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Optimizing the Performance of Wireless Rechargeable Sensor Networks

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Abstract: *Nowadays, the Wireless Rechargeable Sensor Networks (WRSNs) have been concerned as a new trend to solve the energy problems and extend in the lifetime of wireless sensor networks. This technology is promising to replace the present methods. It enables multiple nodes to be charged simultaneously by wireless charging vehicle. This can improve the network lifetime. In this work, the proposed WRSN system introduces the using of cluster-heads method to improve the power consumptions and the lifetimes of WSNs. Besides, it uses the genetic algorithm methodology to optimize the cluster-heads needed to be recharged and the routing (travel) path of the wireless mobile charger used in this process. The suggested system is applied for a simulated WRSN used to communicate between the sensors that observe the conditions around natural radiation source and its control centre. The experimental results show that proposed WRSN-GA can improve the lifetime of the WSN as well as achieve shortest travel path and minimum cost of Wireless Re-chargeable Sensor networks. However, the proposed system has a significant enhancement for the WRSNs in real-time applications.*

Keywords: *Wireless energy transfer, Wireless Re-chargeable Sensor networks, Genetic Algorithm (GA), Mobile Charger (MC), and Travel Path.*

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I. Introduction

An increase the lifetimes of the wireless sensor networks (WSNs) is a main goal for many researchers. WSNs' sensors are mainly battery-powered. The battery storage capacity is limited. So, any WSN can remain works for a limited amount of time [1]. Therefore, although the researchers have achieved some extend of the network lifetime, sensor nodes would deplete their energy eventually.

The recent promising wireless charging technology (WCT) has been introduced as a novel solution for this problem by re-charging wirelessly the batteries of the sensor nodes.

WCT was started by Kurs, et. al.,. It can transfer the energy between magnetically coupled coils. This transferred power is used to recharge the sensors' batteries [2].

More recently for the next generation of WSNs, wireless charging technology has to grow up with hybrid technology to recharge the batteries of the sensor nodes and these networks are known as Wireless Rechargeable Sensor Networks (WRSNs). There are two main wireless transferring power and re-charging techniques; they are: the radiation-based and the magnetic resonant coupling methods. Radiation-based method has very low efficiency and can only transfer a small amount of energy [3]. In contrast, the magnetic resonant coupling has high efficiency and supports transferring hundreds of watts of energy over a large air gap. WRSNs use the mobile chargers carried by autonomous vehicles for the recharging process of the deployed sensors [4, 5]. Mobile chargers can move till the resonant coils and high-density battery packs are become very close. So, the power is delivered wirelessly to the nodes with high efficiency. The charging systems are placed at power stations, parking lots or even under the road surface to recharge the battery packs [6].

Although, this considerable success, it is found that, there is great complexity face the WRSNs. These problems are NP-hard. New algorithms are required till have good results in this area.

In this research, a novel system is introduced to improve the performance and increase the lifetime of Wireless Rechargeable Sensor Networks (WRSNs). In addition, the proposed system uses two genetic algorithms. One of them is used to optimize the number of cluster-heads required to be charged, reliability, and the cost of the recharging process. While, the second one is used to optimize the travel path (routing path) for the re-charging process to improve the performance of the WRSNs.

The rest of the paper is organized as follows: Section 2 handles the related work. In Section 3, an overview about genetic algorithm (GA) is introduced. Section 4 presents the proposed system that uses GA. Section 5 deals with an applicability and experimental simulation of the present work. Section 6 concludes the work.

II. Related Work

A lot of work has been developed to address wireless re-charging process in WRSNs using magnetic resonant coupling. In [7], an optimization problem is studied to maximize the ratio between mobile charger's idling and working time. Another work has proved that a Hamiltonian cycle through all the nodes is considered the shortest recharge path. In [8], a single mobile charger (MC) is studied to joint consideration of data collection and energy replenishment. The MC first has determined the nodes for recharging and achieving the shortest route. In addition; it can guarantee a bounded tour length. In [9], authors have handled the dynamics of the energy consumptions problem that may cause inaccurate recharge decisions. This work has taken into account the reasonable approximations, the Orienteering Problem can be approximated by a Knapsack problem and dynamic programming solutions are used to solve the problem efficiently. In [10], the authors has handled the scheduling of multiple mobile chargers, by minimizing the weighted sum of vehicle's traveling time and node's residual lifetime in each step. In [11], magnetic resonant coupling technique is dealing with many multimedia sensing applications with enormous data communications and sensing activities.

III. Genetic Algorithm

The Genetic Algorithm (GA) has widely been used as a robust optimization and search method in various areas [12]. It is considered a search technique for global optimization in a complex search space. A GA will typically have five parts: (1) a representation of a solution called a chromosome, (2) an initial population of chromosomes, (3) a fitness function, (4) a selection scheme and (5) crossover and mutation operators. Figure (1) shows the flow chart of the genetic algorithm.

The initial population of chromosomes can be randomly produced or manually created. The fitness function measures the suitability of a chromosome to meet a specified objective [13]. Thus, a chromosome is considered fitter if it corresponds to greater coverage. The selection function decides which chromosomes will participate in the evolution stage of the genetic algorithm made up by the crossover and mutation operators. The crossover operator exchanges genes from two chromosomes and creates two new offsprings (chromosomes). While, the mutation operator changes a gene in a chromosome and creates one new chromosome [14]. These tasks have repeated till achieve the optimum solution or reach the determined number of iterations.

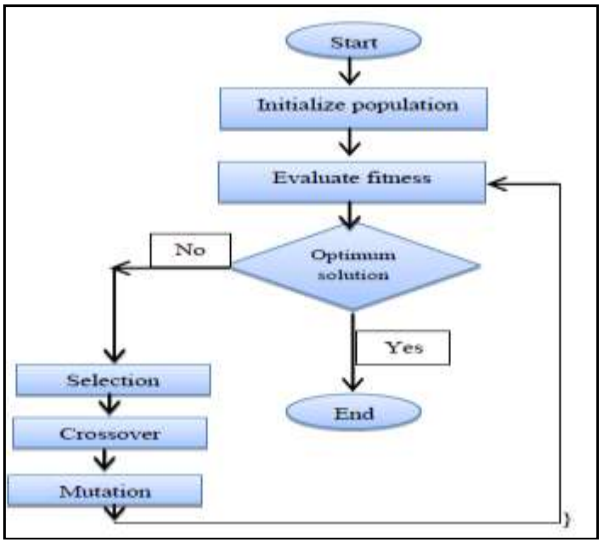


Fig. (1): Flow chart of genetic algorithm (GA)

IV. The Proposed System

Recently, WSRNs are proved their success to solve the power problem of the WSNs to ensure maximum utilization. The proposed system introduces a novel algorithm in the same manner. It can extend the lifetime of the wireless sensor networks by three ways. They are:

1- The proposed system uses the cluster-based methodology to minimize the traffic rate inside the networks. This can decrease the power consumptions and extend its lifetime.

2- It uses the WRSN technique to re-charge the batteries of the sensors taking into account the cluster-based structure. This can enhance the re-charging process.

3- Proposed system uses the genetic algorithm optimization methodology. So, it can minimize the number of re-charged sensor nodes, the process's cost, and their route (travel) path. While, it can maximize the lifetime of the network.

The operation of the proposed system can be explained as:

(1) The proposed system has used the cluster-based technique. It has divided the sensor nodes of the WSNs into a number of small groups that are called clusters. Each cluster consists of a cluster head and the reminder sensor nodes of the group are used as members as shown in fig. (2).

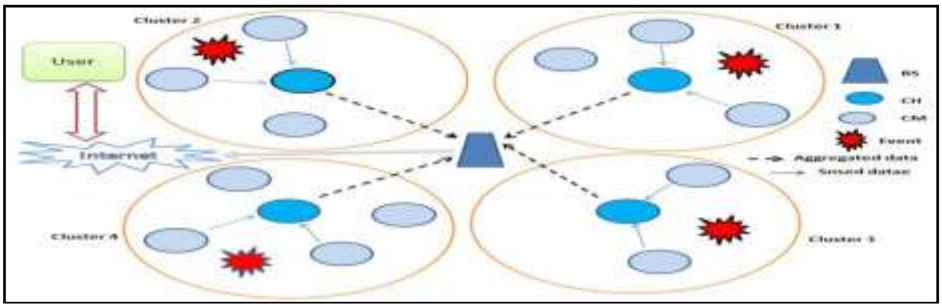


Fig. (2): Cluster-based Methodology in WSNs

The cluster head can collect the data from the cluster members of the cluster and send it to the station base as a single packet. So, the traffic rate and the overhead are reduced. Clustering reduces the energy consumptions by improving the bandwidth. Cluster-heads methodology can extend the network's lifetime by balancing the energy consumptions among nodes and by distributing the load among different nodes from time to time [15].

(2) The proposed WRSN algorithm uses the cluster-heads' structure to improve the recharging process. So, this process is executed in two hierarchical stages. Firstly, mobile charger starts with re-charging the cluster-heads so the computational complexity is reduced. Secondly, the mobile charger concerns re-charging the member sensor nodes only by the cluster-heads.

It is found that, during the first stage of the recharging process, naturally spreading of the electromagnetic waves doesn't recharge the cluster-heads only, but it re-charge also the member sensor nodes near to the cluster heads using the mobile charger. When the first stage is completed, all the cluster heads become overcharged (i.e., charged more than the target level set of the cluster heads) and their near member sensor nodes are overcharged also while far nodes are partially/no charged. To complete the entire re-charging process for all the sensor nodes, energy transfer from cluster-heads to member sensor nodes around them until all the member sensor nodes are re-charged to the target level set for the member sensor nodes.

This hierarchical re-charging process is more efficient than the traditional flat schemes. The mobile charger charges the head clusters only by the power source in the first stage. While, head clusters complete the charging process in the second stage by overcharging them. So, the mobile charger doesn't need to return for the power source to complete the charging process that causes main challenge for WRSNs.

On the other hand, in the practical situations, it is found that, sometimes some cluster-heads need to be re-charged at certain moment while the others need not. This referred to the different operation rate of each cluster-heads and their members that changed based on the required tasks from each cluster. So, re-charging all the cluster heads in the same time cause great losses. To overcome this challenge, the proposed system has used the GA to optimize the performance of the re-charging process by selecting the cluster-heads need to be re-charged only and optimize their route path. This can minimize the cost, time and simplify the complexity of the re-charging process. Figure (3) shows a block diagram of the proposed system.

The proposed system has divided the sensor nodes based on their energy levels of the WSNs into three phases. They are:

1- All the sensor nodes are higher than the threshold energy level based on the critical points of the WSN's application area. In this case the WSN is operating in a normal mode of operation.
2- The energy-levels of some/all the cluster heads are under the threshold energy level. So, the batteries of these cluster-heads need to be recharged.
3- Some/all the cluster heads is/are difficult or high costly to be re-charged. In this case, this/these cluster head(s) is (are) replaced with another sensor node(s) in its cluster and messages are sent for all the networks to inform all the sensor nodes to adapt themselves for the new situation.

The proposed system has used two genetic algorithm modules to optimize the cluster-heads and their path for the re-charging process. The first genetic algorithm module has used the sub-population method to optimize the cluster-heads. While, the second one optimize the path of re-charging the batteries of the selected cluster-heads.

(1) The First Genetic Algorithm

This genetic algorithm has been used to optimize the cluster-heads need to be re-charged. It can be implemented as follows:

a. Chromosomes Representation

The cluster-heads of the WSN represent the chromosomes of each sub-population of the first genetic algorithm (GA). They are represented in a binary digit form.

b. Population Initialization.

As a great number of the cluster-heads in the complex WSNs, the proposed system has divided the cluster-heads in the observation area into groups. Each group constructs a sub-population that has a collection of randomly generated chromosomes. This technique is called sub-populations or sometimes is called multi-populations. The size of the whole population: 245, they are divided into 7 sub-populations. Each of them consists of 35 chromosomes.

c. Selection methodology

The proposed system has used the tournament selection scheme to select the parents (chromosomes) those used for continuing to the next generation.

c. Crossover

Proposed GA uses two points crossover technique. Its rate=0.5.

d. Mutation

Flip bit mutation method has been applied by the suggested system for each chromosome. The mutation rate is: 0.03.

e. Fitness function

The fitness function is the most important part in the genetic algorithm operation. It evaluates the fitness of each chromosome (solution) in the population to test its suitability for continuing the operation in the next generation of the GA.

In the proposed system, the fitness function optimizes the number and locations of the cluster heads in the observed area. Besides, it concerns decreasing the power consumptions, and the cost. The fitness function is described by the following equation:

$$F = \frac{1}{a(hn)} + \frac{1}{b(c)} + \frac{1}{d(p)}$$

Where : a,b and d : constants.

hn : number of cluster-heads (and their locations).

c : cost of the recharging process for the selected cluster-heads.

p : power consumptions in the re-charging process.

f. Termination

In the first genetic algorithm, the termination of any one of these subpopulations occurs independently of the termination of the rest of the sub-populations. A subpopulation terminates if any of the following two conditions is fulfilled: (1) if there exists one (or more) " good " chromosomes and 20 generations have passed without achieving a new optimal chromosome. A good chromosome is one that has a highest value. (2) if the no. of generations is equal to the fixed generating number determined by the system. In the present case, the number of iterations is 100.

However, the optimum solution has been obtained from the first proposed genetic algorithm representing the number and the locations of the cluster heads needed to be recharged.

(b) ***The Second Genetic Algorithm***

The second genetic algorithm module is used to optimize the route (path) of the cluster-heads to be charged. This route algorithm has taken into account the cost, availability, avoiding the repeation of visiting the same cluster-head more than one time and ensuring the efficiency of recharging the cluster-heads to their threshold value. This genetic algorithm has been implemented as follows:

a. Chromosomes Representation

The chromosomes of each population represent the cluster-heads of this proposed Genetic Algorithm (GA). They are represented in string form. The size of the population is 30 chromosomes

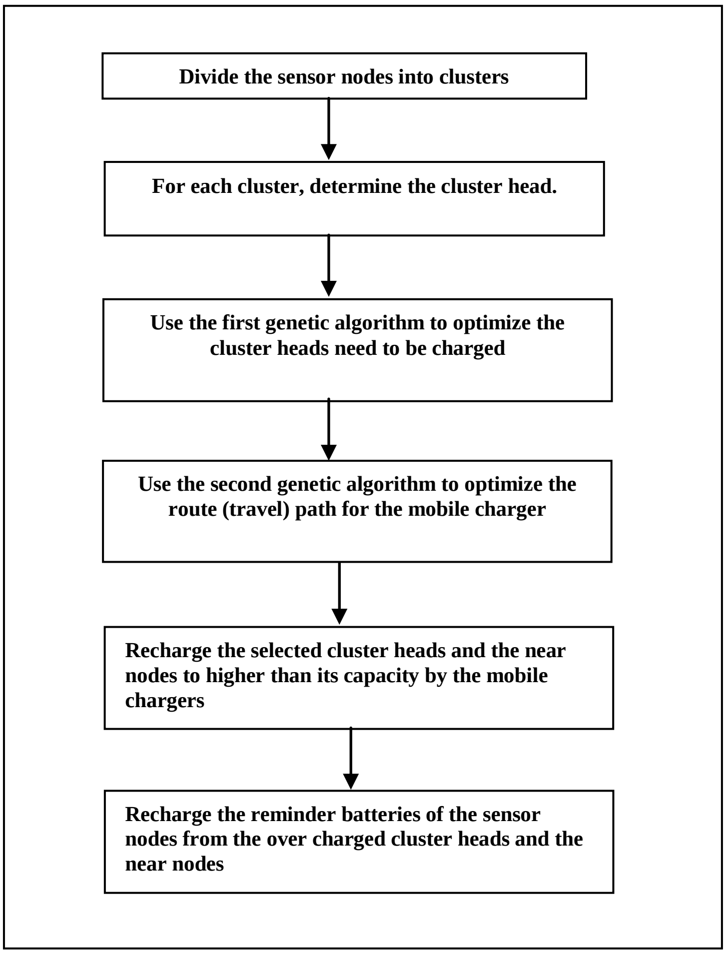


Fig. (3): Block Diagram of the proposed system

b. Selection methodology

The steady-state methodology with the worst-replacement method is used by the proposed system to select the most suitable chromosomes (parents) will continue the iteration to the next generation.

c. Crossover

Proposed GA uses a partially mapped crossover (PMX) mechanism that can prevent the repeation of the same cluster-head within one routing path [16]. Its rate=0.4.

d. Mutation

The insertion mutation has been applied by the suggested system. It randomly chooses a cluster-head in the chromosome, removes it from this chromosome, and inserts it in a randomly selected pairs. The mutation rate is: 0.02.

e. Fitness function

The fitness function evaluates the performance of each chromosome (solution) in the population. For the second genetic algorithm, the fitness function evaluates the cost, efficiency, and availability of the route path in the observed area. The fitness function that is used:

$$F = \frac{1}{a(c)} + b(f) + g(v)$$

Where a,b,g : constants

c : cost of the routing process.

f : efficiency of the routing process
g : availability of the routing process

f. Termination

The second genetic algorithm can be terminated by two methods. They are: at achieving the optimum solution or by having 100 iterations.

However, the cluster-heads (optimum solution) has been obtained from the first proposed genetic algorithm represents the number and the locations of the cluster-heads those are needed to be recharged. The routing path (optimum solution) of the re-charging process can be optimized by the second genetic algorithm. Therefore, using the genetic algorithm modules can enhance the re-charging process of the batteries of the sensor nodes in the wireless sensor network (WRSN).

During the re-charge process, the MC collects data from its neighbor nodes in multi-hops and uploads all gathered data to the base station after completing the re-charging cycle.

V. Applicability Of The Proposed System And Its Results

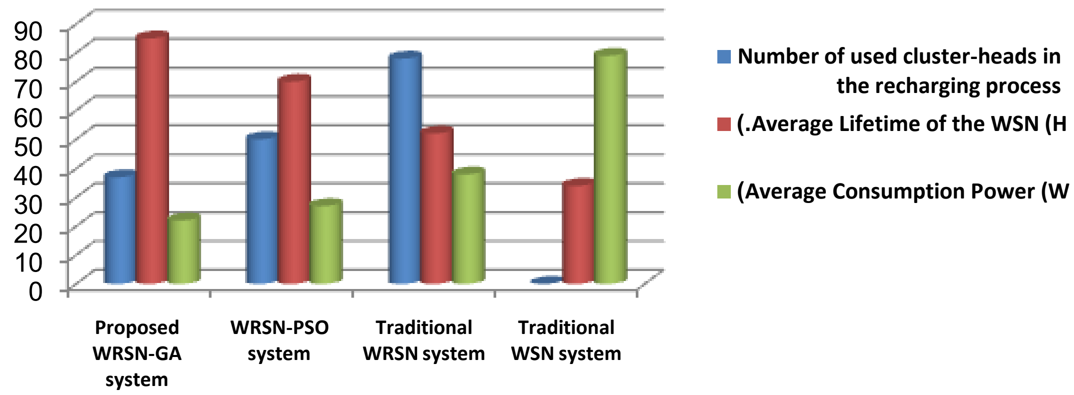
The proposed system has been evaluated using a simulated wireless re-chargeable sensor network (WRSN) that communicates between a system used for measuring the environmental conditions controlling a radiation source in a radiation site (such as water level, measuring the chemicals in the water, and closing the doors) and their control system. Then, the obtained results of the proposed system are compared to three other systems applied for the same application.

The first system is Dijkstra's shortest path algorithm that is a traditional WSN algorithm having no re-charging process [17], the second system used is a traditional WSRN system for WSNs [18]. The third one is a WRSN technique uses particle swarm optimization method [19].

Table (1) represents the obtained results from the four systems. Tables (1) & figures (4-7) show a comparison between the results obtained from the tested systems when all of them have applied for the same WRSN.

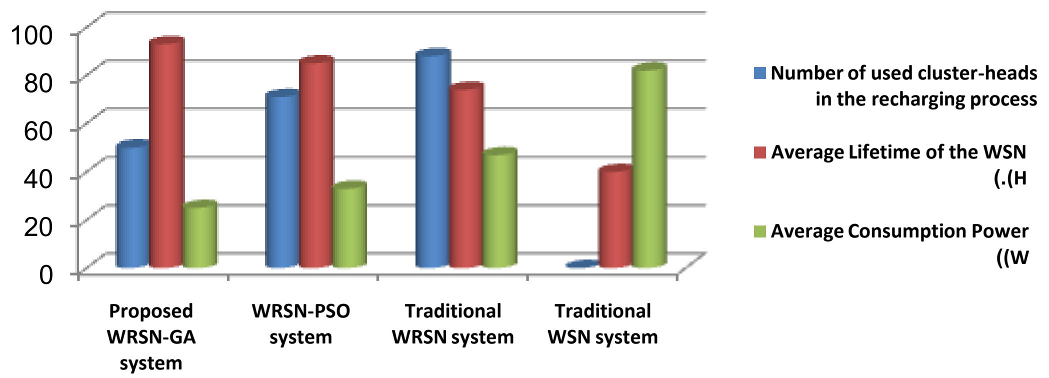
Table (1): A comparison between the proposed system and the other three systems at different number of nodes

The tested systems	Number of Nodes	Number of used cluster-heads in the recharging process	Average Lifetime of the WSN (H.)	Average Consumption Power (W)
Case 1				
Proposed WRSN-GA system	**100**	**37**	**85**	**22**
WRSN-PSO system		**50**	**70**	**27**
Traditional WRSN system		**78**	**52**	**38**
Traditional WSN system		**--**	**34**	**79**
Case 2				
Proposed WRSN-GA system	**200**	**50**	**93**	**25**
WRSN-PSO system		**71**	**85**	**33**
Traditional WRSN system		**88**	**74**	**47**
Traditional WSN system		**--**	**40**	**82**
Case 3				
Proposed WRSN-GA system	**300**	**66**	**150**	**32**
WRSN-PSO system		**79**	**135**	**41**
Traditional WRSN system		**92**	**118**	**59**
Traditional WSN system		**--**	**105**	**78**
Case 4				
Proposed WRSN-GA system	**400**	**73**	**175**	**42**
WRSN-PSO system		**89**	**146**	**53**
Traditional WRSN system		**97**	**128**	**74**
Traditional WSN system		**--**	**111**	**87**



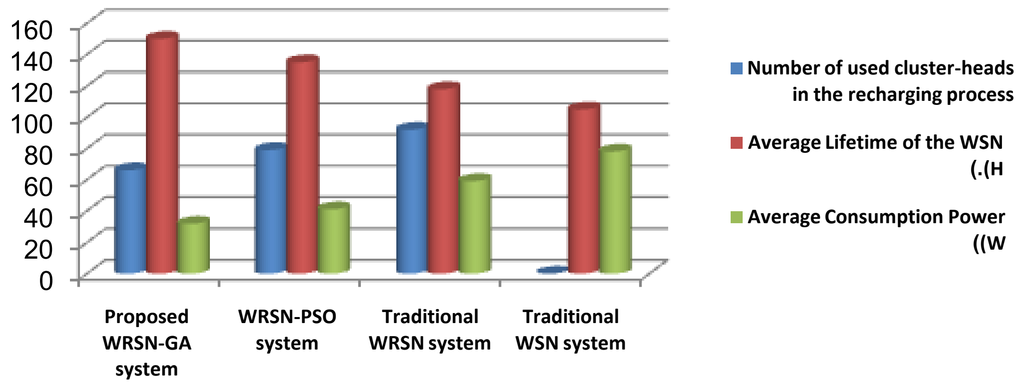
Case 1: Number of Nodes = 100

Fig. (4): A comparison between the proposed system and the other three systems at Number of Nodes = 100



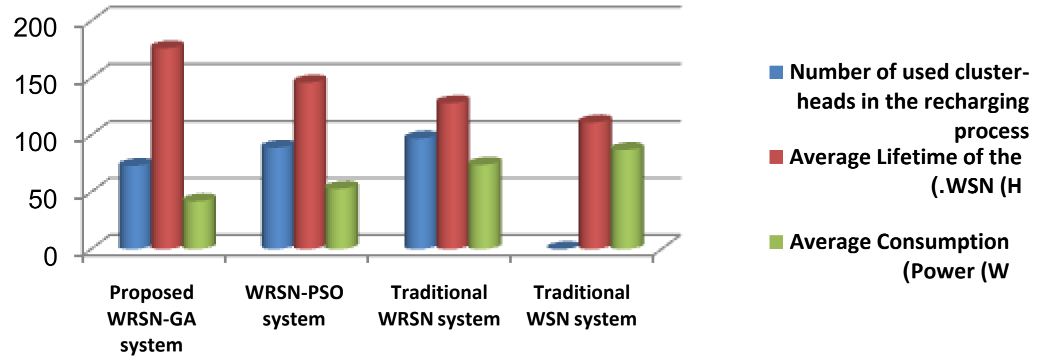
Case 2: Number of Nodes = 200

Fig. (5): A comparison between the proposed system and the other three systems at Number of Nodes = 200



Case 3: Number of Nodes = 300

Fig. (6): A comparison between the proposed system and the other three systems at Number of Nodes = 300



Case 4: Number of Nodes = 400

Fig. (7): A comparison between the proposed system and the other three systems at Number of Nodes = 400

From the obtained results, the proposed system can increase the lifetime; while it can decrease the power consumption of the WRSN rather than the other three systems. This can improve the performance of the WSNs.

For example, in case (1), it is found that, the lifetime of the network using the proposed system increases 1.2% compared to the corresponding value of the system used PSO for WRSN. While, the lifetime of the network has used the proposed system increases by 1.63% rather than the traditional WRSN system using no optimization technique. Thirdly, the proposed system can increase the lifetime of the network by 2.5% rather than the traditional WSN system.

While, for Case (2), it is found that, the proposed system can increase the lifetime of the network by 1.1% longer than the WRSN system that used PSO. While, it can increase the lifetime of the network by 1.25% longer than the traditional WRSN system using no optimization technique. Thirdly, the lifetime of the network used the proposed system can increase 2.3% longer than the traditional WSN system.

However, the proposed WRSN-GA system has proved significant improvement for the WSN's performance. It is found that, the proposed system has proved its goodness by increasing the lifetime of a WSN used in detecting the radiation sites. Also, the proposed system decreases its power consumptions. Therefore, the suggested system can improve the performance of Wireless Rechargeable Sensor Networks those are applied in real time applications.

VI. Conclusion

Although the great effort has been done by researchers to improve the performance of the wireless sensor networks in our daily life, the energy-efficiency still causes many challenges for these networks till now.

Proposed system has suggested the uses of the cluster-based method, wireless re-chargeable senor network and two genetic algorithm modules to face these challenges. The cluster heads have decreased the power consumption and so extend the lifetime of the network. Besides, the WRSN can re-charge the batteries of sensors to increase their lifetime.

The two genetic algorithm modules are used to improve the performance of the proposed system. The first one concerns optimizing the number of cluster-heads needed to be charged. While, the other deals with optimizing the route path for the recharging process of the WRSN.

For evaluating the proposed system, it has been applied for a simulated wireless sensor network used in communicating between the sensors measured the environmental parameters around a radiation source and its control system in a radiation site. The obtained results from the proposed system are compared to three other systems those are applied for the same application.

The suggested system has improved the performance of WRSNs system based on the following features:

1- It uses the cluster-based method that has decreased the packets' traffic. So, the power consumption is decreased and so the lifetime. Besides, it has decreased the congestion and the routing time of the WRSNs.

2- It uses the cluster-based method as a hierarchical structure of the WRSNs. So, it can divide the re-charging process into the same structure. This enables the system to re-charge the batteries of the head-cluster sensors only from the source. This overcome the problems of returning the single mobile recharger to the source many times till complete the re-charging process. In addition, it can decrease the delay time and the time needed till the data reach the base station that may cause great problems for the users. Also, this enchantment can avoid the system needing for the uses of multiple mobile chargers that are more complex and costly.

3- It uses the WRSN methodology that enables the WSNs to re-charge their sensor batteries. However, it can extend the lifetime of the WSNs. This is a great advantage for the critical and complex WSNs.

4- It can improve the re-charging process of the WRSNs by using the genetic algorithm modules. The first GA module can enhance the performance of the WRSNs by selecting the cluster-heads needed to be re-charged only rather than re-charging all of them by the present traditional WRSN systems. This can decrease the re-charging time, cost and complexity of the WRSNs. While, the second GA module can optimize the most suitable route path used by the mobile charger during the re-charging process. This cause more decreasing for the re-charging time, cost, complexity and increasing for the reliability and efficiency.

However, the proposed WRSN-GA system has proved its goodness to be applied for real time WRSN applications.

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