A Lifetime Enhancing Node Deployment Strategy in WSN

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Abstract. Wireless sensor networks (WSNs) consist of a large number of small, battery-powered wireless sensor nodes and thereby constrained with energy resource. The network as a whole must minimize the energy usage in order to enable untethered and unattended operation for an extended period of time. One fundamental way of reducing such energy usage and enhancing lifetime is judicial placement of sensor nodes within the network area. The present work proposes a lifetime-enhancing node-deployment strategy. Primarily more nodes are deployed towards the sink exploiting the fact that more energy is drained out from the nodes close to the sink. Further, locations which are approximately equi-distant from the sink are assigned different classes of priorities according to their responsibility of forwarding data of nodes located in the neighbouring cells. The principle of this strategy is justified by Lemma and corresponding proof. Exhaustive simulation is conducted to observe the impact of node distribution on network lifetime. The result is compared with one of the existing deployment strategies, which shows our scheme outperforms the existing one in terms of network lifetime.

Keywords: node deployment, network lifetime, coverage, connectivity.

1 Introduction

A wireless sensor network (WSN) [1] is a collection of sensor nodes which are deployed in a given area of interest. A sensor node is made up of components such as sensing unit, processing unit, a transceiver unit and a power unit [1], [2]. The sensor nodes collect data from their surroundings and send the collected data to their neighbouring nodes in single hop [3], [4]. The neighbouring nodes in turn send the data to the nodes which are located in single hop distance from them. In this way the data is transmitted to the sink node. The sink node is responsible for receiving data from the nodes present in the network and processing them for sending data to the outside world.

As the sensor nodes are equipped with a battery whose charge cannot be replaced after deployment, a major concern of all WSNs is the need to conserve energy as battery lifetime of all nodes are limited. The nodes which are placed closer to the sink

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node have to do more processing of data and so their battery power also drains out faster causing possible shortening of network lifetime. Therefore, deployment of sensor nodes has serious impact on network lifetime.

The nature of deployment of sensor node depends on the type of sensors, application and the environment where the network will operate. Deployment of sensor nodes can be random or pre-determined. In random deployment nodes are randomly deployed generally in an inaccessible terrain. For example, in the application domain of disaster recovery or in forest fire detection sensors are generally dropped by helicopter in random manner [5]. In pre-determined deployment, the locations of the nodes are specified. It is mainly used in indoor applications. For example, manual placing of sensor nodes in pre-determined locations is done to monitor manufacturing plants, detection of corrosions and overstressed beams [5] in large old buildings etc.

Several works have been carried out to increase the network lifetime of the network. In one such work, M. Esseghir *et al.* [6] have proposed a near-optimal heuristic algorithm for placing the nodes in sensor network targeting to enhance network lifetime. Node-deployment is done in two phases. In the first phase, nodes are placed to ensure coverage whereas in the second phase it is done in such a manner that each point of the network area is served by two distinct sensor nodes.

In another work [7], the authors have proposed a node deployment strategy solving an optimization problem to find out minimum number of deployed sensors under the constraints of quality of monitoring and network lifetime. The scheme assigns different energy levels to sensor nodes as a function of distance from the sink. Based on such energy levels of the nodes, node density is determined.

Sze-Chu Liu has proposed [8] a lifetime-extending deployment strategy based on load balancing concept. In this strategy, communication load among sensors are analyzed first and a node distribution algorithm is thereby proposed to balance the load and extend lifetime. Unlike [7], node density is determined by the location and not by the energy level of the node.

Liu Yunhuai, Ni Hoilun, and L. M. Ngan have proposed a non-uniform, power-aware distribution scheme in [9] to overcome the problem of sink routing hole. Sink routing hole is a phenomenon caused by fast failure of nodes near the sink due to higher relay workload on such nodes compared to that of farther nodes. It results in loss of connectivity. The sink routing hole typically occurs in case of uniform distribution. Simulation results [9] show that the power-aware deployment scheme can significantly improve the long-termed network connectivity and service quality.

Bin Li *et al.* in their work [10] have proposed an optimal distribution for deploying the nodes with a target to prolong network lifetime. They have also analyzed the effect of node deployment strategies on network lifetime following various distributions (optimal, uniform and poisson). They claim that network lifetime has been prolonged greatly using the optimal distribution proposed by them compared to uniform and Poisson distribution.

In most of these works the proposed deployment stategies have guaranteed the increase of network lifetime while maintaining coverage and connectivity of the network. However, most of these deployment strategies do not belong to the class of pre-determined deployment strategy in its truest sense. Most of the works are silent about the exact locations of placing the nodes which is very much important for some applications. Our work describes a deployment strategy where the locations of the nodes are pre-determined.

The rest of the paper is organized as follows. In section 2, regular hexagonal cell architecture based on lifetime-enhancing node deployment scheme is described. Description of the proposed energy efficient node distribution scheme along with an illustrative example is presented in section 3. In section 4, the performance of the scheme is evaluated by providing simulation results. Finally the paper is concluded with some mention about the future scope of the work in section 5.

2 Regular Hexagonal Cell Architecture

We consider regular hexagonal cell (RHC) [10] architecture where the network coverage area is divided into regular hexagonal cells as shown in Figure 1. A cell indicated by C_i^j denotes the jth number cell of the ith layer. For example, cell C_2^6 is located in layer 2 and the cell number within this layer is 6. The sink node is located at the centre cell of the regular hexagonal cell architecture. The sensor nodes are placed in cells of different layers surrounding the centre cell. The cells of the layers are further categorized into two groups- primary and secondary. Primary cells (C_p) in a layer are those cells where the layer takes a turn of 60^0 and share a common boundary with more number of cells of the adjacent layer. Primary cells in the arcitecture are shown as shaded hexagonal cells. Secondary cells (C_s) are those which share a common boundary with relatively less number of cells of the adjacent layer. Secondary cells are shown as non-shaded hexagonal cells. The number of cells in each layer is 6 * i, where i=1, 2, …, N and N is the number of the farthest layer from the sink. We designate the locations on the boundary of two consecutive layers with different classes of priority based on their responsibility of forwarding data of the neighbour nodes located at the adjacent cells and their distances from the sink. The minimum-distant vertices associated with the C_p cells of ith layer on the boundary between ith & (i+1)th layers are categorized as priority-1 vertices ($V_{prior-1}$). For example in Figure 1, on the boundary line between layer 2 & 3 there are two minimum-distant vertices associated with a C_p cell (C_2^5). These two vertices are priority-1 vertices. Similarly the minimum-distant vertices associated with the C_s cell on the same boundary are categorized as priority-2 vertices ($V_{prior-2}$). There is only one minimum-distant vertex with priority-2 associated with a C_s cell (C_2^4) on this boundary. The rest of the vertices (if any) on the boundary are with priority-3 ($V_{prior-3}$).

The following relevant notations are used to describe the architecture:

- r – radius of a cell
- R_s – sensing range of a sensor node
- R_c – communication range of a sensor node

The relationship between cell radius r and node's sensing range R_s must satisfy $r \le \frac{R_s}{2}$ to cover the whole cell area and the relationship between r and communication range R_c must be $r \le \frac{R_c}{\sqrt{13}}$ for ensuring the connectivity between neighbouring nodes [10].

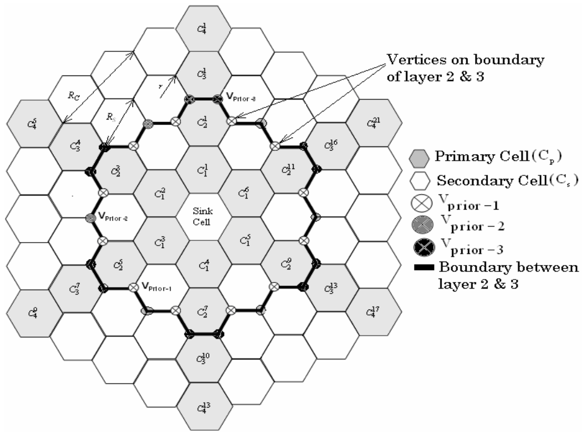

Fig. 1. Regular Hexagonal Cell Architecture

Definition of Coverage: A unit area is said to be covered if every point in the area is within the sensing range of an active node [11].

Definition of Connectivity: A network is connected if any active node can communicate with any other active node either in single hop or in multiple hops [11].

3 Energy Efficient Distribution of Nodes

The nodes are deployed in two phases. In the first phase, nodes are deployed at the centre of each cell ensuring the coverage of the network. If any of the nodes are unable to take part in data routing and/or data sensing, the coverage of the network is broken. Therefore in the second phase redundant nodes are placed throughout the entire network area with a target to enhance network lifetime.

Lemma 1: For a given network area A×A, the number of layers (N) should follow the relationship $N \geq \sqrt{\frac{13}{3}\frac{R}{R_c}}$, where $R = \frac{1}{2} \times A$ in order to maintain connectivity of the network.

Proof: If the radius of each cell of the multi-layered architecture is r, then the distance between the centre of the sink cell and the farthest edge of a cell of any other layer is given by

$$\sqrt{3}ri + \frac{\sqrt{3}}{2}r$$

where i is the layer number.

If the distance between the centre of sink cell to the farthest point in the network area is R, then replacing i by N

$$\sqrt{3}rN + \frac{\sqrt{3}}{2}r \geq R$$

$$\text{or, } N \geq \frac{R - \frac{\sqrt{3}}{2}r}{\sqrt{3}r}$$

replacing, $r \leq \frac{R_C}{\sqrt{13}}$ in above equation, we have

$$\text{or, } N \geq \sqrt{\frac{13}{3}}\frac{R}{R_c}$$

Corollary 1: For a given network area A×A the number of layers (N) must follow the relationship $N \geq \frac{2}{\sqrt{3}}\frac{R}{R_S}$, in order to maintain the coverage of the network.

Proof: From lemma 1, the relationship between R and N is evaluated as,

$$\sqrt{3}rN + \frac{\sqrt{3}}{2}r \geq R$$

replacing, $r \leq \frac{R_s}{2}$ in the above equation, we have

$$N \geq \frac{2}{\sqrt{3}}\frac{R}{R_S}$$

3.1 Deployment Scheme

In the first phase, the scheme requires $\sum_{i=1}^{N} 6*i$ number of nodes whereas the second phase needs at most N*(6N) number of nodes. The deployment scheme is pre-determined in nature and the location (x, y) where the nodes are to be placed can be computed as follows-

$$x= \sqrt{3}\ r\ a\cos(m\frac{\pi}{3}) + \sqrt{3}\ r(i-a)\cos((m+1)\frac{\pi}{3}) + S\cos((2m\pm 3)\frac{\pi}{6}) + Q\cos((2p+1)\frac{\pi}{6}) \quad (1)$$

$$y= \sqrt{3}\ r\ a\sin(m\frac{\pi}{3}) + \sqrt{3}\ r(i-a)\sin((m+1)\frac{\pi}{3}) + S\sin((2m\pm 3)\frac{\pi}{6}) + Q\sin((2p+1)\frac{\pi}{6}) \quad (2)$$

where the variables used in the above expressions are as follows:

m – the network area is divided into six equilateral triangular regions. The value of m identifies each of six regions. One value of m is required to find out the center location of a set of cells as given below:

$$m = \begin{cases} 0 & \text{for } C_i^1, C_i^2, \cdots, C_i^i \\ 1 & \text{for } C_i^{i+1}, C_i^{i+2}, \cdots, C_i^{2i} \\ 2 & \text{for } C_i^{2i+1}, C_i^{2i+2}, \ldots, C_i^{3i} \\ 3 & \text{for } C_i^{3i+1}, C_i^{3i+2}, \cdots, C_i^{4i} \\ 4 & \text{for } C_i^{4i+1}, C_i^{4i+2}, \cdots, C_i^{5i} \\ 5 & \text{for } C_i^{5i+1}, C_i^{5i+2}, \cdots, C_i^{6i} \end{cases}$$

where i = 1, 2, . . . , N

For example, the value of m can be found out for determining the centre location of the cell C_2^5: as i=2, the cell can be mapped with C_i^{2i+1}; so m=2.

$$a = \begin{cases} i & \text{for } V_{prior-1} \text{ of } C_i^{i*(k-1)+1} \text{ cell} \\ 1, 2, \ldots, i & \text{for } V_{prior-2}, V_{prior-3} \text{ and centre location of cell } C_a^k, C_{a+1}^{k+1*(m+1)}, C_{a+2}^{k+2*(m+1)}, \ldots, C_N^{k+(N-a)*(m+1)} \end{cases}$$

where k= m*a + 1

For example, the value of a can be found out for determining the centre location of the cell C_2^5: as i=2 and m=2 (as shown earlier), the cell can be mapped with C_a^k where k = m*a+1 = 2*a + 1 = 5; so a=2.

$$S = \begin{cases} 0 & \text{for } V_{prior-2}, V_{prior-3} \text{ and centre location of each cell} \\ r & \text{for } V_{prior-1} \end{cases}$$

$$Q = \begin{cases} 0 & \text{for } V_{prior-1} \text{ and centre location of each cell} \\ r & \text{for } V_{prior-2} \text{ and } V_{prior-3} \end{cases}$$

$$p = \begin{cases} \text{don't care} & \text{for } V_{prior-1} \text{ and centre location of each cell} \\ 0, \ldots, 5 & \text{for } V_{prior-2} \text{ and } V_{prior-3} \end{cases}$$

3.1.1 Fixed Node Distribution

During node deployment in the first phase, a node is placed at the centre location of each cell. This ensures that network coverage is maintained. Let us consider a 4-layer architecture (Refer Figure 2) where the radius of each cell is 4 (r = 4). As an example, for computing the centre location of cell C_3^2, putting i=3, r=4, m=0, S=0, Q=0, a=2, and p=don't care in equation (1) we get the value of x-coordinate as 10√3. For y-coordinate, putting the same values in equation (2) we get the value of y-coordinate as 6. So (x, y) coordinate of the centre of C_3^2 cell is (10√3, 6). Similarly the coordinates of the centre of other cells can be obtained using the above two equations.

3.1.2 Redundant Node Distribution

To ensure that each cell of each layer gets at least one redundant node, the number of redundant nodes at the farthest (i=4 in example architecture, Figure 2) layer is 6N. The present scheme considers 6N number of nodes to be distributed at each layer. In layer 1 (Refer Figure 2) all the cells are primary and the vertices on the boundary between sink cell and layer-1 have prority-1 ($V_{prior-1}$). So these 6*4 (N=4) redundent nodes are first distributed in the vertices located on this boundary. There are 6 such vertices with priority-1 ($V_{prior-1}$). The remaining (24-6) redundant nodes are distributed equally within each cell area in random manner. The locations for random deployment are found by using equations (3) & (4) as follows-

$$X_{rand} = X_c + \frac{\sqrt{3}}{2} r * rand(0,1) * \cos(2\pi * rand(0,1)) \quad (3)$$

$$Y_{rand} = Y_c + \frac{\sqrt{3}}{2} r * rand(0,1) * \sin(2\pi * rand(0,1)) \quad (4)$$

where X_c and Y_c are the x and y coordinates of the centre of a cell within which the nodes are randomly deployed, whereas the locations for deployment at pre-determined places can be found by using equations (1) & (2). Here the pre-detrermined places or vertices are located on the boundary between the layers. Any vertex located on the boundary between the layers can be identified by three adjacent cells (Refer Figure 2). Now the co-ordinate of each vertex can be found out by putting appropriate values of different parameters (i, r, m, S, Q, a and p) of any of the three adjacent cells of that vertex, though the cells belong to different layers. The coordinate of any vertex can be computed by any set of parameter values of a particular cell. For example in Figure 2, the (x, y) coordinates of one vertex associated with the sink cell, C_1^1 and C_1^2 cells is computed as (2√3, 2). The corresponding parameter values used are i= 0, r=4, m=1, S=4, Q=0, a=0 and p=don't care. Putting all these values in equations (1) and (2) the co-ordinate is computed.

The vertices on the boundary between layer 1 & 2 are having either priority-1 or priority-2. The redundant nodes are deployed first at vertices with priority-1and then at vertices with priority-2. On this boundary there are 6 vertices with priority-1($V_{prior-1}$) and 12 vertices with priority-2 ($V_{prior-2}$). After deploying at priority-1 and priority-2 vertices, 6 (24-(12+6)) nodes remain which are distributed equally within the cell area in random manner. On this boundary, for example, (x, y) coordinates of one priority-1 vertices associated with C_1^1, C_1^2, and C_2^2 cells located on the said boundary are computed as (4√3, 4) by putting the parameter values for C_1^1 cell as i=1, r=4, m=0, S=4, Q=0, a=1, p=don't care in equations (1) and (2). For example, the co-ordinates of priority-2 vertices associated with C_1^1, C_2^1 and C_2^2 cells located on the same boundary are computed as (6√3, 2) by putting appropriate value of i, r, m, S and a in equations (1) & (2) for C_1^1 cell.

The vertices on the boundary between layer 2 & 3 and onwards are having any one of the three types of priorities. The redundant nodes are deployed at vertices with priority-1, priority-2 and priority-3. After placing nodes at the vertices in the order of their priorities, if excess redundant nodes remain, these are distributed within the cell randomly. On the boundary between layer 2 & 3, there are 12 vertices with priority-1 ($V_{prior-1}$), 6 vertices with priority-2 ($V_{prior-2}$) and remaining 12 vertices are with priority-3 ($V_{prior-3}$). In this case, out of the total redundant nodes 6*4 (N=4), 12 nodes are placed at vertices with priority-1 and 6 are placed at vertices with priority-2. So for the 12 vertices with priority-3, only 6 (24-(12+6)) nodes remain. These 6 nodes are placed uniformly i.e., one after another at the 12 vertices with priority-3. The vertex associated with C_2^4, C_3^5, and C_3^6 cells with priority-2 also lie on this boundary. As an example, the location can be found out as (0, 16) by putting i=2, r=4, m=1, S=0, Q=4, a=1and p=1 in equations (1) & (2). The location of another vertex associated with C_2^5, C_2^7 _and C_3^8 cells on the same boundary having priority-3 is (-6√3, 14) is obtained by putting parameters values i=2, r=4, m=2, S=0, Q=4, a=2 and p=2 in equations (1) and (2).

Lemma 2: Energy draining rate of the nodes located in C_p is higher than that of the nodes located in C_s.

Proof: Let E_p and E_s denote the energy consumption by the nodes inside the primary and secondary cell respectively for the additional task of forwarding the data of the nodes located in their respective neighbouring cells.

In addition to its own activity, a Primary cell (C_p) forwards data sent by 3 of its adjacent cells. On the contrary, a Secondary cell (C_s) forwards data sent by 2 adjacent cells. Therefore

$$E_p = 3^* \ E_c \tag{5}$$

$$E_s = 2^* \ E_c \tag{6}$$

where E_c is the component of energy consumption due to a neighbouring cell's data forwarding task.

$$\text{or, } E_p / E_s = 1.5$$

Hence energy consumed by each primary cell is 1.5 times more than that consumed by secondary cell of each layer. Therefore, higher priority is given to primary cells during deployment of redundant nodes.

3.2 Illustrative Example

Let us consider a 4-layer architecture (Refer Figure 2). In the first phase of node deployment, each cell gets a node in its centre (shown by ‘O’). In the second phase, the numbers of redundant nodes to be deployed in a layer are 6*(N = 4) = 24. On the boundary between the sink and layer 1, all six vertices have priority-1. After placing nodes at all such six vertices (shown by ‘■’), 18 (24-6) redundant nodes remain. Now these 18 redundant nodes are equally distributed among the cells of layer 1 in random manner (shown by ‘□’).

On the boundary between layer 1 and 2, there are 18 vertices. Out of these 18 vertices, 6 are with priority-1. Nodes are deployed first at priority-1 vertices (shown by ‘●’). The remaining 12 (18-6) vertices are with priority-2 and therefore nodes are deployed at these locations next (shown by ‘⊕’). Now remaining 6 (18-12) nodes are distributed randomly within the cell area of layer 2 (shown by ‘⊕’).

On the boundary between layer 2 and 3, there are 30 vertices. There are 12 vertices with priority-1 located on this boundary. So nodes are deployed first at these locations (shown by ‘▲’). The remaining 12 redundant nodes are then placed at the 18 (30-12) vertices. Out of these 18 vertices, 6 vertices are with priority-2. So these priority-2 vertices are filled next (shown by ‘△’). After filling the locations at vertices with priority-1 and priority-2, 6 (24-(12+6)) redundant nodes remain. These 6 redundant nodes are placed at the 12 vertices with priority-3 one after another (shown by ‘△’).

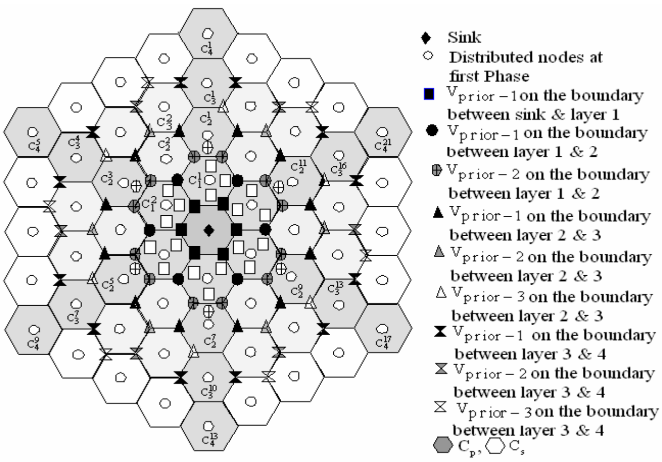

Fig. 2. Distribution of nodes

On the boundary between layer 3 and 4, there are 42 vertices out of which 12 are with priority-1. So these locations are filled first (shown by ‘⧗’). After placing nodes at priority-1 vertices, 12 redundant nodes remain which are to be distributed among the 30 (42-12) vertices. Out of these 30 vertices there are 6 vertices with priority-2 which are filled next (shown by ‘⧖’). After filling vertices with priority-1 and priority-2, 24 (42-(12+6)) vertices remain. The remaining 6 (24-(12+6)) redundant nodes are placed among the 24 vertices with priority-3 one after 3 vertices (shown by ‘⧖’).

4 Performance Evaluation

The effectiveness of the proposed life-time enhancing node deplyment strategy (LENDS), reported in the earlier section is evaluated through simulation. Here we have evaluated the effectiveness of our scheme by comparing with one of the existing schemes.

4.1 Simulation Environment

The simulation is performed using MATLAB (version 7.1). The performance of the scheme is evaluated considering network lifetime as a performance metric.

Network lifetime: It is defined as the number of turns that the network is running [10]. A turn is defined as the time when all sensor cells in the network finish collecting and returning their data to the sink cell once.

During the simulation we have considered that due to the battery consumption some sensor nodes become inoperative. When the amount of energy of a node is less than a particular threshold value, we consider that node as a dead node. In this work, a node is considered as a dead node if the amount of energy of that node is less than 5% of its initial energy. Table 1 lists the relevant parameters and their associated values [10], [12] considered in this simulation.

Table 1. Parameters and their corresponding values used in simulation

Parameters	Value
Initial Energy ($E_{initial}$)	1000 J
Constant sensing energy (E_m)	0.1 J
Constant transmission energy (E_s)	3.5 J
Constant reception energy (E_r)	3 J
Dead node’s threshold energy	50 J
Communication range of sensor (R_c)	160 m
Sensing range of sensor (R_s)	80 m
Antenna	Directional
Network area	1000 × 1000 m

We simulate the network with three, five and seven layers RHCs architecture. Here we have compared our scheme with one existing optimal distribution scheme (OPTDIST) [10]. If there is no node failure, the minimum number of nodes (one node at the centre of each cell) required to ensure the network coverage is shown in Table 2. The number of nodes (redundant 6N number of nodes at each layer in addition to minimum number of nodes) ensuring at least one redundant node at every cell of the network is also shown in the table.

Table 2. Required number of nodes for different network size

Number of layers	Min^{m} number of nodes ensuring coverage	No. of nodes ensuring at least one redundant node at each cell
3	36	90
5	90	240
7	168	468

4.2 Simulation Results

The network running turns in terms of which network lifetime is defined is computed and plotted for varying number of redundant nodes. Three sets of results for three different network sizes are illustrated in Figure 3, 4 and 5 respectively. Figures show that network-running turns steadily rise with the increase of nodes for all sizes of the network. Results signify the fact that network lifetime prolongs with the increase of the number of redundant nodes.

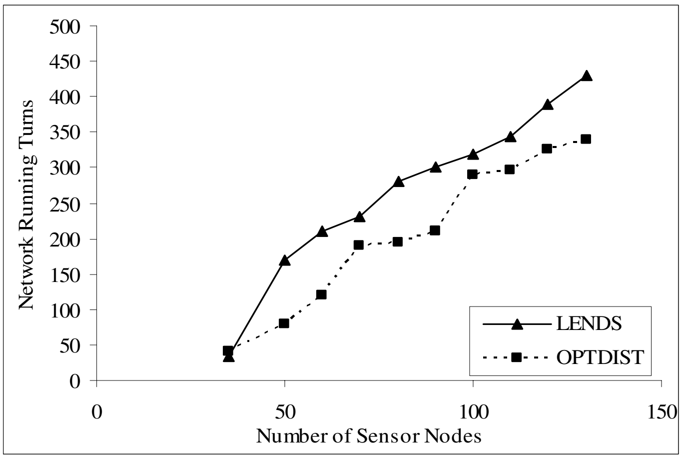

Fig. 3. Network lifetime for three layers of RHCs

Figures also show the results for optimal distributions [10]. For all sets of results, network lifetime of the present deployment strategy is longer than optimal distribution. As more energy is drained out from the nodes based on their proximity to the sink and responsibility of sharing workload of neighbouring nodes, redundant node deployment should be done accordingly. There is a one-to-one mapping between this requirement and the strategy of placing nodes in places, firstly, based on the proximity of location from the sink and secondly based on the workload of the location.

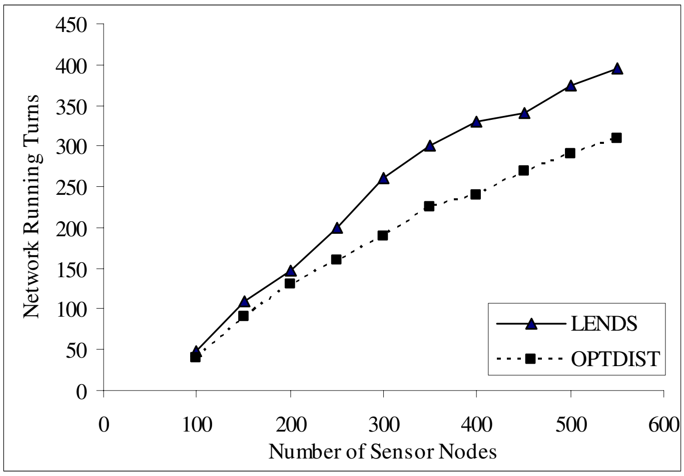

Fig. 4. Network lifetime for five layers of RHCs

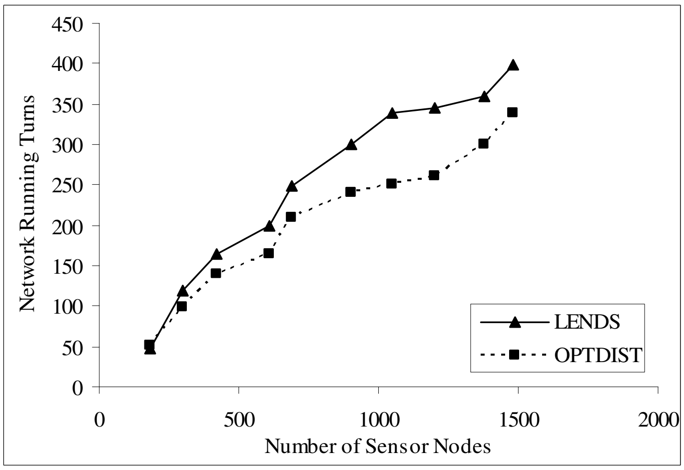

Fig. 5. Network lifetime for seven layers of RHCs

5 Conclusion

The present work proposes a node deployment strategy in wireless sensor network to enhance network lifetime. The merit of the strategy lies on the fact that the nodes are deployed at pre-determined places within the network in such a manner that more nodes are placed towards the sink with a target to combat the problem of shortening of network lifetime arises out of the fast depletion of energy of the nodes towards the sink. To resist the shortening of network lifetime further, certain locations within a layer are identified as prioritized based on the importance of the locations in terms of sharing workload of neighbouring locations. Finally the scheme is simulated and the results are compared with one of the existing schemes [10], which follow optimal distribution of nodes. Network lifetime is greatly enhanced in the proposed pre-determined node deployment scheme compared to the scheme following optimal distribution.

As a future extension, the present scheme may be made more realistic by considering 3-D environment. Moreover the scheme can be further analyzed using different QoS parameters.

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