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Article

Energy-Efficient Multihop Routing to Extend Network Lifetime for Cluster-Based WSN through Improved LEACH

Sushma Priyadarshini[1], Anuradha T[2]

[1]Assistant Professor, Computer Science and Engineering (Data Science), CMR Engineering College, Kandlakoya-501401, Hyderabad, Telangana, India. priyadarshinisushma9@gmail.com
[2]Associate Professor, Computer Science and Engineering, PDA College of Engineering, Kalaburagi-585102, Karnataka, India. Email ID: anuradhat@pdaengg.com.

Abstract: Wireless Sensor Networks (WSNs) find application in environmental monitoring, industrial automation, health care, and the Internet of Things. However, energy restrictions of nodes and faulty routing mechanisms affect network lifetime and communication. To address these issues, this paper presents an Energy-Efficient Cluster-Based Multi-Hop Routing (E2CMR) protocol, an enhanced version of the LEACH routing protocol. The framework suggests RSSI-based methods for node layering, adaptive selection of cluster heads, and energy-aware multi-hop routing to balance energy consumption. Using residual energy, initial energy, and average network energy, an enhanced threshold function is developed to select an optimal cluster head for efficient rotation. Moreover, energy-aware route establishment reduces transmission distance and communication overhead, thereby enhancing packet delivery performance. The proposed protocol was validated in an NS-2 simulation using 100 similar sensor nodes. The following protocols were compared with ECI-LEACH, ESCH, and the ICSI routing protocol. The experimental results show that E2CMR achieves a maximum throughput of 370 kbps, delaying the first node's death to the 30th round. In the 50th round, it maintains 26% residual energy, routing overhead reduces to 26, and network lifetime improves by 38%. The results indicate that E2CMR improves energy efficiency, network stability, and routing performance and is applicable for large-scale energy-constrained WSNs.
Keywords: Wireless Sensor Networks (WSNs); Energy-Efficient Routing; LEACH; Cluster Head Selection; Multi-Hop Routing; RSSI-Based Layering; Residual Energy; Routing Overhead; Network Lifetime; Energy-Aware Communication

1. Introduction

The phenomenal development and their remarkable data-collecting and processing capabilities have propelled them to the forefront of technical discourse in recent times (Bala et al., 2018) [1]. In addition to environmental monitoring, agriculture, medicine, the military, the IoT, and UAVs, WSNs have found utility in a variety of other domains (Bagwari et al., 2023) [2]. Sensor nodes have their uses, but they also have limits in battery life, data transfer rates, memory, and communication range (Alferaidi et al., 2024 [3]; Wajgi & Tembhurne, 2023 [4]). Connected wirelessly, nodes may self-configure and coordinate their communications. Data-collecting nodes, known as sinks or base stations (BSs), receive sensed data via single-hop or multi-hop transmission. Continuous node operation often leads to faster energy depletion, resulting in node death. Nodes are unattended after deployment in a hostile environment; uneven energy consumption and node deaths result in network instability (Almazaideh & Levendovszky, 2020 [5]; Chan et al., 2020 [7]; Khalaf & Abdulsahib, 2020 [6]). The energy-efficiency problem has gained significant attention in WSNs for large-scale network balancing. Thus, energy constraint issues have been investigated and addressed in several WSN routing protocols (Chan et al., 2020 [9]; Daanoune et al., 2021 [8]). Cluster-based routing algorithms offer a solution to energy-efficient routing in WSN and have a key role in balancing. Concerning energy efficiency, energy hole, optimal energy consumption, dependability, and network longevity, several cluster-based

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routing algorithms have been devised (Abd-Elnaby, 2022 [10]; Anastasi et al., 2008 [11]; Cenedese et al., 2016 [12]; Gurusamy & Abas, 2020 [13]; Pachlor & Shrimankar, 2017 [14]; Xu et al., 2019 [15]). However, cluster-based routing algorithms still have their fair share of problems, including inflexibility, static routing, and an inadequate focus on reducing energy consumption (Baradaran & Rabieefar, 2023 [16]; Nithya et al., 2023 [17]). Conventional clustering techniques fail in situations with dense networks, cluster head rotation, or uneven energy distribution.

- By incorporating nodes' residual energy and other energy parameters, an enhanced to find a better threshold value, thereby balancing the load and reducing consumption.
- The E2CMR method is decentralized, and optimal cluster heads and CH rotation are performed, adapting improved threshold values and energy circumstances to prolong network lifetime.
- Energy-efficient optimal routes are determined, and multihop transmissions are adapted to reduce communication overhead.

1.1.Problem Statement and Motivation

Network reliability and extended node operations are threatened when a node's energy consumption is not managed efficiently. To balance the nodes' energy, clustering methods have proven to be an optimal solution for extending network lifetime. Hierarchical WSN routing relies on clustering [18-20]. All data transfers, whether single-hop or multi-hop, are the responsibility of CHs, who also maintain communication within and across clusters. Both centralized and distributed approaches are used in developing. There are two phases in LEACH's operation: steady state and setup. The algorithm conducts distinct rounds. Time-division multiple access (TDMA) data transmission via CH is timed in a steady state to improve energy efficiency and avoid collisions. Due to its shortcomings, several algorithms have been suggested as possible enhancements or replacements for LEACH [21-23].

Improving data transmission, increasing network longevity by using external energy sources, and selecting CH using an optimal fuzzy method are the primary goals of these algorithms. Current clustering algorithms struggle to strike a balance between node energy consumption and CH optimization and rotation [24]. Therefore, an all-encompassing strategy would include finding energy-efficient paths to BS and employing optimization techniques to choose cluster heads at different phases. In light of these concerns, an appropriate cluster-based routing algorithm that effectively balances energy needs while reducing nodes' energy use must be provided. Rotating CHs and accounting for energy characteristics may increase network longevity and energy efficiency [25].

2. Related Works

Among distributed clustering methods, the most famous one is LEACH, which stands for low energy adaptive clustering hierarchy (Balakrishnan, 2000) [26]. LEACH is a popular hierarchical clustering protocol in which cluster heads (CHs) are randomly selected in each round. The protocol consists of two phases: cluster formation in the setup phase and data transmission in the steady-state phase. After selecting cluster heads (CHs), each sensor node connects to the nearest CH. Thereafter, the nodes transmit their data to the CHs using TDMA scheduling. The CHs then aggregate the data and forward it to the base station. Even though LEACH minimizes communication costs through clustering, it suffers from random CH selection, which tends to pick low-energy nodes as CHs. As a result, energy consumption is random, which contributes to energy depletion during direct communication with the base station. As a result, the network lifetime and overall energy efficiency suffer [27].

The remaining energy, the cost function, the transmission range, and the stable connection are all part of this. By achieving effective inter-cluster routing via energy balance in the network, an integrated evolutionary algorithm eliminates the hotspot problem. One node is randomly selected from among the contending nodes based on its location, CH score, and distance to the BS. To communicate among clusters, a genetic algorithm is used during the transmission of multihop CHs. To achieve energy efficiency via energy balancing, simulations are used, which provide reliable data transmission and a long lifetime for the network [28]. However, this method lacks robustness when assessing CH scores for large-scale nodes with fewer components.

Combining LEACH with the analytical hierarchy process (AHP), Gangal et al. (2024 [29]) and Rahman & Hamim (2025 [30]) introduce a distributed clustering approach. Nodes may determine their own CH likelihood using the suggested method, which takes into account. An analytical hierarchy approach is used to obtain values for the CH potential threshold, which are stored in a matrix. For any conceivable combination of energy and distance, we determine two distinct threshold values. The second number aims to optimize remaining nodes. This is what the first value aims to do. The chosen CHs complete their duties for a certain number of cycles, after which they switch roles based on the ratio of nearby SNs with lower energy values and the ratio [31]. We can prevent unnecessary power consumption and provide dependable data flow by using an adaptive threshold. However, the technique cannot achieve large-scale network stability due to additional communication overhead among relay nodes during route finding [32].

The author of (GG, Girija Vasumathi, 2025 [33]) presents a connectivity index-based clustering method that is energy-efficient, enhances LEACH, and includes a cluster head selection procedure based on the connectivity index and relative energy consumption. In this manner, better compatibility and performance parameters are ensured, while power consumption remains optimal. The protocol utilizes hierarchical clustering, TDMA scheduling, and multi-hop communication to improve packet delivery, reduce collisions, and establish a reliable communication path to the base station. The cluster head selection process considers the node's energy, communication cost, stability, and connectivity. This increases the likelihood of selecting energy-rich nodes. Nonetheless, the technique relies on threshold-based random CH selection and incurs additional overhead for cluster formation and route maintenance. In addition, this approach does not effectively account for the impact of other essential energy-related parameters, including initial energy and average network energy, on energy optimization solutions [34].

Saleh et al. 2023 [35] proposed the Intelligent Cluster Selection (ICS) approach in LEACH, which selects a cluster head based on a node's power factor, residual energy, and communication energy cost. It saves energy and increases network lifetime. By selecting optimistic nodes and optimally measuring selected cluster dimensions, the process forms optimal clusters through competitive selection. The simulation results demonstrate higher packet delivery and network lifetime than existing clustering methods. However, this method incurs additional overhead and fails to adapt to network dynamics. In addition, optimal selection of the cluster head improves energy efficiency.

3. Methodology

The n sensor nodes that comprise the E2CMR network are dispersed throughout an m×m area and linked together by wireless radio links. Nodes are static after being deployed in the network area.

- BS is stationary and has unlimited energy and other resources.
- The network is homogeneous; all nodes possess the same initial energy levels.
- All CMs gather surrounding data and transmits to their assigned CH. Data is aggregated at CH, and CH forwards aggregated data to BS via direct or multihop transmission.

3.1.Proposed E2CMR Framework

The Energy-Efficient Cluster-Based Multi-Hop Routing (E2CMR) Framework is proposed to improve network lifetime. The method integrates a node layer based on RSSI, adaptive selection of cluster heads, energy-aware multi-hop routing, and cluster head rotation for Energy Balance Scheduling. As depicted in Figure 1, energy parameters are used to choose optimal cluster heads and reliable routing paths toward the BS (base station).

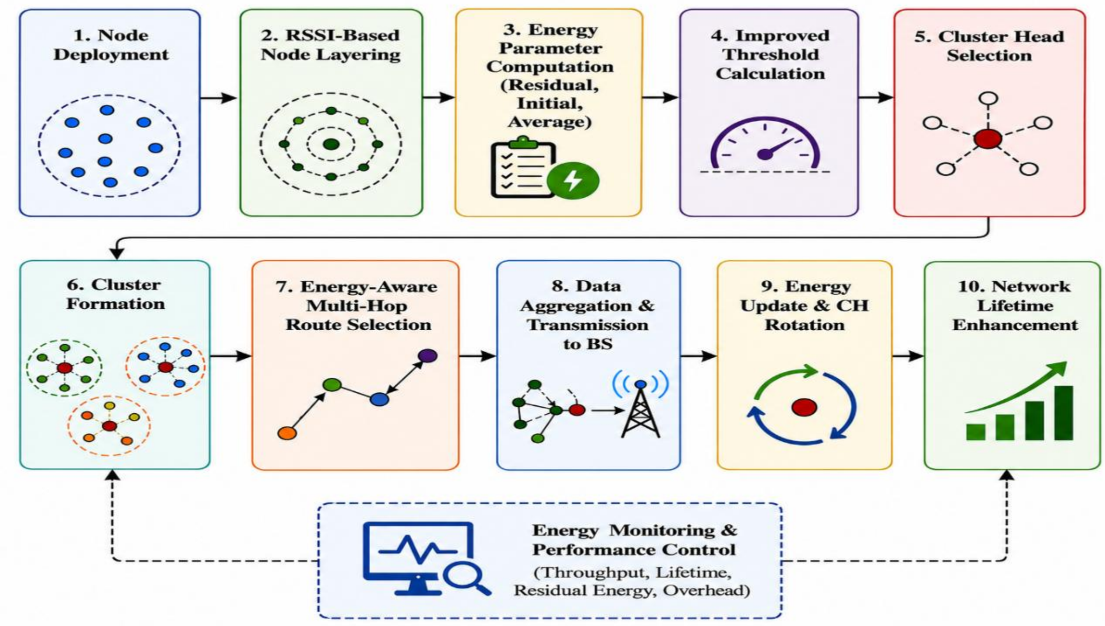

Figure 1. Workflow of the Proposed E2CMR Routing Protocol

The proposed E2CMR routing protocol first deploys sensor nodes through RSSI-based node layering. To find the enhanced threshold for cluster head selection, the energy parameters- residual energy, initial energy, and average network energy are computed. After clusters have been formed, a multi-hop path will be established between cluster heads and the BS. The selected routes are used for data aggregation and transmission, while the nodes' energy is updated. A cluster head rotation, together with energy monitoring, ensures lower energy consumption, lower routing overhead, higher throughput, and longer lifetime.

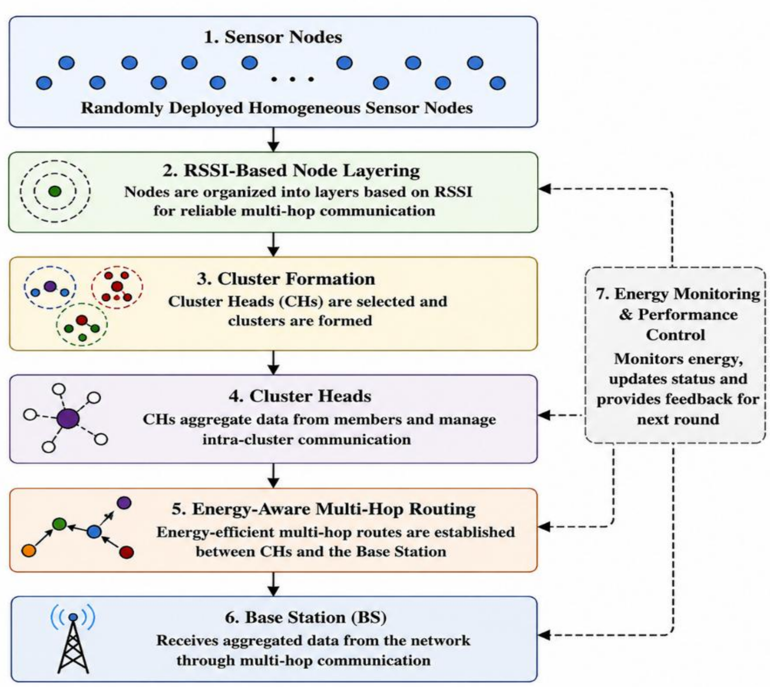

Figure 2. System Architecture of E2CMR

Figure 2. System Architecture of the Proposed Energy-Efficient Cluster-Based Multi-Hop Routing (E2CMR) Protocol

The proposed design of the E2CMR protocol is shown in Figure 2. First, sensor nodes are deployed and organized by layering them based on RSSI. Cluster heads are chosen, and clusters are formed based on energy parameters. Cluster heads gather information from member nodes and create energy-efficient multi-hop paths to the base station. The energy monitoring and performance control module monitors residual energy, throughput, network lifetime, and routing overhead, which inform routing decisions while balancing energy usage within the network.

3.2.Energy Model

After the node is deployed, the BS broadcasts a message across the entire network. Depending on RSSI, nodes are layered according to their distance from the BS to enable reliable multihop communication. Nodes nearer to the BS are excluded to form a layer. BS computes the farthest and the nearest node distances expressed as:

$$d_{n_i} = d_{MAX} - d_{MIN} \quad (1)$$

where d_{n_i} denotes the difference between the farthest and nearest nodes to BS, d_{MAX} represents the farthest node distance to BS, and the nearest node distance to BS is represented as d_{MIN}. The distance between two clusters is the distance between any pair of points such that the clusters are more compact and relatively close to each other.

BS computes each node's cluster radius, which is expressed as:

$$C_R(n_i) = \left[1 - \varphi \frac{d(i)_{BS,MAX}}{\left(d(i)_{BS,MIN}\right) - \rho\left(1 - \frac{E_{Res}(i,r)}{E_{MAX}}\right)}\right] \quad (2)$$

where the radius of node n_i is represented by C_R (n_i), and φ and ρ are weight coefficients in the range of [0,1]. E2CMR uses the energy consumption of the open-space channel (d^2) or the multipath channel (d^4), depending on the distance between the transmitter and receiver. Hence, the calculation for sending a packet of k bits across a distance D is, as per the wireless communication paradigm:

$$E_{TX}(k,d) = \{k * E_{elec} + k * \gamma_{fs} * d^2 \quad d \le d_c \; k * E_{elec} + k * \gamma_{mp} * d^4 \quad d > d_c$$
(3)

Here d denotes transmission distance; energy consumed for digital modulation and coding for the hardware circuit during transmission and reception is given as E_{elec} . The distance constant parameter d_c is calculated as $d_c = \sqrt{\frac{\gamma_{fs}}{\gamma_{mp}}}$, where γ_{fs} is the free-space circuit amplification factor and γ_{mp} is the multipath fading circuit amplification factor. The node's energy significantly rises when the transmission distance exceeds the distance constant.

Energy consumed to receive k bits at the reception node is computed as:

$$E_{RX} = k * E_{elec} \quad (4)$$

Energy required to perform the aggregation of k bits of data is calculated as:

$$E_{DA} = k * E_{RD} \quad (5)$$

Where E_{RD} is the radio energy per packet

The remaining energy of the node is computed as:

$$RE = E_{init} - E_{TX} - E_{RX} - E_{DA} \tag{6}$$

Where E_{init} is the node's initial energy.

When nodes are closer to the BS, E2CMR adopts the free space model. d^2. During each round, the CH energy consumption is evaluated as.

$$CH_E = \left(\frac{n_i}{L} - 1\right) * k * E_{elec} + \frac{n_i}{L} * k * E_{DA} + k * E_{elec} + k * \gamma_{fs} * d^2{}_{BS} \tag{7}$$

$CH_E = \left(\frac{n_i}{L} - 1\right) * k * E_{elec} + \frac{n_i}{L} * k * E_{DA} + k * E_{elec} + k * \gamma_{fs} * d^2{}_{BS}$ where L denotes the number of clusters per current round; in each cluster, the average number of nodes is $\frac{n_i}{L}$, E_{DA} is the energy consumed at CH upon receiving 1 bit, and the square distance between CH and BS is denoted as $d^2{}_{BS}$. Assuming the BS is located far from the nodes at position (a, b) and node $\beta(x, y)$ is distributed in an arbitrary region without loss of generality. The square distance between CH and BS can be calculated as:

$$d(d^2{}_{BS}) = \iint \ ((a-x)^2 + (b-y)^2\beta(x,y)dxdy$$

$$d(d^2{}_{BS}) = \iint \ \frac{(a-x)^2+(b-y)^2}{H} \ dxdy \tag{8}$$

where H is the node distribution region, the energy consumed by a non-cluster head or CM per current round is given as:

$$CM_E = k * E_{elec} + k * \gamma_{fs} * d^2{}_{CH} \tag{9}$$

where $d^2{}_{CH}$ the square distance between the sensor node and CH is expressed as:

$$d(d^2{}_{CH}) = \iint \ (x^2 + y^2)\beta(x,y)dxdy \tag{10}$$

Energy consumption of each cluster is expressed as:

$$Cluster_E = CH_E + (\frac{n_i}{L} - 1)CM_E$$

$$Cluster_E = CH_E + \frac{n_i}{L} CM_E \tag{11}$$

Energy consumption of E2CMR during each round is expressed as:

$$r_E = opt(Cluster_E)$$

$$r_E = k(2n_iE_{elec} + n_iE_{DA} + L\gamma_{fs}d^2{}_{BS} + n_i\gamma_{fs}d^2{}_{CH}) \tag{12}$$

optimal number of CH in each round r_E with respect to L is expressed as:

$$L_{opt} = \frac{\sqrt{n_i}}{\sqrt{2\pi}} = \frac{L}{d_{BS}} \tag{13}$$

When nodes are farther from the BS, E2CMR adopts a multipath model d^4. During each round, the CH energy consumption is evaluated as :

$$CH_E = \left(\frac{n_i}{L} - 1\right) * k * E_{elec} + \frac{n_i}{L} * k * E_{DA} + k * E_{elec} + k * \gamma_{mp} * d^2{}_{BS} \tag{14}$$

The distance is evaluated as:

$$d(d^4{}_{BS}) = \iint \ ((a-x)^2 + (b-y)^2\beta(x,y)dxdy$$

$$d(d^4{}_{BS}) = \iint \ \frac{(a-x)^2+(b-y)^2}{H}\ dxdy \quad (15)$$

$CM_E\ d^2{}_{CH}$, and $Cluster_E$ are the same as the free space model, energy consumption of E2CMR is given as :

$$r_E = opt(Cluster_E)$$

$$r_E = k(2n_iE_{elec} + n_iE_{DA} + L\gamma_{mp}d^2{}_{BS} + n_i\gamma_{fs}d^4{}_{CH}) \quad (16)$$

optimal number of CH in each round r_E with respect to L is expressed as:

$$L_{opt} = \frac{\sqrt{n_i}}{\sqrt{2\pi}}\sqrt{\frac{\gamma_{fs}}{\gamma_{mp}}} = \frac{L}{d^2{}_{BS}} \quad (17)$$

3.3. Cluster Head Selection

Selection of CH in LEACH is based on residual energy; during the setup stage, nodes actively participate in CH selection. Each node generates a uniform random number between 0 and 1. The node whose number falls below a predefined threshold $Th(n_i)$ is chosen as a CH. The threshold value is evaluated as:

$$Th(n_i) = \{\frac{P}{1-P*(r*mod(\frac{1}{P}))},\ n\ \in v\ 0, \qquad otherwise$$

(18)

Where P denotes the percentage of nodes being chosen as CHs among other nodes, r represents a random number, and v denotes the set of nodes not being chosen as CHs in previous $\frac{1}{P}$ rounds. However, LEACH selects a random node as CH, and a node with lower energy can also be chosen as CH in the next round. Thus, LEACH cannot guarantee extended network lifetime. To balance nodes' energy consumption and to extend network lifetime, E2CMR proposes a new improved threshold value evaluation considering energy-adjustment parameters, which is expressed as:

$$ITh(n_i) = \{\frac{P_a}{1-P_a*(r*mod(\frac{1}{P_a}))},\ n_i\ \in v\ 0, \qquad otherwise$$

(19)

The energy adjustment parameters P_a for the proposed E2CMR to calculate the improved threshold are computed as:

$$P_a = \frac{P_{ch}*n_i*C_r^{n_i}*I_e}{T_e*A_e} \quad (20)$$

where P_{ch} is the proportion of choosing the optimal cluster head, the current ith node residual energy is denoted by $C_r^{n_i}$, and I_e ith node initial energy. T_e The average energy of all nodes, as determined by E2CMR after R rounds of operations, is given as:

$$A_e = \frac{T_e(1-\frac{R}{R_{Max}})}{n_i} \quad (21)$$

Algorithm for cluster formation and data transmission

procedure cluster formation

begin

CM determines its nearest CH through CH_ADV and location

CM sends a JOIN_REQ message to CH

CH receives JOIN_REQ from CM

stores in the CM list

forms cluster

end procedure

Procedure data transmission

begin

Compute cluster radius $C_R(n_i)$ *from the equation. (2)*

for single-hop transmission

The energy consumed E_S *is given by the equation. (23)*

for multihop transmission

The energy consumed E_S *is given by the equation. (25)*

end procedure

end

4. Simulation results and analysis

Using the NS2 discrete network simulation tool, we ran simulation tests to test the feasibility of the E2CMR. The proposed E2CMR results are compared with ECI-LEACH (G. & Deepa, 2025), ESCH [34](Salman et al., 2023), and ICSI (Saleh et al., 2023). The detailed experimental parameters are shown in Table 1.

Table 1. Simulation parameters

Parameters	Value
Homogeneous nodes	100
MAC	802.11
Experiment run time	100 sec
Deployment Area	200 x 200 mts
Packet size	512-bytes
Comparing protocols	ECI-LEACH (GG, Girija Vasumathi) [33], ESCH (Salman et al., 2023) [34]
	and ICSI (Saleh et al., 2023) [35]
Traffic	CBR

Base Station	1
Initial Energy	0.5 J

4.1.Throughput

The proposed E2CMR's throughput graph in Figure 3 compares it with ECI-LEACH, ESH, and ICSI. The graph clearly shows that the number of packets transmitted to the BS grows. Even with the same node distribution, the farthest node uses more power to send data. The proposed E2CMR achieves higher throughput than other routing schemes, as shown in Table 2.

Table 2. Throughput Comparison of E2CMR with Existing Methods.

No of rounds	E2CMR	ECI-LEACH	ESCH	ICSI
10	100	100	100	100
20	100	86	75	78
30	95	64	51	58
40	74	51	37	43
50	52	32	16	21
60	35	18	0	8
70	19	0	0	0
80	0	0	0	0

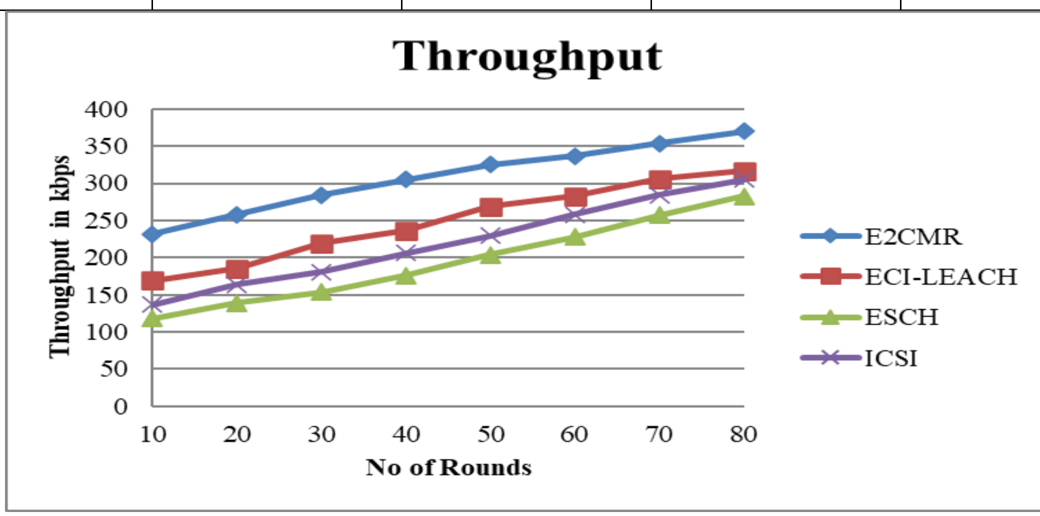

Figure 3. Classification Throughput vs. Number of Rounds

This is because E2CMR computes the distance between two clusters as the distance between any pair of points, such that clusters are more compact and relatively close to each other. Computation of cluster radius and multihop transmission aims to deliver a larger number of packets to the BS. However, ECI-LEACH evaluates path stability through prioritizing minimum energy consumption and has a greater chance of node death during relay selection. An improved energy threshold in E2CMR ensures balanced energy consumption, and RSSI values are used to layer nodes according to their distance to the BS for reliable multihop communications. Optimal CH selection in the proposed E2CMR yields higher network performance, and multihop transmission via reliable, energy-efficient nodes delivers more packets to the BS. However, other schemes ignore energy-efficient paths and rely on shortest paths found by minimizing cost.

4.2.Network Lifetime

To improve network lifetime, network efficiency is tested to minimize early node death. Network efficiency improves with increased network stability. Network stability is the time from when the first data packet from the node is transmitted across the network until the network is reliable and node energy consumption is balanced. In a large network, single-hop transmission has no impact on network stability compared to multihop transmission, as shown in Table 3.

Table 3. Alive Nodes vs Number of Rounds

No of rounds	E2CMR	ECI-LEACH	ESCH	ICSI
10	100	100	100	100
20	100	86	75	78
30	95	64	51	58
40	74	51	37	43
50	52	32	16	21
60	35	18	0	8
70	19	0	0	0
80	0	0	0	0

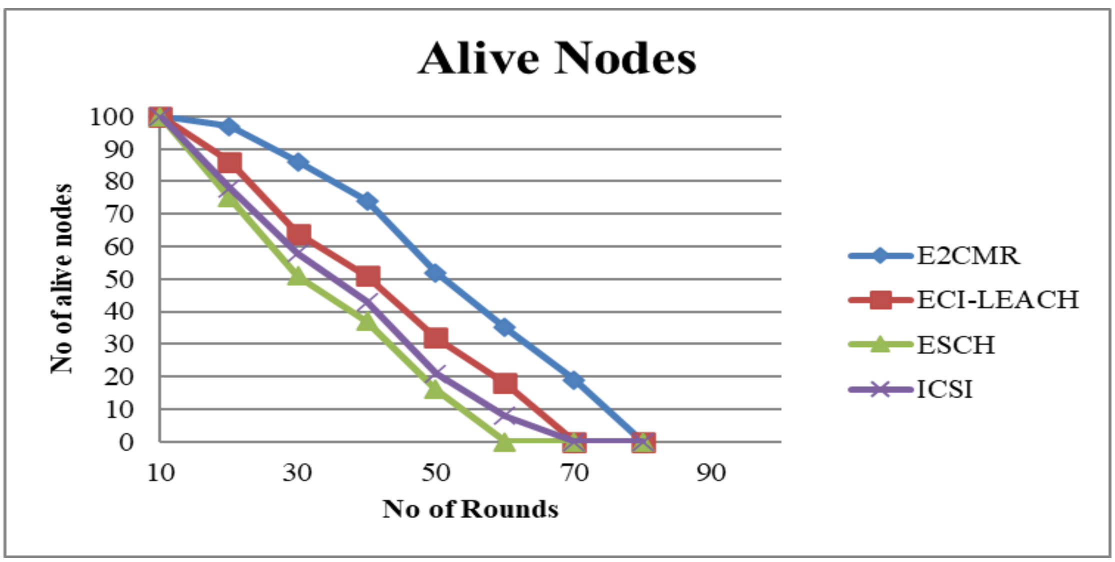

Figure 4. Alive Nodes vs. Number of Rounds

Figure 4 illustrates the proposed E2CMR compared with other methods during different rounds. E2CMR has a delayed occurrence of first node death (FND) while also delivering a greater number of packets. In E2CMR, the first node death occurs in the 30th round, whereas ECI-LEACH, ESCH, and ICSI experience FND in the 20th round. The proposed E2CMR outperforms ECI-LEACH, ESCH, and ICSI in terms of network stability by adapting threshold value calculation using energy adjustment parameters to prevent low-energy nodes from serving as relay nodes, thereby avoiding premature node death. E2CMR computes node layers based on RSSI and their distance to the BS for reliable multihop communication.

The proposed E2CMR protocol reduces packet loss and retransmissions through compact cluster formation, TDMA-based scheduling, and energy-efficient multi-hop routing. Compared with ECI-LEACH, ESCH, and ICSI, E2CMR achieves superior energy balancing and extends the network lifetime by 38%, outperforming the existing methods by 24%, 18%, and 21%, respectively.

The number of dead sensor nodes over successive communication rounds for the proposed E2CMR protocol and the existing ECI-LEACH, ESCH, and ICSI methods. The results demonstrate that E2CMR delays node failures and maintains fewer dead nodes throughout the simulation, indicating superior energy balancing and an extended network lifetime present in Table 4.

Table 4. Dead Nodes vs Number of Rounds

No of rounds	E2CMR	ECI-LEACH	ESCH	ICSI
10	0	0	0	0
20	3	14	25	22
30	14	36	49	42
40	26	49	63	57
50	48	68	84	79
60	65	82	100	92
70	81	100	100	100
80	100	100	100	100

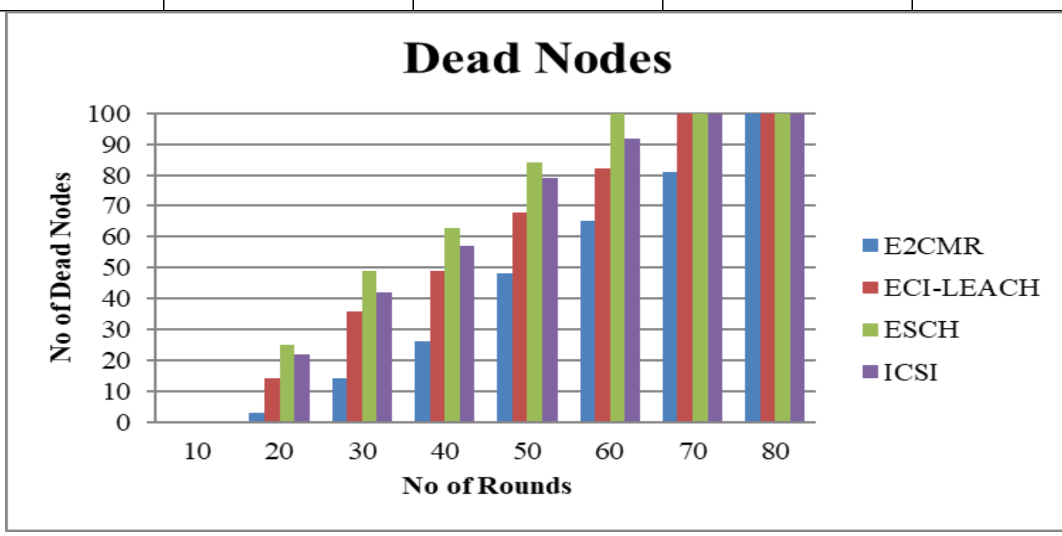

Figure 5. Dead Nodes vs. Number of Rounds

In Figure 5, the graph clearly shows that nodes start dying off at round 20 and that, compared to ECI-LEACH, ESCH, and ICSI, the proposed E2CMR has a lower number of dead nodes (3 vs. 14, 25, and 22, respectively). The enhanced threshold value, obtained by adjusting the energy parameters, is the basis for CH determination and rotation in E2CMR.

4.3.Leftover power

The suggested E2CMR approach has more residual energy than the others because nodes close to the BS do not take part in layer building, leading to a high RSSI intensity and, therefore, a slower energy decline (as shown in Table 6). Alternatively, under this arrangement, the nodes die because they are too busy relaying data to the BS.

Choosing an appropriate CH by adjusting the threshold and using multihop transmission to minimize longer communication distances reduces retransmissions and balances energy among nodes. The graph shows that at round 50, the residual energy of ECI-LEACH is 3%, while ESCH and ICSI have zero energy, compared to E2CMR with 26% remaining energy is shown in Figure 6.

Table 5. Remaining Energy vs Number of Rounds

No of rounds	E2CMR	ECI-LEACH	ESCH	ICSI
10	50	50	50	50
20	47	28	31	23
30	40	21	20	12
40	32	12	7	6
50	26	3	0	0
60	13	0	0	0
70	0	0	0	0
80	0	0	0	0

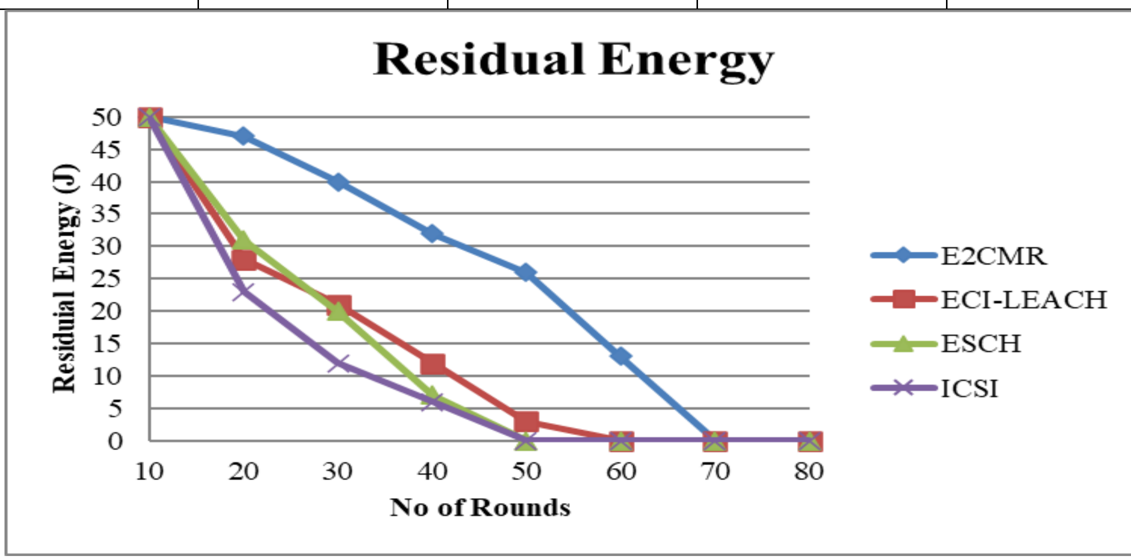

Figure 6. Remaining Energy vs. Number of Rounds

4.4.Overhead

The proposed E2CMR achieves the lowest routing overhead (26) compared to ECI-LEACH (43), ESCH (38), and ICSI (49) by leveraging RSSI-based node layering and energy-efficient multi-hop routing. This approach minimizes packet retransmissions and unnecessary energy consumption, resulting in more efficient route management.

Table 6 compares the routing overhead of the proposed E2CMR protocol with ECI-LEACH, ESCH, and ICSI across successive communication rounds.

Table 6. Overhead vs Number of Rounds

No of rounds	E2CMR	ECI-LEACH	ESCH	ICSI
10	8	14	12	15
20	10	17	14	22

30	12	24	18	29
40	14	27	21	33
50	16	31	25	38
60	19	35	29	42
70	22	39	32	46
80	26	43	38	49

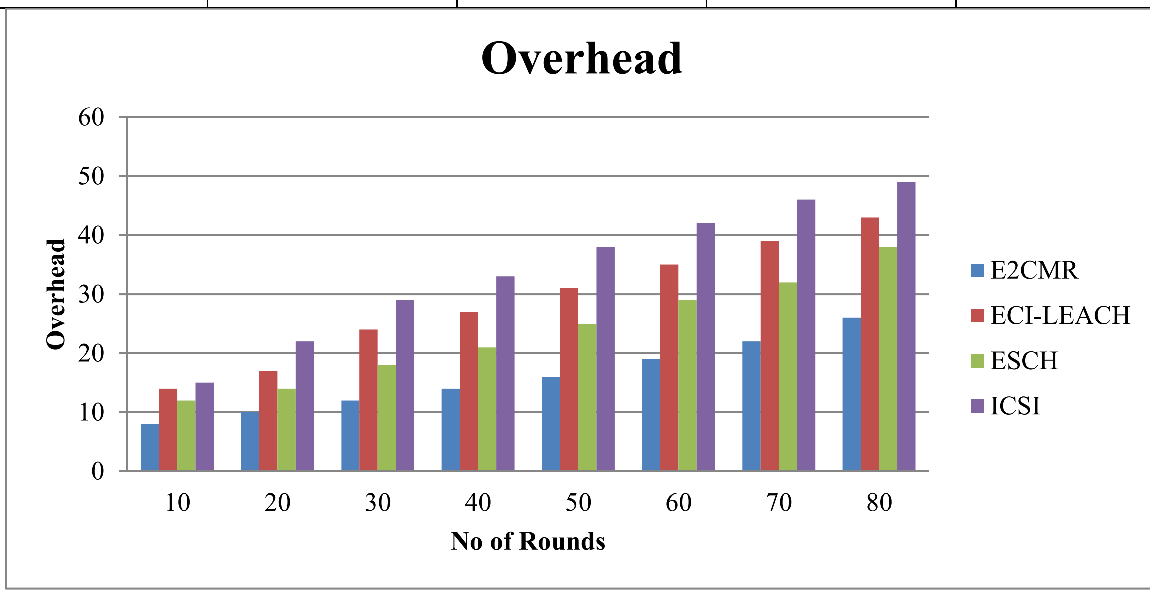

Figure 7. Overhead vs. Number of Rounds

Figure 7 to provide a comprehensive evaluation of the proposed E2CMR protocol, a comparative analysis was conducted against ECI-LEACH, ESCH, and ICSI using key performance metrics, including throughput, first node death (FND), residual energy, routing overhead, and network lifetime improvement. Table 7 summarizes the overall performance of all routing protocols and highlights the effectiveness of the proposed E2CMR framework in achieving balanced energy consumption, reliable data transmission, and extended network operation.

Table 7. Overall Performance Comparison of Routing Protocols

Performance Metric	ECI-LEACH	ESCH	ICSI	Proposed E2CMR
Throughput (kbps)	320	285	305	370
First Node Death (Round)	20	20	20	30
Residual Energy at Round 50 (%)	3	0	0	26
Routing Overhead	43	38	49	26
Network Lifetime Improvement (%)	24	18	21	38

Overall performance comparison of E2CMR against ECI-LEACH, ESCH, and ICSI across multiple evaluation metrics. The proposed E2CMR achieves the highest throughput (370 kbps), delays the first node death to the 30th round, retains 26% residual energy at round 50, and reduces routing overhead to 26. In addition, E2CMR attains the highest network lifetime improvement of 38%. These results demonstrate that integrating adaptive cluster head selection, RSSI-based node layering, and energy-aware multi-hop routing significantly enhances network efficiency and prolongs the operational lifetime of the wireless sensor network.

5. Conclusion

The paper presented E2CMR, an Energy-Efficient Cluster-Based Multi-Hop Routing protocol, to not only improve network lifetime but also optimize communication in Wireless Sensor Networks. The suggested framework includes RSSI-based node layering, adaptive cluster head selection, energy-aware multi-hop routing, and dynamic cluster head rotation, which overcome the drawbacks of conventional LEACH-based routing schemes. E2CMR uses an improved threshold computation that accounts for residual energy, initial energy, and average network energy, which helps balance cluster head selection and prevents sensor nodes from depleting energy too soon.

Simulations conducted in NS-2 utilizing the proposed method, comparable to ECI-LEACH, ESCH, and ICSI, affirmed its effectiveness. Based on the results, the E2CMR yielded 370 kbps throughput, delayed the first node death from the 20th to the 30th round, had 26% residual energy at round 50, reduced routing overhead to 26, and improved network lifetime by 38%. Efficient cluster formation, compact multi-hop communication paths, and optimized energy usage across the network can achieve these.

Generally, the E2CMR offers a dependable and scalable routing solution for energy-constrained WSN applications requiring reliable communication and prolonged network operation. In the future, we will develop security mechanisms that account for trust parameters and intelligent optimization methods, as well as frameworks that detect malicious nodes, thereby enhancing routing reliability and network energy efficiency in a wireless sensor environment. Therefore, E2CMR provides a robust and scalable solution for energy-constrained WSN environments where prolonged network operation and reliable data delivery are critical. Future research may focus on integrating trust-aware security mechanisms, malicious node detection, and intelligent optimization techniques to further enhance routing reliability, energy efficiency, and network resilience in dynamic WSN deployments.

REFERENCES

1. T. Bala, V. Bhatia, S. Kumawat, V. Jaglan, A survey: issues and challenges in wireless sensor network, Int. J. Eng. Technol. 7 (2018) 53–55.
2. A. Bagwari, J. Logeshwaran, K. Usha, An enhanced energy optimization model for industrial wireless sensor networks using machine learning, IEEE Access 11 (2023) 96343–96362.
3. A. Alferaidi, K. Yadav, Y. Alharbi, J.S. Alshudukhi, et al., Challenges in human centric intelligent systems for wireless sensor networks: a state of art, Trans. Emerg. Telecommun. Technol. 35 (4) (2024) e4850.
4. D.W. Wajgi, J.V. Tembhurne, Localization in wireless sensor networks and wireless multimedia sensor networks using clustering techniques, Multimed. Tools Appl. 83 (3) (2024) 6829–6879.
5. M. Almazaideh and J. Levendovszky, "Novel reliable and energy-efficient routing protocols for wireless sensor networks," Journal of Sensor and Actuator Networks, vol. 9, no. 1, 2020.
6. O. I. Khalaf and G. M. Abdulsahib, "Energy efficient routing and reliable data transmission protocol in WSN," International Journal of Advances in Soft Computing and Its Applications, vol. 12, no. 3, pp. 45–53, 2020.
7. L. Chan, K. Gomez Chavez, H. Rudolph, and A. Hourani, "Hierarchical routing protocols for wireless sensor network: a compressive survey," Wireless Networks, vol. 26, no. 5, pp. 3291–3314, 2020
8. I. Daanoune, B. Abdennaceur, and A. Ballouk, "A comprehensive survey on LEACH-based clustering routing protocols in wireless sensor networks," Ad Hoc Networks, vol. 114, article 102409, 2021.
9. Chan, L.; Chavez, K.G.; Rudolph, H.; Hourani, A. Hierarchical routing protocols for wireless sensor network: A compressive survey. Wirel. Netw. 2020, 26, 3291–3314.
10. R. Abd-Elnaby, et al., Energy-Efficient routing protocol based on adaptive soft thresholding for wireless sensor networks, Wirel. Pers. Commun. 124 (3) (2022) 2661–2676.
11. G. Anastasi, M. Conti, M. Di Francesco, et al., Energy conservation in wireless sensor networks, Ad Hoc Netw. 7 (3) (2009) 537–568.
12. A. Cenedese, M. Luvisotto, and G. Michieletto, ''Distributed clustering strategies in industrial wireless sensor networks,'' *IEEE Trans. Ind. Informat.*, vol. 13, no. 1, pp. 228–237, Feb. 2017.
13. D. Gurusamy and S. Abas, ''Modified clustering algorithms for energy harvesting wireless sensor networks—A survey,'' in Proc. 21st Int. Arab Conf. Inf. Technol. (ACIT), Giza, Egypt, Nov. 2020, pp. 1–11.

14. R. Pachlor and D. Shrimankar, ‘‘VCH-ECCR: A centralized routing protocol for wireless sensor networks,’’ *J. Sensors*, vol. 2017, pp. 1–10, Jan. 2017.
15. K. Xu, Z. Zhao, Y. Luo, et al., An energy-efficient clustering routing protocol based on a high-QoS node deployment with an inter cluster routing mechanism in WSNs, Sensors 19 (12) (2019) 2752.
16. A.A. Baradaran, F. Rabieefar, NEECH: new energy-efficient algorithm based on the best cluster head in wireless sensor networks, Iran. J. Sci. Technol.: Trans. Electr. Eng. 47 (3) (2023) 1129–1144.
17. R. Nithya, R. Alroobaea, A. Binmahfoudh, et al., Distributed multi-hop clustering approach with low energy consumption in WSN, Comput. Syst. Sci. Eng. 45 (1) (2023) 903–924.
18. N. Moussa, Z. Hamidi-Alaoui, and A. El Belrhiti El Alaoui, ‘‘ECRP: An energy-aware cluster-based routing protocol for wireless sensor networks,’’ *Wireless Netw.*, vol. 26, no. 4, pp. 2915–2928, May 2020.
19. Z. Wang, H. Ding, B. Li, L. Bao, Z. Yang, and Q. Liu, ‘‘Energy efficient cluster based routing protocol for WSN using firefly algorithm and ant colony optimization,’’ *Wireless Pers. Commun.*, vol. 125, no. 3, pp. 2167–2200, Aug. 2022.
20. A. D. Gupta and R. K. Rout, ‘‘An effective optimization method for energy efficient clustering in EH wireless sensor networks,’’ in *Proc. Int. Conf.Technol. Advancements Innov. (ICTAI)*, Tashkent, Uzbekistan, Nov. 2021, pp. 699–702
21. R. Priyadarshi, ‘‘Energy-efficient routing in wireless sensor networks: A meta-heuristic and artificial intelligence-based approach: A comprehensive review,’’ *Arch. Comput. Methods Eng.*, vol. 31, no. 4, pp. 2109–2137, May 2024.
22. B. M. Sahoo, H. M. Pandey, and T. Amgoth, ‘‘GAPSO-H: A hybrid approach towards optimizing the cluster based routing in wireless sensor network,’’ *Swarm Evol. Comput.*, vol. 60, Feb. 2021, Art. no. 100772.
23. Z. Al Aghbari, A. M. Khedr, W. Osamy, I. Arif, and D. P. Agrawal, ‘‘Routing in wireless sensor networks using optimization techniques: A survey,’’ *Wireless Pers. Commun.*, vol. 111, no. 4, pp. 2407–2434, Apr. 2020.
24. S. Mohapatra, P. K. Behera, P. K. Sahoo, S. K. Bisoy, K. L. Hui, and M. Sain, ‘‘Mobility induced multi-hop LEACH protocol in heterogeneous mobile network,’’ *IEEE Access*, vol. 10, pp. 132895–132907, 2022.
25. H. Sun, D. Pan, D.Wang, and Z. Meng, ‘‘LPLL-LEACH: A study of a lowpower and low-delay routing protocol based on LEACH,’’ *Ad Hoc Netw.*, vol. 140, Mar. 2023, Art. no. 103064.
26. W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, ‘‘Energyefficient communication protocol for wireless microsensor networks,’’ in *Proc. 33rd Annu. Hawaii Int. Conf. Syst. Sci.*, 2000, p. 10.
27. Z. Beiranvand, A. Patooghy, and M. Fazeli, ‘‘I-LEACH: An efficient routing algorithm to improve performance & to reduce energy consumption in wireless sensor networks,’’ in *Proc. 5th Conf. Inf. Knowl. Technol.*, Shiraz, Iran, May 2013, pp. 13–18.
28. Xuguang Chai, Yalin Wu, Lei Feng, Energy-efficient scalable routing algorithm based on hierarchical agglomerative clustering for Wireless Sensor Networks, Alexandria Engineering Journal, Volume 120, 2025, Pages 95-105, ISSN 1110-0168, https://doi.org/10.1016/j.aej.2025.02.018.
29. V. Gangal, I. Cinemre and G. Hacioglu, "A Distributed Leach-AHP Routing for Wireless Sensor Networks," in IEEE Access, vol. 12, pp. 19307-19319, 2024, doi: 10.1109/ACCESS.2024.3359750.
30. Azamuddin Ab Rahman, Sakib Iqram Hamim, Improved K-means clustering and adaptive distance threshold for energy reduction in WSN-IoTs, Array, Volume 27, 2025, 100436, ISSN 2590-0056, https://doi.org/10.1016/j.array.2025.100436.
31. L. Wu, A. Y. Dawod, and F. Miao, ‘‘Data transmission in wireless sensor networks based on ant colony optimization technique,’’ *Appl. Sci.*, vol. 14, no. 12, p. 5273, Jun. 2024.
32. S. K. M, G. A. S. K, Efficient hybrid energy optimization method in location aware unmanned WSN, *I*ntell. Autom. Soft Comput. 35 (1) (2023) 705–725.
33. GG, Girija Vasumathi. "Optimized energy-aware cluster head selection mechanism for enhancing wireless sensor network lifetime." AKCE International Journal of Graphs and Combinatorics (2025): 1-15. https://doi.org/10.1080/09728600.2025.2572776
34. Salman, Fadhil Mohammed, Ahssan Ahmmed Mohammed, and Ahmed Fakhir Mutar. "Optimization of LEACH protocol for WSNs in terms of energy efficient and network lifetime." Journal of Cyber Security and Mobility 12.3 (2023): 275-296.
35. Saleh, S.S.; Alansari, I.S.; Farouk, M.; Hamiaz, M.K.; Ead, W.; Tarabishi, R.A.; Khater, H.A. An Optimized Hierarchal Cluster Formation Approach for Management of Smart Cities. Appl. Sci. 2023, 13, 13143. https://doi.org/10.3390/app132413143.