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Energy-hole avoidance and lifetime enhancement of a WSN through load factor

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Abstract: In wireless sensor networks, nonuniform communication load across a network often leads to the problem of energy holes or hot spots, i.e. nodes nearer high activity regions deplete their energy much faster than nodes elsewhere. This may partition the network into unreachable segments and thus adversely affect network lifetime. The problem is more acute in random and sparsely deployed networks. Therefore, we propose a deployment strategy that, using the least possible nodes, prolongs network lifetime by avoiding energy holes and also ensures full sensing and communication coverage. The scheme handles the energy imbalance by selecting an appropriate set of communication and sensing ranges for each node based on effective load on that node. After adjusting these ranges, nodes are strategically placed at locations where their energy drains uniformly and thus network lifetime is prolonged. The approach is verified analytically and validated through ns-2 based simulation experiments. The results reveal significant improvements over existing schemes.

Key words: Communication range, network lifetime, nonuniform deployment, sensing range, wireless sensor networks

1. Introduction

Modern sensor nodes are versatile and can sense various physical parameters like humidity, temperature, pressure, and vibrations. Thus, wireless sensor networks (WSNs) are used in almost every field. Most applications expect the network to operate for weeks and months. Sensor nodes are powered by batteries having finite energy. Due to deployment of these nodes in unfriendly and unattended environments, replenishing/recharging of these batteries is not possible. Another facet here is the slow improvement in battery power capacities over the years as compared to processing power, communication, and memory capacity enhancements [1]. Therefore, proper utilization of available energy is the only option for prolonging the network's lifetime.

The energy of a node is mainly consumed in sensing and transmission/reception by radio [2-4]. The radio not only consumes power when transmitting and receiving, but also when listening. Steam and Katz [2] show that the ratio of energy consumption during idle:receive:transmit operations is 1:1.05:1.4, while more recent studies show that the ratio is 1:2:2.5 [3] or 1:1.2:1.7 [4]. The growing use of WSNs for monitoring complex phenomena has highlighted that some sensors like pressure, humidity, flow control, and proximity also consume substantial energy during sensing [5]. If the data acquisition period is longer than the transmission time, then the power consumption in sensing is significantly more than the communication. Therefore, energy consumption during sensing cannot be neglected. The traditional sensors assume a sensing model with fixed sensing range. However, with advancements in technology, sensors with adjustable ranges are now available. Photoelectric sensors, photoelectric sensors [6], thermocouple-based temperature sensors [7], under water sensors [8], etc.

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are a few of such commercially available sensors. Therefore, both sensing and communication ranges can be adjusted in order to balance the energy consumption of nodes.

In a typical WSN, certain nodes transmit more data than others and hence deplete their energy faster. For example, nodes closer to a sink not only transmit their data but also relay the data sensed by other nodes. Thus, the relay load on nodes increases towards the sink. Consequently, nodes nearer the sink deplete their energy much faster and thus exhaust earlier than nodes far away. This problem is called energy-hole creation and can be avoided by reducing the energy dissipation rate of nodes nearer a sink. Hence, we propose a scheme that balances the energy dissipation rate of nodes by adjusting communication and sensing ranges of nodes. The scheme first calculates the distribution of relay load over the network and accordingly finds a suitable set of communication and sensing ranges for nodes. These ranges are reduced as relay load on a node increases so that extra communication is compensated by low power transmission and thus network lifetime is prolonged.

The rest of the paper is organized as follows. In next section, we introduce the system model for the proposed scheme. In section 3, a deployment scheme is proposed. Section 4 gives the simulation results followed by the conclusion and future work in section 5.

2. Network model

There are N sensor nodes $s_i, I \in$ {1,2,3......N } deployed in a two-dimensional (2D) region of interest (RoI). All nodes are identical and consume the same amount of energy in transmission, reception, and sensing. Initially all nodes have the same energy level E_0. Moreover, all sensor nodes have the capability of re-adjusting their sensing and communication ranges in the range R_{smn} to R_{smx} and d_{mn} to d_{mx}, respectively. The sensing area of a sensor s_i can be thought of as having three different regions: inner, middle, and outer, where Rs_i is the radius of the inner region and Ru_i is the width of the middle region. The probability of sensing an event at a point $X(x, y)$ for all three regions is modeled as [9]:

$$Ps_i(X) = \begin{cases} 1 & \text{if} \quad d(X) \leq Rs_i & //\text{Inner Region} \\ e^{-\lambda a^{\beta}} & \text{if} \quad (Rs_i < d(X) \leq (Rs_i + Ru_i) & //\text{Middle Region} \\ 0 & \text{if} \quad (Rs_i + Ru_i) < d(X) & //\text{Outer Region} \end{cases}, \tag{1}$$

where d(X) is the Euclidian distance between point X and sensor s_i, $a = (d(X) - Rs_i)$, and λ and β are the parameters that measure detection probability when an event occurs in the middle region of width $(Rs_i - Ru_i)$. Figure 1 shows the detection probability in different cases.

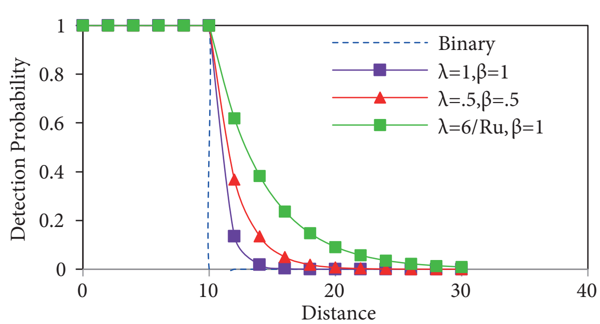

Figure 1. Detection probability verses distance for binary and probability sensing model.

An area is also said to be covered if it is covered by one or more sensors jointly. If N sensor nodes are deployed in the entire RoI, the joint sensing probability for a certain area can be calculated as [10]

$$P(A_{cvr}) = 1 - \prod_{i=1}^{N} (1 - Ps_i), \tag{2}$$

where Ps_i can be calculated by (1).

The scheme adopted the communication energy model of [11] as

$$E_{com} = E_{trans} + E_{rec} = E_{cr} + E_{ct} + \varepsilon_{emp} d^{\alpha}, \tag{3}$$

where E_{com}, E_{trans}, and E_{rec} represent energy consumed in communication, receiving, and transmission, respectively. E_{ct} and E_{cr} are the energy consumed in transmitting and receiving circuitry, which can be modeled as constant for any communication range d. α is the path loss exponent, which is about 2 for free space and goes up to 4 in the presence of obstacles. ε_{emp} is the energy consumption by the transmitting amplifier to achieve an acceptable signal strength. According to [12], energy consumption in sensing (E_{sense}) is calculated as

$$E_{sens} = E_{cs} + E_s \times Rs^{\beta}, \tag{4}$$

where E_{cs} and E_s are the device specific constants. Rs is the sensing radius and parameter β is related to the sensing technology used and typically varies between 2 to 4 in the case of sensors adopting an active sensing technology.

3. Proposed scheme

For avoiding energy holes and maintaining a uniform energy dissipation rate across the network, the following three tasks are performed: (1) a recursive procedure is presented to find the probable communication load distribution over every node in the network, (2) a suitable set of communication and sensing ranges is found for each node according to the communication load such that all nodes deplete their energy uniformly and die out nearly at the same time, and (3) a node placement strategy is proposed for placing nodes with modified ranges at appropriate locations such that they provide full coverage in terms of sensing and connectivity and drain their energy uniformly.

3.1. Procedure for finding load factor (Lf)

The load factor of a sensor node is the probable estimation of communication performed by the node. All sensor nodes sample data at a specific rate and transmit it towards the sink. Therefore, each node has a specific communication load of transmitting its own data. All sensor nodes (except one hop neighbors of the sink) transmit their sampled data to some intermediate nodes in their radio range for relaying it towards the sink, which increases communication load on intermediate nodes. A node, however, can send its data to any intermediate node amongst all neighboring nodes in the direction of the sink. Thus, increment in the communication load of a particular intermediate sensor node depends on the number of its neighboring nodes selecting it for further relaying and their load factors. Say, an intermediate sensor node s_{in} has an initial communication load Lf_{in} and relays the data of k sensor nodes s_j $(1 \le j \le k)$ with load factor Lf_j. If each node s_j has M_j number of possible relay neighbor nodes, then the resultant load factor of s_{in} is calculated as

$$Lf_{in} = Lf_{in} + \sum_{j=1}^{k} \frac{Lf_j}{M_j} \tag{5}$$

Generally, due to overlapped sensing regions, intermediate nodes receive redundant data, which is filtered [13]. Apart from redundant data, closely related data readings may also be diffused. The diffusion of data reduces communication load on nodes. For simplicity, the amount of change in load factor due to diffusion can be expressed as a diffusion coefficient ξ_{in}. Hence, the resultant load factor can be expressed as

$$Lf_{in} = \xi_{in} \left(Lf_{in} + \sum_{j=1}^{k} \frac{Lf_j}{M_j} \right) \tag{6}$$

Similarly, the load factor of other sensor nodes can be calculated.

The Lf calculation is elaborated in Figure 2. The figure depicts a portion of a network where some sensor nodes are connected to the sink through some links. All nodes initially have their own sampled readings for transmission and thus have load factor 1. Sensor nodes A and B are outer nodes that do not receive any data from their neighbors to relay and hence their final load factor remains 1. The node A sends its all data to node C, while node B has three options to relay its data through C, F or to D. Therefore, the enhanced load factor of node C is the sum of load factor of node A and one third of the load factor of node B, which is 1.33. Node C already has its initial load factor as 1; therefore the updated load factor of C is 2.33 (the sum of its own load and the load received from nodes A and B). Similarly, load factors of all intermediate nodes can be calculated as shown in Figure 2.

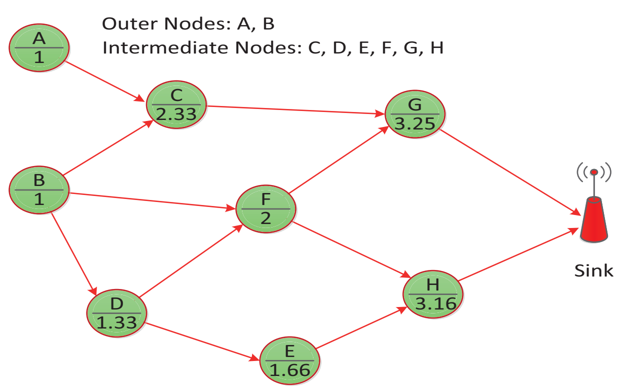

Figure 2. Illustration of load factor on sensor nodes.

3.2. Procedure for finding a suitable set of sensing and communication ranges

Initially, say all sensor nodes are sensing and transmitting their own data and no one is performing as relay node. Moreover, all sensor nodes are acquiring and transmitting data at the rate of B_1 and B_2 bits per unit time t respectively. Then partial energy consumption (without considering energy consumption in relay) of a particular sensor node during time t is the energy consumed in acquiring B_1 bits and transmitting B_2 bits, which can be calculated by using Eqs, (3) and (4) as

$$E_{part} = t\left[B_2(E_{ct} + \varepsilon_{emp} d^{\alpha}) + B_1(E_{cs} + E_s \times Rs^{\beta})\right] \tag{7}$$

However, apart from acquiring and transmitting its own data, almost every intermediate sensor node that does not have any in-neighbor has to perform extra responsibilities of relaying data. Therefore, the extra energy consumed by a sensor node while acting as a relay (i.e. energy consumed in receiving and transmitting relay information) can be calculated by Eq. (4) as

$$E_{relay} = Lf \times t\,[B_2(E_{cr} + E_{ct} + \varepsilon_{emp} d^{\alpha})] \tag{8}$$

Then total energy consumption during time t at an intermediate sensor node is found by using Eqs. (7) and (8) as

$$E_{total} = t\left[B_2(E_{ct} + \varepsilon_{emp} d^{\alpha}) + B_1(E_{cs} + E_s \times Rs^{\beta})\right] + Lf \times t\,[B_2(E_{cr} + E_{ct} + \varepsilon_{emp} d^{\alpha})] \tag{9}$$

In the case a sensor node is an outer node having no information to relay, then the total energy consumed by it during time t is the same as E_{part}. If transmitter and receiver circuitries consume the same energy per bit per time as generally considered and if sensor node is acquiring and transmitting data at the same rate per unit time$t$, then total energy is given as

$$E_{total} = t \times B\left[E_{cs} + E_c(1 + 2Lf) + \varepsilon_{emp} d^{\alpha}(1 + Lf) + E_s \times Rs^{\beta})\right], \tag{10}$$

where $E_{ct} = E_{cr} = E_c$ and $B_1 = B_2 = B$.

The radio transmission model in Eq. (10) is a function of distance and the amount of energy consumed, which significantly depends on power α. From Eq. (11), it can be clearly seen that for long distance communication up to a certain number of hops, multihop transmission is better than single-hop. This is due to the behavior of the antenna for long distance versus many short distances, i.e.

$$(d_1 + d_2 + d_3 + \cdots + d_n)^{\alpha} >> (d_1^{\alpha} + d_2^{\alpha} + d_3^{\alpha} + \cdots d_n^{\alpha}) \tag{11}$$

However, the energy consumption in multihop communication is significantly dominated by the energy consumed in internal circuitry, which restricts the distance between two sensor nodes to be less than a certain distance, say d_{mn}.

Therefore, a sensor node can save its energy by reducing the communication distance up to d_{mn}. However, now the question is, what communication distance should be set for a sensor node and how much lifetime it needs to prolong? This intuitively means that for adjusting communication and sensing ranges, a reference sensor node is required so that the lifetime of the rest of the nodes be prolonged according to the life of this node. If we try to prolong the lifetime of every sensor node as per the lifetime of a node that has maximum lifetime (probably the outer sensor node with no relay load), then it is probably a bad choice as this sensor node has much lower load and energy consumption rate. Balancing the energy consumption rate of other nodes with it may lead to a sharp reduction in communication and sensing ranges and may reach minimum values just after a few hops and thus the network may become too dense too early. The better choice here is to prolong the lifetime of the network to the lifetime of a sensor node that has minimum communication and sensing ranges d_{mn} and R_{smn}, respectively, with maximum load factor Lf_{mx}. The lifetime of such a sensor node is calculated as

$$T_{mx} = \frac{E_0 \times t}{E_{mx}}, \tag{12}$$

where

$E_{mx} = t \times B\left[E_{cs} + E_c(1+2Lf_{mx}) + \varepsilon_{emp}(d_{mn})^{\alpha}(1+Lf_{mx}) + E_s \times R_{smn}^{\beta})\right]$ and Lf_{mx}=max{Lf_1, Lf_2, Lf_3, ... Lf_N}

If a sensor node s_i has initial energy E_0 and Etotal_i as energy consumption during time t then the following must hold for some values of sensing and communication ranges:

$$E_0 \times t = T_{mx} \times E_{total_i} \tag{13}$$

$$E_0 = T_{mx} \times B\left[E_{cs} + E_c(1+2Lf_i) + \varepsilon_{emp} d_i^{\alpha}(1+Lf_i) + E_s \times Rs_i^{\beta})\right] \tag{14}$$

Eq. (14) above has two variables, i.e. communication distance d_i and sensing range Rs_i. Therefore, for finding values of these variables, an additional relation between communication and sensing range is required. If we consider the arrangement of two sensor nodes as shown in Figure 3, where sensing range of a node is assumed as a circular region, then for providing full coverage sensor nodes must overlap in their sensing regions. If two sensor nodes overlap in their sensing regions by an overlapping threshold T_h and if Rs is the initial sensing radius of a sensor node and d is the distance between two sensor nodes, the relation between d and Rs can be found with the help of Figure 3. For full coverage, the arrangement depicted in Figure 3 can be considered the placement of two nodes in hexagonal grid deployment. Thus, ΔOAB will be equilateral and $\angle AOE = \angle BOE = \theta/2 = 30°$. Thus, in ΔAOE, Cos 30° = OE / OA and

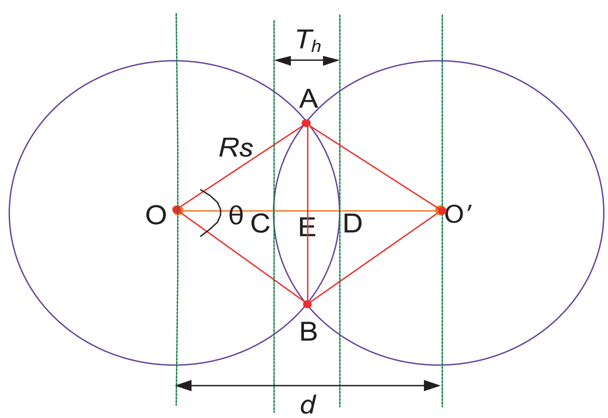

Figure 3. Two overlapping sensor nodes for full coverage.

$$d = \sqrt{3}Rs \tag{15}$$

If sensor nodes follow the binary sensing model, then for full coverage the above relation is true. However, when sensor nodes follow the probability model, the full coverage can be calculated by analyzing the joint probability of sensors in the overlapping region. If a point X is jointly covered by k sensor nodes with probability $P(X)$, then the coverage of X is given as by Eq. (2):

$$P(A_{cvr}) = 1 - \prod_{i=1}^{k}(1-Ps_i) = P(X)$$

$$1-(1-Ps)^k = P(X) \quad \Rightarrow Ps_i = 1 - \sqrt[k]{(1-P(X))}$$

After substituting value of Ps from Eq. (1),

$$e^{-\lambda(d(X)-Rs)^{\beta}} = 1 - \sqrt[k]{(1-P(X))}$$

It can be seen in Figure 1, when λ = 6 / R$_U$ and β =1, the detection probability drops gradually from 1 to 0 in the entire range of R_U [11]. Thus,

$$d(X) = Rs - \frac{Ru}{6}\ln(1-\sqrt[k]{(1-P(X))}) \Rightarrow d = \sqrt{3}\left(Rs - \frac{Ru}{6}\ln(1-\sqrt[k]{(1-P(X))})\right) \tag{16}$$

If T_h is the overlapping threshold for maintaining full coverage in the hexagonal grid arrangement, then for maintaining the same threshold T_h after the readjustment of communication distance and sensing radius, the relation between modified communication range d and sensing range R_s is

$$T_h = 2Rs - d \ \Rightarrow Rs = \frac{T_h + d}{2} \tag{17}$$

If Rs_i is written in term of communication distance, then from Eq. (14)

$$E_0 = T_{mx} \times B\left[E_{cs} + E_c(1+2Lf_i) + \varepsilon_{emp} d_i^{\alpha}(1+Lf_i) + E_s \times \left(\frac{T_h + d_i}{2}\right)^{\beta}\right] \tag{18}$$

Eq. (18) of d has solutions for different values of α and β that depend on the environmental conditions and varies from 2 to 4. In the best case, when there are no obstacles in the field, the value of α = 2 and β3 = 2. Hence, the above equation can be written as

$$\left(\varepsilon_{emp} \times (1+Lf_i) + \frac{E_s}{4}\right) d_i^2 + \left(\frac{E_s \times T_h}{2}\right) d_i + Z = 0, \tag{19}$$

where $Z = \left(E_{cs} + E_c(1+2Lf_i) - \frac{E_0}{T_{\max} \times B}\right)$ is a constant term.

The solution of Eq. (19) can directly be found for positive value of d_i as

$$d_i = \frac{-\left(\frac{E_s \times T_h}{2}\right) \pm \sqrt{\left(\frac{E_s \times T_h}{2}\right)^2 - 4Z\left(\varepsilon_{emp} \times (1+Lf_i) + \frac{E_s}{4}\right)}}{2\left(\varepsilon_{emp} \times (1+Lf_i) + \frac{E_s}{4}\right)}, \tag{20}$$

where $d_{min} \le d_i \le d_{\max}$.

The effective sensing range of sensor node s_i can be calculated by substituting the value of d_i in Eq. (17) as

$$Rs_i = \frac{T_h + d_i}{2}, \tag{21}$$

where $R_{smn} \leq$3 Rs$_i$ $\leq R_{smx}$.

With the help of the above two equations (20) and (21), the optimized communication and sensing ranges for each sensor node can be found.

3.3. Communication and sensing range optimization (CSRO) algorithm

CSRO re-adjusts sensing and communication ranges of sensor nodes and relocates them in order to prolong their lifetime to T_{mx}. T_{mx} is the lifetime of a sensor node having maximum relay load with minimum communication and sensing ranges. Therefore, such sensor nodes with lifetime T_{mx} can be thought of as the one-hop neighbors of sink. The deployment of sensor nodes starts from the sink towards the boundary of the RoI. First, sensor nodes are placed at one-hop vicinity of the sink by adjusting their communication and sensing ranges according to T_{mx}. Thereafter, second-hop sensor nodes are adjusted and a similar procedure is repeated for the remaining nodes until the boundary of the RoI is not reached in all directions. Communication and sensing ranges of sensor nodes are increased gradually towards the boundary of the RoI since because the load factor of such nodes decreases in a similar fashion. Therefore, in a large RoI it may happen that, before reaching the boundary, some nodes may reach their maximum limit of both R_{smx} and d_{mx}. The region from sink to these nodes is called D_{fit}. Within D_{fit}, the proposed scheme achieves 100% coverage with threshold T_h. In the case the RoI is larger than D_{fit} in any direction, the proposed algorithm compromises with T_h up to a certain level of coverage. The re-adjustment in sensor nodes' parameters and their locations is done using the strategy given in THE proposed algorithm 1 that follows. The algorithm initially considers a uniformly deployed WSN with n sensor nodes s_i and single sink s_{sink}. All sensor nodes compute their load factor $3Lf_i$ and location coordinates x_i and y_i during the load factor calculation phase. Thus, CSRO utilizes these values to relocate sensor nodes to new coordinates x_{ni} and y_{ni} according to modified communication and sensing ranges denoted as R_{sni} and d_{ni}, respectively, where$i \in_{\{}$ $31, 2, 3...n\}$. The algorithm uses three data structures, 3*INLINK*, $3OUTLINK$, and 3*N-QUEUE*, during network re-adjustment operation. The procedure starts from the sink and moves towards the boundary by re-adjusting parameters of sensor nodes hop-by-hop. Sensor nodes are fetched from 3*N-QUEUE* and processed according to algorithm 1. Initially, 3*N-QUEUE* contains all neighbors of the sink. Once a sensor node finds the optimized communication range, sensing range, and new coordinates, it is evicted from 3*N-QUEUE*. Sensor nodes in 3*INLINK* of that node are inserted into 3*N_QUEUE* for further processing. The process of range re-adjustment continues until 3*INLINK* of all sensor nodes in 3*N-QUEUE* is not empty. The algorithm relocates all sensor nodes in WSN to new locations with appropriate sensing and communication ranges.

3.4. Proof for coverage

Theorem 1 3If three sensor nodes having sensing ranges R_1, R_2, and R_3 (where $R_1 \geq R_2 \geq R_3 >3\ 0$) are deployed in such a way that their sensing ranges overlap by the same threshold T_h, which is an overlapping threshold in the case of hexagonal deployment of sensors with identical sensing range R_1, then there is no uncovered point within the triangular region formed by joining the centroids of all three sensing regions.

Proof If for full coverage, sensor nodes are deployed in a hexagonal grid as shown in Figure 3, then overlapping threshold (T_h) is calculated as $T_h = (2 - \sqrt{3})R_1$. □

Suppose there are three sensor nodes 1, 2, and 3 as shown in Figure 4. Nodes 1 and 2 intersect at a point $P(x_p, y_p)$. Then the coordinates of point P can be calculated as

$$x_p = \frac{(R_1^2 - R_2^2 + d_1^2)}{2d_1}, \quad y_p = -\sqrt{R_1^2 - \left(\frac{(R_1^2 - R_2^2 + d_1^2)}{2d_1}\right)^2}$$

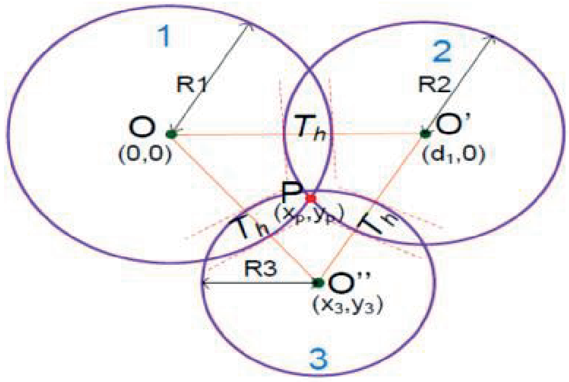

Figure 4. Arrangement of three sensor nodes overlapping by T_h with different sensing ranges.

Similarly, the coordinates of point O" are

$$x_3 = \frac{(d_1^2 + d_2^2 - d_3^2)}{2d_1}, \quad y_3 = -\sqrt{d_2^2 - \left(\frac{(d_1^2 + d_2^2 - d_3^2)}{2d_1}\right)^2},$$

where the distances between $3OO'$, $3OO''$, and $O'O''$ are denoted as d_1, d_2, and d_3, respectively, and are calculated in terms of R_1, R_3, and R_3 as

$$d_1 = (\sqrt{3} - 1)R_1 + R_2 \qquad d_2 = (\sqrt{3} - 1)R_1 + R_3 \qquad d_3 = R_2 + R_3 - (2 - \sqrt{3})R_1$$

If the point P is inside the sensing range of sensor 33, then it can be observed that there is no point uncovered inside $\Delta OO'O''$ as P is the farthest point from O'' that is not covered by sensor 1 and sensor 2. The point P will be inside sensor 3, if the condition $(x_3 - x_p)^2 + (y_3 - y_p)^2 \leq (R_3)^2$ holds.

In order to verify coverage of point P, if we consider the values of $R_2 = R_1$ and $R_3 = R_1/2$ then values of d_1, d_2, x_3, y_3, x_p, and y_p are

$$d_1 = \sqrt{3}R_1, \qquad d_2 = d_3 = \frac{(2\sqrt{3} - 1)}{2}R_1, \qquad x_3 = x_p = \frac{\sqrt{3}R_1}{2}, \qquad y_3 = -\frac{R_1}{2}, \qquad y_p = -\frac{R_1}{2}\sqrt{(5 - 4\sqrt{3})}$$

and

$$\frac{R_1}{4}\left(16 - 12\sqrt{3}\right) \leq \frac{R_1}{4}y_3^2 + y_p^2 - 2y_3y_p \leq \frac{R_1}{4}$$

After substituting these values in the above equation, we get:

The above condition is true for ranges assumed as $R1$, $R2$ and $R3$ and is also true for all similar ranges. Hence, there is no uncovered point inside $\Delta OO'O''$.

4. Analysis and results

4.1. Simulation setup

The proposed approach is simulated on a widely used network simulator ns2.35 (The Network Simulator NS-2) with MannaSim framework. For simulating the proposed scheme, sensor and sink nodes are deployed in a 700 $\times$ 700 m^2 RoI. The antenna parameters are set as $G_r = 1.0$, $G_t = 1.0$, $H_r = 0.8$, $H_t = 0.8$ and different radio ranges are assigned to sensor nodes by modifying RXThresh_, Pt_, CPThresh_, and frequency parameters according to the propagation model. The values of other parameters are set as given in the Table. The required protocols are implemented by programming the simulator. Three different scenarios are used to extensively analyze the performance of the proposed approach.

Table. Simulation parameters.

Simulation parameters	Values
E_0	5 J
ε_{emp}	100 pJ/bit/m^2
E_{ct}	50 nJ/bit
E_{cr}	50 nJ/bit
E_{cs}	40 nJ/bit
E_s	10 pJ/bit/m^2
Number of sinks	01
RoI dimensions	700×700 m^2
Packet size	100 bit
Sensing frequency	5 packet/s
Transmission frequency	1 Packet/s

Case 1: Nodes are deployed according to hexagonal grid arrangement and are assumed to disseminate data to the sink by using the Gossiping [14] routing protocol.

Case 2: Nodes are deployed according to proposed scheme and Gossiping is used as the data dissemination protocol.

Case 3: Nodes are deployed according to the proposed scheme and the load-balanced routing scheme [15] is used as the data dissemination protocol.

In addition, the performance of the proposed approach is compared with the energy balanced node deployment scheme (EBNDS) [16].

4.2. Performance evaluation

Initially, the WSN is deployed as per Case1 and the results are recorded. It is observed that sensor nodes near the sink node deplete their energy faster and die earlier than other nodes. Simulation results reveal that nodes nearer the sink die in the interval of 600 ms to 700 ms, which is much earlier than the interval when comparatively outer nodes die. Figures 5-7 delineate the lifetime of an individual sensor, whereas Figure 8 depicts a comparative analysis of lifetime of the network in all three cases. The results in Figure 9 show the difference in remaining energy levels of sensor nodes in terms of standard deviation. As all sensor nodes initially have nearly the same energy level, the results show the standard deviation in remaining energies is very low. However, as sensor nodes start transmitting information towards the sink, the standard deviation in energy levels increases sharply. This variation is due to the fact that some nodes play an additional role of relay while disseminating information towards the sink. The comparative coverage in all three cases is shown in Figure 10. Initially, in the proposed approach the coverage is a little less than in Case1 when most of the nodes are functioning properly. However, with the passage of time as total energy of some of nodes exhausts, the effective coverage in Case1 decreases more rapidly than in other cases.

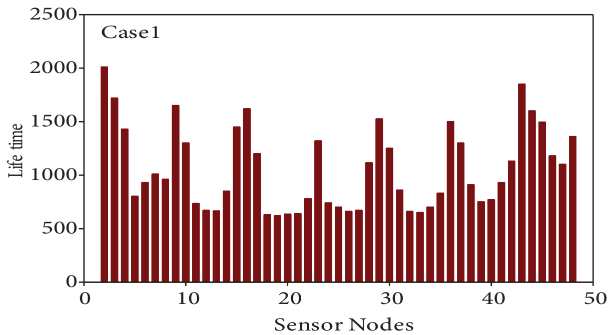

Figure 5. Lifetime of different nodes in Case 1.

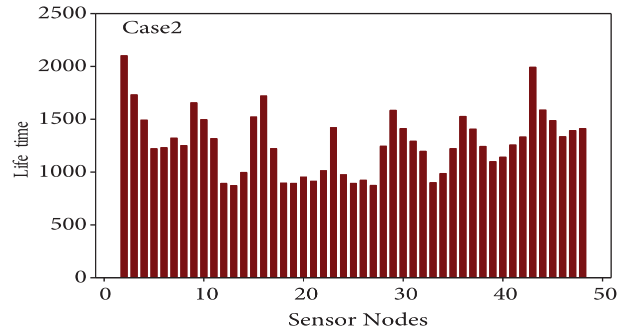

Figure 6. Lifetime of different nodes in Case 2.

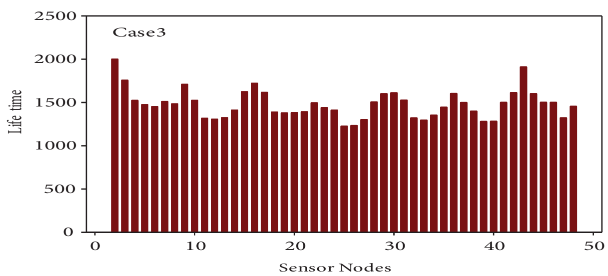

Figure 7. Lifetime of different nodes in Case 3.

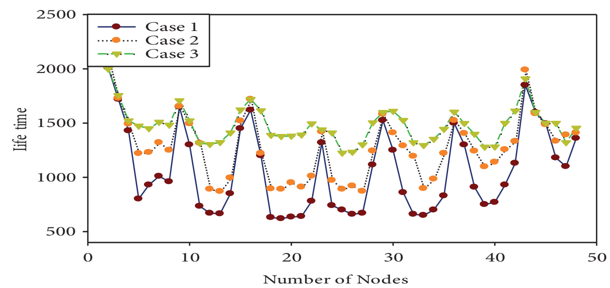

Figure 8. Difference in lifetime of nodes for all three cases.

For Case2, the sensing and communication ranges are adjusted according to the proposed strategy and the performance is analyzed. In this scenario, the network exhibits a significant improvement in lifetime and coverage. The results in Figure 6 show an improvement in nodes' lifetime. The lifetime of nodes earlier dying in the range of 600 ms to 700 ms is now prolonged until nearly 1000 ms. An improvement of nearly 53% in the lifetime of sensor nodes performing the additional role of relaying data can be seen. The scheme is also able to maintain a balance in energy depletion rates of different nodes. The fact is delineated in Figure 9 in terms of standard deviation.

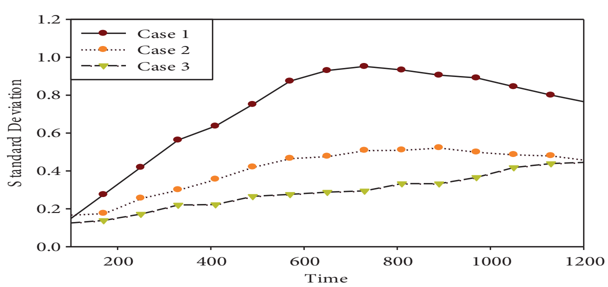

Figure 9. Standard deviation with respect to time.

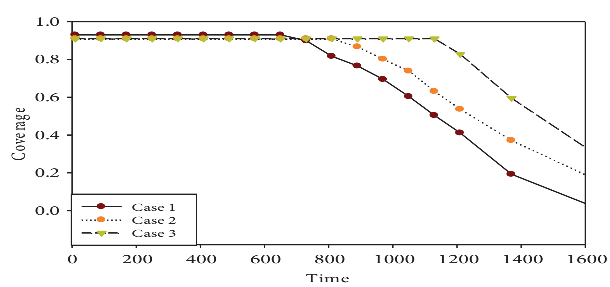

Figure 10. Coverage with respect to time.

In Case3, a load balanced routing scheme is used to utilize the strategic arrangement of sensor nodes effectively. In comparison to Case2, an improvement of 35% in the lifetime of sensor nodes is achieved (Figure 7). The nodes in the vicinity of the sink continue their services for a longer time. Thus, the results in Figure 10 show that the network is able to maintain an adequate coverage for a longer period than in Case1 and Case2. Figure 9 depicts that the proposed scheme maintains less standard deviation as compared to Case1 and Case2. Thus, nodes deplete their energy evenly and prolong the network nearly until 1350 ms.

The performance of the proposed scheme in terms of network lifetime is also compared with the scheme EBNDS as shown in Figure 11. The proposed approach reports nearly the same lifetime as in EBNDS. Even in some layers our approach performs better than EBNDS. Furthermore, the proposed scheme is more cost effective since the nodes required in each layer are less (Figure 12).

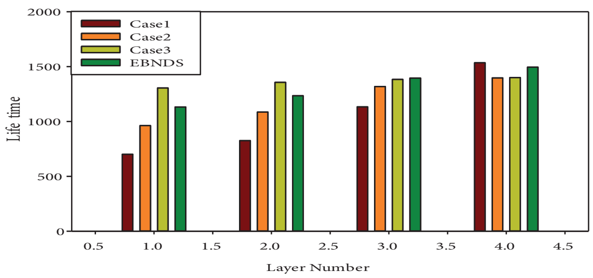

Figure 11. Comparison of lifetime of nodes in different cases.

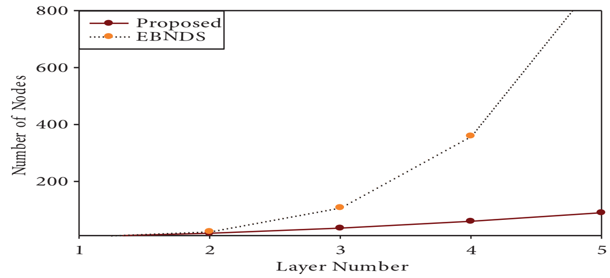

Figure 12. Sensor nodes vs. layer number.

5. Conclusion and future work

This work targets optimizing the sensor node's radio and sensing ranges according to relay load on it in a manner that provides full coverage and also ensures gradual energy depletion in all sensor nodes in the network. The strategy aims at overcoming the obstacle of uneven energy depletion by ensuring gradual energy drain in all sensor nodes throughout the network. By avoiding rapid energy drain in nodes nearer the sink, the scheme enhances the network lifetime nearly by 35%.

In future, the approach can be extended for finding the load factor of a cluster rather than a single node where the energy depletion rate of each cluster can be adjusted dynamically by adjusting certain energy dependent parameters like sensing range, sensing and transmitting frequency, and communication range.

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