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A Robust an Adaptive Energy Efficient Load Balancing: A Novel Routing Algorithm IoT Networks

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The Internet of Things (IoT) relies on numerous battery-powered devices, requiring efficient energy management to extend network lifespan. Key challenges include achieving load balancing, minimizing power consumption, and reducing operational costs, especially since many IoT devices operate on batteries due to limited access to electrical grids in remote areas. Efficient energy usage becomes critical during high traffic periods, where selecting optimal next-hop nodes and less congested channels helps mitigate congestion and balance network loads.
Wireless Sensor Networks (WSNs), a vital component of IoT, are self-configured systems that collect and transfer data from sensor nodes to a Base Station(BS). Despite advances in routing protocols like Dynamic Source Routing (DSR), Destination-Sequenced Distance Vector (DSDV), and Ad-hoc On-Demand Distance Vector (AODV), challenges such as high energy consumption, increased end-to-end delay, and moderate throughput still hinder performance.
To address these issues, this proposed work introduces the Energy Efficient Depth-Based Routing Protocol (EEDBR), which enhances the DSR protocol. EEDBR employs an elite group-based routing mechanism to select sensor nodes and cluster heads, improving energy efficiency. Simulations conducted in the NS-2 environment assessed key performance metrics, identifying EEDBR as an optimal solution for energy-efficient routing in contemporary WSNs.
The proposed adaptive, energy-aware routing algorithm dynamically balances load among nodes, minimizing energy use while maintaining efficient data transmission. This approach significantly enhances the performance, reliability, and sustainability of IoT networks, supporting their growing demands.
Keywords: Internet of Things, energy-aware routing, load balancing, adaptive

algorithms, network conditions.

1. Introduction

Wireless sensor networks (WSNs) are broadly used throughmany applications such as environmental monitoring, agriculture, healthcare, smart cities, defense, and asset tracking. The integration of the Internet of Things (IoT) with WSNs enhances data accessibility, scalability, interoperability, real-time monitoring, and energy efficiency. IoT-enabled WSNs rely on critical factors such as architecture, connectivity, RF range, node compatibility, security, and cost. Processes like node deployment, clustering, routing, traffic analysis, and energy-aware selection are essential for efficient operation.

WSNs consist of low-cost, low-power sensor nodes that face challenges like battery constraints, limited bandwidth, and data distribution. Routing protocols in WSNs are categorized into data-centric, hierarchical, and location-based, aiming to optimize energy usage and reduce communication overhead. Designing effective routing protocols requires balancing energy efficiency with the performance of data transmission.

Recent advancements in MEMS, embedded systems, and low-power wireless communication has enhanced the efficiency of sensor operation, making WSNs ideal for military surveillance, disaster prediction, and environmental monitoring. The key challenge remains energy management, especially in remote or harsh environments where battery replacement is impractical. As WSNs continue to evolve, there is great potential for further improvements in routing protocols and energy-efficient technologies to meet the increasing demands of IoT applications.

In response to this challenge, the WSN clustering routing protocol was developed. This protocol organizes numerous sensor nodes into clusters, creating a hierarchical structure from cluster members (CMs) to cluster heads (CHs) and base stations (BS). By effectively managing energy consumption, this approach extends the network's operational lifespan, allowing for more rounds of data transmission and processing shown in figure 1.

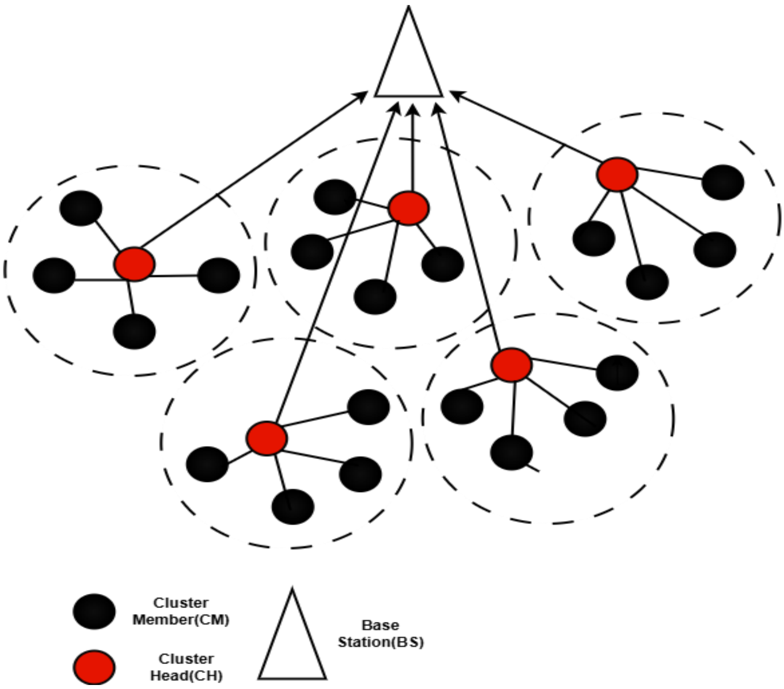


Figure 1Structure of clustered WSN

Challenges in WSNs: The research paper highlights challenges in WSNs, particularly energy holes, where some nodes deplete energy faster, causing premature failure and reducing network efficiency and lifespan.

Need for Load Balancing:The introduction emphasizes load balancing techniques and clustering schemes to improve energy efficiency, reduce packet loss, and extend the network's lifetime by addressing energy hole issues.

Power Constraints in WSNs:The paper highlights power limitations in WSNs and emphasizes the need for energy-efficient protocols to extend sensor network lifetimes due to limited power resources.

Adaptive Sleep-Wake Scheduling:Prior research supports adaptive duty cycling, where nodes adjust sleep/wake times based on energy levels, minimizing consumption while maintaining communication efficiency.

Channel Utilization and Load Balancing:The paper introduces a channel prioritization method to address saturation, emphasizing load balancing to prevent bottlenecks and ensure fair resource distribution among nodes.

Opportunistic Routing:The paper highlights opportunistic routing within a forwarding zone, aiming to improve reliability and efficiency in data transmission, reflecting current WSN research trends.

Research gap:The research identifies a gap in advancing IoT-WSN, highlighting the need for lightweight algorithms to address nodes' limited computational resources and reliance on battery power.

Balancing power efficiency and network performance is a key challenge in IoT-WSNs. Research is needed on node deployment, clustering, routing, authentication, load balancing, and security to enhance the sustainability and functionality of these systems.

2. Literature Review

The paper "Load-balanced and energy-aware opportunistic routing with adaptive duty cycling for multi-channel WSNs" addresses key challenges in multi-channel wireless sensor networks (WSNs), focusing on power consumption and network lifetime. Recent advancements in microelectronics and wireless communication have enabled the development of small, cost-effective, battery-powered sensor nodes that measure and process environmental data. These nodes form WSNs, enabling data integration and dissemination across large areas[1-5].

WSNs are used in military, industrial, and civilian applications, such as battlefield surveillance, environmental monitoring, and healthcare. However, WSNs face unique challenges, including high node density, unreliable nodes, and limited energy, computation, and storage capacity. These limitations have driven research to enhance WSN design, architecture, and deployment.

A typical WSN consists of sensor nodes with sensing, processing, and transmission units. However, energy constraints and communication bandwidth limitations impact network performance. Routing protocols in WSNs address challenges like node deployment, data reporting methods, balancing energy consumption with data accuracy, and supporting data aggregation to reduce redundant transmissions.

WSNs use three main routing protocols: data-centric, hierarchical, and location-based, each with its advantages and limitations. This paper examines several routing protocols in WSNs, emphasizing their application in energy-efficient data relay, route discovery, and extending network lifespan through optimized energy management [6-10].

Rui et al. [11] highlight that load balancing is critical in distributed environments, including the cloud and IoT systems. Their study introduces a novel approach to address this challenge using the Simplified Swarm Optimization (SSO) algorithm. This algorithm, inspired by sharks' hunting behavior and their ability to detect the scent of fishing lines from a distance, is a powerful meta-hybrid solution for solving NP-hard problems. Additionally, the study proposes incorporating fuzzy logic and Dynamic Voltage and Frequency Scaling (DVFS) to optimize load distribution. By dynamically reducing the frequency of IoT nodes, this approach effectively minimizes energy consumption.

Kaur et al. [12] explored resource optimization challenges in both single-hop network topologies and broader cooperative multi-hop network architectures, employing various cooperative methodologies. The study developed an optimal strategy for each source-to-destination communication link using a dual optimization framework. This approach reduces transmission power through efficient channel allocation and optimal relay selection while maintaining quality of service (QoS) standards. Additionally, Kaur proposed an energy-efficient power-routing method and derived closed-form equations for the outage probability of the cooperative relaying protocol, aiming to maximize data transmission efficiency.

In 2023, Gharge et al. [13] introduced a hybrid genetic algorithm-based cluster head selection (HGACHS) method, based on the LEACH protocol, to enhance WSN performance. HGACHS optimizes network efficiency in scenarios like the first, half, and last node dead. Using MATLAB for simulations, they evaluated throughput, jitter, node death rate, and energy consumption. Results showed reduced energy use and extended network lifetime, especially with 200 nodes in a 200-square-meter area. However, the limited simulation space and node count do not reflect real-world conditions, and the method increased end-to-end delay, presenting a limitation.

Kushwaha et al. [14] introduced SACMUF, a multi-criteria decision-making approach using Fuzzy Analytical Hierarchy Process, to address WSN traffic congestion. SACMUF selects cluster heads based on node potential, energy, traffic burst rate, and load rank. MATLAB simulations with 100 nodes over 200 square meters evaluated energy consumption and node death rates. Results showed improved energy savings, reduced consumption, and fewer dead nodes. SACMUF also demonstrated more remaining energy at certain timestamps. However, it did not address critical metrics like throughput, communication delays, and packet delivery rate, which were identified as limitations.

3. Case and Methodology

The proposed EEDBR algorithm optimizes energy use and ensures efficient data transmission in IoT devices by adapting to traffic loads and network conditions. It considers residual energy, link quality, and data needs, adjusting routing paths in real time. Leveraging machine learning, the algorithm predicts traffic patterns to minimize energy consumption and improve throughput, enhancing device longevity and network reliability. This is crucial for smart city infrastructure, where efficient communication supports resource management and service delivery. By integrating intelligent routing, cities can optimize energy use, improve public services, and promote sustainable growth. Real-time data analytics foster dynamic responses to changing conditions, enabling better access to information and encouraging civic engagement. These innovations encourage alliance among governments, private sectors, and communities, supporting broad urban planning that prioritizes sustainability, economic growth, and social equity, ultimately fostering livable, resilient cities.

3.1 System Model:

The methodology can be adapted to IoT with the following steps:

3.1.1 Network Model

In this research, we focus on a field data-gathering Wireless Sensor Network (WSN) application, where sensor nodes perform spatial and temporal measurements of specific parameters within a sensor field. A distinctive use case for such a WSN could be monitoring environments for catastrophic events, such as fire outbreaks in agricultural and forestry sectors. Each sensor node accumulates data from the physical environment and forwards data packets on behalf of other nodes that lack direct connectivity to a sink node. Unlike regular sensor nodes, the sink node is assumed to have relatively abundant resources, whereas sensor nodes are reserved in terms of memory, processing power, bandwidth, and energy, relying on small, often non-replaceable and non-rechargeable batteries.

This study assumes a single sink node to which every data packet in the network istransmitted. The WSN is represented as a directed connectivity graph $(N,)$ where Ndenotes the set of all nodes in the network, and E represents the set of communication links between nodes capable of direct interaction. Each sensor node $n \in N$ has an isotropic transmission radius (n) and sensing radius (n). For simplicity, we undertake that all nodes share the same (n) value, which determines the set of directly communicable neighbouring nodes, denoted by $N(n)$. Nodes outside this range are represented as $\overline{N}(n)$.Bidirectional and symmetric links exist between every source node and its neighbouring node $m \in Nn(n)$. Hence, for any two nodes that are directly connected $\{u,\} \in N$ the link (u,v) is identical and symmetric to $link(v,u)$. Each sensor node n maintains a set of routes, $R(n)$, to the sink node. Each route$(n) \in Routes(n)$ represents the i^{th} route stored in the node's route cache. Throughout this research, for simplicity, (n) and (n) are assumed to be equal for all sensor nodes.

3.1.2 Channel Model

The wireless channel model in this study emulates the dynamic and non-uniform characteristics of a transmission channel. The transmitted signal strength is influenced by factors such as distance loss, shadowing, and multi-path fading as the signal propagates through the air interface. An exponential path-loss model with log-normal fading effects is employed to represent the wireless channel between nodes. This model has been experimentally validated to accurately represent low-power communication in Wireless Sensor Networks (WSNs), as demonstrated in prior research ([14]), and is widely adopted for analytical studies and simulations in WSN communication.

In this model, path loss describes the attenuation of the received signal strength over a given distance between a transmitter and receiver node. As per the findings in [14]–[16], the path-loss (d) in decibels (dB) at a distance d (in meters) is expressed as:

$$\mathrm{PL}(\boldsymbol{d})\boldsymbol{dB} = \boldsymbol{PL}(\boldsymbol{d}\mathbf{0}) + \mathbf{10}\boldsymbol{n}\mathbf{log10}(\boldsymbol{d}/\boldsymbol{d}\mathbf{0}) + \boldsymbol{X\sigma} \quad (1)$$

Where:

$(d0)$ is the path loss at the reference distance,

$d0$ (assumed to be 1 meter), is the path-loss attenuation factor,

$X$is a zero-mean Gaussian random variable with a standard deviation,

σ (in dB), representing the shadowing effect.

For this work, a plain ground environment is assumed, with values of n=3.12 and σ=1.83, based on the one-slope path-loss propagation model.

The established signal strength (d) is derived as:

$(d) = PTx - (d)$PRx (d)=PTx −PL(d)(2)

Where d represents the distance between the transmitting and receiving nodes. Equation (2) establishes the received signal strength as a function of the distance between two communicating sensor nodes.

3.1.3 Energy model

In IoT systems, efficient energy management is crucial to ensure the longevity and performance of sensor nodes. Since IoT devices often rely on limited energy resources, optimizing energy usage through data transmission is essential. The energy consumption model for transmitting 1-bit of data, EN_{TX},shown in equation (3) can be adapted as follows:

$$EN_{TX} = \begin{cases} lE_{elec} + le_f D^2, & D < D_0 \\ lE_{elec} + le_m D^4, & D \geq D_0 \end{cases} \quad (3)$$

Where:

- E_{elec}: Energy consumed for processing 1-bit of data.
- D: Distance between the transmitter and receiver.
- e_m, e_f: Energy coefficients for free-space and multipath fading models, respectively.
- l: Length of the data packet.

The threshold distance, D_0, which determines the transition between free-space and multipath fading energy consumption models shown in equation(4), is given by:

$$D_0 = \sqrt{\frac{e_f}{e_m}} \quad (4)$$

To account for energy requirements for data collection in IoT systems, the energy EN_{RX} required for receiving L-bit information can be expressed as shown in equation(5):

$$EN_{RX} = LE_{elec} \quad (5)$$

This model adapts to changing node distances and energy states, enabling energy management and load balancing by dynamically selecting routes to minimize consumption.

4. Distance Model for Adaptive Routing in IoT Systems

In IoT networks, cluster heads (CHs) broadcast packets to notify sensor nodes (SNs), which associate with the optimal CH based on minimal communication range. An adaptive routing algorithm reduces energy usage by bypassing CHs if the communication range exceeds a threshold, enabling more efficient data transmission to the Base Station(BS).

The optimal clustering structure is maintained using a communication ring, which is computed using the following formula (6):

$$D = \cos(\theta) = \frac{xy}{||x||\,||y||} \quad (6)$$

Where:

- x and y represent the coordinates of the CH nodes.

This distance calculation helps the adaptive routing algorithm dynamically reorganize nodes to decrease energy consumption and extend the network lifespan.

5. Signal Channel Model for Energy-Aware Routing

In IoT environments, wireless signal propagation is often affected by environmental factors such as obstructions and multipath effects. These factors introduce uncertainty in signal intensity and link quality, necessitating an adaptive approach to routing.

The signal attenuation of the link (SL) is modelled as follows in (7):

$$\boldsymbol{SL = 10n\log D + B + X} \quad (7)$$

Where:

- SL denotes the signal attenuation of the link,
- n is the signal attenuation coefficient,
- D represents the distance between transceiver nodes,
- B is a fixed value,
- X accounts for random environmental factors.

To ensure energy-efficient communication, the link quality (LIq) of node i is calculated as shown in equation (8):

$$\boldsymbol{LIq_c(i) = \frac{1}{m}\sum_1^m LIq_{ci}} \quad (8)$$

The adaptive routing algorithm minimizes retransmissions, balances data traffic, and adjusts paths based on link quality to optimize energy use, reduce data loss, and improve reliability and load balancing in IoT networks.

6. Metrics for Energy-Aware Routing

EEDBR employs key metrics to ensure energy-efficient and load-balanced routing:

To assess the effectiveness of energy-aware routing in IoT systems, several key performance metrics should be considered. These metrics help assess energy efficiency, network longevity, and overall performance of the routing algorithm in dynamic and resource-constrained environments.

6.1 Energy Consumption (EC)

The whole amount of energy consumed by the IoT network during data transmission, reception, and processing in the equation (9).

$$\boldsymbol{EC = \sum_{i=1}^{N}\left(E_{TX_i} + E_{RX_i} + E_{idle_i} + E_{sleep_i}\right)} \quad (9)$$

Where:

- E_{TX_i} = Energy consumed for transmission,
- E_{RX_i} = Energy consumed for reception,
- E_{idle_i}= Energy consumed in idle state,
- E_{sleep_i}= Energy consumed in sleep mode,
- N= Total number of nodes.

Goal: Minimize energy consumption to encompass the network lifetime.

6.2. Network Lifetime (NL)

The duration until the first or a significant fraction of nodes deplete their energy.

$$NL = max(T_{node_i}) \quad (10)$$

Where:

- T_{node_i}Represents the operational lifetime of node .

Goal:Increasenetwork lifetime to ensure long-term operation of the IoT system.

6.3. Packet Delivery Ratio (PDR)

The ratio of successfully received packets to the total packets transmitted across the network.

$$PDR = \frac{\sum_{i=1}^{N} P_{received_i}}{\sum_{i=1}^{N} P_{sent_i}} \quad (11)$$

Where:

- $P_{received_i}$= Packets successfully received,
- P_{sent_i}= Packets transmitted by nodes.

Goal: Maintain a high PDR to ensure reliable communication.

6.4. Average Energy Consumption per Packet (AEPP)

The average sum of energy consumed to successfully transmit one packet of data.

$$AEPP = \frac{EC}{\sum_{i=1}^{N} P_{sent_i}} \quad (12)$$

Goal: Optimize routing to minimize energy per packet.

6.5. End-to-End Delay (E2ED)

The total time taken for a data packet to travel from the source node to the destination.

$$E2ED = \sum_{i=1}^{N} (T_{arrival_i} - T_{sent_i}) \quad (13)$$

Where:

- $T_{arrival_i}$= Time packet is received at the destination,
- T_{sent_i}= Time packet was transmitted.

Goal: Reduce delay to meet real-time IoT application requirements.

6.6. Energy Efficiency (EE)

The amount of useful data delivered per unit of energy consumed.

$$EE = \frac{P_{delivered}}{EC} \tag{14}$$

Where:

- $P_{delivered}$= Number of successfully delivered packets.

Goal: Maximize efficiency to ensure energy is utilized effectively.

6.7. Load Balancing Factor (LBF)

Measures the uniform distribution of energy consumption across all nodes to prevent early failures.

$$LBF = \frac{\sigma_E}{\mu_E} \tag{15}$$

Where:

- σ_E= Standard deviation of energy consumption across nodes,
- μ_E= Mean energy consumption.

Goal: achieve a lower load balancing factor to prevent energy depletion in specific nodes.

6.8. Residual Energy (RE)

The remaining energy of nodes after a certain period of operation, indicating the sustainability of the routing algorithm.

$$RE_i = E_{initial} - EC_i \tag{16}$$

Where:

- $E_{initial}$= initial energy of node$i$,
- EC_i= Energy consumed by node$i$.

Goal: Maximize residual energy to prolong the network lifespan.

6.9. Number of Hops (NH)

The number of intermediate nodes a data packet traverses from source to destination.

Goal: Minimize the number of hops to reduce energy consumption and delay.

6.10. Control Overhead (CO)

The relation of control packets (e.g., routing updates) to the total number of transmitted packets.

$$\boldsymbol{CO} = \frac{\boldsymbol{P_{control}}}{\boldsymbol{P_{total}}} \tag{17}$$

Where:

- $P_{control}$= Number of control packets,
- P_{total}= Total packets transmitted.

Goal: Reduce control overhead to save bandwidth and energy.

These metrics provide a comprehensive evaluation framework for energy-aware routing algorithms in IoT systems, ensuring balanced energy consumption, improved load distribution, and sustained network operation.

7. Adaptive Routing Algorithm

The EEDBR-based algorithm works dynamically to adapt to changing network conditions, effective routing in IoT systems requires mechanisms to balance the energy consumption across nodes, optimize energy usage, and ensure network longevity through proactive maintenance strategies. Below is an in-depth discussion on these aspects:

- Energy-Efficient Dynamic Source Routing (EEDSR): The core contribution of the paper is the design of a modified version of the DSR protocol, termed Energy-Efficient Dynamic Source Routing (EEDSR). This modification aims to enhance energy efficiency while maintaining effective communication in WSNs. The design focuses on reducing energy consumption, which plays a crucial role in the performance ofsensor networks [1].
- Simulation Using NS-2: The authors conducted simulations of the routing protocols using the NS-2 simulation environment. This method allows for the evaluation of the performance of the proposed EEDSR protocol against traditional protocols. Various performance parameters, such as energy consumption, end-to-end delay, and throughput, were measured and analyzed during these simulations [1].
- Performance Measurement and Analysis: The paper emphasizes the importance of measuring and analyzing several performance parameters to determine the efficiency of the proposed routing protocol. The results from the simulations provide insights into how EEDSR performs compared to other protocols, ultimately leading to the conclusion of an optimal energy-efficient routing paradigm for modern WSNs.

7.1 Energy Efficient Depth-Based Routing Protocol (EEDBR) Architecture

Components of the EEDBR Architecture:

- Sensor Nodes:
    - These are the devices deployed in the environment to collect data. They are typically battery-powered and are responsible for sensing various parameters.
    - Each node is furnished with a transmitter, receiver, and processor.

- Cluster Head (CH):
  - A subset of nodes may be elected to be Cluster Heads shown in Figure 2.
  - The CH aggregates the data collected by the sensor nodes in its cluster and forwards it to the sink node.
  - The role of the CH decreases the energy consumption of individual sensor nodes by minimizing the communication range and power consumption.
- Sink Node (SN):
  - The Sink Node acts as the central point of the network, receiving data from all cluster heads or directly from some sensor nodes.
  - The Sink Node typically has more computational and energy resources compared to the sensor nodes.
- Data Routing Layer:
  - This layer handles the routing decisions based on energy-aware metrics. It confirms that data packets are transmitted in a way that minimizes energy consumption.
  - Routing protocols are built on the following criteria:
    - Energy remaining of nodes (prefer nodes with higher energy).
    - Distance to the destination (shorter distances reduce energy consumption).
    - Residual energy of nodes (prioritize nodes with more energy).
- Energy Management System (EMS):
  - The EMS is responsible for controlling the energy usage of nodes, scheduling sleep modes, and dynamically regulating the transmission power to optimize energy efficiency.
- Multi-hop Communication:
  - Instead of sending data directly to the sink node, sensor nodes can forward their data through intermediate nodes, reducing the direct communication distance and conserving energy.
  - The routing protocol selects intermediate nodes based on energy and distance to ensure that energy consumption is balanced throughout the network.
- Routing Decision Algorithm:
  - The algorithm periodically evaluates the status of nodes (energy levels, network topology) and makes routing decisions.

○ It employs techniques like energy-based clustering and priority-based routing to ensure efficient energy consumption.

- Sleep Mode:

○ Nodes that are not dynamically transmitting data enter a low-power sleep mode to conserve energy.

- Adaptive Communication Mechanism:

○ This component dynamically adjusts communication strategies based on real-time network conditions, such as traffic load and energy consumption patterns.

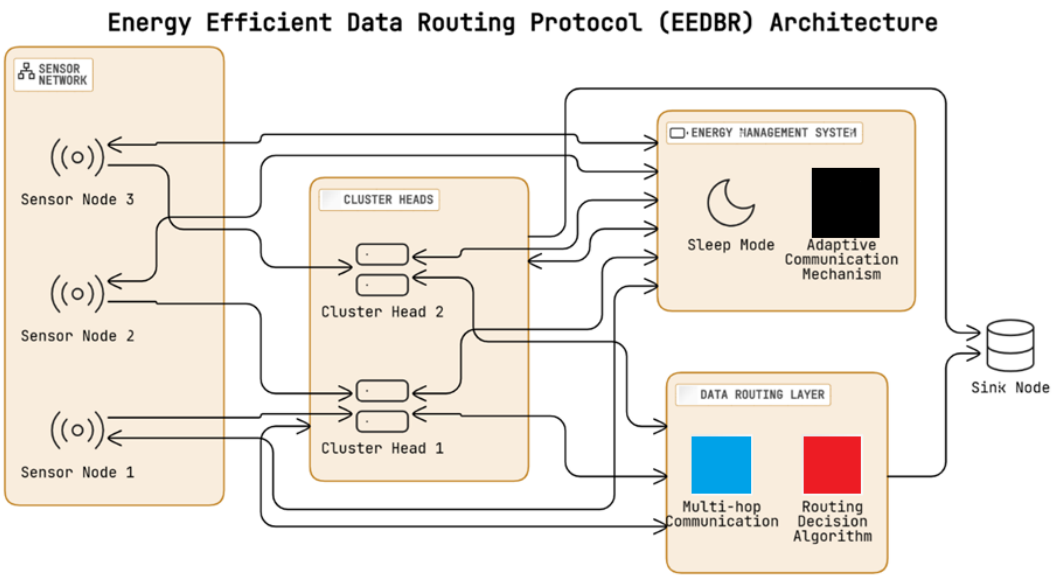


Figure 2: Energy Efficient Depth-Based Routing Protocol (EEDBR) Architecture.

7.2 EEDBR (Energy Efficient Depth-Based Routing Protocol) for Wireless Sensor Networks (WSN)

The Energy Efficient Depth-Based Routing Protocol (EEDBR) is a routing methodology precisely designed for Wireless Sensor Networks (WSNs) to optimize energy consumption, extend network lifetime, and ensure reliable data transmission. Here is a detailed explanation of EEDBR tailored for WSNs:

Objective

The primary objectives of EEDBR in WSNs are:

- Energy Efficiency: Reduce energy consumption during data routing.
- Prolonged Network Lifetime: Ensure equitable energy utilization across nodes to avoid early depletion of critical nodes.

- Reliability: Facilitate fault-tolerant and consistent data delivery under varying network conditions.

Key Features

- Energy Awareness: Uses the residual energy of nodes as a primary metric to make routing decisions.
- Load Balancing: Distributes traffic across multiple nodes to prevent overloading and improve overall network stability.
- Adaptive Path Selection: Dynamically adjusts routes based on node energy, link quality, and network traffic conditions.
- Scalability: Efficiently handles a large number of nodes, making it suitable for dense WSN deployments.

7.3 EEDBR Methodology

A. Node Initialization

Each sensor node is initialized with:

○ Residual Energy (RE): Tracks the remaining energy of each node.

○ Neighbor Information: Maintains a list of neighboring nodes and their respective metrics.

○ Link Quality Indicator (LQI): Measures the quality of links with neighboring nodes.

B. Metrics Used

- Residual Energy (RE):

○ Indicates the energy available in a node.

- Residual Energy (RE) is equal to the remaining energy divided by the initial energy.

$$\boldsymbol{RE = \frac{E_{remaining}}{E_{initial}}}$$

- Link Quality Indicator (LQI):

○ Represents the consistency of the connection between nodes.

○ Elements such as Signal-to-Noise Ratio (SNR) and Received Signal Strength Indicator (RSSI) are used to compute LQI.

- Hop Count (HC):

○ Determines the sum of intermediate nodes between the source and the sink.

- Load Balancing Factor (LBF):

- Measures the traffic load on a node, calculated as: LBF=1Queue Length1$\boldsymbol{LBF = \frac{1}{Queue\ Length}}$

- Path Score (PS):
  - A composite metric derived from the above parameters, influencing route selection.

C. Routing Mechanism

- Route Discovery:
  - Find all possible paths between the source node and the sink.
- The Path Score (PS) is calculated as the weighted sum of specific metrics, represented as follows:

PS is equal to $w_1$multiplied by Residual Energy (RE), plus w_2 multiplied by Link Quality Indicator (LQI), minus w_3 multiplied by Hop Count (HC), plus w_4 multiplied by Load Balancing Factor (LBF).

- Here, w_1,$w_2, w_3, w_4$are weights assigned to prioritize the respective metrics.
- Mathematically, it is written as:

$$\boldsymbol{PS = w_1.RE + w_2.LQI - w_3.HC + w_4.LBF}$$

- Path Selection:
  - Select the path with the highest Path Score to optimize energy usage and data reliability.
- Data Transmission:
  - Transmit data along the selected path.
  - Implement traffic splitting to distribute load across multiple paths when available.
- Fault Tolerance:
  - Monitor node performance during data transmission.
  - Detect and bypass faulty nodes to ensure uninterrupted data delivery.
- Dynamic Path Adjustment:
  - Periodically recalculate metrics and re-evaluate paths based on changing network conditions (e.g., energy depletion or link failures).

D. Energy Optimization Strategies

- Duty Cycling: Nodes alternate between active and sleep states to conserve energy.
- Data Aggregation: Reduce redundant transmissions by combining data from multiple nodes.
- Clustering: Group nodes into clusters to minimize communication overhead and enhance scalability.

E. Advantages of EEDBR in WSN

- Energy Conservation: Reduces overall energy consumption by routing data through nodes with higher residual energy.
- Fault Tolerance: Ensures data delivery despite node failures by dynamically adapting routes.
- Scalability: Supports large-scale WSNs by efficiently managing resources and routes.
- Reliability: Maintains consistent data transmission even in dynamic or harsh network conditions.

EEDBR ensures a reliable, energy-efficient routing solution for WSNs, addressing the unique challenges of IoT-enabled sensor networks while extending their operational lifespan.

F. EEDBR Model Structure for WSN Using a List of Sensors

To construct an EEDBR (Energy Efficient Depth-Based Routing Protocol) model for a Wireless Sensor Network (WSN) using the given list of sensors, the network architecture and routing methodology can be organized as follows:

Network Design

A. Sensors Deployment

- Sensors are deployed in a hierarchical or mesh topology.
- The setting out area is divided into regions or clusters to simplify data routing and improve energy efficiency.

B. Sensor Roles

Each type of sensor contributes to the network as follows:

- Temperature Sensors: Monitor environmental temperature.
- Humidity Sensors: Measure humidity levels.
- Pressure Sensors: Detect pressure variations in the environment.
- Motion Sensors: Identify movement for security or activity monitoring.
- Light Sensors (LDR): Measure ambient light levels.

- Proximity Sensors: Detect nearby objects or obstacles.
- GPS Sensors: Provide geolocation for mobile or stationary nodes.
- Accelerometer Sensors: Measure acceleration for vibration or tilt detection.
- Battery Power Monitoring Sensors: Track the energy levels of nodes.
- RF Signal Strength Sensors: Assess link quality between nodes for reliable data transmission.

C. Cluster Formation

- Nodes are grouped into clusters based on proximity or signal strength.
- A Cluster Head (CH) is selected from each cluster based on:
  - Residual energy (nodes with higher energy are prioritized).
  - Link quality (strong connections with neighboring nodes).
  - Sensor capabilities (e.g., RF signal strength for reliable communication).

Routing Mechanism

EEDBR relies on a combination of metrics to ensure efficient data routing.

A. Metrics Used in Routing

- Residual Energy (RE):
  - Calculated using battery power monitoring sensors.
  - Nodes with higher energy are preferred for routing to extend network lifespan.
- Link Quality Indicator (LQI):
  - Measured using RF signal strength sensors.
  - Reliable links minimize retransmissions and save energy.
- Hop Count (HC):
  - Shorter paths are preferred to reduce energy consumption.
- Proximity Information:
  - Proximity sensors assist in detecting nearby nodes for efficient routing.
- Data Priority:
  - Critical sensors (e.g., motion, GPS) are prioritized to ensure timely data delivery.

B. Path Selection

Compute a Path Score for all possible paths:

$PS = w_1 \cdot RE + w_2 \cdot LQI - w_3 \cdot HC$

- Paths with the maximum scores are selected for data transmission.
- Weights w_1, w_2, w_3 are adjusted based on network priorities (e.g., energy conservation vs. reliability).

C. Multipath Routing

- Multiple paths are established to balance the load and improve fault tolerance.
- Data is distributed across these paths based on their Path Scores.

D. Fault Tolerance Mechanism

- Fault Detection:
  - Faulty nodes are identified using performance monitoring from battery and RF signal strength sensors.
  - Cluster Heads periodically test node functionality using hypothesis-based testing.
- Redundancy:
  - Data is temporarily stored in backup cluster heads to prevent loss during node failures.
- Dynamic Path Adjustment:
  - When a fault is detected, alternate paths are recalculated dynamically.

E.Data Aggregation

- Data collected from sensors (e.g., temperature, humidity, light) within a cluster is aggregated at the Cluster Head.
- Redundant data is removed to reduce transmission overhead.

F.Energy Optimization Strategies

- Duty Cycling:
  - Sensors alternate among active and sleep modes to conserve energy.
  - For instance, motion and proximity sensors remain active only when needed.
- Adaptive Sampling:

○ Sensors like temperature and humidity adjust their sampling rate based on environmental changes.

G. Performance Evaluation

- Monitor the following parameters to evaluate the model:

i. Energy Efficiency: Average energy consumption across nodes.

ii. Network Lifetime: Time till the first node depletes its energy.

iii. Reliability: Packet Delivery Ratio (PDR) and data accuracy.

iv. Load Balancing: Even distribution of traffic across nodes.

This model ensures energy-efficient, reliable, and fault-tolerant data routing in WSNs by leveraging the capabilities of the listed sensors.

Table 2EEDBR Model Components

Component	Sensors Involved	Function
Cluster Heads	Battery, RF Signal Strength	Monitor and manage cluster operations, aggregate data.
Fault Detection	Battery, RF Signal Strength	Detect and isolate faulty nodes.
Path Selection	Battery, RF Signal Strength, Proximity	Select energy-efficient and reliable routes for data transmission.
Data Aggregation	Temperature, Humidity, Light, Pressure, Motion	Aggregate sensor data to reduce redundancy.
Energy Monitoring	Battery, Accelerometer	Optimize duty cycling and reduce energy consumption.
Routing Reliability	RF Signal Strength, GPS	Ensure reliable communication and geolocation.

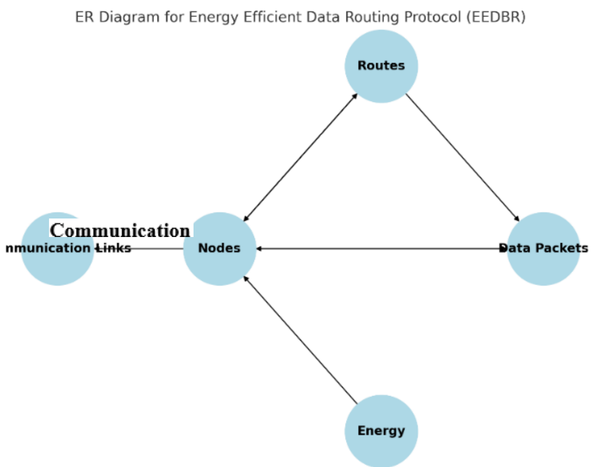


Figure 3: The ER diagram for the EEDBR model shows entities like Nodes, Data Packets, Routes, Energy, and Communication Links, with directed edges illustrating relationships such as communication links, energy consumption, and data packet transmission between nodes via routes.

7.4. Algorithm Steps

Algorithm: Energy-Aware Clustering and Routing

1. Initialize Energy Levels

for each node i:

Initialize E_i (initial energy level)

Calculate residual energy $R_i = E_i - (E_{txi} + E_{rxi})$

2. Neighbor Discovery

for each node i:

Discover neighboring nodes within communication range

Exchange energy (R_i), load (L_i), and traffic (T_i) information

3. Traffic and Load Measurement

for each node i:

Calculate traffic load L_i (incoming + outgoing packets)

Calculate traffic intensity T_i (rate of packet forwarding)

4. Cluster Formation

Group nodes into clusters

for each node i:

Compute Cluster Head Selection Criterion $Ch_i = R_i / d_i$

(where d_i is the distance to the sink node)

Assign nodes with highest Ch_i as Cluster Heads (CHs)

5. Cluster Head Assignment

for each node i:

Assign to the closest CH based on distance and energy levels

6. Data Aggregation

for each CH:

Collect data from member nodes

Aggregate and forward data to the sink node

7. Load Balancing and Routing

for each node i:

Calculate load L_i

if $L_i > L_{max}$:

Trigger load balancing

Redistribute excess load to nearby nodes with lower load

Select routing path based on:

Residual energy R_i

Load L_i

Distance to destination

Ensure selected path:

Meets residual energy requirements

Distributes load evenly

Has a distance $\leq H_{max}$ (maximum hop count)

8. Energy-Aware Routing

for each node i:

Calculate energy required to send a packet along a path

Consider energy consumption per hop (based on$d_{i,j}$ and node load)

9. Adaptive Mechanism Based on Network Conditions

if node density is high:

Form smaller clusters to reduce communication overhead

if traffic intensity $>T_{max}$:

Reduce transmission rate or schedule data transmission

if nodes are mobile:

Dynamically adjust routing paths and update CH assignments

10. Energy Conservation and Sleep Mode

for each node i:

if$R_i<R_{max}$ or $L_i>L_{max}$:

Place node into sleep mode

Minimize energy consumption during sleep

11. Termination

Monitor network energy levels

Remove nodes with depleted energy

Compute network lifetime as the time till the first node depletes its energy

End Algorithm

7.5. Implementation

- Simulation Setup: Describe the simulation environment and tools used for testing the algorithm.
- Performance Metrics: Define the metrics used to evaluate algorithm performance, such as energy consumption, network lifetime, packet delivery ratio, and load distribution.

Cluster Formation and Cluster Head Selection

- Cluster Formation

Nodes are assembled into clusters based on proximity and energy levels. Nodes with higher residual energy and lower load are preferred candidates for Cluster Heads (CHs).

- Cluster Head Selection Criterion

The selection criterion for each node is computed as:

Where is the residual energy of node and is the distance from node to the sink node.

- Cluster Head Assignment

Nodes with the highest values are selected as CHs. Non-CH nodes assign themselves to the nearest CH based on distance and energy levels.

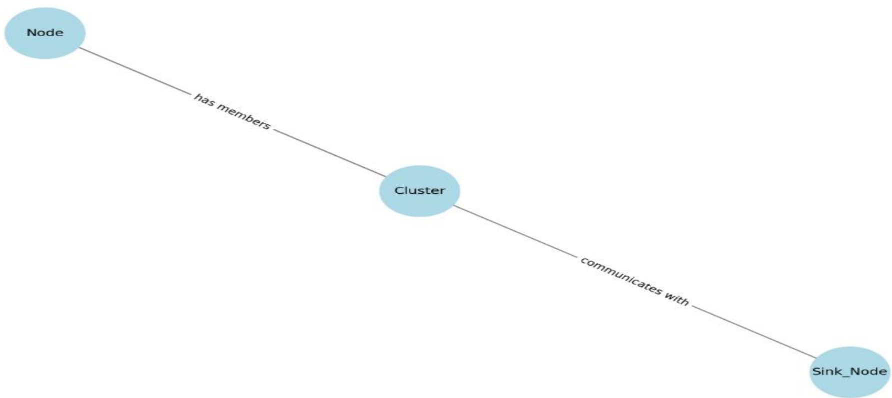


Figure 4: E-R Diagram for Cluster Formation and Cluster Head Selection.

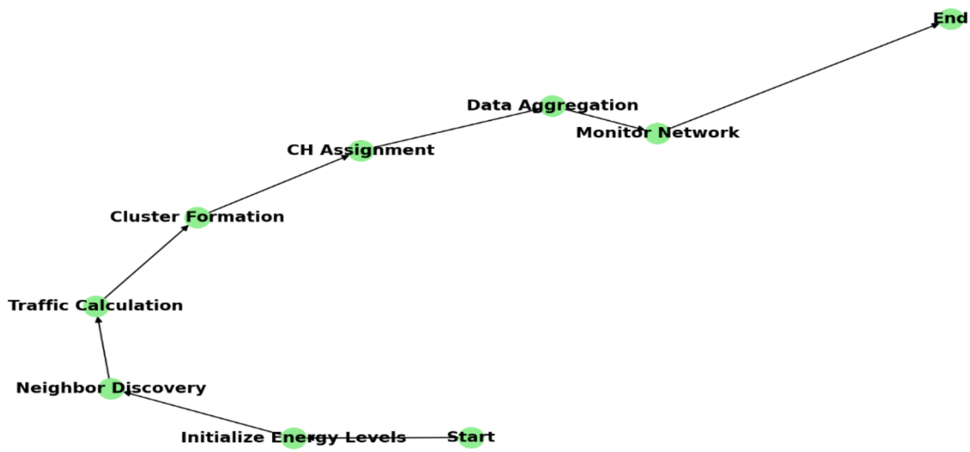


Figure 5: Flow chart for Energy-Aware Clustering and Routing.

- Data Aggregation

Cluster Heads accumulate data from their cluster members and aggregate it before forwarding the collected data to the sink node. This reduces the overall communication overhead and energy consumption.

- Energy-Aware Routing

Nodes calculate the energy essential to send a packet along a path by considering:

- Energy consumption per hop based on distance.
- Node load along the path.

Table 3 Descriptions of States and Messages

State or Message	Description
Candidate	The node is designated as a candidate node.
Head	The node is selected to serve as the cluster head.
Plain	The node operates as a member node.
Compete_Msg	Contains only the sender's ID.
Join_Msg	Includes the sender's ID and the cluster head's ID.
Weight_Msg	Comprises the sender's ID, weight, energy attribute (Ea), and residual energy (Eresidual).
Schedule_Msg	The cluster head allocates time slots for its member nodes.

8. Results and Discussion

8.1 Simulation and Results

This subsection evaluates EEDBR and other protocols under varying message arrival and channel error rates. Figure 5-16 shows nodes averaging six neighbors, with a maximum of twelve. Results reveal that EEDBR reduces energy consumption while ensuring reliable packet delivery, leveraging enhanced routing metrics that incorporate channel reliability into route evaluation.

Table 4 Simulation Parameters

Parameters	Values
Sensor network field	500m x 500m
Number of nodes (N)	100 Nodes
Transmission range ($Rt(n)$)	25 Meters
Current consumption (RR)	18.8P mA
Current consumption (TR)	17.4mA
Current consumption	426.0P µA
Data rate	250 kbps
Packet size	64 Bytes
Routing control packet	32 Bytes

The technical specifications for the Energy-Efficient Depth-Based Routing (EEDBR) Protocol in Wireless Sensor Networks (WSNs) can be described as follows, based on the general context of EEDBR and the provided graphs:

- Node Specifications
  - Sensor Nodes: Nodes equipped with sensing, communication, and computational capabilities.
  - Sink Node: A resource-rich node used for data collection.
  - Transmission Power: Adjustable based on node proximity and channel conditions.
  - Energy Source: Non-rechargeable or limited rechargeable batteries.
  - Memory and Processing Power: Limited to handle lightweight computations and routing tasks.
- Wireless Channel Model
  - Path Loss Model: Exponential with log-normal fading for real-world accuracy.
  - Channel Conditions: Includes distance loss, shadowing, and multi-path fading.
  - Transmission Range: Defined radius for direct communication between nodes.
- Traffic and Data Specifications
  - Traffic Model: Poisson process for message arrivals.

- Packet Specifications:
  - Size: Fixed at 64 bytes per packet.
  - Transmission Rates: Adaptive, depending on network load and channel reliability.
- Duty Cycle: Higher for nodes near the sink due to increased relay responsibilities.

- Routing Protocol Details

- Routing Metric: Combines energy availability, channel reliability, and hop count.
- Dynamic Route Discovery: EEDBR updates routes dynamically based on network and energy conditions.
- Energy Awareness: Prioritizes low-energy paths to extend network lifetime.
- Load Balancing: Ensures even distribution of traffic across nodes to prevent premature depletion.

- Energy Model

- Transmission Energy: Depends on the distance and number of retransmissions required.
- Reception Energy: Includes the cost of decoding incoming packets.
- Energy Conservation: Incorporates channel conditions to reduce retransmissions and energy wastage.

- Simulation Environment

- Deployment Scenarios: Nodes deployed at varying densities (e.g., 25%, 85%, 100%) to study scalability.
- Topology: Random or grid-based placement of nodes.
- Simulation Time: Extended durations to evaluate long-term performance.
- Evaluation Metrics:
  - Energy consumption
  - Network throughput
  - Load balancing
  - Packet delivery ratio
  - Node downtime and recovery.

- Performance Parameters

- Average Neighbors per Node: Around 6 with a maximum of 12 in typical configurations.

- Energy Efficiency: Achieved through optimized routing and minimal retransmissions.
- Critical Environment Adaptability: EEDBR is tested under high error rates and dense deployments to assess robustness.

8. Hardware and Software Requirements

- Hardware: Low-power wireless sensor devices with transceivers (e.g., ZigBee or IEEE 802.15.4).
- Software: Simulation tools like NS-2, NS-3, or MATLAB to model and evaluate protocol behavior.

These technical specifications demonstrate how EEDBR is designed to optimize energy efficiency, reliability, and scalability in WSNs while addressing real-world constraints.

The performance metrics for evaluating the Energy-Efficient Depth-Based Routing (EEDBR) protocol in Wireless Sensor Networks (WSNs) are critical in determining its effectiveness in energy efficiency, reliability, and overall network performance. Below are the key performance metrics relevant to this protocol:

o Energy Consumption

- Definition: The total energy consumed by the sensor nodes during data transmission, reception, and processing.
- Purpose: To assess the protocol's ability to minimize energy use across the network.
- Measurement:

o Energy consumed per node.

o Entire network energy consumption over a simulation period.

o Energy spent on transmissions, retransmissions, and idle states.

- Expected Outcome: EEDBR should reduce energy consumption compared to standard DSR, particularly under varying traffic loads and channel conditions.

o Packet Delivery Ratio (PDR)

Definition: The ratio of successfully delivered packets to the total packets generated.

Purpose: To evaluate the reliability of the protocol in delivering data to the sink node.

$$\text{PDR}=\frac{\textbf{Number of packets delivered}}{\textbf{Number of packets generated}}$$

This ensures clarity and consistency in expressing PDR as the ratio of successfully delivered packets to the total packets generated.

Expected Outcome: EEDBR should maintain a high PDR, even in scenarios with high error rates or dense node deployments.

- Throughput

Definition: The rate at which data is successfully delivered to the sink node, typically measured in bits per second (bps).

Purpose: To analyze the protocol's efficiency in utilizing the network's capacity.

Expected Outcome: EEDBR should achieve higher throughput by leveraging energy-efficient and reliable routes.

- Load Balancing

Definition: The even distribution of traffic load across all nodes in the network.

Purpose: To prevent specific nodes from depleting their energy prematurely, which could lead to network partitioning.

Measurement: Variance in energy levels across nodes.

Load handled per node (packets processed or forwarded).

Expected Outcome: EEDBR should ensure balanced energy usage across nodes, extending the network's operational lifetime.

- Network Lifetime

Definition: The time till the first node in the network depletes its energy or the network becomes disconnected.

Purpose: To conclude how long the protocol can maintain a functional network.

Measurement:Time until 10%, 50%, or 100% of the nodes die.

Time until the sink node is isolated.

Expected Outcome: EEDBR should encompass the network lifetime compared to traditional routing protocols.

- Routing Overhead

Definition: The added control message load introduced by the routing protocol to maintain routes and manage the network.

Purpose: To evaluate the protocol's effectiveness in handling route discovery and maintenance without overwhelming the network.

Measurement:Ratio of control packets to data packets.

Total bandwidth used by control messages.

Expected Outcome: EEDBR should have lower routing overhead due to its energy-efficient route discovery mechanism.

- Delay (End-to-End Delay)

Definition: The time taken for a data packet to travel from the source node to the sink node.

Purpose: To measure the protocol’s efficiency in delivering time-sensitive data.

Delay =Arrival Time−Departure Time

This represents the time taken for a packet or data to travel from its source to its destination.

Expected Outcome: EEDBR should maintain low delays by selecting reliable and efficient routes.

- Node Downtime

Definition: The duration for which nodes are non-functional due to energy depletion or other failures.

Purpose: To analyze the protocol's impact on network availability.

Measurement:

Sum of nodes experiencing downtime over time.

Percentage of active nodes throughout the simulation.

Expected Outcome: EEDBR should minimize node downtime by balancing energy consumption and improving routing reliability.

- Recovery Rate

Definition: The capability of the protocol to recover from node or link failures and establish alternate routes.

Purpose: To measure the adaptability and robustness of the protocol.

Measurement:

Number of successful route recoveries.

Time taken for recovery.

Expected Outcome: EEDBR should demonstrate high recovery rates with minimal delay.

- Scalability

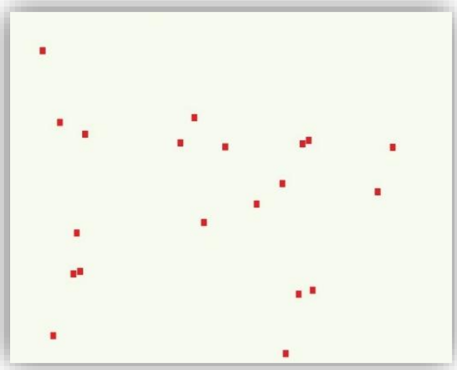
Definition: The protocol's performance as the network size or density increases.

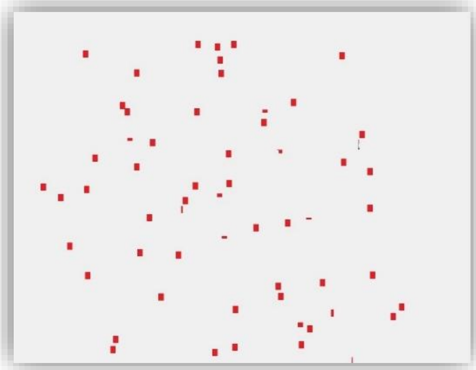
Purpose: To confirm that the protocol remains efficient under varying deployment scenarios.

Measurement: Performance metrics (e.g., energy consumption, PDR) are analyzed under different node densities and network sizes.

Expected Outcome: EEDBR should scale efficiently, maintaining high performance in large or dense networks.

These performance metrics collectively evaluate the energy efficiency, reliability, robustness, and scalability of the EEDBR protocol, providing insights into its suitability for resource-constrained WSN environments.





Data:

Figure 5: Nodes Deployed at 25%.Figure 6: Nodes Deployed at 85%

Based on the figures 5-16 mentioned in this paper, how they relate to the Energy-Efficient Depth-Based Routing (EEDBR) Protocol for Wireless Sensor Networks (WSNs):

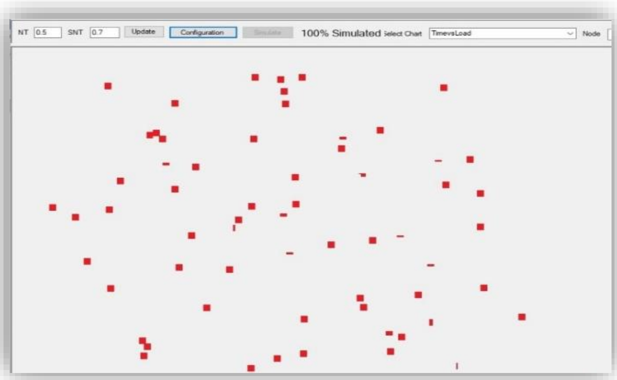
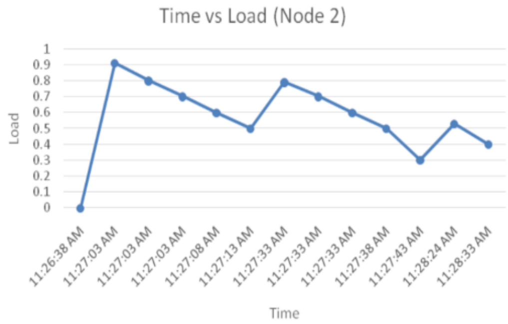


Figure 7: Nodes Deployed at 100% simulation.

Figure 5, 6 and 7 shows the Nodes Deployed at Different Percentages (25%, 85%, and 100%) These figures likely represent the spatial deployment of sensor nodes at varying densities. They help illustrate the impact of node density on the energy efficiency and communication reliability of the EEDSR protocol. At higher densities, the protocol can better balance the load and route traffic effectively.



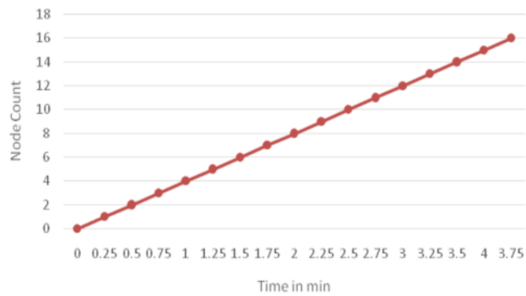
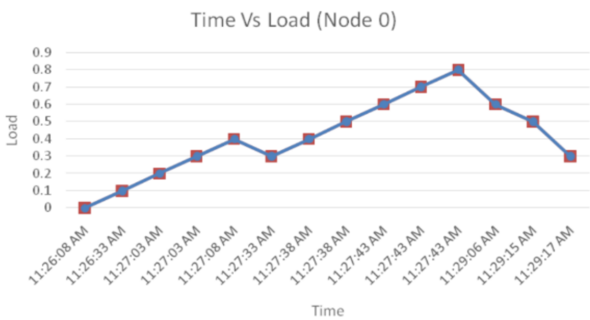


Figure 8: Number of nodes deployed vs TimeFigure 9: Node deployed vs Load at node2

This graph illustrates node deployment over time, showing EEDBR's adaptability to network changes like node failures. It also analyzes load distribution at specific nodes, highlighting EEDBR's ability to balance traffic and reduce energy depletion in overloaded nodes.



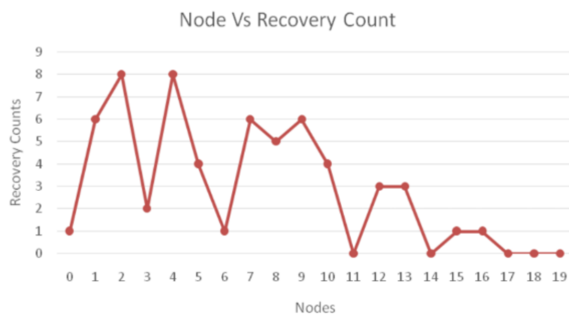


Figure 10: Node deployed vs Load at node0.

Figure 11: Nodes recovered with reference to energy efficient.

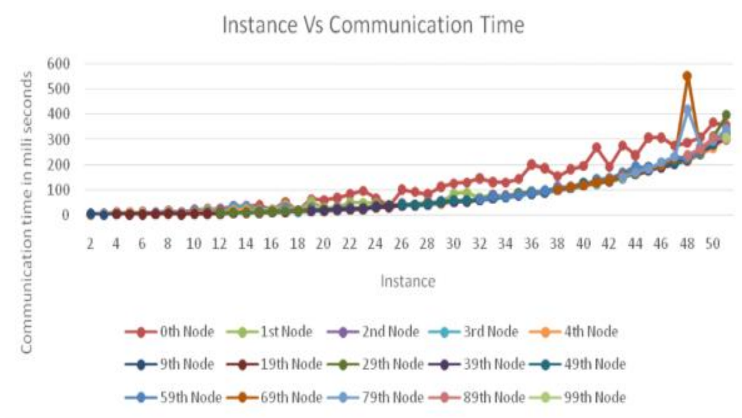


Figure 12:Nodes deployed and instance communication as energy efficient

It emphasizes the protocol's ability to conserve energy and extend the network's operational lifespan.

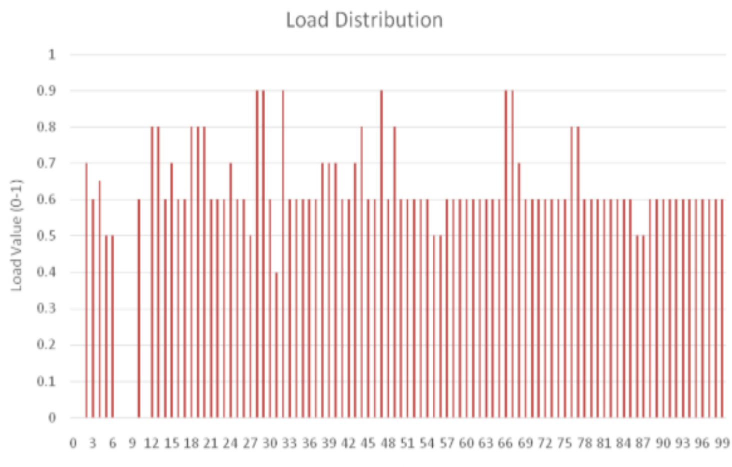


Figure 13: Nodes deployed energy distribution in terms of load balancing.

Nodes Deployed Energy Distribution in Terms of Load Balancing This graph demonstrates how the EEDBR protocol distributes energy usage evenly across the network. Effective load balancing prevents premature node failures, ensuring consistent performance.

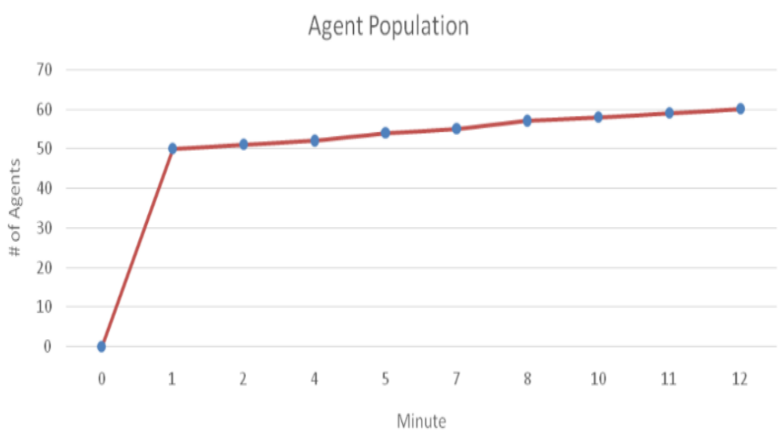


Figure 14: Nodes energy efficient in critical environment.

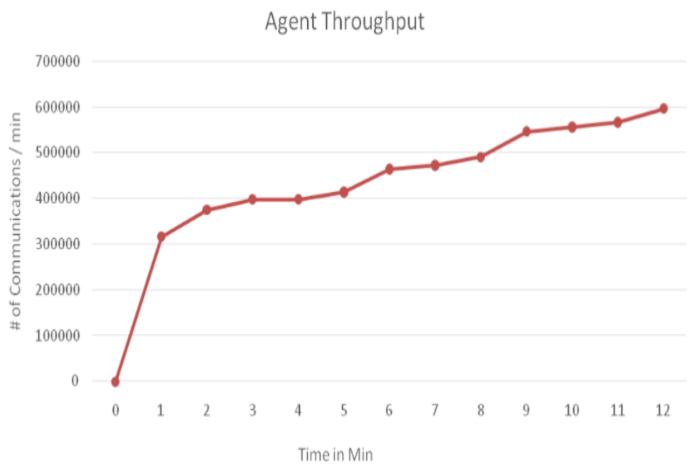


Figure15: Nodes energy efficient throughput with reference to communication.

The figure 14 and 15 demonstrates EEDBR's energy efficiency in challenging environments, highlighting its robustness in high-error or dense scenarios. The throughput graph shows how EEDBR maintains high data delivery while minimizing energy consumption.

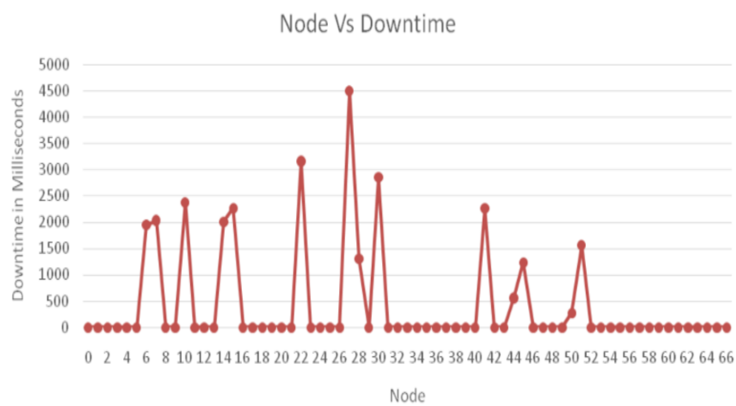


Figure 16: Nodes downtime with reference to energy efficient

Nodes Downtime with Reference to Energy Efficiency
Figure 16shows the relationship between downtime and the energy-efficient operation of the protocol. Reduced downtime indicates better network availability and efficiency, achieved through effective routing and energy conservation.

Each graph collectively highlights the strengths of the EEDBR protocol in managing energy consumption, balancing load, and maintaining communication reliability, particularly in resource-constrained WSN environments.

TABLE 5Comparison of Various Protocols with Energy Efficient Depth-Based Routing Protocol (EEDBR).

Protocol	Energy Efficiency	Adaptive Routing	Load Balancing	Suitability for IoT	Primary Focus
CoAP	Moderate	Low	Low	High	Lightweight communication.
MQTT	Moderate	Low	Moderate	High	Publish-subscribe messaging.
6LoWPAN	High	Moderate	Low	High	IPv6 communication in IoT.
XMPP	Low	Low	Low	Moderate	Real-time messaging.
TEEN	High	Moderate	Low	High	Energy-efficient threshold-based sensing.
EEDBR	High	High	High	High	Energy-efficient routing and load balancing.

9. Conclusion

The Energy-Efficient Data Routing Protocol or Energy-Efficient Depth-Based Routing Protocol (EEDBR) is a highly adaptive solution addressing energy management and load balancing challenges in Wireless Sensor Networks (WSNs) for IoT systems. It incorporates dynamic clustering, cluster head (CH) selection, and adaptive routing to optimize energy usage, reduce congestion, and extend network lifetime. These features ensure reliable data transmission and improved system performance.

A notable feature of EEDBR is its ability to evenly distribute energy consumption among nodes, minimizing risks like energy holes and network partitioning. The protocol dynamically adjusts to network conditions, including changes in node density, traffic intensity, and mobility, maintaining high reliability and throughput. Simulations demonstrate its superiority over traditional protocols, highlighting significant energy savings, reduced delays, and extended node lifetimes.

EEDBR's scalability is particularly beneficial for dense IoT deployments. It forms smaller clusters to minimize communication overhead and energy usage per hop while maintaining efficient data forwarding using energy-aware criteria. Additionally, its integration of machine learning introduces predictive capabilities, enabling the protocol to anticipate network demands and optimize routing decisions proactively.

Real-world implementation remains critical to validate EEDBR's performance under practical conditions. Future research will focus on addressing hardware variations, environmental factors, and advanced security measures to safeguard data integrity and promote widespread adoption.

EEDBR’s versatility extends to applications like disaster monitoring, smart cities, and industrial automation, where its adaptability and energy efficiency are essential. For example, in smart cities, EEDBR can enhance resource allocation and streamline service delivery through reliable communication among devices.

EEDBR represents a significant leap in energy-aware routing for IoT ecosystems. By prioritizing energy efficiency, load balancing, and adaptability, it enhances network sustainability and performance, making it a vital component for the future of interconnected systems.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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