INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

ORIGINAL ARTICLE

Path Quality Aware Energy Efficient Technique to Increase Packet Delivery Ratio in the Internet of Things

A. Thomas Felix[1]*, **P. Calduwel Newton**[2]

1 Department of Computer Science, Government Arts College, Kulithalai, Tamilnadu, India, Affiliated to Bharathidasan University, Tiruchirappalli, Tamilnadu, India
2 Department of Computer Science, Government Arts College, Trichy-22, Tamilnadu, India, Affiliated to Bharathidasan University, Tiruchirappalli, Tamilnadu, India

OPEN ACCESS

Received: 23/02/2025

Accepted: 29/03/2025

Published: 06/05/2025

Citation: Thomas Felix A, Calduwel Newton P (2025) Path Quality Aware Energy Efficient Technique to Increase Packet Delivery Ratio in the Internet of Things. Indian Journal of Science and Technology 18(15): 1201-1219. https://doi.org/10.17485/IJST/v18i15.347

* **Corresponding author**.

athomasfelix@gmail.com

Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Abstract

Objectives: The key objectives are to enhance the performance of Internet of Things (IoT) networks to attain a high packet delivery ratio (PDR), efficient residual energy (RE) usage, minimum energy consumption, and decrease packet loss during data transmission. Performance metrics are used to discover and choose high, top-notch, and long-living paths, increasing network lifetime and optimizing resource management by preventing the participation of non-essential nodes and inefficient paths in the network routing process. **Methods:** To devise an energy-efficient technique and refine it with decision-making for selecting an optimal path, which employs a composite metric path quality index (PQI) to enhance path quality, comprising RE for priority of nodes with maximum remaining energy, link quality score (LQS), packet delivery ratio (PDR) and hop count (HC) to minimize the path length must be integrated into the routing process to make data transmission more efficient. Hence, intermediate nodes ensure path quality, determine if packet flow is good or bad, eliminate unnecessary nodes, and optimize the whole routing by deciding on a path. The proposed technique simulates IoT network scenarios in which nodes dynamically compute these metrics and select optimal paths for transmitting data to the sink node. **Findings:** The proposed technique achieves a much higher PDR and an energy-proficient routing mechanism by balancing the quality of the optimal path, the residual energy, and the number of hops, which can not only prolong the network lifetime but also ensures that resources are being used efficiently, in turn all leading to a better network performance than existing methods. Simulation results show that the proposed technique significantly improves the PDR over the existing methods and reduces overall energy consumption. In this work, the validated results show that metrics PQI, RE, LQS, and HC collectively improve data delivery and ensure higher survivability of the network by optimizing the path choosing and eliminating the unnecessary nodes from the source to the target. The proposed technique simulation showed a 32.15% increase in network RE and a 36.44% improvement in PDR. **Novelty:** The technique presented in this paper introduces a routing approach designed with the unique integration of RE, LQS, PDR, and HC, deriving PQI metric, which will improve the path selection in IoT networks. Unlike existing methods, this method considers energy efficiency, path quality instead of link quality, and path length together to avoid over-utilizing energy-draining nodes while favoring stable, efficient paths. The approach fills a gap in existing IoT environments by focusing on energy-wise efficiency and path reliability and reducing the number of nodes unnecessarily concerned with the dynamic optimal path selection. As IoT deployments increase, so does the need for energy-efficient data transmission, and the proposed technique supports the sustainability of IoT networks.

Keywords: Energy Efficiency; Path Quality Indicator; Residual Energy; Hop Count; Quality of Service

1 Introduction

The IoT is a system of interrelated physical objects, including sensors, actuators, and wearables, that can connect, collect, store, and transmit data without human involvement. Such systems often operate under constraints, including limited energy resources, unstable wireless connections, and the need for scaling and energy-efficient operation. Due to the limited storage and power characteristics of sensor nodes and applications, innovative methods are devised to reduce the power consumption. Sensor nodes require designs and protocols that conserve energy for operational longevity. However, without sacrificing their functionality or map structure, sensors must be identified to accurately predict the energy consumption required to create new networks with little energy consumption. In this light, energy is traded for longevity, quality of service (QoS), and reliability. Detecting and sustaining the paths with the best energy efficiency between nodes is significant for IoT devices. All other IoT devices besides the sink node (SN) have restrictions on energy, memory size, and the ability to compute. The limited energy of batteries hinders the time and scalability of the IoT network. Studies have focused on low-power protocols, network structuring, routing protocols, and coverage problems. Many systems have concentrated on improving IoT sensor networks' energy efficiency and communication reliability.

Though energy consumption management is proficient, the present technique is limited in offering great analytics about energy distribution per node, the impact of link quality metrics on node clustering, the impact of signal quality metrics on network performance, and the total influence of multi-hop improvement on the performance of the network [1]. The low energy and overhead (LEO) metric is an energy-sensitive routing that guarantees cluster head (CH) option maintaining away from duplicate transmissions. Packet reception ratio (PRR) and signal-to-noise ratio (SNR) can be defined as a joint planar line function; however, no investigation is available that follows this relationship for estimating link reliability and energy efficiency. Moreover, the existing method fails to take advantage of received signal strength indicator (RSSI) and SNR information for link quality-based path selection. RSSI and SNR must be used to evaluate a link's quality because they can be calculated passively, avoiding active sensing and added overhead [2]. These challenges can be addressed with a transition towards dependable routing such as energy efficiency, fault tolerance, etc., and the integration of these characteristics into intelligent algorithms based on Internet of things (IoT)-based wireless sensor networks (WSN) for stable and sustainable network performance [3]. In such a scenario, a WSN security and energy optimization protocol that leverages a coupled ensemble selection approach (CESA) with optimal type-2 fuzzy logic (OT2FL) for managing node energy and link quality uncertainties to optimize CH selection and CH-admitted route stability is suggested. Although an innovative solution was presented, it only addressed the aspect of energy efficiency, while other important issues such as energy distribution of various topologies, routing based on live residual energy depletion rate of different nodes and impact of link quality (RSSI, SNR) and hop count on network performance was not addressed [4]. An artificial bee colony-traffic aware energy efficient routing (ABC-TEER) -based clustering algorithm dynamically selects the CH base as a trade-off of the residual energy of the nodes and the distance to the CH. It has been shown to perform better regarding energy uptake, network lifetime, energy usage, and delivery ratio. ABC algorithm does not consider the actual traffic loads and energy consumption measures for different network conditions, which may cause energy waste. While these concepts are recognized, optimizing hop-count across diverse network topologies is not examined [5].

To improve the efficiency of route replies controlled by the route reply (RREP) function, a multipath-optimized ad hoc on-demand distance vector (M-O-AODV) algorithm is introduced. The algorithm deals with the reliability and stability problems of Bluetooth Low Energy (BLE) mesh networks of various IoT applications. Yet, in this upcoming state, no protocols exist to ensure energy will not be consumed unevenly at random nodes. In addition, the residual energy of nodes is often neglected, as routing decisions and network performance are typically based only on some hop count, disregarding signal quality metrics [6]. As a solution to this, a multi-parameter, heterogeneous wireless sensor network-based IoT (HWSN-IoT) incorporating dynamic relay node selection and CH rotation is suggested to mitigate energy consumption and prolong network lifespan. Further, this strategy yields inconsistent energy consumption patterns for heterogeneous nodes and does not consider the quality of link, hop count, and signal metrics [7]. The bio-inspired energy-efficient clustering and routing (BICR) approach is proposed to preserve the nodes' battery power when communicating with the sink. These are disaster recovery-based algorithms that focus on network lifetime. However, as BICR ensures the rotation of CH in fixed time intervals, it wastes energy in no-traffic phases. Also, when CH selection is the only focus, packet collisions are not sufficiently limited in dense clusters, reducing the PDR during disaster peaks[(8)]. To this end, we propose a new multipath optimized routing protocol for low-power and lossy networks (MO-RPL) algorithm that seeks to enhance energy efficiency and reliability in real-time traffic applications in the IoT. However, MO-RPL does not adjust multipath routing parameters (residual energy, hop count, SNR) in service of QoS requirements, which leads to energy wastage. Though this method decreases energy usage, it raises the processing burden on low-power nodes via the multi-criteria path selection algorithm[(9)]. A new innovative genetic algorithm is discussed, called energy-efficient genetic algorithm (EEGA), based on an evolutionary algorithm to produce a near-optimal path. To achieve this, the algorithm dynamically optimizes energy efficiency to balance energy consumption, the backward edge, and the stability of the IoT network. However, the weights assigned to energy and hop count in the fitness function parameter in the EEGA is a fixed value and remains unchanged under different traffic and node mobility. Moreover, overall path quality is not considered during routing, which is a potential area for improvement[(10)].

1.1 Research gaps

The different algorithms indicate classic dynamic network conditions and global energy optimization issues. However, critical research gaps remain, leading to open challenges in essential performance metrics.

1. The energy-space dynamic of nodes' energy consumption, which is likely to change dynamically, needs to be optimized. In addition, these algorithms do not use an adaptive mechanism in dynamic environments, while residual energy constant thresholds are employed to select the paths.
2. Path selection is energy efficient and based on hop count. Still, it does not account for time-averaged link quality indicators during the link selection, which can lead to repeated transmissions and packet drops in noisy environments.
3. Some methods consider hop count under certain conditions, but a more fluid integration of multi-hop dynamics relative to the rest of the information landscape is left to explore. Such methods might adjust trajectories with low hop density.
4. No current routing algorithms explicitly handle RSSI and SNR parameters, suggesting valuable opportunities to improve routing algorithms to incorporate these parameters. On the other hand, if the RSSI/SNR degradation is momentary, the algorithms may not trigger the updating of the paths, leading to unnecessary transmissions and energy consumption.
5. Algorithms include more adaptive methods for power-efficient networks able to self-tune to disperse network problems. However, these algorithms assume homogeneous battery capacities and lack adaptive node thresholds. The performance of the PDR can further be enhanced in larger-scale networks.

To overcome these challenges, we must establish dynamic, flow-simulation-based energy thresholds at the nodes and additional link mitigation methods to address isolated nodes as the real-time fluctuating traffic, node mobility, energy conservation features, and adaptive methodologies which establish a balance of real-time metrics like RE, SNR, LQS, and lightweight computations are needed. Latency-sensitive traffic is optimized by a dynamic hop-count, which negates the need for any energy consumption to packet reception trade-offs. Access to all links is essential as the stability of the path is dependent on it.

The novelty of this study is the introduction and the use of composite metric PQI, comprising parameters such as RE, LQS, SNR, and HC. To address this issue, this work proposes a qualified energy efficient path selection mechanism through energy conservation extending the lifetime of sensor nodes to sustain energy balance among nodes, improving PDR and thus improving the QoS. Dynamic threshold adjustment is adopted in on-demand energy optimization (OEE), where nodes are integrated into the best path if its unused energy is greater than the energy set by the predetermined energy threshold (E_{THR}). The goal is not to transmit through any node but to do that with consideration to the E_{THR} criterion: if some node fails to satisfy E_{THR}, it will be omitted from the optimal path. This study was motivated by the above-mentioned research gaps. The main strengths and weaknesses of recent studies are summarized in Table 1.

2 Methodology

The proposed path quality aware energy efficient technique (PAQE2T) uses composite metrics, RE, SNR, LQS, and HC to derive PQI to decrease energy utilization along the optimal path and to avoid lengthy and unnecessary paths using dynamic adaption. The network conditions must be predicted using the surrounding node's RE, SNR, and HC to estimate path quality. They calculate the node's energy required for each potential path. To improve PDR, QoS, and energy efficiency in IoT applications, nodes must plan dynamically and adapt to path selection. The PQI parameter estimates the quality of the end-to-end path. When

Table 1. Advantages and limits of recent works

Citations	Authors	Algorithms used	Advantages	Disadvantages
(1)	Juwaied A et al.,	KNN	• Efficient energy management • Security	• Nonadaptability
(2)	Fitos M et al.,	LEO	• Power adjustment • Dynamic adaption	• Flooding of packets
(3)	Nimmala S et al.,	Intelli BEF	• Energy efficient • Less latency	• Performance issues • Scalability
(4)	Ambareesh S et al.,	IT2FLS	• Optimized clustering • Improved lifetime • Security	• Network complexity
(5)	Gupta M et al.,	ABC-TEER	• Throughput • Performance improvement	• Nodes died prematurely
(6)	Ghori MR et al.,	M-O-AODV	• Improved PDR • Lower overhead • Robustness	• Link disruptions • Node density • Security
(7)	Shafique T et al.,	HWSN-IoT	• Increased energy efficiency • Throughput • Heterogeneity • Scalability	• Complexity • Communication overhead • Dependency
(8)	Ahmed S et al.,	BICR	• Improved RE • Throughput • Improved network lifetime	• Packet drops
(9)	Abujassar RS	nPSIR	• Stability • Less end-to-end delay	• Adaption to various topologies
(10)	Akhter F et al.,	EEGA	• Improved energy efficiency • Reduced packet loss• Centralized method	• Dependency • Overhead • Complexity• Adaption time
(11)	Sheikh AM et al.,	ISERP	• Improved network lifetime • Better energy efficiency	• Complexity • Implementation cost
(12)	Tekulapally V et al.,	IMP-RES-EL	• Energy efficiency • Improved packet transmission • Improved network lifetime	• Network requirements • Complexity
(13)	Somula R et al.,	EACH-COA	• Network longevity • Throughput • Reduced energy consumption • Faster convergence	• Complexity
[Proposed Technique]	Thomas Felix A et al.,	PAQE2T	• Improved RE and network lifespan • Improved PDR • Low energy consumption • Minimum packet loss	• No adaption for heterogeneous networks

choosing the most energy-efficient path, using the most significant PQI estimate is best instead of the link quality indicator (LQI) parameter, which fails miserably under different conditions and is unreliable. The energy-efficient alternative optimal path with the next highest PQI estimate is selected. This metric maximizes the PDR, minimizes packet failure and re-transmissions by a node, and improves QoS [14].

In the real-world network, embedded devices use an IEEE 802.15.4-compliant RF transceiver radio modules like the Texas Instruments^{TM} Chipcon CC2620 [15]. The CC2620 uses a correlation range of 50–110 to correlate incoming packets, with 110 being the highest quality frame and 50 the lowest. LQI is a measure provided by the IEEE 802.15.4 physical layer. The LQI value is obtained from the RSSI, SNR, or both factors. Much research has shown that the LQI correlates with the packet error rate (PER) and the link delivery ratio (LDR). Chipcon advises converting correlation values into a scale of 0 to 255 via linear conversion. LQI is the link quality among two nodes. The single LQI value did not include end-to-end path quality. Thus, path discovery requires cross-layer information. The empirical results of CC2620 are shown in Table 2 [16].

Table 2. LQI classification of CC2620

LQI	Connectivity Quality
LQI = 255	**Best Link**
LQI < 165	**Bad Link**
165 ≤ LQI < 255	**Uncertain Link**

The LQI estimation by devices is explicit to a vendor. So, the two LQI values measured by various vendors' devices differ. Only the links for which LQI meets the condition $165 \leq LQI < 255$ require more data retransmission. RE, SNR, and HC metrics are updated with each transmission. Then, it calculates PQI and estimates the path quality. The nodes should determine path quality, know nearby node RE, and calculate the total hops required to reach the endpoint node, adapting the dynamic energy-efficient path selection technique. This method determines the most energy-efficient path between two points. Each node records its battery level and periodically compares it to the stored level when an app starts. Suppose the energy intensity of the current optimum path is exhausted before the data transmission is completed; in that case, the alternate path is immediately employed to complete the data transfer without the re-route discovery process.

2.1 Network Model

In this study, we employ a network model where sensor nodes are randomly dispersed over an area with a dimension of N x N. The SN is in the center of the network and has strong computing power. This study does not account for SN energy loss, as SN energy may be restored by itself. The following assumptions may be drawn from this:

1. The moment sensor nodes and sinks are deployed, they remain immobile. Nodes cannot supplement their energy levels, and data transmission between them can take one or more hops.
2. The sensors can adjust their transmission power levels. The sink is not energy-limited compared to the energy of the other sensors in the network.
3. The signal intensity allows us to determine the distance between any two nodes and tweak the transmission power.
4. The SN is immobile and has not moved from its current position.
5. Real-world variables like air temperature, humidity, light intensity, wind speed, and direction are not accounted for in the idealized simulation setting.

2.2 Energy Model

The proposed technique, PAQE2T, demonstrates the first-order radio model energy dissipation for sensing, transmitting, and receiving and adopts the following energy model for every sensor node. The rate of energy dissipation for a node needed to transmit a "k"-bit packet across a distance of "d" (Euclidean distance) is specified as follows [17], [18],

$$ETX_i(k,d) = \left\{ \begin{array}{l} k * ETX_{elec} + k * \Sigma_{fs} * d^2 \\ k * ETX_{elec} + k * \Sigma_{mp} * d^4 \end{array} \right\} when \left\{ \begin{array}{l} d < d_0 \\ d \geq d_0 \end{array} \right\} \tag{1.1}$$

$$ERX_i(k) = k * ERX_{elec} \tag{1.2}$$

Where ETX and ERX are transmission and receiving energy, d^2 and d^4 are the distances based on free-path and multi-path losses, respectively, and $\sum_{fs}$ and $\sum_{mp}$ signify the power amplification coefficients for free space channels (fs) and multipath fading channels (mp). The threshold distance d_o is defined as,

$$d_0 = \sqrt{\frac{\Sigma_{fs}}{\Sigma_{mp}}} \tag{2}$$

In a two-dimensional space, the Euclidean distance between the nodes X_i and Y_i are the i^{th} nodes, and sink nodes X_{SN} and Y_{SN} are calculated as,

$$d_i = \sqrt{(X_i - X_{SN})^2 + (Y_i - Y_{SN})^2} \tag{3}$$

The energy consumption (EC) for node *i* is given in **equation (4)**, and RE is shown in **equation (5)**, where E_{IDLE} denotes the idle CPU,

$$EC_i = ETX_i + ERX_i + E_{IDLE} \tag{4}$$

$$RE_i = RE_{initial} - EC_i \tag{5}$$

The EC[19] formula is extended to calculate energy for a round (E_R) is modified in **equation (6)** as follows,

$$E_R = 4000 * \left(2*n*ETX + K*EDA + K*E_{mp}*d^4 + n*E_{fs}*d^2\right) \tag{6}$$

Where n is the number of nodes, ETX is the transmitted energy, EDA is the data aggregation energy, K is the number of cluster heads, E_{fs} is the free space loss, E_{mp} is the multi-space loss, and d is the Euclidean distance.

2.3 PQI metric derivation

The proposed PAQE2T contemplates the PQI metric to evade dispatching the data packets on unpredictable paths. Path quality estimation enables nodes to pick the optimal path for delivering the data to the target. The PQI estimates the path quality, and the energy-efficient path from the origin to an endpoint is selected. The PQI is calculated using the following equations. The path energy (PE) is the sum of residual energy of nodes on a path from S to D computed in **equation (7)** given as,

$$\text{PE(S, D)} = \sum_{i=1}^{n} \text{Residual Energy of Nodes on Path (S, D)} \tag{7}$$

The path energy ratio (PR) is a percentage of the residual energy of the chosen path relative to all possible paths calculated in **equation (8)** given as,

$$PR(S,D) = \frac{PE(S,D)}{\max\left(PE_{all-paths}\right)} \tag{8}$$

Where $0 \leq \text{PR(S, D)} \leq 1$. This formula ensures that we prioritize paths with higher RE. Receiving RSSI and LQI readings from the radio CC2620 is as simple as accessing the associated internal registers. The $RSSI_{VAL}$ is the RSSI value provided by CC2620, a 12-bit register, and $RSSI_{OFFSET}$ is -45dBm, an empirical correction value, according to the CC2620 datasheet. The CC2620 calculates LQI numbers only on successfully received packets but continuously calculates RSSIs. The software can read RSSI whenever it wants to determine the ambient RF energy. LQI indicates the quality of the received packets; the higher the LQI, the better the quality of the received packet. The empirical results of RSSI predictions are given. We use the RSSI value in **equation (9.1)** and **equation (9.2)** to determine the received power given as,

$$RSSI' = RSSI_{VAL} + RSSI_{OFFSET}(dBm) \tag{9.1}$$

$$RSSI = \begin{cases} RSSI' \geq -85.65 \text{ dBm, then Best link} \\ -87 < RSSI' \leftarrow 85.65 \text{ dBm, then Uncertain link} \\ RSSI' \leq -87 \text{ dBm, then Bad link} \end{cases} \tag{9.2}$$

SNR is used to measure the quality of link behavior. Background noise to received signal strength ratio When the receiver has to estimate SNR, it would first log the received packet RSSI and then read the rest of the background noise. The SNR[20] is calculated in **equation (10)** as,

$$SNR = RSSI - Background\ noise\ (dBm) \tag{10}$$

Empirical results of PDR predictions are calculated as in **equation (11)**[21],

$$PDR = \begin{cases} PDR \geq 0.75, \text{ then Best link} \\ 0.3 < PDR < 0.75, \text{ then Uncertain link} \\ \text{PDR} \leq 0.3, \text{ then Bad link} \end{cases} \tag{11}$$

The proposed PAQE2T uses combined metrics RSSI, SNR, and PDR metrics to estimate the link quality. The link quality estimator (LQE) is computed in **equation (12)**,

$$LQE = \begin{cases} 1, \text{ if } RSSI \geq -85.65 \text{ dBm} \cup \text{SNR} \geq 40 \text{ dBm} \cup \text{PDR} \geq 0.75 \\ 0.5, \text{ if } RSSI < -85.65 \text{ dBm} \cup \text{SNR} < 40 \text{ dBm} \cup \text{PDR} < 0.75 \\ 0, otherwise \end{cases} \tag{12}$$

Using the normalized geometric mean method for link qualities, we obtain a link quality score (LQS) as given in **equation (13)**,

$$LQS(S,D) = \left(\prod_{i=1}^{n} LQE_i\right)^{\frac{1}{n}} \tag{13}$$

Where $0 \leq$ LQS(S, D) ≤ 1. This formula ensures the path's reliability. Now, the hop count for a path (HC_{Path}) is calculated in **equation (14)**,

$$HC_{Path} = \text{Total Hop Count(S, D)} \tag{14}$$

The hop count ratio (HCR) is calculated using **equation (15)** as follows,

$$HCR(S,D) = \frac{\min\left(\text{Total Hop Count}_{all-paths}\right)}{HC_{Path}} \tag{15}$$

The HCR favors the selection of the shortest paths in the network. The PQI is calculated from the three combined metrics, PR, LQS, and HCR, as given in **equation (16)**,

$$PQI = PR(S,D) \times LQS(S,D) \times HCR(S,D) \times 100 \tag{16}$$

Where $0 \leq PQI \leq 100$. A higher PQI indicates a path with balanced energy reserves, reliable links, and fewer hops. This structure ensures that no single metric dominates; all factors must be decisive. The PQI balances energy, quality, and brevity without bias. It also emphasizes energy balance and weakest-link sensitivity, making it ideal for dynamic network routing.

2.4 PAQE2T – The proposed technique

In the proposed PAQE2T, 'S' is the origin, and 'D' is the destination node of the data transfer. The network's two paths, P_a and P_b, are compared using PQI, RE, and HC metrics. If the first path P_j's hop count is fewer than the second path P_{j+1}'s, the additional parameters PQI and RE are considered. The path with the higher RE, minimum HC, and maximum PQI is always the ideal option, whereas the path with the least residual energy is deemed critical and is always avoided. This approach avoids dead nodes, reduces packet re-transmissions, and conserves energy. When the number of hops for paths P_j and P_{j+1} is equal, one of the paths is chosen for data transfer. An alternate path is kept for data transfer to avoid retransmissions of packets and discovery of reroutes. The various steps in the proposed technique PAQE2T are defined as follows,

Begin

Input: S ← SRC, D ← DST

Paths: P ← num_paths(S, D)

Energy Model: TX = 0.0091 J, RX = 0.0059 J, Idle = 0.0 J, Switch = 0.0001 J

E_{THR} ← [Base_Threshold × (1 − Node_Density / 100)]

Output: P_{opt}

for ∀ P_j, P_{j+1} ∈ P do

1. Calculate Residual Energy:

   RE ← Find_RE = LiIonEnergySource → GetRemainingEnergy()

2. Critical Node Check:

   $$\text{flag\_cn} \leftarrow \text{Find\_Critical\_Nodes(RE)} = \begin{cases} 1, \text{ if RE} > E_{THR} \\ 0, \text{ else discard path} \end{cases}$$

3. Find Energy Dominant Node:

   $\text{mn\_id} \leftarrow \text{Find\_Max\_Energy\_Nodes(RE)} = \arg\max_{i \subset nodes} RE_i$

   if mn_id ∈ P_j ∧ $PQI_j > PQI_{j+1}$ then

   $P_{opt} \leftarrow P_j$

   else

   $P_{opt} \leftarrow P_{j+1}$

   end

4. Optimal Path Selection:

   $$P_{opt} \rightarrow \begin{cases} P_j, \text{ if } (PQI_j > PQI_{j+1} \wedge HC_j < HC_{j+1}) \vee (PQI_j = PQI_{j+1} \wedge HC_j = HC_{j+1} \\ P_{j+1}, \text{ else} \end{cases}$$

5. Find Weak Links:

   SNR_{THR} ← 40 dBm

   Signal ← DbmToW()

   Noise ← 7 × 1.3803e-23 × 290 × (20 × 1e6) // Channel Width = 20MHz

   if ∃ link ∈ P_{opt} : (Signal / Noise) < SNR_{THR}

   then Discard P_{opt} // Discard Weak Path

   end

   end for

6. Output:

   Return P_{opt}

End

function Find_HC(HC)

Begin

```
if link exists between Node_m and Node_m+1 in path 'S' ← 'D' then
   for ∃ packets do
    if pkt_id(Node_m+1) = pkt_id(Node_m) then
     HC ← HC + 1
    end if
   end for
end if
return HC
```

End

PQI, RE, and HC metrics compare the network's paths, namely P_j and P_{j+1}. The parameters PQI and RE are considered if the number of hops on the first path, P_j, is less than that on the second path, P_{j+1}. No matter what, the best course of action is the one with the highest RE and PQI; however, we should never choose the vital route with the lowest residual energy. This strategy eliminates dead nodes, decreases packet retransmissions, and conserves energy. A data transmission path is selected when the number of hops for paths P_j and P_{j+1} are equal. By minimizing HC and increasing PQI, the suggested method identifies the best course of action. There will be no need to retransmit packets or find re-routes because an alternate path is maintained for data transport. The optimal path is energy-balanced, reliable (no weak links or critical nodes), and efficient (high PQI, low hop count). The proposed technique ensures robustness while dynamically adapting to network conditions.

3 Results and Discussion

The proposed PAQE2T is evaluated for efficiency by considering different network scenarios. The scenarios consider six nodes: S, A, B, C, D, and E, where the source node is 'S' and the destination node is 'D'. According to the empirical data of CC2620, the parameters are defined as TX = 9.1 mA, RX = 5.9 mA, packet size = 4000 bits, acknowledgement packet size = 112 bits, data/acknowledgment rate = 48 Mbps, and voltage = 3V, initial energy parameter REinitial = 100 J for each node in the network. These parameters derive the empirical values: ETX_{DATA} = 0.000002275 J, ERX_{DATA} = 0.000001475 J, ETX_{ACK} = 0.0000000637 J, ERX_{ACK} = 0.0000000413 J, and E_{IDLE} = 0.0000019968 J. The energy consumption for a single packet is calculated as,

$$\begin{gathered} EC = ETX_{DATA} + ERX_{DATA} + ETX_{ACK} + ERX_{ACK} + E_{IDLE} \\ EC = 0.000002275 + 0.000001475 + 0.0000000637 + 0.0000000413 + 0.0000019968 \\ \therefore EC = 0.0000058518\ J \end{gathered} \quad (17)$$

For each node, the ETX and ERX values are calculated in **equation (18)** as follows,

$$\begin{gathered} \mathrm{ETX} = \mathrm{ETX_{DATA}} + \mathrm{ERX_{ACK}} = 0.000002275 + 0.0000000413 = 0.000002316\ \mathrm{J} \\ \mathrm{ERX} = \mathrm{ERX_{DATA}} + \mathrm{ETX_{ACK}} = 0.000001475 + 0.0000000637 = 0.000001539\ \mathrm{J} \end{gathered} \quad (18)$$

The EC for source node, intermediate nodes, and destination node is calculated using **equation (18)** as follows,

$$\begin{gathered} \mathrm{EC_{SRC\_NODE}} = \mathrm{ETX} + \mathrm{E_{IDLE}} = 0.000002316 + 0.0000019968 = 0.000004313\ \mathrm{J} \\ \mathrm{EC_{INTER\_NODE}} = \mathrm{ERX} + \mathrm{ETX} + \mathrm{E_{IDLE}} = 0.000002316 + 0.000001539 + 0.0000019968 = 0.000005852\ \mathrm{J} \\ \mathrm{EC_{DEST\_NODE}} = \mathrm{ERX} + \mathrm{E_{IDLE}} = 0.000001539 + 0.0000019968 = 0.000003536\ \mathrm{J} \end{gathered} \quad (19)$$

The EC of the source node is designated as EC_{SRC_NODE}, the EC of the intermediate nodes is defined as EC_{INTER_NODE}, and the EC of the destination node is designated as EC_{DEST_NODE}.

3.1 Scenario 1 - Eliminating critical nodes

A node is termed a 'critical node' if the remaining energy level of that node is less than the E_{THR} parameter because no more data transfer can be carried out. The link containing the critical node is termed a 'critical link'. The E_{THR} parameter given in **equation (20)** is the minimum energy level required for a device or node to perform specific operations or transmit data and is a crucial factor in optimizing the performance and longevity of IoT networks. In scenarios where power consumption is a critical concern, the E_{THR} parameter plays a vibrant part.

$$\mathrm{E_{THR}} = \left\{ \begin{array}{c} \text{Non-Critical Node, if } \mathrm{E_{THR}} \geq \left(\mathrm{B_{THR}} \times \left(\frac{1 - Node\ Density}{100}\right)\right) \\ \text{Critical Node, else} \end{array} \right\} \quad (20)$$

Here, B_{THR} is the base threshold, which is defined as 20% of the maximum residual energy. Initially, the value of $\mathrm{E_{THR}} = 20\% \times (1 - 6/100) = 18.8\%$. The E_{THR} parameter is calculated dynamically for each round using the **equation (20)**. This method ensures that no node is victimized. Table 1 gives the energy levels for this scenario. In this scenario, the proposed PAQE2T prefers paths that do not contain the critical node 'C'.

The critical node 'C', which has an energy of 4.75 J, is part of multiple paths, such as S→A→C→E→D, S→C→A→B→D, S→C→E→B→D, S→A→C→E→B→D, S→C→A→B→E→D, and S→C→E→D. The links having the critical node 'C' are

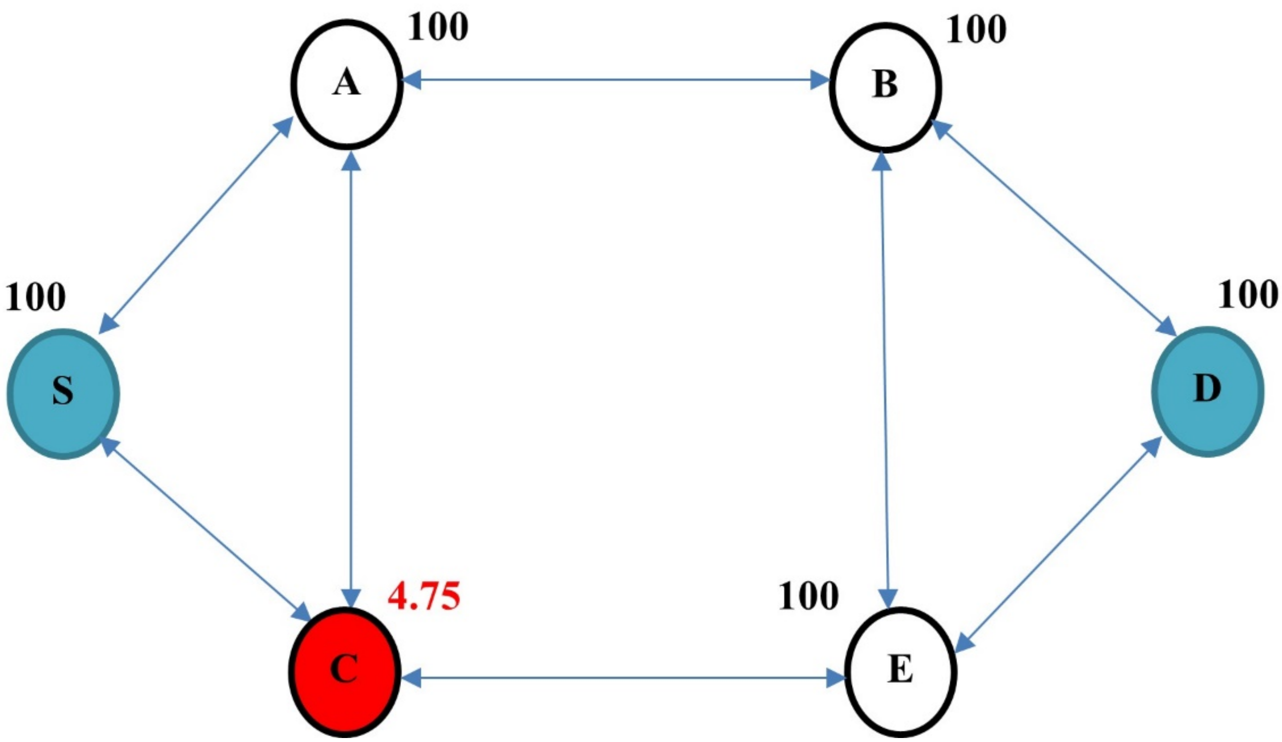

Fig 1. Scenario 1 – Network with critical node

identified and eliminated from inclusion into the optimal path by PAQE2T. Using the **equations (7), (8), (12), (13), (14), (15), (16)**, the PQI for each path is calculated as follows,

$$PE_{S\rightarrow A\rightarrow B\rightarrow D} = 100+100+100+100 = 400 \tag{21.1}$$

$$PR_{S\rightarrow A\rightarrow B\rightarrow D} = \left(\frac{400}{504.75}\right) = 0.7924 \tag{21.2}$$

$$LQE_{S\rightarrow A\rightarrow B\rightarrow D} = [1,1,1] \tag{21.3}$$

$$LQS_{S\rightarrow A\rightarrow B\rightarrow D} = (1*1*1)^{\frac{1}{3}} = 1 \tag{21.4}$$

$$HC_{Path} = 3 \tag{21.5}$$

$$HCR_{S\rightarrow A\rightarrow B\rightarrow D} = \left(\frac{3}{3}\right) = 1 \tag{21.6}$$

$$PQI_{S\rightarrow A\rightarrow B\rightarrow D} = (0.7924*1*1)*100 = 79.24 \tag{21.7}$$

Table 3. The optimal path and alternate path selected in scenario 1

Sl. No.	Path	PE	PR	LQE	LQS	HCR	PQI
1	S→A→B→D	400	0.7924	[1, 1, 1]	1	1	79.24 [Optimal path]
2	S→A→C→E→D	404.75	0.8018	[1, 0.5, 0.5, 1]	0.707	0.75	42.52
3	S→A→B→E→D	500	0.9905	[1, 1, 1, 1]	1	0.75	74.28 [Fallback path]
4	S→C→A→B→D	404.75	0.8018	[0.5, 0.5, 1, 1]	0.707	0.75	42.52
5	S→C→E→B→D	404.75	0.8018	[0.5, 0.5, 1, 1]	0.707	0.75	42.52
6	S→A→C→E→B→D	504.75	1	[1, 0.5, 0.5, 1, 1]	0.758	0.6	45.48
7	S→C→A→B→E→D	504.75	1	[0.5, 0.5, 1, 1, 1]	0.758	0.6	45.48
8	S→C→E→D	304.75	0.6038	[0.5, 0.5, 1]	0.629	1	37.97

Similarly, the PQI of other paths can be calculated by applying the same formulas, as illustrated in Table 3.

LQE is the link quality estimator derived from **equation (12)**. Table 3 shows that the PAQE2T selects the path S→A→B→D with PQI = 79.24, high LQS, no critical nodes, and with shortest hops as the energy-proficient optimal path. In case of emergency, the alternate optimal path available is S→A→B→E→D with PQI = 74.28, which also does not contain the critical node 'C'. The paths 2, 4, 5, 6, 7, and 8 have lower PQI due to poor link quality. The longer paths 6,7 are penalized by HCR. In this scenario, node 'C' is classified as the critical node, and it can transmit only a few data packets of 4000 bits each, after which node 'C' becomes a dead node. So, paths containing node 'C' cannot be considered optimal.

3.2 Scenario 2 - Eliminating weak links

Weak links refer to connections with poor signal strength or intermittent connectivity. In contrast, bad links refer to a connection or communication channel within the IoT network that is unreliable, unstable, or prone to errors. These issues can lead to heavy packet loss, increased latency, and reduced overall network efficiency, making it crucial to address them effectively. In this scenario, the PAQE2T prefers the paths that do not contain the weak links evaluated by the LQE in Table 2. When the LQE = 0 for a node, the links to other nodes from this node are categorized as weak links. When selecting the optimal path, the PAQE2T avoids the paths with weak links containing node 'A', which requires frequent retransmissions.

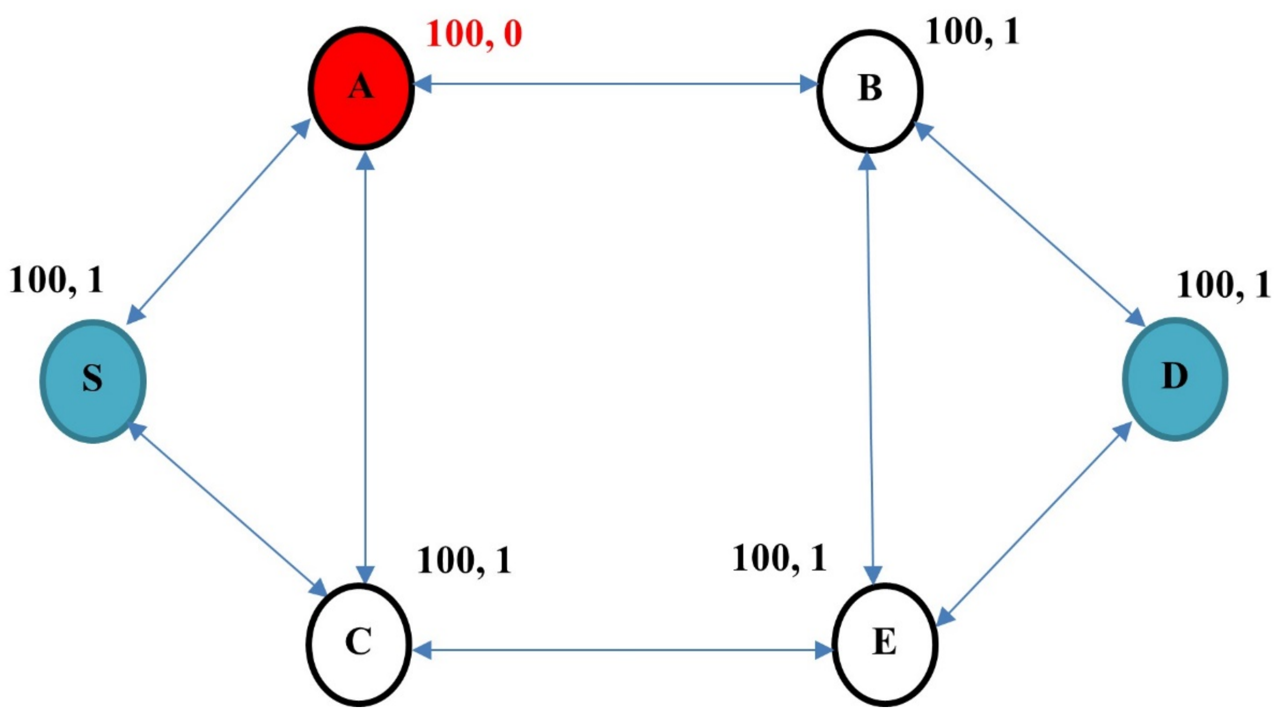

Fig 2. Scenario 2 – Network with weak links

The paths S→A→B→D, S→A→C→E→D, S→A→B→E→D, S→C→A→B→D, S→A→C→E→B→D, and S→C→A→B→E→D are ignored by PAQE2T because they are deemed weak links. Transmission through weak links will result in packet retransmission. Using the **equations (7), (8), (12), (13), (14), (15), (16)**, the PQI for each path is calculated as follows,

$$PE_{S\to A\to B\to D} = 100+100+100+100 = 400 \tag{22.1}$$

$$PR_{S\to A\to B\to D} = \left(\frac{400}{600}\right) = 0.6667 \tag{22.2}$$

$$LQE_{S\to A\to B\to D} = [0,0,1] \tag{22.3}$$

$$LQS_{S\to A\to B\to D} = (0*0*1)^{\frac{1}{3}} = 0 \tag{22.4}$$

$$HC_{Path} = 3 \tag{22.5}$$

$$HCR_{S\to A\to B\to D} = \left(\frac{3}{3}\right) = 1 \tag{22.6}$$

$$PQI_{S\to A\to B\to D} = (0.6667*0*1)*100 = 0 \tag{22.7}$$

The PQI of other paths can be calculated using the same method, as illustrated in Table 4. Only paths without node 'A' are considered for discovering an optimal path because the paths with node 'A' will result in parameter LQS = 0, which is a weak link.

Table 4. The optimal path selected in scenario 2

Sl. No.	Path	PE	PR	LQE	LQS	HCR	PQI
1	S→A→B→D	400	0.6667	[0, 0, 1]	0	1	0
2	S→C→E→B→D	500	0.83	[1, 1, 1, 1]	1	0.75	62.25 [Fallback path]
3	S→C→E→D	400	0.66	[1, 1, 1]	1	1	66 [Optimal path]

Table 4 shows that the PAQE2T selected path S→C→E→D with PQI = 66 as the optimal path due to its high LQS and optimal shortest hops. It also does not contain weak links. The alternate optimal path selected is path S→C→E→B→D with PQI = 62.25. Because of the number of hops, it has moderate PQI but maintains reliability. PAQE2T does not consider the other paths because they will result in LQS = 0 and PQI = 0.

3.3 Simulation Results

Simulation results are based on the network setup using a grid of 1000 nodes. Performance evaluation is done based on the metrics RE and PDR. The performance of the PAQE2T is assessed using simulation. In the network layer, the PAQE2T is implemented by modifying the lightweight on-demand ad hoc distance vector routing protocol–next-generation (LOADng) protocol. The MAC layer and radio were changed to collect signal strength RSSI, SNR, and the residual energy level. The RREQ and RREP packet structures are modified to contain the values of RE and PQI. The path quality approach is the main distinction between PAQE2T and existing methods. The PAQE2T considers PQI as the primary metric in the optimal path selection. It uses residual energy and node energy to balance energy dissipation effectively. The PAQE2T performance is compared to existing methods concerning residual energy, energy consumption, PDR, and average energy consumption. Table 5 shows the network simulation settings.

Table 5. Simulation parameters used to implement PAQE2T

Parameters	Values
Nodes	1000
Transmission Range	500 x 500 mts
Simulation Time	300 Secs
PHY / MAC	802.15.4
Radio Type	Chipcon CC2620
Network Bandwidth	48Mbps
Metrics	PQI, RE, LQE, RSSI, SNR, HC
$\sum_{fs}$	10pJ / (bit / m^2) [22]
$\sum_{mp}$	0.0013pJ / (bit / m^4) [22]
ETX_{elec}, ERX_{elec}	50 nJ / bit [22]
ETX_{DATA}	0.000002275 J
ERX_{DATA}	0.000001475 J
ETX_{ACK}	0.0000000637 J
ERX_{ACK}	0.0000000413 J
E_{IDLE}	1.9968E-06 J [23]
Packet size	4000 Bits
Distribution of Nodes	Uniform [21], [24]

3.3.1. Residual Energy

In the proposed PAQE2T protocol, each node must maintain a real-time record of its RE percentage. After every discrete time interval t, the current RE value (E(t)) is evaluated against its preceding state $(E(t-1))$. A discharge event is triggered when the differential energy depletion, defined as $|E(t)-E(t-1)|$, exceeds the E_{THR}, necessitating immediate battery recharge. The E_{THR} parameter, which governs energy monitoring across nodes, is initialized as 18.8% of the node's total RE derived from **equation (20)** and dynamically recalibrated in response to network conditions during each operational round. PAQE2T maintains steady energy efficiency even in ultra-dense networks, whereas other algorithms suffer from the excessive overhead of data and control packets. To reduce the energy dissipated, PAQE2T probably leverages adaptive dynamic resource allocation. Also, PAQE2T maintains a multi-layered optimization strategy, prioritizing renewable energy source nodes, minimizing transmission loads, and ensuring fair energy consumption across nodes.

Using a composite metric PQI enables PAQE2T to conserve energy usage (approximately half of the overall operational rounds) with improved energy efficiency. This metric guarantees continuous network stability, motivating nodes to keep enough RE to transmit data packets consistently. The protocol minimizes the aspect of energy depletion and prolongs network lifetime by assessing link quality and residual energy to optimize forwarder selection. The overall result reveals that in PAQE2T, the RE is prolonged regardless of the number of rounds and volume of nodes. The PAQE2T increased the network's overall average RE by 32.15%, higher than the existing methods.

Simulations were conducted across 50, 100, 250, 500, and 1000 rounds and validated. The proposed PAQE2T is benchmarked with state-of-the-art algorithms and other algorithms in terms of RE. For 100 nodes, the PAQE2T reaches the highest RE of 98.73% among algorithms compared to the state-of-the-art algorithms such as low-energy adaptive clustering hierarchy (LEACH)[1] by 15.96%, stable election protocol (SEP)[1] by 10.61%, distributed energy-efficient clustering (DEEC)[7] by 19.43%, LOADng[19] by 10.37%. At 1000 nodes, PAQE2T outperforms state-of-the-art algorithms by 33.4%, 39.84%, 57.69%, and 34.42% over LEACH, SEP, DEEC, and LOADng, respectively. The average improvement of PAQE2T over state-of-the-art LEACH, SEP, DEEC, and LOADng algorithms is 22.49%, 19.39%, 34.036%, and 20.66%, respectively. For 50 nodes, PAQE2T achieves 99.36% RE, outperforming the IT2FLS[4] (98.1%) by 1.26%. At 100 nodes, PAQE2T obtains 98.73% RE, while LEO[2] (89.16%), improved smart energy-based routing protocol (ISERP)[11] (82.11%) degrade with clustering overhead. PAQE2T achieves 93.69% RE at 500 nodes, while HWSN-IoT[7] (61.05%) demonstrates low load balancing. Specifically, at 1000 nodes, the RE for PAQE2T is 87.39%, which considerably outperforms the KNN[1] by 24.3%, LEO by 31.38%, IT2FLS by 34.65%, ABC-TEER[5] by 52.29%, HWSN-IoT by 51.34%, BICR[8] by 55.15%, ISERP by 59.89%. As nodes scale from 50 to 1000, RE% for PAQE2T declines only by 12%, from 99.36% to 87.39%. Table 3 presents the PAQE2T comparative study with other algorithms.

In LEACH[1], the first node died in the 2000th round, and the last node died in the 3500th round. In SEP[1], the first node died in the 1500th round, and the last node died in the 3500th round. In KNN[1], the first node died in the 2641st round, and

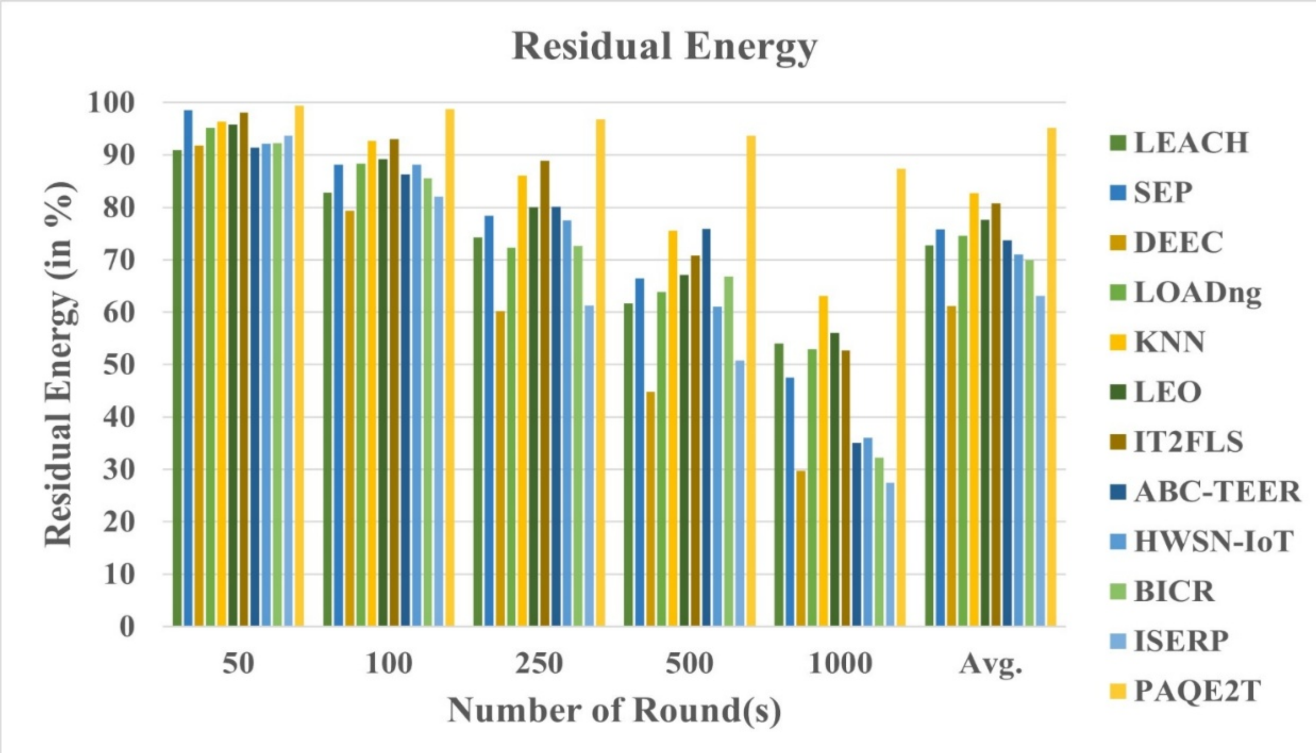

Fig 3. PAQE2T RE comparative study

the last node died in the 3727th round. The first node for ABC-TEER [5] died at about 1500 rounds, and the last node died in 3500 rounds. In HWSN-IoT [7], the first node perished at the 2702nd round, and the last node's death occurred around the 2830th round. In EEGA [10], node one failed after round 2600, and 80% of the nodes died while achieving the target of 4000 rounds. In ISERP [11], the first node fails at round 880, and the last node fails at round 1900. However, the coati optimization (EACH-COA) [13] results in the first living node at round 1750, and after that, all nodes die within 2000 rounds. The first node died at round 1200 in the crow search approach (CSA) [22], and the whole network died after finishing 2000 rounds. In region-based routing protocol (REERP) [24], the first node dies at the round 1000, while all nodes dies upto round 5000. Meanwhile, in PAQE2T, the first node did not die until the 2753rd round. At approximately the 5000th round, half of the nodes are alive, while half are dead. This shows that the proposed PAQE2T has the upper hand in terms of network lifespan.

Table 4 shows the survival rate of nodes over the operational time of 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500, and 5000 rounds. The proposed PAQE2T enhances the entire network's lifetime remarkably. It conserves energy balance across the network, particularly by partitioning energy-demanding jobs, such as data aggregation and communication between nodes with higher residual energy.

3.3.2. Packet Delivery Ratio

The PDR is the ratio between the number of data packets successfully delivered to their destination and the number of data packets generated at the source node. It is thus a key metric to evaluate the performance of routing protocols in a WSN. The successful probability of the end-to-end packet transfer is assessed using the PDR metric. It defines the reliability of data transfer and is calculated as the rate of packets received by the endpoint to the number of packets produced by the source. The modified PDR is computed as stated in **equation (23)** [25] and fine-tuned based on the PAQE2T surroundings,

$$PDR = \sum_{i=1}^{\text{All links in the path}} \frac{1}{1+e^{16.9491-(0.2125*LQI)}} * 100 \tag{23}$$

The CC2620 returns a correlation value as the first eight symbols of a packet arrive. This correlation value ranges from 50 to 110, where 50 represents the lowest frame quality for the chip and 110 represents the highest frame quality. Chipcon [25] proposed

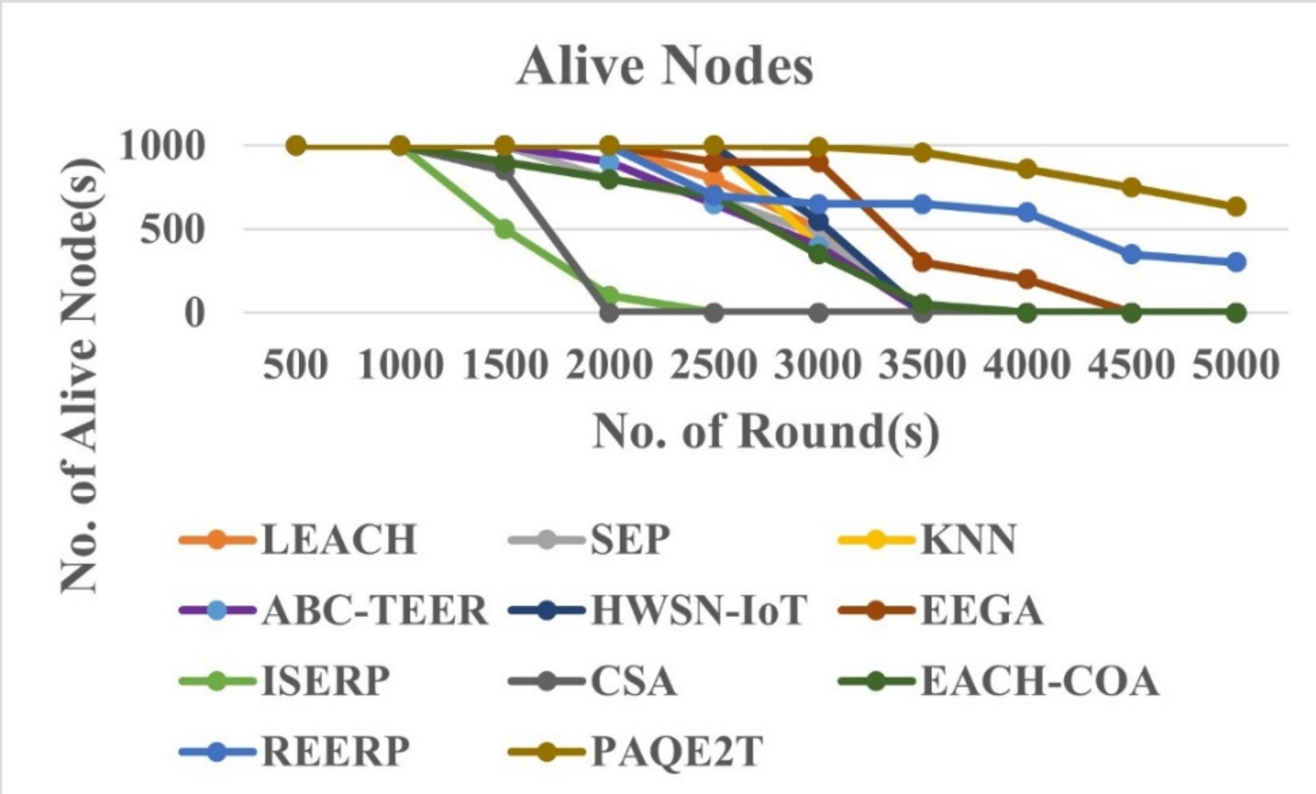

Fig 4. Comparative study of alive nodes

using an empirical approach to translate the correlation values based on PER measurements linearly. In the range of [50, 70], the LQI maximum fluctuation indicates that the bit error ratio (BER) fluctuation is significant when the LQI appears in this range, which shows that the link quality is not steady. PER is 0 when LQI is in the range [100, 110], which means the error ratio is relatively low, and the fidelity in the link quality is excellent. Based on **equation (23)**, the PDR for a single link with LQI = 110 is,

$$PDR = \frac{1}{1+e^{16.9491-(0.2125*110)}} * 100 = \frac{1}{1+e^{-6.4259}} * 100 \tag{24.1}$$

$$PDR = \frac{1}{1+0.0016} * 100 = 0.9984 * 100 = 99.84\% \tag{24.2}$$

Using **equation (23)**, the PDR for a single link with LQI = 50 is calculated as,

$$PDR = \frac{1}{1+e^{16.9491-(0.2125*50)}} * 100 = \frac{1}{1+e^{6.3241}} * 100 \tag{25.1}$$

$$PDR = \frac{1}{1+557.8555} * 100 = 0.0017 * 100 = 0.17\% \tag{25.2}$$

Similar steps are taken to calculate the PDR for other links. As LQI increases, the PDR increases. Suppose we want to see the correlation between LQI and PDR in a more noticeable way of working. In that case, empirical studies have already used the correlation between LQI and PDR to estimate link quality. The results are shown in Table 6 for scenario 2.

As can be seen from Table 6, the PDR is higher for the paths S→C→E→B→D and S→C→E→D. Since PDR is very high, PAQE2T considers either of the two paths to be optimal. Regarding delivering data packets more reliably, the PDR is highest

Table 6. PDR% of paths using PAQE2T for scenario 2

Path	PDR Ratio (%)	PDR (S, D) (%)
S→A→B→D	$99.84+0.17+99.84=199.85$	$199.85/3=66.62$
S→A→C→E→D	$99.84+0.17+99.84+99.84=299.69$	$299.69/4=74.92$
S→A→B→E→D	$99.84+0.17+99.84+99.84=299.69$	$299.69/4=74.92$
S→C→A→B→D	$99.84+0.17+99.84+99.84=299.69$	$299.69/4=74.92$
S→C→E→B→D	$99.84+99.84+99.84+99.84=399.36$	$399.369/4=99.84$ [Fallback path]
S→A→C→E→B→D	$99.84+0.17+99.84+99.84+99.84=399.53$	$399.53/5=79.91$
S→C→A→B→E→D	$99.84+0.17+99.84+99.84+99.84=399.53$	$399.53/5=79.91$
S→C→E→D	$99.84+99.84+99.84=299.52$	$299.52/3=99.84$ [Optimal path]

for PAQE2T since PAQE2T considers the PQI metric for the path quality of the optimal path. The high PDR ratio improves the network's energy efficiency and reduces the number of packet re-transmissions. The energy consumption of PAQE2T is lower than that of the existing methods. PAQE2T is better because,

1. Keep nodes alive without depleting energy, maximizing PDR and managing traffic to avoid packet loss.
2. Increased node handling with no performance drop.
3. Load balancing to avoid traffic congestion. The PQI metric gives a path quality that is more excellent than link quality. Path selection efficiency is established on PQI accuracy.

The data shows that PAQE2T's PDR for all node counts is significantly higher than that of all other algorithms, precisely 94.95% on average. PAQE2T's PDR is 95.55% for 5 nodes and 88.46% for 25 nodes. The proposed PAQE2T scales to levels of 16.77% and 5.78% using state-of-the-art algorithms such as ad hoc on-demand distance vector (AODV)[6] and LOADng[19]. It scales remarkably, demonstrating scalability at 92.78% for 50 nodes, 95.91% for 100 nodes, and 99.84% for 500 nodes. The IT2FLS[4] performance is poor, from 60.8% to 52.26%, due to the overhead of data packets. The M-O-AODV[6] performs well initially with 95.2% for 5 nodes but drops significantly to 88.31% with 25 nodes as its route maintenance is poor. In dense networks, congestive collapse is degraded to 63.72% for 500 nodes. The BICR[8] demonstrates relative variation attributed to inefficient load balancing. The network performance stability using the intelligent routing protocol (nPSIR)[9] suffers from poor route recovery, which leads to 62.95% for 50 nodes and 48.27% for 100 nodes. The EEGA[10] lowers from 96.6% to 72.48% yet still is outperformed because of static clustering. The improved residual energy low-energy adaptive clustering hierarchy (IMP-RES-EL)[12] fails for 44.8% at 500 nodes on unoptimized retransmission limits. The opportunistic energy-efficient dynamic self-configuration routing (OEDSR)[21] falls from 90.25% to 29.61%, while REERP[24] falls from 93.7% to 80.97% due to cluster head congestion. With its lightweight mechanisms for neighbor discovery and dynamic route prioritization, PAQE2T does not incur any additional overhead, leading to a near-optimal PDR across sparse networks. PAQE2T utilizes dynamic path recalibration to skip congested or unstable paths according to real-time link quality metrics, such as RSSI, SNR, etc. PAQE2T employs a congestion control mechanism that alters routing tables and adjusts transmission rates to mitigate packet loss. Table 5 illustrates the PDR comparative study for 5, 25, 50, 100, 200, and 500 nodes.

PAQE2T requires the least energy to compute the cost of sending data packets. The PAQE2T approach stands out in satisfying nearly all performance demands in data transmission, sharply contrasting with data-related routing approaches in IoT-based applications. The positioning of relay nodes in this proposed work is a pair's role in balancing the performance of PAQE2T. Moreover, introducing the PQI metric reduces transmissions between the sensor and sink nodes, directly affecting performance indicators, such as RE and PDR.

3.3.3. Complexity analysis of PAQE2T

The complexity analysis suggests that PAQE2T uses a path-based comparison algorithm. Essentially, PAQE2T finds multiple paths based on the energy and path dimensionality metric PQI and compares them. Its computational complexity will depend on both the number of paths considered and the complexity of the functions used to evaluate them. The computational overhead of PAQE2T is lower than that of simple path-based energy-aware routing techniques based on the selection criteria. It has one of the lowest computational complexities, which is O $(C+n)$, where C is the number of optimal paths discovered by PAQE2T and n is the number of nodes in the network. It appears that the cost of the complexity of the PAQE2T is at the path selection stage, which is a less common operation because there is no transaction for each iteration; hence, the complexity of each iteration is

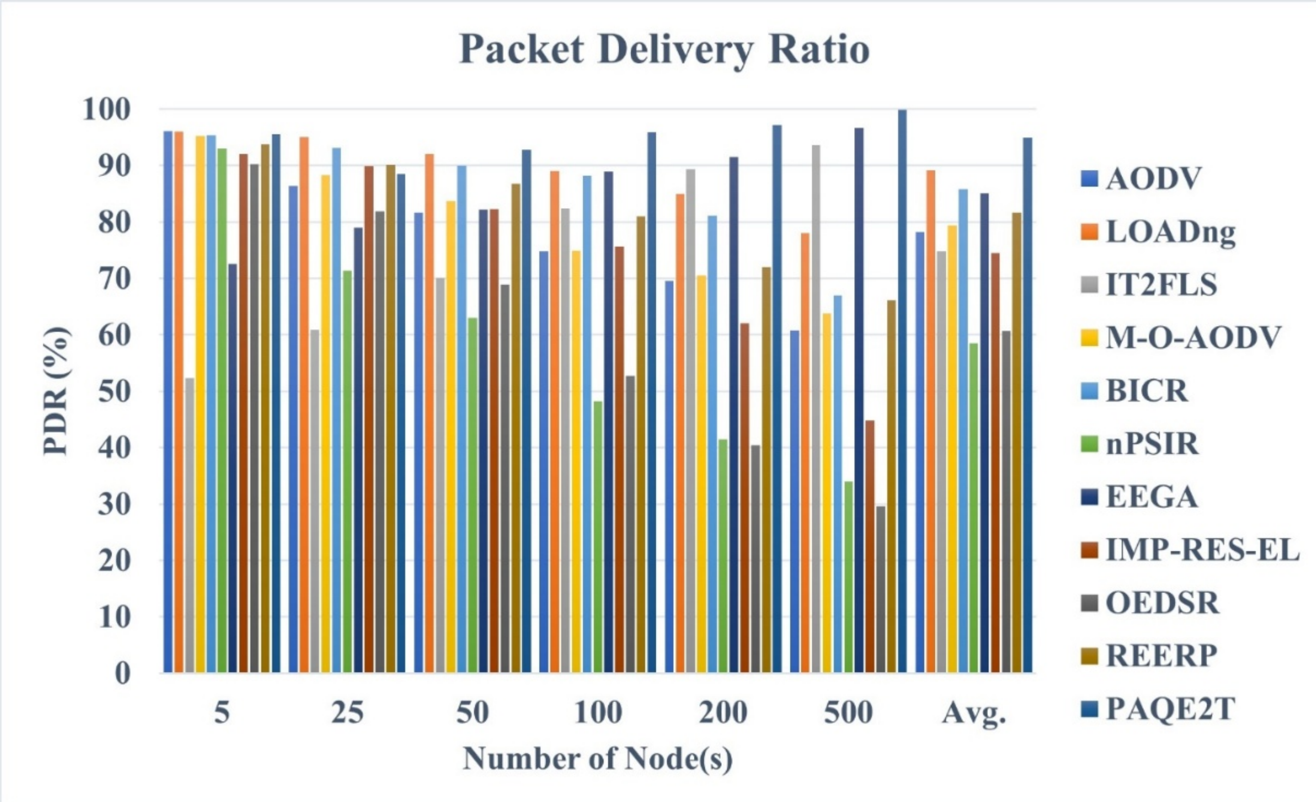

Fig 5. PAQE2T PDR comparative study

O $(n+L)$ where L is the cost for selection of an optimal path. All of this can be done in O $(C+n)$ time overall for n pairs. In the worst-case scenario, L can be close to n, so the complexity is simplified to O $(C+L\times n)$.

LEACH attempts to improve energy efficiency by forming clusters and periodically rotating cluster heads. It does not perform explicit multiple path traversals and path selections like PAQE2T. The complexity of LEACH is distributed across rounds and is lower per node per round compared to the path selection phase of PAQE2T. PAQE2T focuses on energy efficiency at the path level, while LEACH is aimed at efficiently organizing the network. AODV is one of the reactive routing protocols for mobile ad hoc networks. It can potentially discover multiple paths, but the conventional AODV chooses first discovered path. Unlike the path selection of base AODV, which is based on hop count, PAQE2T considers two paths in the path selection process and then evaluates them based on energy and link quality. The potential advantages of PAQE2T are,

1. Path planning prioritizes high-energy nodes with heuristic considerations that explicitly consider RE.
2. Discards invalid paths by linking SNR and considering quality.
3. PQI permits the inclusion of other relevant path metrics.
4. Critical node avoidance to prolong the lifespan of low-energy nodes.

A potential disadvantage is that if PQI is a dynamic metric, maintaining its value for all paths may introduce overhead. A comparison of the computational complexity of PAQE2T concerning other methods is divided into three categories: time complexity, space complexity, and communication complexity. Time complexity is used to choose the best optimal path—space complexity depends on how the paths are stored. Communication complexity refers to the communication overhead required for optimal path discovery. A comparison of the proposed PAQE2T with state-of-the-art algorithms is presented in Table 7.

Here, C is the number of optimal paths discovered, and L is the cost for the selection of an optimal path. Since PAQE2T has significantly lower time and space complexity compared to LEACH, AODV, and LOADng for the following reasons, it utilizes a composite metric PQI to find and store optimal paths. The path discovery mechanism is also very efficient, and it is expected that the communication complexity will be low.

Table 7. Complexity analysis of algorithms

Method(s)	Time complexity	Space complexity	Communication complexity
PAQE2T [Proposed Work]	$0(C+n)$	$0(C+L\times n)$	$0(C\times L\times n)$
LEACH [(1)]	O (n) per round	O (k)	O (n) per round
AODV [(6)]	O (n)	O (Number of destinations)	O (n)
LOADng [(19)]	O (n)	O (1)	Depends on topology and network size

4 Conclusion

Energy conservation is a constant primary concern in IoT. The PAQE2T proposes three innovations from the rest of the energy-aware routing protocols in IoT. In multi-criteria path selection, it derives PQI metric combining RE, LQS, and HC holistically to consider energy efficiency and link reliability and latency. This is in contrast to current approaches that focus on a single metric. The dynamic critical node avoidance method avoids critical nodes of energy beforehand and moves to the secondary path. Unlike static protocols, which revert to the reactive route repair mechanism, this adaptive mechanism ensures continuous data flow. The energy dissipation model with path-quality feedback incorporates real-time PQI metric into energy calculations, allowing context-aware decisions. Most previous models fail to provide such feedback loops. The proposed PAQE2T can achieve measurable performance improvements such as 32.15% more network RE and 36.44% better PDR compared to baseline protocols, providing a new synergy of energy saving and QoS enhancement.

In the future, investigate extending PAQE2T to support multiple sink nodes to facilitate load balancing for large-scale IoT deployments. This would lessen hotspots and drive PDR further up. We adapt PAQE2T to mobile IoT nodes, such as drones or vehicles, by extending the path selection stage to include mobility prediction. The PAQE2T can be embedded with lightweight encryption into the routing framework to solve the energy-efficient secure communication that lacks in existing IoT protocols. We can implement forward error correction (FEC) or network coding to minimize retransmissions, specifically focusing on reducing the packet loss ratio (PLR) while maintaining energy efficiency. Formulate traffic-load-based dynamic thresholds for path switching using PAQE2T to reduce energy consumption in peak and off-peak hours.

References

1) Juwaied A, Jackowska-Strumillo L, Sierszeń A. Enhancing Clustering Efficiency in Heterogeneous Wireless Sensor Network Protocols Using the K-Nearest Neighbours Algorithm. *Sensors*. 2025;25(4):1029. http://dx.doi.org/10.3390/s25041029.
2) Fitoš M, Ďuďák J, Gašpar G, Machaj J, Brída P. LEO: An innovative metric for energy-efficient routing in wireless sensor networks. *Internet of Things*. 2025;29:101472. http://dx.doi.org/10.1016/j.iot.2024.101472.
3) Nimmala S, Mahendar M, Manasa P, Raghavendar K, Rambabu B, Bhavani DD. An Intelli BEF: An Intelligent Bio-Inspired Energy-Efficient and Fault-Tolerant Routing for IoT-Enabled WSNs. *2025 6th International Conference on Mobile Computing and Sustainable Informatics (ICMCSI)*. 2025;p. 942–947. http://dx.doi.org/10.1109/icmcsi64620.2025.10883389.
4) Ambareesh S, Chavan P, Supreeth S, Nandalike R, Dayananda P, Rohith S. A secure and energy-efficient routing using coupled ensemble selection approach and optimal type-2 fuzzy logic in WSN. *Scientific Reports*. 2025;15(1). http://dx.doi.org/10.1038/s41598-024-82635-w.
5) Gupta M, Kr S, Kumar P, Kumar P, Kumar P, Venkateswarlu P. Efficient Routing and Lifetime Prolongation in IoT founded Wireless Sensor Network Performance with Bee Colony-Inspired Lifetime Enhancement. *Journal of Intelligent Systems and Internet of Things*. 2025;14(1):221–229. https://doi.org/10.54216/JISIoT.140117.
6) Ghori MR, Wan TC, Sodhy GC, Aljaidi M, Rizwan A, Sadiq AS, et al. Enhancing Reliability and Stability of BLE Mesh Networks: A Multipath Optimized AODV Approach. *Sensors*. 2024;24(18):5901. http://dx.doi.org/10.3390/s24185901.
7) Shafique T, Soliman AH, Amjad A, Uden L, Roberts DM. Node Role Selection and Rotation Scheme for Energy Efficiency in Multi-Level IoT-Based Heterogeneous Wireless Sensor Networks (HWSNs). *Sensors*. 2024;24(17):5642. http://dx.doi.org/10.3390/s24175642.
8) Ahmed S, Hossain MA, Chong PHJ, Ray SK. Bio-Inspired Energy-Efficient Cluster-Based Routing Protocol for the IoT in Disaster Scenarios. *Sensors*. 2024;24(16):5353. http://dx.doi.org/10.3390/s24165353.
9) Abujassar RS. A multi path routing protocol with efficient energy consumption in IoT applications real time traffic. *EURASIP Journal on Wireless Communications and Networking*. 2024;2024(1). http://dx.doi.org/10.1186/s13638-024-02377-1.
10) Akhter F, Near JP. Energy Efficient Data Routing for IoT Networks Using Genetic Algorithm. *2024 International Conference on Smart Applications, Communications and Networking (SmartNets)*. 2024;p. 1–8. http://dx.doi.org/10.1109/smartnets61466.2024.10577690.
11) Sheikh AM, Joshi S. Improved smart energy-based routing approach for IoT networks in wireless sensor nodes. *Journal of Engineering and Applied Science*. 2024;71(1). http://dx.doi.org/10.1186/s44147-024-00435-5.
12) Tekulapally V, Chali D, Abose TA. An Energy Optimization Clustering Methods for Homogeneous Networks of Wireless Sensors. *Deep Sciences for Computing and Communications*. 2024;p. 32–42. http://dx.doi.org/10.1007/978-3-031-68908-6_3.
13) Somula R, Cho Y, Mohanta BK. EACH-COA: An Energy-Aware Cluster Head Selection for the Internet of Things Using the Coati Optimization Algorithm. *Information*. 2023;14(11):601. http://dx.doi.org/10.3390/info14110601.
14) Shilpa KC, Chetan S, Anand HD. Performance Analysis by Improving Energy Efficiency in IoT Based Wireless Sensor Network for Routing Algorithm. *Indian Journal Of Science And Technology*. 2023;16(11):785–794. http://dx.doi.org/10.17485/ijst/v16i11.2388.
15) SimpleLink 32-bit Arm Cortex-M3 Zigbee RF4CE wireless MCU with 128kB Flash. Available from: https://www.ti.com/product/CC2620.

16) Sindjoung MLF, Minet P. Estimating and predicting link quality in wireless IoT networks. *Annals of Telecommunications*. 2021;77(5–6):253–265. http://dx.doi.org/10.1007/s12243-021-00835-1.
17) Tan ND, Nguyen DN, Hoang HN, Le TTH. EEGT: Energy Efficient Grid-Based Routing Protocol in Wireless Sensor Networks for IoT Applications. *Computers*. 2023;12(5):103. http://dx.doi.org/10.3390/computers12050103.
18) Mustafa MM, Khalifa AA, Cengiz K, Ivković N. An Energy-Efficient Protocol for Internet of Things Based Wireless Sensor Networks. *Computers, Materials & Continua*. 2023;75(2):2397–2412. http://dx.doi.org/10.32604/cmc.2023.036275.
19) Newton PC, Felix AT. ETX-Aware Energy-Efficient Algorithm to Reduce Packet Retransmissions in the Internet of Things. *Indian Journal of Science and Technology*. 2022;15(1):28–43. http://dx.doi.org/10.17485/ijst/v15i1.2100.
20) Wen J, Dargie W. Characterization of Link Quality Fluctuation in Mobile Wireless Sensor Networks. *ACM Transactions on Cyber-Physical Systems*. 2021;5(3):1–24. http://dx.doi.org/10.1145/3448737.
21) Tumula S, Ramadevi Y, Padmalatha E, Kumar GK, Gopalachari MV, Abualigah L, et al. An opportunistic energy-efficient dynamic self-configuration clustering algorithm in WSN-based IoT networks. *International Journal of Communication Systems*. 2023;37(1). http://dx.doi.org/10.1002/dac.5633.
22) Dlamini T, Mwashita W. Enhancing Energy Efficiency in IoT-WSN Systems via a Hybrid Crow Search and Firefly Algorithm. *Journal of Sustainability for Energy*. 2023;2(4):197–206. http://dx.doi.org/10.56578/jse020403.
23) Aqeel I. Enhancing Security and Energy Efficiency in Wireless Sensor Networks for IoT Applications. *Journal of Electrical Systems*. 2024;20(3s):807–816. http://dx.doi.org/10.52783/jes.1378.
24) Dogra R, Rani S, Gianini G. REERP: A Region-Based Energy-Efficient Routing Protocol for IoT Wireless Sensor Networks. *Energies*. 2023;16(17):6248. http://dx.doi.org/10.3390/en16176248.
25) Liu W, Xia Y, Zheng D, Xie J, Luo R, Hu S. Environmental Impacts on Hardware-Based Link Quality Estimators in Wireless Sensor Networks. *Sensors*. 2020;20(18):5327. http://dx.doi.org/10.3390/s20185327.