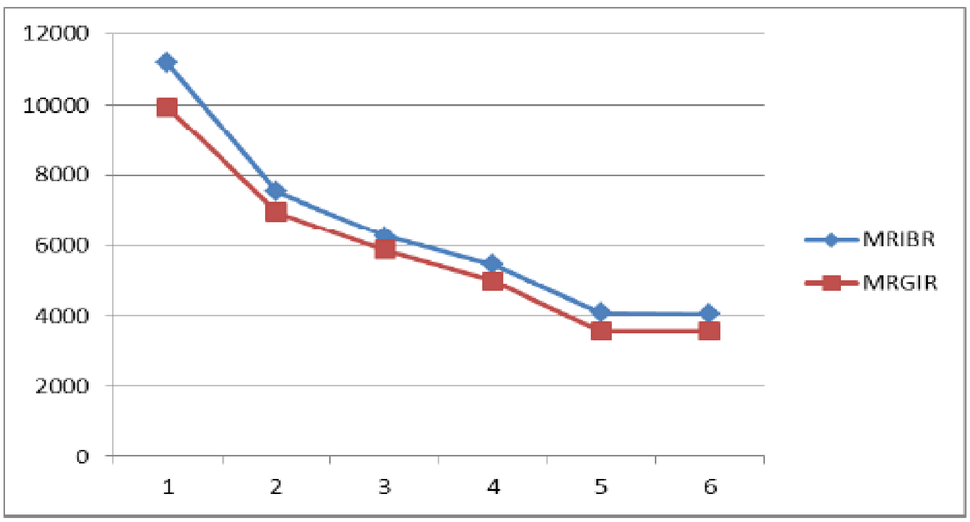

Figure 5 : Average Travelled Distance/Numbers of robots

Figure 5 shows the average travelled distance by a mobile robot according to the number of used mobile. We remark that the travelled distance decreases when the number of used. But this numbers starts to be static from a certain threshold.. Figure 5 shows also that MRGIR outperforms MRIBR.

6.3. Connectivity Rate

The connectivity rate (CR) is he average of connected sensors in the network, this metric should be maximized to enhance the performance of the tested algorithm. CR is giving by the following equation:

$$\frac{\text{Number of connected sensors to the MainIsland}}{\text{Number of deployed sensors}}$$

We present the connectivity rate according to the number of mobile robots as described in figure 5 and then we present this connectivity according to the numbers of sensors as described in Figure 6.

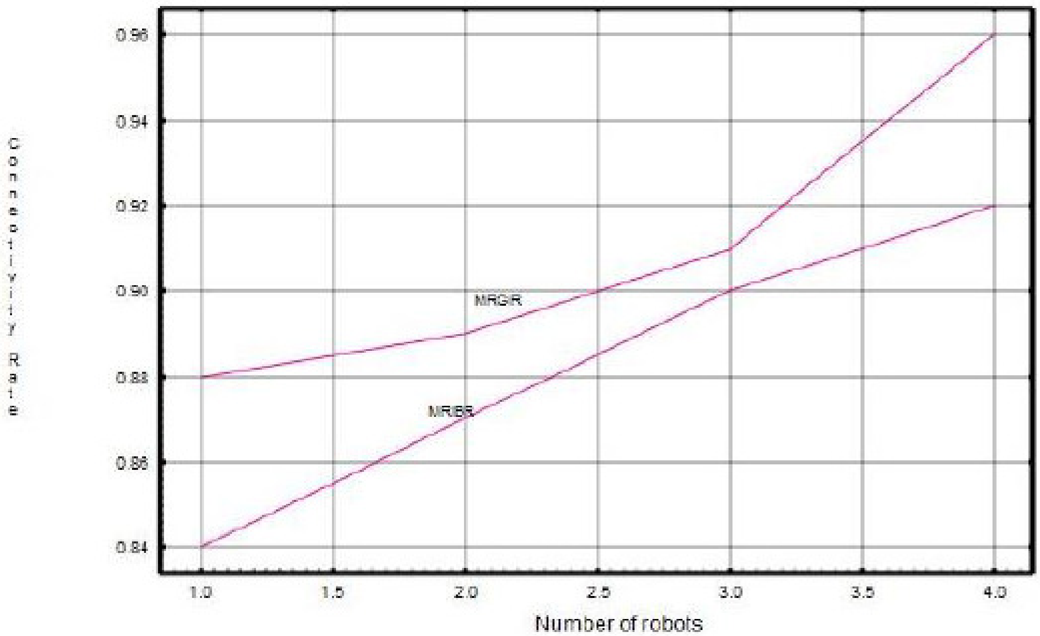

Figure 5: Connectivity Rate/Numbers of robots

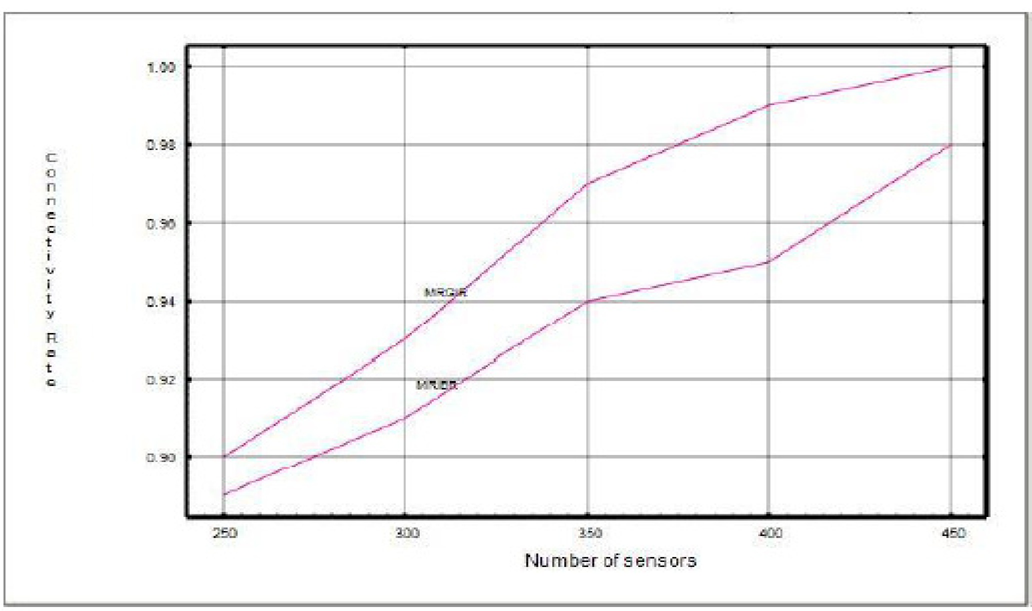

Figure 6: Connectivity Rate/Numbers of sensors

We remark that the connectivity rate increases when the number of robots and the number of sensors increases too. We note also from these figures that MRGIR outperforms MRIBR in terms of connectivity rate.

6.4 Results Interpretation

Based on the three fixed criteria we show that MRGIR outperforms MRIBR, this can be explained by the importance of the use of hybrid solution mixing the Island concept with the Grid-based partition of the controlled area. For MRGIR strategy, the controlled area is divided into rectangular zones, each zone is handled by one mobile robot. This robot is responsible by connecting all deployed nodes in its zone. This functioning reduce the responsibility of a mobile robot comparing to MRIBR strategy in which the movement of robot is not limited to a given zone and is more random.

Our study can be used especially to analyse the trade-off between the number of robots to use and the quality of connectivity. Hence, according to the application we can use our configuration.

For example, the needed rate of connectivity for a precision agriculture application is not the same for a military application in which the total connectivity must be guaranteed.

From this study, we can also determine the optimal number of mobile robots to achieve a given connectivity time or rate.

Hence through this study we can fix the characteristics of our application like the needed connectivity time, the minimum connectivity rate and then we can determine the optimal number of deployed sensors and the optimal number of used robots.

7. CONCLUSION

Ensuring and maintaining connectivity in WSN is a challenging issue especially for WSN in Hazardous and risky areas like military applications (battlefield survey, intrusion detection). In this paper, we deal with a WSN deployed with a random manner. This deployment leads to partition of the networks and a set of disconnected Islands is formed and redundant sensors are identified.

We propose to use many mobile robots in order to relocate redundant sensors and connect all nodes in the network. We present two techniques in our work, the first one is an Island-based technique (MRIBR) and the second one is Grid-based Island-Based strategy (MRGIR), here we used the concept of islands and we divided into virtual grid, the movement of each robot is made considering this grid. We show through extensive simulation that MRGIR outperforms MRIBR in term of connectivity time, connectivity rate and the average travelled distance, this result can be explained by the fact that in MRGIR strategy, the controlled area is divided in a grid and each robot is responsible by one zone.

The movement of each robot is limited in one grid. Nevertheless, in MRIBR strategy, the movement of robot are more random. We notice that our study can be used especially to make a trade-off between the number of deployed sensors and the numbers of the used mobile robots for each kind of application. We can also fix the number of needed robots for a given connectivity rate and a given connectivity time depending on the type and the specifities of the needed application.

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