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Research paper

Wireless Sensor Networks with Dynamic Advanced Node Selection for Longer Network Lifetime in Energy Hole Evolution

S. Suren Kumar [1]*, Dr. S. Murugan [2]

[1] Research Scholar, Department of Computer Science and Information Science, Annamalai University, Chidambaram, Tamil Nadu, India
[2] Assistant Professor, Dr. M. G. R. Gvt Arts and Science College for Women, Villupuram, Tamil Nadu, India
**Corresponding author E-mail: joesuren.87@gmail.com*

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Abstract

Wireless sensor networks (WSNs) that collect data using battery-powered sensor nodes that sometimes detect their surroundings and send the samples they acquire to a sink node are evaluated using network lifespan, a critical performance metric. The network's performance deteriorates due to two main issues. One is the void hole that develops in a certain area due to the forwarder nodes not being available. The other is the existence of an energy hole brought on by an uneven load of data traffic on intermediary nodes. This research aims to identify the boundaries of an energy hole in a WSN that collects data and offers a mathematical framework to determine the network's lifetime from the beginning to the end. Theoretically, the traffic load, energy usage, and sensor node longevity are calculated throughout the entire network lifetime. In this paper, we present a scientific approach to determine the energy opening limit in an information-gathering WSN and measure the entire organization's lifetime from network introduction till it is completely crippled. Experimental implementations of the proposed framework show significant energy savings, network lifespan extension, and QoS improvements. AI-Driven Power Optimization in IoT-enabled WSN is proven effective and flexible.

Keywords: *Wireless Sensor Networks; Traffic Volume; Energy Usage; Network Lifetime; Energy Hole Issue.*

1. Introduction

Wireless sensor networks, which can perform wireless communication, detection, and computation, are typically linked to several applications, including environmental monitoring, military observation, office and structure conclusion, and other industrial applications. Numerous fuelled sensor hubs make up a data-gathering WS, which senses the monitored region and sends the observed findings to the sink regularly. Extending the network lifetime of WSN is crucial because battery-controlled sensor hubs are limited in energy resources and typically operated in unsupervised, unfavorable environments [1]. Multiple-hop communication helps collect data for vitality conservation in the meantime, since vitality demand is greatly increasing with the division of interaction based on the vitality expenditure display. A vitality gap is created around the sink, though, because the hubs close to it should be forwarding the data packets from other hubs, which quickly weakens them. Because the network is isolated by the vitality gap, the entire system is susceptible to abrupt death.

We present a logical approach to ascertain the energy release limitation in a data collection WSN and measure the network lifetime from network activation to the point at which it is completely disabled. Specifically, we speculatively assess the activity stack, energy usage, and lifespan of sensor hubs throughout the network's lifetime. Additionally, we look at the geographical and global evolution of energy opening and use the findings of our investigation to WSN direction with the explicit objective of increasing network lifetime and consuming less energy [2]. The validity of the suggested explanatory model in assessing the network lifespan and energy is demonstrated by the results of extensive simulations of the opening creation procedure.

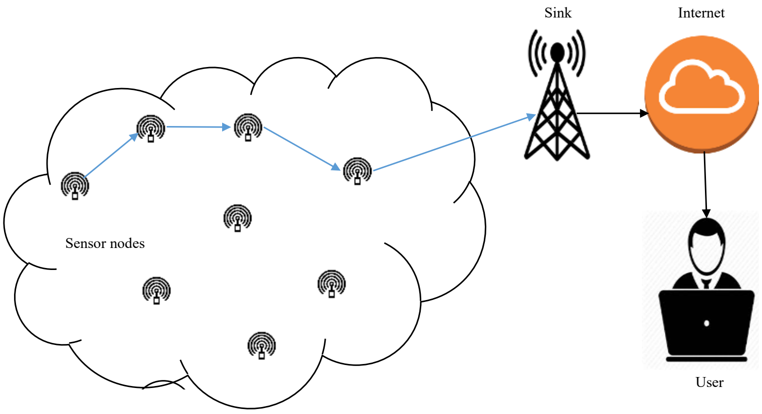

Fig. 1.1: Sensor Nodes in A WSN Paradigm.

Figure 1.1 illustrates the diagrammatic representation of the WSN model with sensor nodes. Energy holes are important and difficult for WSN lifetime analysis since they can cause the network to die too soon. First, establish which is the power hole issue in the WSN is unavoidable under certain circumstances [3], and then examine the conditions under which the energy holes may manifest. It talks about load balancing strategies to address the energy whole issue in massive amounts of WSNs and proposes a distributed algorithmic method for achieving equilibrium sensor node energy usage by modifying transmission power. Cluster-based WSNs have also been the subject of research on the energy hole issue.

In this study, we suggest an analytical approach to estimate the energy hole limit in data-gathering WSNs and anticipate the entire network life from network commencement to network complete disablement. To precisely assess sensor node energy consumption, we consider both idle listening and the power consumption of information transmission and reception. We provide three contributions.

- To calculate traffic volume, energy usage, and sensor node lifetime throughout the network lifetime, we suggest an analytical approach. Based on our analytical findings, we also determine the network's residual energy and its lifetime when a specific fraction of nodes are dead. Numerous simulations show that the proposed analytical method may estimate the network lifetime with an error rate of less than 5%.
- We examine the historical and geographical history of energy holes in WSNs, from their emergence to their division, based on the lifetime examination of sensor nodes. This gives us a theoretical foundation for reducing or even avoiding energy holes in WSNs.
- We relate our analytical findings to WSN routing to confirm how well they direct the design of the WSN. Based on our investigative findings, the enhanced routing strategy effectively balances energy usage and greatly extends network lifetime.

The following portions of this work are arranged as follows: In Section 2, relevant research on spotting bogus news is summarized. The proposed paradigm and our research methodology are presented in Section 3. In Section 4, we present comprehensive findings on the performance of the prediction models, including all other models developed for this investigation. In Section 5, the paper ultimately ends.

2. Related works

Research on network longevity was initially examined. Large-scale WSN lifespan is the primary focus of the study on network lifetime upper bounds. It solely took into consideration the amount of energy that communication between nodes since it was anticipated that this was the primary energy expenditure [4]. Nodes perceive hexagonal cells as their range, and the observation zone's center is where the sink is placed. In addition to information on how to choose the best network characteristics, including the size of hexagonal cells and the spread division of each node, to get the most longevity, the primary elements affecting the lifetime of the network were also presented. An algorithm based on many single hops was also suggested.

Nodes close to a mobile sink would shift over time. Energy holes can be prevented in this way. Like this, a data mule has been proposed for data collecting, in which mobile nodes act as forwarding agents before delivering sensory information to the sink. Static sensors in these methods only transmit information when the sink is within their communication range. A mobile relay technique is presented by [5] to increase the network lifetime. They demonstrate that the network centre is the ideal location for the curved sensor's sink system to attain maximum energy efficiency. The authors also show that it is advantageous to use a mobile sink, in which, in this scenario, the mobility direction should follow the outer boundary of the Internet.

In WSN, sensor node scheduling is the process of modifying the working mode of Nodes for sensors to optimize network longevity or penetration. The duty cycle concept is used by most scheduling techniques now in use. This method's primary objective is to separate the nodes with sensors into smaller groups so that every subset can finish the area surveillance task on its own. The authors of [6] use a greedy approach to solve it after considering both the remaining energy and the overlapping target coverage. The network lifetime maximization issue with target coverage was investigated by the authors. Following that, a heuristic method is employed to optimize the system's lifetime by planning the sensor nodes.

WSN steering agreements are divided into two kinds based on organizational structure: level and progressive conventions. Device hubs directly transmit data to the sink during level steering. It's interesting to note that sensor hubs transmit data to the sink during a leap-by-bounce in a progressive direction. It makes use of bunch head (CH) information collection to ensure accurate grouping [7]. Bunch-based steering plans increase the organization's lifespan and use less energy. On the other hand, over the past several years, meta-heuristic augmentation schemes have gained increased notoriety. To solve large-dimensional composite enhancement problems and obtain more advanced advancements in the search location, meta-heuristic computations are performed. The advantages of bunching-based conventions are thought to be versatility and lifespan enhancement.

A wireless sensor network combines networking and electronics. Enhanced scalability and resilience are two benefits of networked sensing. Although WSNs can be used for many different purposes, some characteristics and necessary mechanisms of these systems are evident [8]. The writers provided detailed explanations of a variety of applications. Additionally, they enumerated the elements that affect sensor network architecture, including energy, hardware limitations, connectivity, coverage, fault tolerance, scalability, environment,

node deployment, data collection, level of service, and connection. Additionally, they offer insights into various energy management strategies and point out that radio energy use is far greater than data processing energy usage.
To verify the conditions of the environment by monitoring variables like humidity, temperature, sound, and video, among others, WSN devices are outfitted with numerous autonomous sensors in a variety of fields. The data is then shared with the target sites concurrently. If the battery fails and needs to be replaced, the sensors are powered by the battery [9]. However, replacing the depleted batteries is either impossible or very expensive. Energy limitations are a very important topic in modern technology, particularly in the context of WSNs, as they may be the cause of the system's overall network lifetime being shortened, particularly when it comes to data collection.

3. Methods and materials

The conceptual System for WSN design optimization is described in the section that follows, keeping these difficulties in mind.

3.1. The suggested model

The primary objective of layout optimization is to demonstrate "how efficiently an area of land or a collection of targets can be tracked by deployed nodes of sensors in a WSN." This problem's ideal solution belongs to the NP-hard producing class and involves making trade-offs between multiple conflicting goals, including cost, service, lifetime, association, WSN reliability, and energy. Layout efficiency becomes a more challenging problem when WSN sizes and node sensor variety increase [10]. Because sensor nodes have limited communication, identification, energy, and processing capabilities, it is challenging to calculate the goals of large-scale WSNs in a way that makes sense for optimal layout planning.
This WSN degradation has a significant effect on the functioning and speed of real-time programs. The diagrammatic representation of the overall suggested concept for WSN layout optimization is provided in Figure 3.1 [11].

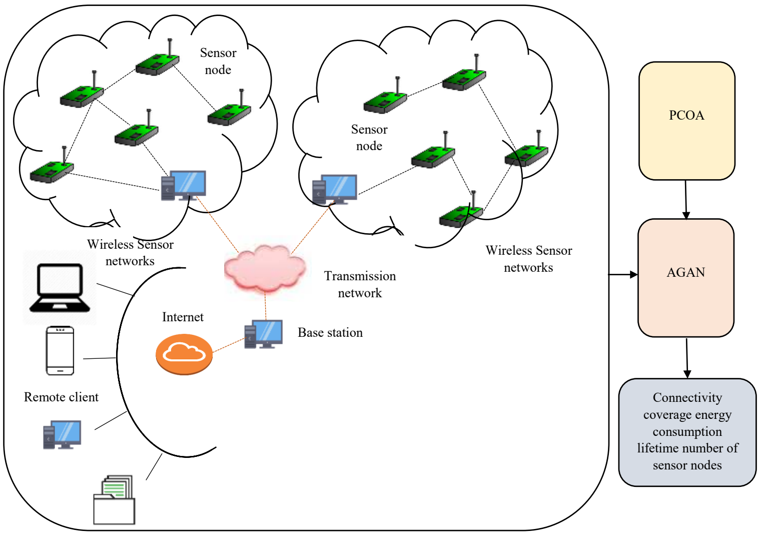

Fig. 3.1: Overall, the Suggested Paradigm for WSN Layout Optimization.

3.2. WSN modeling

The region in issue is square and level, allowing sensor nodes to interact with any remaining nodes under and monitor items inside the Sensor. The HECN, which is situated in the centre of the area, should communicate with every sensor. Either direct communication or hops through nearby sensors can take place. This consideration does not affect generalizability and is purely for convenience. It is believed that each sensor has the same quantity of energy in its battery at startup, describing the sole energy source. Additionally, it is assumed that after each data transfer, this energy decreases by an arbitrary unit.
The parameters used in the layout are represented by the vertical and horizontal coordinates of the sensor. This study only looks at WSNs with a set number of sensorso, so that the size of the design variable vector $\overrightarrow{dv}$ is always 2o.

$$\overrightarrow{dv} = [y_1\ z_1\ \dots\ y_o\ z_o] \tag{1}$$

Similar objectives with different design vectors will be achieved by similar designs with their orientation altered around the origin. Therefore, talking about the world's best layout might be suitable, but talking about a perfect vector related to coordinates would not be.

- Objective function

The weighted total of all fitness metrics is used to calculate the health of any given solution. WSN objectives for node measure, coverage, lifetime, relationship, and energy consumption are determined using the following techniques.

- Lifetime

The lifespan of a WSN is determined by the failure related to the network's initial node. The lifetime of one node is computed using the projected energy of initialization and the energy used by each node. The duration of a node's operation is established, as seen in (2). (3) states that when the first node fails, the network collapses, and the minimum lifetime of an active node is used to calculate the overall network lifetime.

$$lt_j = ie_j / ec_j \tag{2}$$

$$\text{lifetime} = \min\{\text{lt}_j\} \quad (3)$$

- Energy consumption

Each sensor node in a WSN can perform several tasks, including processing, sensing, transmitting and receiving data, and maintaining the system. Energy consumption is necessary for these operations, and the shortest data transmission line should be used for the best configuration. To calculate the energy consumption related to each node, the data transfer cost for the shortest route to the data sink is determined using the least spanning tree technique. In line with the surrounding nodes from where information may be received, the node management energy, transmission energy, and reception energy are totalled [12]. The energy consumption of the network can be calculated using the total energy expended by the active nodes in the network.

$$\text{ec}_j = \text{m}_j + \text{path}_j \times \text{tra}_j + \text{in}_j \times \text{rec}_j \quad (4)$$

$$\text{total energy} \sum_{j=1}^{o} \text{ec}_j \quad (5)$$

Every node's ability to interact directly or indirectly is ensured via connectivity. Energy consumption is the amount of power required for detecting and communicating duties, whereas coverage quantifies the monitored area.

- Connectivity

A WSN is considered linked when each sensor node is connected to the data sink via a single or multiple-hop transmission channel. Reducing the number of unconnected nodes in the framework is the primary objective of optimization techniques to create a network that is completely connected. The relationship between each design solution is investigated by constructing a structure with connections as its edges and a straightforward expanding tree with the data sink as the root node. Two nodes are considered linked if their distance from one another is less than their communication radius. Next, as indicated, the border mass is positioned at the separation between them. The Bellman-Ford unique origin shortest path technique is then used to find the shortest paths between each functioning node and the knowledge sink, which is in the middle of the monitoring region. If you have no practical way to reach the data sink, the nodes are regarded as disconnected.

$$\text{ew}_{jk} = \begin{cases} e_{jk} \text{ if } e_{jk} < s_{comm} \\ \infty \text{ else} \end{cases} \quad (6)$$

- Coverage

There are two ways to calculate the coverage: an area-oriented method and a grid-oriented one. Both strategies use a binary sensing technique, where a node's sensing region is viewed as a circular disc with a set sensing range U_j. An object that is present but farther away than the node's sensory range can be detected by the node. This is the Euclidean distance, concerning the fixed sensing radius sensor node T_j, between the target point and the node's center.

$$Q_j = \begin{cases} 1 \text{ if Dist}(T_j, U_j) < S_{sense} \\ 0 \text{ else} \end{cases} \quad (7)$$

The area-oriented technique randomly distributes the sensor nodes around the monitoring region. The region that a sensor node covers is determined by its sensing radius, which is the same for all sensor nodes in a homogeneous WSN. To obtain comprehensive area coverage, the overlap between nodes that sense is eliminated once the total area spanned by those nodes is calculated.

$$\text{area coverage} = \sum_j^o \pi\, S_{sense}^2 - \text{Overlap}(\text{sensor}_1, \text{Sensor}_o) \quad (8)$$

The grid-oriented approach divides the monitoring zone into equal-sized square grids. The Euclidean distance between each sensor node and the grid center is calculated to assess whether or not any nodes completely cover a grid. The largest area that each sensor node location (yj, zj) may cover is determined by the sensing radius S_{sense}, the grid's total covered points on the grid are then normalized using the region's total points.

$$\text{Point coverage} = \left[V_j = 1^o S_{sense}^2 (yj, zj)\right] / \text{total points} \quad (9)$$

When there are only a few nodes for sensors and a small surveillance zone or group of scores, the grid-oriented method works rapidly; however, as the WSN's size grows, the reach of numerous nodes slows it down. The region-oriented and grid-oriented methods are used to determine area coverage and point coverage, respectively, to avoid the algorithm's efficacy from deteriorating.

- Number of nodes

The amount of Active-Inactive (A/I) mode bits determines how many nodes each solution has. One A/I mode bit, when set to one, is utilized to identify nodes that are active in solutions about homogeneous WSNs.

3.3. Traffic load estimation

One of the most important aspects of network lifetime optimization is data flow control. The network is separated into little areas called sectors S to control the data flow. It is difficult to predict the data burden at each S by calculating the node because of the network field's division. It is commonly recognized that upstream nodes only send their data, whereas downstream nodes handle a heavy data load. The amount of data packets generated by the present S may now be approximated [13]. Assume that Sn is a sector that is close to the sink and has a distance of d. The combined amount of the traffic generated by sectors Sn+1 before it equals the total traffic generated by sector Sn. The mathematical formulation is as follows:

$$\text{TF}_{js_n} = N_{s_n} + N_{s_{n-1}} + N_{s_{n-2}} + \cdots + N_{s_1} \quad (10)$$

If one wishes to calculate the typical amount of traffic on Sn, Equation (10) may be expressed as follows:

$$ATF_{s_n} = \frac{TF_{js_n}}{N_{s_n}} \tag{11}$$

We can utilize ATF to determine the traffic volume in each sector, as it represents the mean traffic volume in a sector close to the sink.

$$ATF_{s_n} = \begin{cases} (T_1 + 1) + \frac{T_1(1+T_1)}{2x}, \text{if} x \geq c \\ \frac{1}{2}(T_2 + 2)c^2\theta\rho + \frac{1}{2}T_2 c\theta\rho(T_2 + 1), \text{otherwise} \end{cases} \tag{12}$$

Where T1 and T2 are equal to 1. Algorithm 1 discusses the traffic load working technique. It demonstrates that prior to each round's commencement, as covered in the section.

Algorithm 1: Calculating Traffic Load and Energy Consumption at each round
Input: Network rangeR, transmission range r between the sensor, NN normal node, SN super node, node densityρ etc.
Output: for a node i $\in$ {NN}Determine The traffic load $t_{li}^{r_o}$, energy consumption $e_i^{r_o}$ at round r_o
1: Initialize Limitations
2: for round r_o
3: for each node i $\in$ {NN} and at each round r_o calculate distance $d_{(i,j)}$ where node i is a node of sector S and node j is a node of sector S_n also n is the number of sectors
4: if $d_{(i,j)} \leq r$
5: Transmit node I's data to node J. Determine the energy usage for data transfer and reception using Equations (11) and (12), then calculate the traffic load using Equation (10).
6: also
7: Find SN in each division
8: if $d_{(NN,SN)} \leq r$
9: send data of NN to SN
10: Determine the power usage and traffic load for SN's data reception and NN's data transmission.
11:else
12: SN receives the statistics by itself
13: Compute the traffic load and energy feasting for data receiving for SN
14: whereas the sink receives data d_o
15: Determine the overall energy consumption and lifetime of nodes at round r_o

3.4. An explanation of algorithm 1

This section provides a quick, step-by-step explanation of Algorithm 1 for your benefit. Input indicates that control parameters must be established before algorithm startup, NN and SN deployment, broadcast range, and system radius. Step 2, known as the loop of rounds, is started once Step 1, which involves the placement of nodes, sinks, & connection setup, has finished initializing the network settings. To determine the quickest route for transmitting its data bits to the location, each node calculates the distance from every other node at step 3. Additionally, NN determines the distance from both NN and SN. When NN and SN are separated by multi-path surroundings, NN seeks out another NN to multi-hop its packets in the direction of the SN. Avoiding long-distance routes is justified by the high likelihood of data propagation and amplification, which increases the likelihood of packet corruption.

To lessen the previously mentioned problems, a shorter route is used to deliver the data packet to the target. To ensure that the recipient is inside the transmission range of the information packets being delivered across the path, step four measures the distance. The data traffic forecasting at each hop is among the most important components of our suggested project to avoid having too much knowledge on the intermediary super nodes after the mathematical calculation of distance and the identification of the sending node in the transmission area.

4. Implementation and experimental results

In this part, we use simulations to assess how well our suggested approach performs. Since all methods use corona-based models [14], LiMHA is compared through calculations with the current systems ODTS, LAEHA, N-SEP, and P-SEP. Table 1 contains a list of simulation variables.

Table 1: Control Parameters

Parameters	Value
Integer of Coronas	12
Total Quantity of Knots	150
Count of Regular Knots	150
Number of Super Nodes	40
Number of Zones	40
Normal Beginning Energy Knots	1
Initial Energy of Super Knots	1.5-6
Diffusion range	60
Span	100-800
Number of bands	10
v(m/s)	33×10^8

4.1. Analysis of network lifetime

The lifespan of the network under various radii is contrasted in Figure 4.1. The figure makes it is clear that as the network radius increases, the network lifetime diminishes. This is because nodes are getting farther apart, which raises energy usage. Additionally, when the network radius increases, the likelihood of a void hole increases as well, resulting in a shorter lifespan. On average, LiMHA has a 15% longer network lifespan than ODTS and a 45% longer lifetime than LAEHA. Each super connector in a sector reduces the likelihood of a void hole in the LiMHA network, which is segmented into sectors.

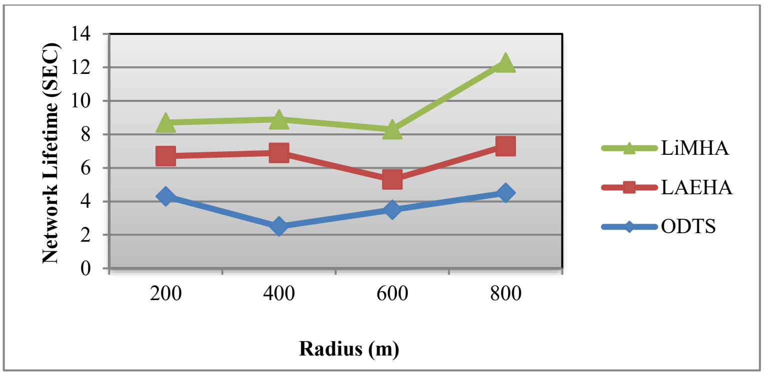

Fig. 4.1: Lifetime of the System at Different Radii.

4.2. Comparison of energy taxes

Figure 4.2 illustrates how energy taxes rise as node density rises. As the more nodes increases, the farther apart they are falls, requiring less energy to transmit data to the sinks. ODTS performs better than the others in sparse area networks. When transmitting data to the sink [15], ODTS selects the most balanced and energy-efficient route. As a result, less energy is used. Because there are fewer nodes in the connection, the disparity between them grows, forcing nodes to convey data using more energy, which raises the nodes' total energy consumption and, consequently, the energy tax.

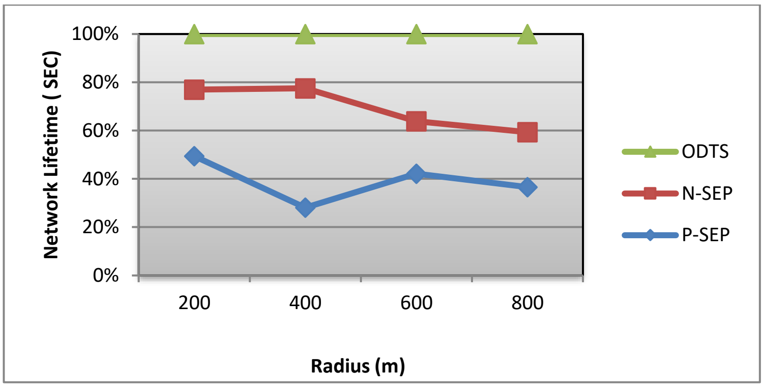

Fig. 4.2: Tax on Energy with Various Nodes ρ.

4.3. Comparison of end-to-end delays

Figure 4.3 compares the E2E delays of LiMHA, ODTS, LAEHA, N-SEP, and P-SEP. Unlike the energy cost, the E2E delay reduces as the number of nodes grows. Since sending a heavy traffic load takes a long time in the lowest zone, the E2E delay increases as the number of nodes rises. Additionally, the total waiting time is increased when packets collide between nodes. In comparison to LiMHA, ODTS has a lower latency.
The primary cause of this is that when there are fewer nodes in an area, the Nodes and ants are getting farther apart. Ants must wait for the package to arrive for them, lengthening the sending time overall while still being superior to LiMHA.

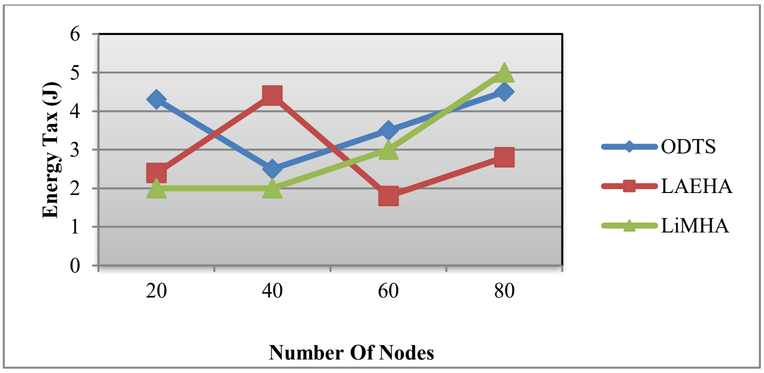

Fig. 4.3: End 2 End Interruptions.

4.4. Trade-off in performance

When it comes to reaching the minimum delay level, LAEHA performs better than ODTS because LAEHA does not adopt this phenomenon, whereas ODTS does. This is because ODTS considers the time required to choose the optimal route for sending data, which lengthens the time it takes to send a package and affects the network show. In sparse deployment, N-SEP achieved energy savings and an effective network lifetime; nevertheless, the k-means clustering approach minimizes E2E latency. Table 2 displays the performance trade-off table.

Table 2: Performance Trade-Off

Protocol	Technique	Metrics	Achievement	Cost to Pay
LiMHA	Mixed Routing	Distance and Energy	Network lifetime prolongs	High E2E delay
ODTS	Mixed Routing	Distance and Energy	longer network lifetime and lower energy consumption in sparse situations,	High E2E Delay for sparse case
LAEHA	Mixed Routing	Distance and Energy	Reduced energy consumption in dense cases, with a higher minimum E2E delay level	Less network lifetime
N-SEP	Mixed Routing	Distance and Energy	High Communication Radii and High Energy Dissipation	Less network lifetime
P-SEP	Mixed Routing	Distance and Energy	Lowest E2EDelay	Less network lifetime

5. Conclusion

Our goal the purpose of this research is to increase the network's longevity by proposing a transmission mechanism that can eliminate holes. The successful implementation of diverse nodes in every area was demonstrated by the balanced data transfers via a middle node. Furthermore, the network field's split made a sufficient contribution to the networking node energy balance. It achieves balanced energy dissipation by selecting the best forwarder at each hop.

Our analytical findings have also revealed two network properties that can be used to direct the design and optimization of WSNs. Our simulation findings show that the suggested analytical model can provide an error-rate estimate of the network's lifetime and current hole development mechanism of under five percent. Our analytical findings have now been applied to WSN routing. Our analytical results have led to an enhanced routing strategy that can effectively balance energy usage and increase network lifetime. We used linear optimization to determine a feasible region, and the results show that the electrical usage in that area always facilitates network nodes' operation for the longest possible period. Furthermore, the network field's split made a sufficient contribution to the energy balance between the network nodes. Even energy dissipation is accomplished by choosing the best forwarder at each hop. Nonetheless, the suggested algorithm's evaluation of the data load at each hop turned out to be highly successful in choosing the best path to the destination. The results show that, regarding the energy and longevity of the network usage, the suggested work performed better than the chosen existing equivalent system.

We plan to expand our work in various ways in the future. The network's distributed nodes will first be randomly deployed; that is, they can be positioned anywhere within a sector. Second, we will determine how many nodes are best suited to transmit data to intermediate nodes.

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