COVERAGE PROBLEM IN HETEROGENEOUS WIRELESS SENSOR NETWORKS

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Abstract

A heterogeneous wireless sensor network consists of different types of nodes in sequence. Some of these nodes have high process powers and significant energy, which are called the manager nodes or super-nodes. The second type nodes, which have normal process power, are only used as monitoring nodes or act as relay nodes in the path to the manager nodes are called the normal nodes. In this paper, an energy-aware algorithm is presented for the optimum selection of sensor and relay groups that are used for monitoring and sending messages from goals in point coverage, using the competition between the nodes. This algorithm is effective in decreasing the energy consumption of the network and increasing its life-time. Moreover, providing that no node saves the information about the routing table and relay nodes; therefore, it will have less complexity and overload.

Keywords: Coverage problem, Wireless Sensor Networks, Heterogeneous network

I. Introduction

Wireless Sensor Networks (WSNs), are constructed from tiny autonomous sensor nodes and are utilized for various applications, such as civilian and environmental monitoring.

In sensor networks which used to monitor an area, the goal is to have each location, in the physical area of interest, within the sensing range of at least one sensor (Cardei & Wu, 2004). Therefore, coverage is an important issue in these networks and is classified in the literature as: area coverage, point coverage, and barrier coverage. Based on the subject that will be covered, different coverage problems can be formulated. In the point coverage problem, the objective is to cover a set of points of interests (Fig. 1). As an example in the study done by Urrutia (2000), the Art Gallery Problem seeks to determine the number of observers and their placement necessary to cover an art gallery room where every point is seen by at least one observer.

Sensor networks are often intended to be deployed in remote environments, such as a forest or desert. Since the power capacity of the sensor nodes is restricted, it seems to be impossible to recharge or replace the battery power of all the sensor nodes. However, in many monitoring applications it is expected that the system will operate as long as possible, therefore, some methods should be employed to conserve energy.

As shown in Fig. 1, the best method for conserving energy is to put as many sensors to sleep (inactive mode) as possible. At the same time, the network must maintain its connectivity that lets the base station (or monitoring station) communicates with any active sensors. Since every node shares common sensing tasks, not all of them are required to be active, as long as there are enough working nodes to assure system functionality. Therefore, the system lifetime can be prolonged correspondingly if we can schedule sensors to work. In continuously operating sensor networks, redundant sensors are deployed, from which only a few subsets are active at a time, while the major part of sensors are turned off and thus preserve energy. By decreasing the portion of active time, the overall time until all sensors run out of energy is increased and the lifetime is extended proportionally by a factor equal to the number of disjoint subsets (Bulut & Korpeoglu, 2007).

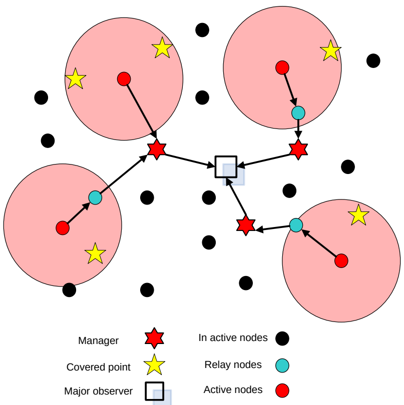

Fig. 1. Coverage the set of points of interests

In this paper, we propose a method for selecting disjoint subsets by employing a competitive algorithm: a heterogeneous network, in which two types of nodes are deployed forming a hierarchy, is taken into consideration. The first type of nodes is called ‘managers’ who have high energy resources and long communicative ranges. These nodes are responsible for maintaining network’s connectivity. The second type, those with lower energy resources are termed as ‘normal’ nodes. In the assumed network, the total number of normal nodes is supposed to be greater than the managers.

II. Background

The coverage problem has been considered extensively in several studies. This problem can be classified in different metrics. Different approaches to address the coverage problem are stochastic or deterministic sensor deployment; homogeneous or heterogeneous sensing area; and additional design constraints such as energy efficiency, minimum number of sensors that need to be deployed, or the network connectivity.

Point coverage, which is considered in this paper, has also been studied in Cardei and Du (2005), Cardei et al. (2002), Cardei et al. (2005), Kar and Banerjee (2003), and Dasgupta (2003). Area coverage, in order to monitor a specified region, has been considered in Slijepcevic and Potkonjak (2001), Wang et al. (2003), and Zhang and Hou (2004). The problem of finding the maximum number of disjoint covers in a sensor network presented in Slijepcevic and Potkonjak (2001), where a disjoint cover was defined as a set of nodes which could completely cover the monitored area. The work has been reported in Tian and Georganas (2002) attempted to solve the complete coverage problem with centralized solution, although a large number of nodes were required to operate in the active mode. The work reported in Chakrabarty e al. (2002) adopted a linear programming solution to minimize the cost of sensors with complete coverage of the sensor field. Chakrabarty e al. (2002) have formulated an integer linear programming problem to solve the cost minimization problem in a grid-based sensor deployment network. However, the energy consumption of nodes and the lifetime of heterogeneous sensor deployment have not been taken into account in their study. Meguerdichian et al. (2001) studied the coverage problem in a wireless sensor network by using Voronoi diagram tools. The authors proposed an algorithm to determine a maximal breach path for a given sensor network topology.

Heterogeneous sensor deployment has been discussed in Chakrabarty e al. (2002), Mhatre and Rosenberg (2004), and Kumar et al. (2003), considering the cost of deployment. Chakrabarty e al. (2002) and Mhatre and Rosenberg (2004) have focused on minimizing the total deployment costs while guaranteeing certain requirements. Gupta and Younis in (2003) studied a heterogeneous sensor network (with two types of nodes) and investigated the impact on clustering of node failure at the higher level of the node hierarchy.

EEDG (Energy-Efficient Data Gathering in Heterogeneous Wireless Sensor Networks) has been proposed by Cardei and Awada (2006). They introduced the heterogeneous connected set covers problem that has as objective finding a maximum number of set covers such that each set cover monitors all targets and is connected to at least one node with higher capabilities. A sensor can participate in multiple set covers, but sum of the energy spent in all sets is constrained by the initial energy resources.

Cardei et al. (2005) introduced adjustable range set covers problem to extend network lifetime in the adjustable sensing ranges WSN. The multiple sensing units have not been taken into account though. Energy-Efficient Distributed Target Coverage algorithm (EDTC) in Liu (2007) addressed the energy-efficient target coverage problem in Heterogeneous Wireless Sensor Networks (HWSN). The main principle behind EDTC is to introduce the concept of sensor priority. The priority is obtained by two parameters of sensing ability and the remaining energy. The combination of these parameters has not been discussed by Liu (2007). Our work differs from Liu (2007) by integrating different parameters for selecting the relay and sensor nodes. At the end we achieved more lifetime and more residual energy in comparison with EDTC.

III. Subset Selection Algorithm

Operation of a network during its lifetime is done in several rounds. Each round consists of two phases: the setup phase and the steady state phase (Fig. 2).

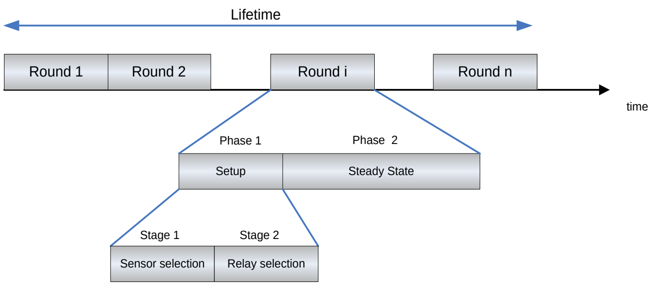

Fig. 2. Organization of network lifetime

In the setup phase, the subsets of active nodes are determined among normal nodes. During the steady state phase, these nodes are supposed to operate until the end of corresponding round.

Frequent usage and the physical position of nodes has the most impact on energy consumption. If an individual node is used several times, it quickly runs out of energy. Moreover, each node has to consume energy for communication purposes, which is directly related to the distance to the manager. In other words, in order to break the communicative distance, some nodes, as relays in the interim, have to be activated (see Fig. 1). Thus, to optimize the energy consumption, a tradeoff must be made between frequency of usage and distant communication.

Suppose that N normal nodes (s_{n1} to s_{nN}) and M managers (s_{m1} to s_{mM}) are randomly deployed in the network (M<N). Normal nodes have

energy, E_i , by the time they are deployed. Moreover, Managers are powerful nodes with high processing capabilities that are connected to each other all the time. Suppose that there are K points with deterministic positions in the area that must be covered all the times by at least one sensor in the subset. When a subset is selected to operate in the current round, some nodes set their status as sensors and some as relays.

The main purpose of the subset selection algorithm is to determine subsets of normal nodes (C1 to CJ) in the current round so that:

- every k point is covered by at least one sensor node. This is the definition of a connected covered network,
- every sensor node must be connected to a manager directly or through a relay node,

Each active node belongs to one subset C_i ($i \in [1,J]$). This means other nodes in the network remain inactive until the end of the current round and thus preserve energy.

Primarily, every normal node has an initial energy E_i, the communication range R_C, and the sensing range R_S (it is assumed that $R_C > R_S$). By definition, a point is covered if and only if it is located inside the sensing range of the node, i.e. the Euclidian distance between the sensor node and the point is less than R_C.

The derived information is forwarded to at least one manager and to the final destination from there. It is mainly focused on minimizing the energy consumption of monitoring nodes while avoiding transmission of redundant data.

A. Determining active nodes

At this stage, a competition is set among all normal nodes that are qualified to be sensor nodes. The qualification requirements are:

- the residual energy of the node is more than the minimum required for sensing and transmission,
- there exists at least one point of interest in the sensing range of the node.

It is assumed that every sensor node consumes an average amount of energy (E_S) during each round. This approximation would be more reasonable in dense wireless sensor networks. Thus, if a node's residual energy is less than E_S, the first qualification factor is not met and that node will not take a part in the competition stage. If the second requirement is not met, the node also will not participate.

There are k specific points in the area that must be covered (P_1, P_2,…,P_k,). At the beginning of the setup phase, every normal node, S_{ni}, detects the points located in its coverage radius and arranges a set, SP_i, consisting of these points. For example, in Fig. 3, the sets of covered points by nodes S_{n1} and S_{n2} are $SP_1 = \{P_1, P_2\}$ and $SP_2 = \{P_2, P_3, P_9\}$.

In our definition, a neighbor node is the node who shares the same point in its set with the first node. In the above example, Sn2 is a neighbor of Sn1 in the point P2, since it covers this point as well. Moreover, a node whose set is not empty needs to know any other of its neighbors who could cover the same points as well. For that reason, each node sends a short length message within its communication range. The message contains the covered points' ID(s) by the corresponding node and its residual energy.

Next, the competition stage starts in which each node, Snj, backs-off for a time and then advertises, in order to introduce itself as an active monitoring sensor node for the assigned covered points. The back-off time is inversely proportional to the number of other nodes sharing the same coverage points and their residual energy:

$$T_{back-off}^{S_{nj}} = \left[\sum_{i} \frac{1}{n_i}\left(1 - e^{-\frac{E_{res-j}}{Eav_i}}\right)\right]^{-1} \quad i = 1, 2, \ldots, L, \qquad (1)$$

where, n_i is the number of nodes who have detected the i^{th} point. In other words, n_i is the number of node's neighbors that share the i^{th} point with it. E_{res-j} and Eav_i are the residual energy of the corresponding node and the average energy of its neighbors respectively. Assuming that the set SP_j has L members, this sum is counted on every point that is a member.

From (1) it is clear that, the more residual energy would result in less back-off time. In other words, if a point of interest is shared among several nodes, the most qualified node would be the one with more residual energy. In addition, the more members in the SP_j (i.e. the larger the L) the shorter back-off time would result. This means a node that covers more points will advertise sooner. In Fig. 3, if both S_{n1} and S_{n2} have equal residual energies, then S_{n2} would win the competition and advertise sooner since it covers more points.

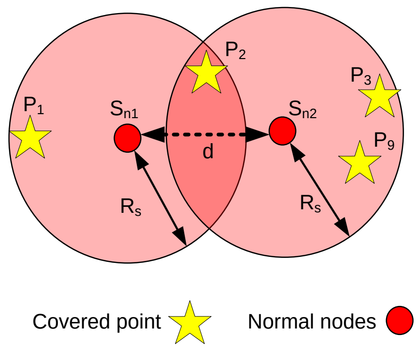

Fig. 3. Target Coverage

B. Advertising

Each node whose back-off time is over will advertise in its communication range and announce the corresponding points that it will cover during the current round. The communication range is assumed to be at least twice of the sensing range (i.e.$R_C \geq 2R_S$). This assures that neighbors will hear the advertisement and decide to act based on their policy. Assuming that S_{n2}, in Fig. 3, has won the competition, in order for S_{n1} to hear the advertisement, R_{c2} must be larger than d. The worst case scenario is when $d = 2R_S$, which means the shared point is located on the border of the sensing ranges of the nodes.

During the setup phase, every unqualified node would set its status to inactive mode. Other active nodes wait until their turn for advertising. They listen to any incoming messages from neighboring nodes advertising themselves. When hearing an advertisement, the node updates its set by eliminating the declared points in the advertisement message. Thus, according to the above example, the shared point(s), P_2, will be omitted from SP_1.

If the back-off time is over and the set contains some points that have not been announced to be covered by any other nodes before, then the corresponding node would send the advertisement declaring to cover them. Otherwise, if the set is empty, there is no need to advertise and the node will quit the competition and set its status to inactive mode during the current round.

Finally, if a node exists with a set that is not empty and qualification requirements that are not met (i.e. its energy is less than the minimum required for sensing and transmission), the network operation is useless since some points are not covered. That would be the end of network lifetime.

IV. Relay Selection

As the communication range of a sensor node is not large enough to access a long distant observer, they need to send their gathered data to a manager. Managers are powerful nodes that are deployed in the area and they have a high resource capacity. They have to be connected to each other all of the time.

Although managers are randomly uniform distributed in the network area, they still may not be reached directly by some sensor nodes. As it is depicted in Fig. 1, there must be some nodes in the middle to carry their traffic to managers. Even if a manager is accessible, it would be worthwhile for sensor node to hire a relay node to carry its data since this helps to break the communication distance into smaller parts and save more energy (because of the merits of multi-hop routing). At this stage, a route beginning from a sensor, passing the relay nodes and ending at a manager is selected.

Several routing algorithms have been proposed in the literature, each of which focuses on meeting the Quality of Service (QoS) requirements, such as latency, minimum energy consumption or shortest path. The common point in all these algorithms is that the starting node (that the route starts from the source node) has to pay the cost of finding the optimized route, to meet the presumed quality of service. In other words, other nodes in the middle do not handle the energy and processing load at all.

In this article, a relay selection and routing algorithm which is based on reverse flooding is proposed. In this process, managers are in charge of finding the best route to the active sensor node(s). Thus, the selected route is independent of the source. Let's begin with defining two values: Relay_Value and PreRelay_Value. Relay_Value is defined as the grade of each node in order to become a relay, while PreRelay_Value is the primary grade of each node which is set to the maximum received Relay_Value of its neighbors.

When the process starts, the managers set their Relay_Values to 1 and broadcast a RELAY_UPDATE message around to their one-hop neighbors. Every node in the neighborhood updates its Relay_Value based on the following:

$$\text{Relay\_Value} = \text{PreRelay\_Value} \times \frac{E_r}{E_i} \times e^{-\frac{N}{N_m}} \qquad (2)$$

where, E_r and E_i are the residual and initial energy of the node respectively. Also, the exponentially decreasing function is based on negative ratio of the number of nodes and managers (N and N_m respectively).

The PreRelay_Value would be the maximum received Relay_Value from the other sources. It equals to 1 since it is initiated from managers.

Meanwhile, at the beginning of the selection phase, the relay nodes of these values in all of the normal nodes are zero. In the next step, the algorithm of the manager nodes sends its Relay_Value parameter to all the normal nodes, which are located at the one-hop neighborhood of that manager node, using the RELAY_UPDATE message. This message contains the Relay_Value of the node sending that signal and the relay path of that node to its nearest manager node. At the beginning of choosing the path of the relay nodes, it is obvious that each manager node is the starter of the choosing phase of the relay path. Therefore, the manager node is the most significant of each path from the sensor to itself, so at the beginning, its relay path is only consisted of its manager node ID.

In general, the nodes receiving their neighboring nodes' RELAY_UPDATE signals compare the Relay_Value of the sender with the Relay_Value of all its one-hop neighboring nodes, which have sent this signal to them.

If a node does not receive an amount of Relay_Value for itself from its one-hop neighbor nodes, it sets the presumption Relay_Value related to that neighbor equal to zero. Otherwise, the presumption Relay_Value is equal to the minimum Relay_Value among the Relay_Values of the node one-hop neighbors. Furthermore, the chosen path of each node is equal to the relay path of the signal sender node plus the path which consists of the signal sender itself together with this node.

Consequently, a set of nodes which have been chosen as an active monitoring and relay nodes are set awake and the other nodes go into sleep mode. This will remain unchanged until the end of the current executing round. After the end of one round, all of these stages repeat for choosing the sensor and relay nodes for the next round. Meanwhile, all of the nodes having suitable physical situations are evaluated as the candidates of active nodes.

In the suggested algorithm, the relay node selection is different from the previous typical methods. This is different in the sense that the cost of different paths is not calculated by the transmitter nodes; the Relay_Value of each node is calculated in the network and this value is independent from the transmitter node. This independency leads to reduce the calculating process and the traffic of the communication load in the network because there is no need for calculations and there is no complexity to find interface paths for every active node.

V. Simulation Results

We consider a network where 300 sensor nodes are placed in a 500 m × 500 m area. In the point covering network scenario, T_{ak} number of goals exist in the considered area, and all of which have to be covered in each round and creates a connected covering network. A number of manager and normal nodes were placed randomly in the network and the number of the clipped sensor nodes is less than the number of the manager nodes.

Fig. 4 shows a sample of the protocol response to the selection of the monitoring and relay nodes and the chosen path for one round. The black squares are the goals. The normal nodes are demonstrated as stars and the manager nodes as circles.

1. Evaluation of the Algorithm for the Sensor Nodes Selection

To evaluate the function of the suggested algorithm, it has been compared to algorithms introduced by Cardei and Awada (2006) and Liu (2007). Moreover, Liu (2007) compared its suggested method with two other methods and has demonstrated the superiority of its method in comparison to theirs.

As can be seen in Fig. 5, the results of simulation show that the lifetime of the suggested algorithm is greater than that of EEDG algorithm, which has been proposed in Cardei and Awada (2006) and is equal to the lifetime of EDTC, which has been mentioned in Liu (2007) as well.

Assuming the selection of the monitoring nodes by the same algorithm in each of the three algorithms, it is observed that the energy consumption of the network in the suggested algorithm is less than the EEDG and the EDTC algorithms in most of the cases. Furthermore, the lifetime of the network has increased by 12% compared to the EEDG algorithm. The remaining energy at the end of the network is larger in the suggested algorithm than that of the other two.

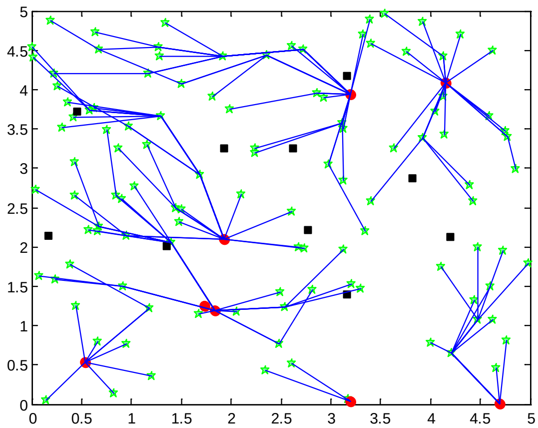

Fig. 4. Sample for algorithm response

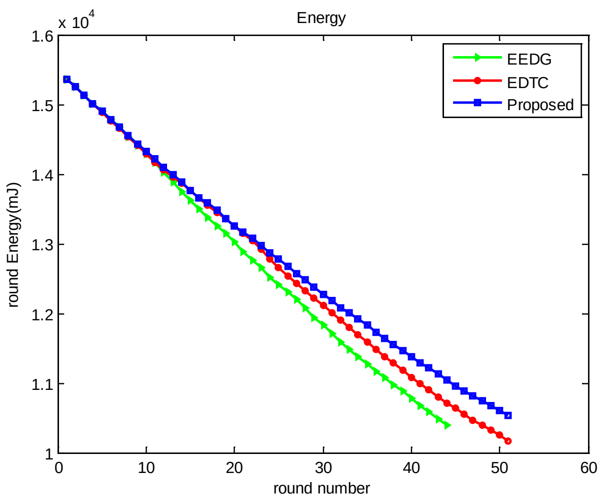

Fig. 5. Lifetime in the proposed algorithms

In Fig. 6, the energy consumption in each round has been illustrated separately. As can be seen, the consumption of the energy is less in the suggested algorithm than the other two.

Fig. 7, shows the lifetime of the network versus the number of goals in the network. Based on what has been expected, the lifetime versus the goal should have a falling trend. The fluctuation of the diagram is due to the variation in the topology of the network and its further arrangement in accordance with the change in the number of goals. As can be seen in the diagram, the suggested algorithm has a longer lifetime compared to the other two algorithms.

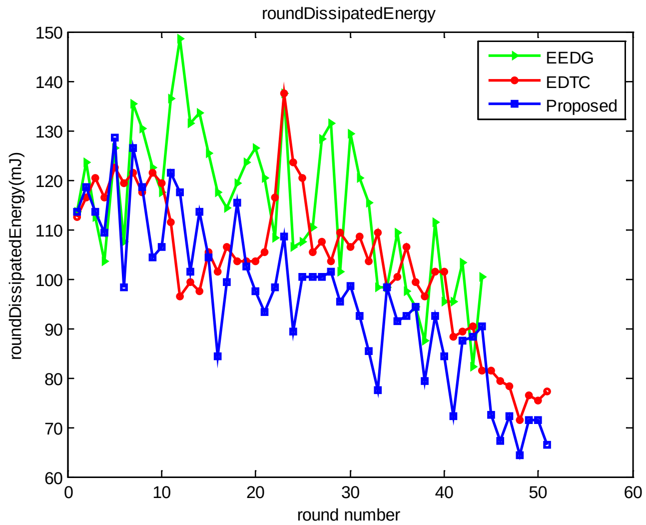

Fig. 6. Energy consumption in each round

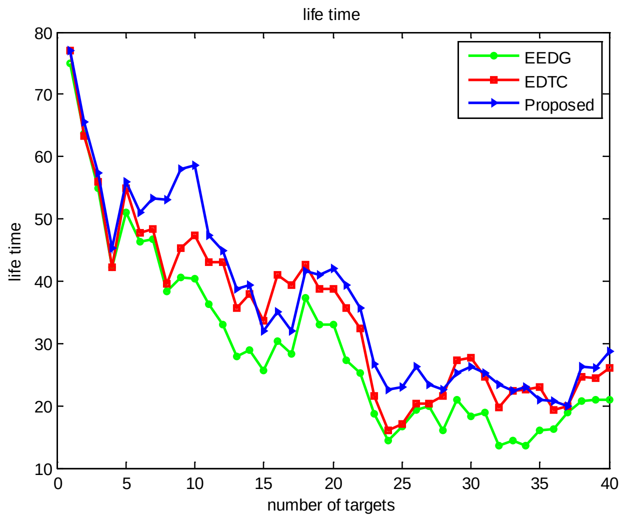

Fig. 7. Lifetime versus the number of goals

2. Evaluation of the Algorithm for the Relay Nodes Selection

To assess the suggested relay node selection method, the proposed methods are compared to two well-known algorithms namely the greedy routing method, and the shortest path method. Each one of these algorithms employs different protocols for the relay node path selection. The simulation parameters are shown in Table I.

From the implementation results, it is clear that the proposed method is more energy efficient than the existing routing methods, in which the node itself plays an important part and node itself should process and select the route.

Table I. Values of the simulation parameters

Parameter	Value
Network Size	500 m x 500 m
Nodes location	Random
Nodes initial energy	0.1 J
SuperNode initial energy	0.5 J
Communication range	90 m
Sensing range	60 m
Number of nodes	300
Number of SuperNode	25
Number of target	20
E_{elec}	50 nJ/bit

Comparing the amount of consumed energy in each round for the three aforementioned algorithms is shown in Fig. 8. The energy consumption is reduced by nearly 0.20J compared to the shortest path algorithm and by 0.33J compared to the greedy algorithm. Furthermore, it can be seen that proposed algorithm balanced the energy consumption among all sensor; therefore, the network lifetime increased.

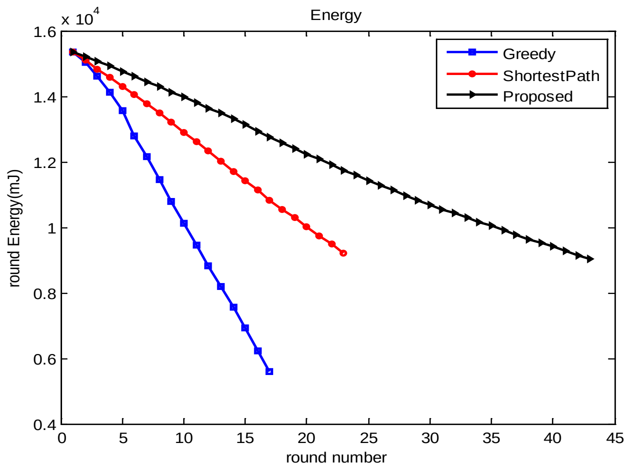

Fig. 8. Energy consumption in different methods

The results of simulation also show that the network lifetime in the proposed algorithm increased by 70% and 40% on average, compared to the greedy and shortest path algorithms respectively (Fig. 9).

In addition to the reduction in energy consumption and increasing the lifetime in proposed algorithm, the simulation time for each round of the proposed algorithm is significantly less than the other simulated algorithms. This is due to its simplicity and small overload. These results explain that the proposed algorithm outperforms the other two algorithms.

Fig. 10 shows the average number of the relay nodes in the simulated algorithms. It is clear that the average number of the relay nodes in the suggested algorithm is less than the other two, and taking its longer lifetime into account, it has more moderate changes.

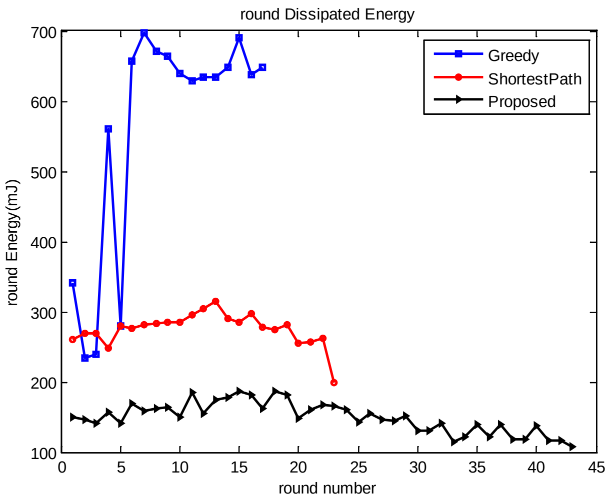

Fig. 9. Energy consumption in different methods

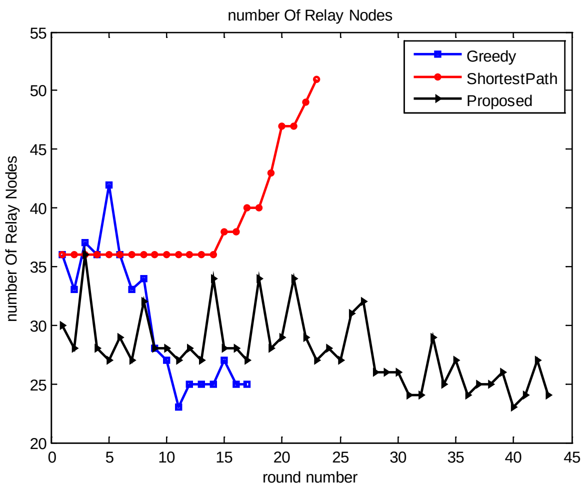

Fig. 10. Energy consumption in different methods

In Fig. 11, the bar chart shows the amount of the energy consumption when choosing the relay nodes in each three algorithms. In the bar chart, the results from the simulation show that in the suggested method, due to the simplicity of the algorithm, the energy consumption in choosing the relay nodes level is less than the other two methods. In the suggested method due to simplicity, high pace in selection, and the optimum path indication, much less energy is reduced because of this selection from the network. Also the overload caused by the effort of choosing the relay nodes is less in the suggested method than in the other two. The very short time of execution needed in the simulation of this algorithm to reach the optimum path is a proof of this claim.

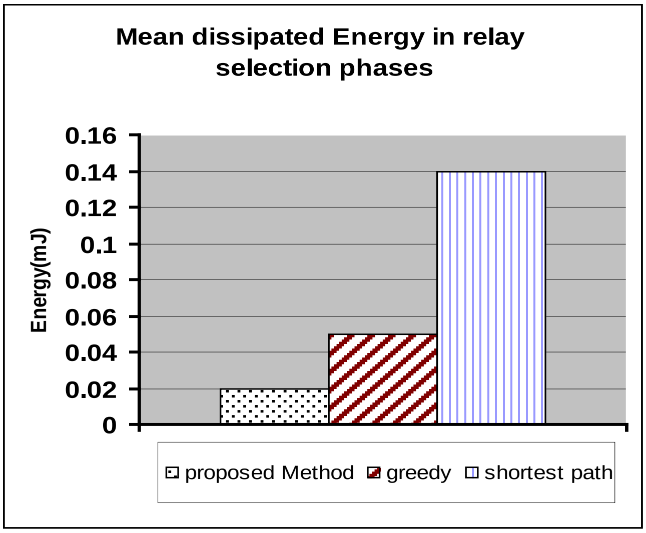

Fig. 11. Energy consumption for choosing relay node

VI. Conclusion

In this paper, the active sensor nodes are selected based on the competition between the nodes surrounding each node. In this work, the network lifetime is increased by the maximum usage of the nodes in each area and by moderating the energy consumption. Comparing the proposed algorithm results with the previous methods showed the superiority in performance respect to the other methods. Moreover, the efficiency of the suggested method in decreasing the energy consumption and increasing the lifetime of the covering network is demonstrated. Furthermore, the complexity and communication overload caused by the effort in choosing the relay nodes is much less in the suggested algorithm compared to the other methods, and the execution time is very short for reaching the optimum response.

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