A Genetic-based Algorithm to Solve Priority-based Target Coverage Problem in Directional Sensor Networks

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Abstract – The Directional Sensor Networks (DSNs) have recently drawn considerable attention with respect to their extensive applications in various situations. In this regard, covering a set of targets in a specific region while maximizing network lifetime is considered as a major problem related to the DSN, which is resulted from limitation in sensing angle and battery power of directional sensors. The problem gets more challenging when the targets have different coverage quality requirements. In the present study, this problem is referred to as Priority-based Target Coverage (PTC) that has been proved to be an NP-complete problem. In this regard, a genetic-based algorithm along with a repair operator is developed, which is able to select a proper subset of directional sensors for providing the coverage quality requirements for all targets. In order to evaluate the performance of the proposed algorithm, several experiments were performed and the results were compared to those of another algorithms already introduced to literature.

Keywords: Directional sensor networks, genetic algorithm, target coverage problem

1. Introduction

Wireless sensor networks (WSN) have spread widely regarding the fast progress of wireless communication technology and embedded systems over the past few years. WSNs are employed in collecting data from harsh and remote environments, which have some application such as observing fire in the forest and tsunami in the deep sea, as well as battlefield surveillance. Sensor nodes are mostly deployed more randomly than accurately owning the risk and or cost considerations in such environments and applications. Due to risk and/or cost considerations in such environments and applications, sensor nodes are deployed typically in a random manner rather than accurate placement. The random deployment demands deploying more sensors than actually required, which makes the network more resistant to faults because each target can be monitored by more than one sensor. Each sensor is equipped with a limited-lifetime battery that cannot be replaced in remote or harsh environments. As a result, extending the network lifetime is one of the most important problems in designing WSNs for such environments [18]. Conventional researches conducted on sensor networks assume that sensors known as omnidirectional operate at a 360-degree angle. There is another type of sensor network in which the sensors have exceptional characteristics, including viewing angle, working direction, and line of sight. According to these networks referred to as Directional Sensor Networks (DSNs), sensors have the ability to rotate around their center, and geometrically, the observed area in a

directional sensor is viewed as a sector. Although a directional sensor is capable of sensing in several directions, it can be activated in just one direction and at aspecific angle within a unit of time. Directional sensors are mainly ultrasonic, infrared, and video sensors [1, 2].

Coverage problem is considered to be another major concern in directional sensor networks, which refers to the collection of different types of data from the environment. The coverage problem can be classified into two main subcategories, namely area coverage and target coverage [18]. In the former, the entire target area should be constantly observed; while in the latter, it is just required to observe some crucial points (targets) in the environment. From a different perspective, the target coverage problem can be classified into three types: simple target coverage, k-coverage, and priority-based target coverage. With simple

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coverage, each target should be observed by at least one sensor. Simple coverage has a low accuracy in its monitoring operation. Consequently, attentions shift toward the k-coverage wherein each target is monitored by at least k sensors and it improves the reliability and accuracy of the observations. However, in real applications, targets may have different coverage requirements, which causes k-coverage to be unfit to such situations. This feature of k-coverage pushes us to take PTC into consideration, in which a target is monitored by different number of sensor nodes based on its coverage requirement (priority). The required coverage refers2to the minimum quality of observation that each target requires. The coverage requirement is denoted by a value that can be adjusted with respect to the problem nature.

Although numerous studies have conducted on the target coverage problem in DSNs, the PTC problem has not drawn sufficient attention. This paper has primarily developed a GA-based scheduling algorithm to solve the problem. The algorithm attempts to construct the cover set with minimum number of active sensor directions while satisfying the coverage quality requirements of all the targets. So as to evaluate the performance of the proposed algorithms, several experiments were conducted through which the effect of various parameters was investigated. The results obtained from the proposed algorithms were compared with a greedy algorithm. The results indicated the efficacious participation of the proposed algorithm in solving the problem.

This paper is organized as follows: Section 2 briefly reviews the studies related to solving target coverage problem. Section 3 introduces PTC problem in DSNs. Section 4 briefly describes GA. In Section 5, the GA-based algorithms are presented for solving the problem. In Section 6, the performance of the proposed algorithms is evaluated through several experiments. Finally, Section 7 provides the conclusion and future directions.

2. Related work

This paper investigates the problem of PTC and, at the same time, concerns the maximization of the network lifetime. Regarding the densely deployment of sensors in the environment, the sensor scheduling is considered as one of the techniques that is broadly used to extend the network lifetime. According to this technique, the sensors are classified into several cover sets, ensuring that the sensors in each cover set can provide the coverage for the targets during a particular period[3, 4, 9, 10, 11]. At each unit of time, only sensors belonging to a cover set are activated, and the remaining sensors switch to inactive mode. The technique significantly extends network lifetime in two respects. First, sensors consume much less energy in the idle mode than the active mode; consequently, they save a lot of energy. Second, the battery of a sensor will last longer when it oscillates between active and idle mode. In the following, some prominent studies conducted based on this technique for solving coverage problem in DSNs are presented.

Ma and Liu [21], as the first researchers who worked on DSNs, implemented some sensor deployment strategies in a way to satisfy the area coverage requirements. The authors in [2] dealt for the first time with the target coverage problem using directional sensors. They aimed to provide coverage on the maximum number of targets in a certain area with activating the minimum number of sensors. A number of algorithms were proposed in their study to solve the problem defined. In [5], the multiple directional cover set problem was confirmed as an NP-complete one. In their paper, for the creation of proper non-disjoint coversets, different heuristic algorithms were suggested, in which each cover set was responsible for covering all of the targets that existed in the network. In another study [6], two algorithms were proposed for the aim of both maximizing the number of cover sets and managing the critical targets. To this end, the first algorithm made use of a greedy approach, whereas the second algorithm implemented GA for the same purpose. In [6, 7, 8], a number of LA-based scheduling algorithms were proposed for the solution of the target coverage problem. These algorithms included two stages: 1) selecting the working directions of the sensors, and 2)forming the required cover sets. In the former, an algorithm was suggested in order to choose the most suitable working direction of each sensor. Then, in the latter, several algorithms were suggested for the aim of creating cover sets containing the minimum number of activated sensors. In [8], LA were used in order to find the best solution to the connected target coverage problem. In their study, LA were utilized for both choosing proper sensor directions to cover the area of interest and transferring the data gathered through the best path.

The aforementioned studies have been performed to design efficient algorithms to solve the simple target coverage in the DSN. It is worth noting that these algorithms mostly assume that the coverage quality requirements of all the targets are the same and is no affected by the distance between the target and the sensor. Therefore, these algorithms cannot perform well in the real condition when the targets require different coverage quality requirements. Wang et al. [15] introduced the problem of PTC in DSNs, which aimed at choosing a minimal subset of directional sensors satisfying the prescribed priorities of all targets. In order to solve the problem, they proposed a genetic-based algorithm and used a directional sensing model in which more than one direction of the sensor can be activated simultaneously. Moreover, their algorithm has developed just one cover set. Yanget al. [16] also assumed that targets need different coverage quality requirements depending on their role in the application. Furthermore, they supposed that the quality of coverage is influenced by sensors and targets. In this vein, they used a directional sensing model in which just one direction of each sensor can be activated. They proposed a greedy-based scheduling algorithm capable of finding a sequence of possible cover sets to extend the network lifetime. Although greedy algorithms are able to solve the problem, the performance of these algorithms4is dependent on the proximity of the initial candidates to the optimal solution. Therefore, the scheme can result in a local minimum due to its heuristic search.

In [14], an LA-based scheduling algorithm was proposed to find a near-optimal

solution to the PTC problem. The algorithm attempts to construct a maximum number of cover sets each of which is able to satisfy the coverage quality requirements of all the targets. In addition, they devised a pruning rule to avoid both the selection of redundant directions and the selection of more than one direction of a sensor. In [13], researchers for the first time investigated priority-based target coverage problem in DSNs where the sensors can adjust their sensing ranges and the targets require different coverage quality requirements. In order to solve the problem, two scheduling algorithms, i.e., greedy-based and learning automata-based algorithms were proposed. The proposed algorithms were assessed for their performance via a number of experiments. Additionally, the effect of each algorithm on maximizing network lifetime was also investigated via a comparative study. Both algorithms were found successful in solving the problem.

3. Problem Definition

The following scenario was studied in this research. Several targets with specific locations were distributed in a two-dimensional Euclidean environment. Each target needs different coverage quality requirements indicating its importance. Simply put, the higher the quality of the coverage demanded by a target, the higher the importance of that target. In this environment, a number of directional sensors are randomly positioned approximate to the target for providing their coverage quality requirements. Each directional sensor contains several non overlapping directions. Nevertheless, at a given time, just one of its directions can be activated, which is known as the working direction. Targets may be covered by directional sensors if only are positioned within the sensor radius as well as within the working direction of the sensors. It should be noted that the quality of coverage is dependent on the distance between the sensor and the target. That is, with an increase in the distance, the coverage quality usually decreases, and vice versa. Note that a target may require to be monitored by more than one directional sensor simultaneously in order that its coverage quality requirement could be fully satisfied. A general assumption is that the coverage quality requirement of a target that could be satisfied is equal to the sum of coverage provided by the sensor directions that cover the target. Table 1 presents the notations used in this paper.

Table 1: Notations

notation	meaning
m	The number of targets
n	The number of sensors
w	the number of directions per sensor
t_z	the z-th target, $1 \leq z \leq m$
s_i	the i-th sensor, $1 \leq i \leq n$
d_{ij}	the j-th direction of the i-th sensor, $1 \leq i \leq n$, $1 \leq j \leq w$
T	the set of targets, $t_1.t_2.\ldots.t_m$
S	the set of sensors, $s_1.s_2.\ldots.s_n$
u(x)	the coverage quality function; where x signifies the ratio of the distance between the sensor and target to the sensing range
g(z)	the required coverage quality of target t_z

It should be noted that the functions u(x) and g(m) depend on the context of networks and the application requirements. These functions are defined as follow[16]:

u(x) = 1−x2 and the value of g(z) is selected between 0 and 1 randomly and uniformly.

Problem: The problem is that how to form a cover set with the appropriate sensor directions capable of providing different coverage requirements of all the targets while extending the network lifetime?.

Definition: A cover set involves a subset of sensor directions by which the coverage quality requirements of all the targets can be satisfied.

4. Genetic Algorithm

There are different methods in evolutionary computation field, including genetic algorithms, evolutionary programming, evolution strategies, genetic programming, and differential evolution. GAs are based on the survival of the *fittest theo*ry of Darwin and gene recombination [17]. The GA method is adaptive; thus, it can be applied to solving search and optimization problems. Obtaining an optimal solution cannot be guaranteed through merely using GAs; however, they are capable of providing appropriate solutions to various optimization problems. Gas are powerful optimization techniques that do not need any inherent parallelism and gradient information in searching the design space.

GAs contain a population of individuals each of which represents a potential solution to a given optimization problem. Depending on the qualification of each solution, a fitness score is assigned to that. In order to generate offspring (new solutions)by means of crossover and mutation mechanisms for the next generation, individuals are chosen from the population and recombined. GA continues until the evolutionary procedure meets a particular evolution stopping criteria. Gamily contains three operations [**?**] as follow.

Crossover: this operation produces offspring from two individuals selected from among the population. This is performed through exchanging some bits in the individuals. Therefore, the offspring inherit some features from each parent.

Mutation: this operation produces offspring through changing randomly one or some bits in an individual. Thus, offspring may gain different features from their parents. Due to creation of random diversity in the population, the mutation operation can be used as a significant element in solving the problem of premature convergence.

Selection: this operation uses some predefined rules to choose some offspring for survival. This operation keeps the size of population and, with a high probability, it puts good offspring into the next generation.

5. Proposed Algorithm

This section proposes a memetic algorithm to solve the PTC problem in a network involving sufficient sensors. The MA adapts both the GA scheme and the repair operator that is a local enhancement operator designed specifically for solving the PTC problem. The framework of the proposed MA is shown in Algorithm1. The algorithm aims at creating a cover set with minimal sensor working directions that can satisfy the coverage quality requirements for all targets in the

network. In this vein, network operations are divided into a number of rounds. In each round, a MA is used to form an appropriate cover set. Once a cover set is returned as the output of the algorithm, it is assigned a working time value, which is then included in the network lifetime. Afterwards, the energy of the sensors in the cover set is updated and the energy-less sensors are removed from the list of available sensors. The process of creating cover sets continues until the sensors are able to satisfy the coverage quality requirements of all targets in the network. The proposed algorithm is described in detail in the following.

Similar to the GA scheme, in MA, the operation starts with making an initial population of possible solution, each of which is identified by a set of genesso-called chromosomes. With the aim of specifying the suitability of each chromosome, the solutions in the initial population are then evaluated using the fitness function. In minimization problems, a better solution is corresponding to lower fitness, while in maximization problem, a better solution is corresponding to higher fitness. In the next step, MA starts the evolutionary process. To this end, first, two chromosomes are selected from the population by the selection operator in order to serve as parents. Then, the information needed for producing offspring is exchanged between the two parents by the crossover operator. The probability of performing crossover is determined by a predefined crossover rate. Then, in order to alter slightly some of the genes in the offspring, mutation is performed based on mutation rate. In this study, we develop a repair operator as a local enhancement operator for the MA, which is applied to the offspring following the mutation operation. The reproduction process (selection, crossover, mutation, then repair operation) continues until the offspring population is completed. Based on the "Survival of the Fittest" theory of Darwin, the fittest chromosomes from the offspring population are selected by the survivor operator. The selected chromosomes are applied to the generation of the next population. As the evolution goes on, the MA attempts to direct the search towards the global optima. In the following, the elements of the proposed MA are elaborated.

Algorithm 1 . Memetic algorithm

```
Initialize population P;
Evaluate P;
While (not terminated)
P_s = Select (P);
P_c = Crossover (P_s);
P_m = Mutate (P_c);
P' = RepairOperator (P_m);
Evaluate P';
P = Survival (P, P');
End while
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Representation: This study uses an integer-based representation to model a chromosome. Each chromosome is regarded as a solution(a cover set) and each gene of the chromosome represents the status of an individual sensor node. In other words, the value of each gene is corresponding to the status of one sensor. Each chromosome is encoded by means of an integer vector of length n, where n indicates the number of sensors in the network. The value assigned to a gene can be either 0 (indicating that sensor i is not in the cover set) or in the range of 1, ...,w

(indicating that sensor i with its j-th working direction is in the cover set). That is to say, if the value of the gene is 0, then the sensor corresponding to that gene has selected the inactive mode. In doing so, additional coverage of network targets is avoided. Here is an example illustrating the proposed model. Considering that the number of sensors in the network is set to 6, the length of each chromosome is also set to 6. Fig. 4 gives an example of a chromosome.

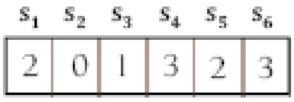

Figure 1: An example chromosome for the network.

Fitness: In EAs, the fitness function is of a great importance due to its explicator implicit effects for searching in the solution space. An appropriate fitness function(which is essentially dependent on problem) provides adequate information about the search direction and it distinguishes between proper and improper candidate solutions. Simply put, the value of the fitness function measures the quality of a chromosome in accordance with the determined targets. In our problem, fitness function is considered as the number of active sensor directions in each coverset, which satisfy the coverage quality requirements of the targets. Note that the

fitness function of a cover set is better than that of other cover sets if the cover set has a lower number of active sensor directions than others. Therefore, the algorithm is intended to find candidate solutions with the minimum number of active sensor directions, leading to increasing the network lifetime.

The Operators of Selection, Crossover, and Mutation In order to select two parents for crossover, the method of binary tournament selection is used in this study. To this end, two chromosomes are chosen uniformly and randomly from the current population and their fitness values are compared to each other. Accordingly, the better chromosome is selected to be a parent with probability p; otherwise, another chromosome is selected. The same process is performed to select the second parent. In order to produce a child chromosome from the two selected parents, the single-point crossover operator is used. To this end, the crossover point is randomly selected, and then the parent chromosomes exchange their information. See Fig. 5 to understand better the single-point crossover operations. Fig. 5 represents two chromosomes that are selected as parents. Furthermore, the crossover point is specified. After the production of the child chromosome, the mutation operation is performed. For this purpose, the gene corresponding to

each sensor is checked to know whether the sensor is present in the child or not. If its presence is verified, the sensor is switched to inactive mode with probability pm. Otherwise, the sensor through one of its working directions is inserted into the child with probability pm (see Fig. 6). In the proposed algorithm, elitism is considered in order to a give chance to the best individual of each generation to be survived during the evolution process.

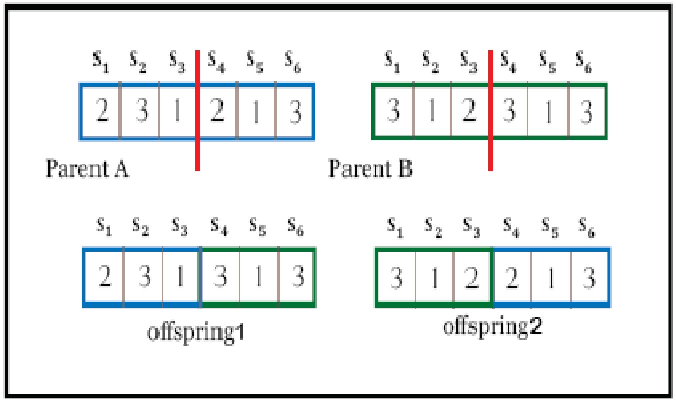

Figure 2: An example of single point crossover operation

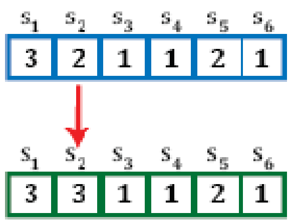

Figure 3: An example of mutation operation

Repair operator: In order to assure the feasibility of the child chromosome produced during the crossover and mutation operation, we developed a repair operator originally proposed in [1]. The repair operator performs two tasks: (i)transforming the child into a feasible cover set and (ii) improving the coverage rate of each cover set through eliminating the redundant sensors. To perform the first task, the repair operator checks each target whether its coverage quality requirement is satisfied or not. If one target is not satisfied, the operator adds new sensors to the cover set until the given target is satisfied. In other words, when a target is not satisfied, the operator activates those sensors that are currently in inactive mode but they (one of their working directions) can potentially satisfy the coverage quality requirement of the unsatisfied target. If the operator recognizes that the inactive sensors do not have the potential to satisfy the coverage quality requirement of the given unsatisfied target, it makes changes to the work direction of the currently active sensor nodes in such a way the coverage quality requirement of the target can be satisfied. This process is performed on the whole targets until the coverage quality requirement of all targets is satisfied. The second task of the repair operator is the improvement of the coverage rate of each cover set by removing the redundant sensors. To this end, the operator deactivates the sensors in the cover set one by one, then checks whether the coverage quality requirement of all the targets is still satisfied or not. If it is satisfied, it means that the considered

sensor is redundant; thus, it would be eliminated from the cover set. This process is performed on all of the active sensors in the cover set.

Initial population generation: Each chromosome of the initial population is produced randomly. Then, the active sensor directions in the chromosome (coverset) are checked to see whether they can satisfy the coverage quality requirements of all the targets. If even the coverage quality requirement of one target is not satisfied, the repair operator is applied to the chromosome in order to perform its both tasks mentioned above. Otherwise, only the second task of the repair operator is performed on the chromosome. Note that once a new chromosome is

generated, this is compared to already-generated chromosomes in the population to see whether this is similar to them or not. In case of similarity, the generated chromosome is discarded; otherwise, this is added to the initial population.

Stopping criterion: In this study, the maximum number of consecutive iterations is taken into account as stopping criterion.

6. Simulation Results

This section presents several experiments conducted to examine the effects of various factors on the size of constructed cover sets. The proposed memetic algorithm was implemented by the MATLAB and run on a computer with 1:5 GHz CPU and 2 GB memory. In the proposed algorithm, the probability of crossover and mutation operation was set to 0.2 and 0.05, respectively. The directional sensor network was configured as follows: N sensors with uniform sensing range$r$ and sensing angle $\frac{2\pi}{3}$, and M targets were distributed randomly and uniformly within a square area of size 400(m) _ 400(m). By default, the sensing range was fixed to 125(m) and the number of sensors and targets was set to 100 and 10,respectively. The sensors that could not monitor any target and the targets that were not monitored by any sensor were ignored in the network. Each simulation scenario was executed 15 times, and the average size of the cover sets was then calculated for each scenario. The results obtained from the experiments were compared with those of a greedy-based algorithm.

Experiment 1.This experiment was conducted to examine the relationship between the number of sensors and the size of constructed cover set. The number of sensors was ranged from 40 to 90 with incremental step 10. The results presented in Fig. 4 show that with increasing the number of sensors, the size of cover set linearly decreases. This was because some directional sensors were able to monitor more targets simultaneously. The results also showed that the proposed algorithm was more successful in constructing cover sets with minimum number of active sensor directions in comparison with the greedy-based algorithm. Note that constructing

cover sets with lower number of active sensor directions can contribute to increasing the network lifetime.

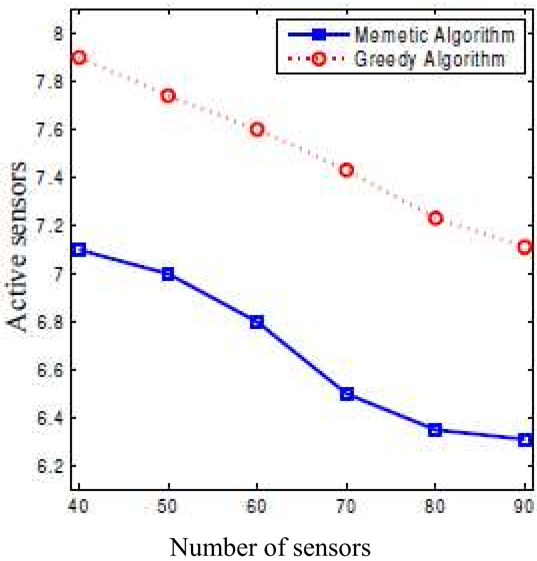

Figure 4: Effect of the number of sensors on the number of active sensors

Experiment 2.This experiment was carried out to investigate the relationship between the number of targets and the size of constructed cover set. For this purpose, the number of targets was ranged from 4 to 20 with incremental step4. The results presented in Fig. 5 show that an increase in the number of targets causes a linear increase in the size of cover set. This is natural because when then umber of targets increases, more number of active sensor directions are needed to satisfy the coverage quality requirement of all the targets. The obtained results demonstrated the superiority of the proposed algorithm over the greedy-based one in all conditions in terms of constructing cover sets with minimum number of active sensor directions.

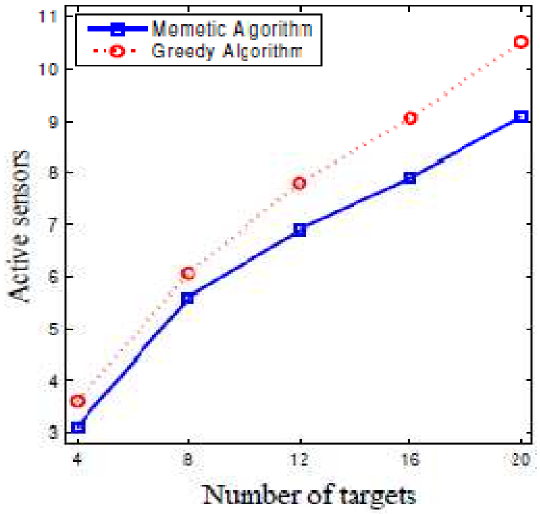

Figure 5: Effect of the number of targets on the number of active sensors

Experiment 3.This experiment examined the impact of the sensing range on the size of constructed cover sets. The sensing range was varied between 75(m)and 200(m) with incremental step 25(m). The results presented in Fig. 6 indicate that an increase in the sensing range helps to construct cover set with lower number of active sensor directions. This is because once the sensing range enlarges, sensor nodes are capable of monitoring more targets and, as a result, fewer sensors are required to satisfy the coverage quality requirement of all targets.

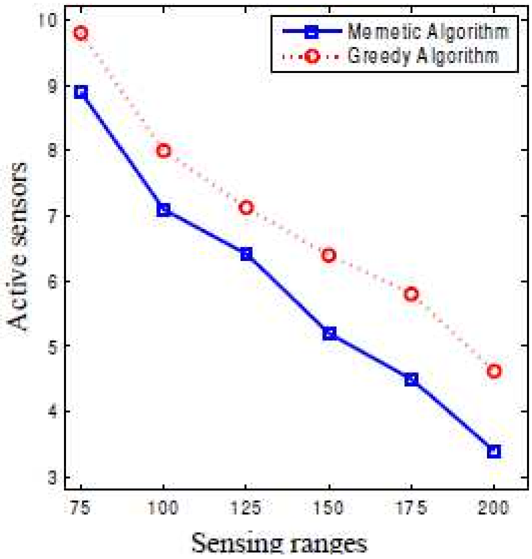

Figure 6: Effect of sensing range on the number of active sensors

7. Conclusion

This paper addressed the problem of target coverage in DSNs in which the sensors were limited in their sensing angle and battery power, and the targets had different coverage quality requirements (the problem was known as PTC problem).To solve this problem, we developed a GA-based scheduling algorithm along with a repair operator capable of constructing cover sets with minimum number of active sensors, which can satisfy coverage quality requirements of all the targets and extend the network lifetime in the over-provisioned network. In this context,

several experiments were conducted to evaluate the performance of the proposed algorithms and the obtained results were compared to those of a greedy algorithm. The results indicated that the algorithm performed better than the greedy-based algorithm with regard to extending the network lifetime by making cover sets with the minimal number of active sensor directions.

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