Diyala Journal of Engineering Sciences Vol (17) No 4, 2024: 168-179

Diyala Journal of Engineering Sciences

Journal homepage: https://djes.info/index.php/djes

ISSN: 1999-8716 (Print); 2616-6909 (Online)

Efficient Energy Management in Wireless Sensor Networks Using Edge Sensor Node-Based Routing Protocols

Dhari Ali Mahmood*[,1], Yahiea Al Naiemy[2]

[1] Department of Computer Engineering, University of Technology- Iraq, Baghdad, 10066, Iraq

[2] Department of Computer Science, College of Science, University of Diyala, Diyala, 32001, Iraq

ARTICLE INFO

Article history:
Received August 18, 2024
Revised October 12, 2024
Accepted October 16, 2024
Available online December 1, 2024

keywords
Edge Sensor Node
Routing
WSN
Energy
lifespan

ABSTRACT

Wireless Sensor Networks (WSNs) provide infrastructure for Various environments and applications that require these sensors must operate in, leading to many challenges, including energy. An Energy-Efficient Edge Routing Protocol (EEERP) has been presented in this paper, the proposed protocol addresses the critical challenge of energy efficiency by leveraging edge sensor nodes(ESNs) strategically positioned at the borders of clusters to act as gateways. The proposed protocol increases the efficiency of whole network by introduce ESNs that facilitate efficient data transmission between sensor nodes and the Base Station(BS). The process of node selection take into consideration in EEERP, where the node with low energy level automatically assigned new ESN, to ensuring continuous network operation and optimal performance. Analysis of the EEERP results validate through MATLAB simulation to compareing it against established protocols such as the performance efficient data aggregation protocol(PEDAP) and high quality of service routing algorithm(HQRA). The results show that EEERP significantly enhances energy efficiency, network stability, and overall operational lifespan. The reliability of the WSN increases as demonstrated in results based dynamic clustering with gateways at cluster border-based ESNs.

1. Introduction

Recent developments in wireless communication have created low-cost, low-energy, multi functional sensors. These tiny sensors possess modest signal processing, communication capabilities, and detecting abilities (i.e., light, temperature, etc.) [1, 2]. However, Wireless Sensor Networks (WSNs) differ from conventional wireless and ad hoc networks due to these energy and size constraints. Consequently, to extend the network's lifetime critical for scenarios like military field observations and habitat monitoring new protocols emphasizing power efficiency must be created based on their applications [3–6].

Integrating Internet of Things (IoT) technologies in modern industrial processes is pivotal in enhancing operational efficiency and real-time data monitoring. A common challenge in these settings is the physical feasibility of connecting numerous sensors via a wired network, which can often be impractical due to spatial and economic constraints. Wireless IoT devices emerge as a robust solution, offering efficient data communication and flexible network configuration. In such systems, sensor-equipped nodes with wireless transceivers collect data and transmit packets to a central Base Station (BS), where sophisticated data processing and system evaluations are conducted.

This paper explores various strategies to enhance the energy efficiency of WSNs based on different paradigms, such as routing approaches. The authors propose an energy-efficient protocol based on ESNs and cluster techniques [7]. Clustering algorithms, such as the Low Energy Adaptive Clustering Hierarchy (LEACH), have emerged as a significant method for reducing energy consumption [8]. LEACH introduces a dynamic clustering mechanism where nodes are periodically elected as cluster heads, ensuring an even distribution of network energy consumption, thereby delaying the depletion of any single node's battery.

A cluster head's primary responsibility is collecting data from the nodes within its cluster. Since nodes are

---

*Corresponding author
E-mail address: dhari.a.mahmood@uotechnology.edu.iq
DOI: 10.24237/djes.2024.17410

typically closer to their cluster heads than the BS, this localized communication requires less energy. The cluster head performs data aggregation compressing incoming data from various nodes into a single message, significantly reducing the volume of data transmitted to the BS, thereby conserving energy further.

By minimizing the distance over which individual nodes transmit data and reducing the payload size through aggregation, LEACH effectively decreases the overall energy expenditure of the network. This enhances the network's operational efficiency and substantially extends its lifespan compared to networks where nodes transmit collected data directly to the BS without intermediate sensor aggregation.

Several improvements and optimizations to enhance energy usage and network performance have been proposed in subsequent research, which has built upon the foundation established by LEACH [9]. These studies have explored dynamic cluster head selection algorithms, adaptive duty cycling, and energy-efficient routing protocols, highlighting their importance and effectiveness in managing the energy constraints of wireless IoT networks.

Many use cases of WSN based on energy consumption have been identified in [10, 11], including:

1. Low power based on hardware design:
    - Sensing transducer;
    - A/D Converter;
    - Computation unit;
2. Data aggregation;
3. Security mechanism;
4. Communication overhead:
    - Routing Protocols; Traditional routing protocols like Ad Hoc On-Demand Distance Vector (AODV) or Dynamic Source Routing (DSR) require the exchange of routing tables or control packets at regular intervals. This continuous communication overhead leads to increased energy consumption, especially in large-scale networks with frequent changes in network topology.
    - Control messages; Sensor nodes may need to exchange control messages for network management functions, including neighbor discovery, connection quality evaluation, and route optimization. These control signals use more energy and bandwidth, especially if broadcast or propagated over the network.
    - Synchronization Maintaining synchronization among sensor nodes is crucial for scheduling time division multiple access (TDMA), data fusion, and coordination of distributed algorithms. However, synchronization mechanisms often require periodic messages or beacon exchanges, leading to energy overhead.
    - Reliable communication WSNs often involve the exchange of acknowledgments (ACKs) and retransmissions to ensure message delivery. This process introduces overhead regarding additional message exchanges and processing, which can consume significant energy, especially in noisy or unreliable wireless environments.
    - Network Management: Tasks such as address assignment, channel allocation, and network reconfiguration also contribute to communication overhead in WSNs. These management tasks require additional signaling and coordination among sensor nodes, increasing energy consumption.

The concept of clusters based on Edge Sensor Nodes (ESN) has been considered in developing a new protocol called the Energy-Efficient Edge Routing Protocol EEERP. The key contributions of paper:

- Integration of Edge Sensor Nodes (ESNs): EEERP introduces ESNs as gateways at cluster borders, reducing energy consumption and improving data transmission efficiency in WSNs.

- Dynamic Node Selection Process: A unique mechanism in EEERP automatically updates ESN assignments based on node energy levels, that leads to enhanced network lifespan and reliability through extensive simulations, EEERP demonstrates superior performance, achieving a 15% improvement in network lifespan and up to 98.7% reliability compared to existing protocols.

The rest of the paper is organized as follows. The related work is summarized in Section 2. Routing Protocols for WSN is provided by Section 3. The system model presented by Section 4. In Section 5, proposed routing algorithm based-on ESN. Next section 6 performance evaluate the routing algorithms and numerical results also take into consideration. Finally, Section 7 concludes the paper.

2. Related Work

2.1. Greedy Routing Algorithms

In networking, routing is a significant algorithmic issue. A great deal of effort has gone into developing effective routing algorithms. However, for some networks (e.g., WSNs), traditional routing strategies could be more practical due to inefficiency in space and high setup overhead.

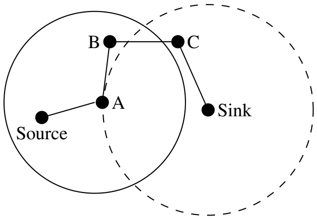

Figure 1: Greedy Packet forwarding with local minimum situation [12]

Geometric routing has been suggested as an alternative. Geometric routing computes the routing paths using the geometric coordinates of the vertices. Greedy routing is the simplest type of geometric routing; a vertex forwards messages to a neighbor closer to the destination than itself. Greedy routing methods are theoretically straightforward and construct routing paths using local coordinate information but can only sometimes ensure that messages are delivered [12, 13].

The packet addressed to the sink is dropped at node A since every node within its transmission range is moving backward, even though the greedy routing algorithm cannot ensure packet delivery [14], even if a path exists, as illustrated in Figure 1.

2.2. *Basic One-hop Strategies*

In WSNs, one-hop strategies allow neighboring nodes to communicate directly within a single-hop range, facilitating efficient data transmission. Neighbor discovery and packet forwarding using a greedy strategy proposed by [15] apply the same concept but take distance into account rather than progress. The source forwards the packet to the neighbor node closest to the sink node. Compass routing aims to reduce Euclidean path length by using this method.

2.3. *Basic Multi-hop Strategies*

WSNs use multi-hop strategies to transmit data packets through multiple intermediate nodes before reaching the destination node [9]. These strategies are essential in extending the communication range, improving network coverage, and conserving energy, compared to direct one-hop communication [16]. Nodes close to the sink quickly deplete their batteries compared to nodes at the source because they have to send a lot of data traffic from peripheral nodes to the sink in multi-hop networks. Usually, their batteries are not replaceable since Nodes located closer to the sink tend to have their batteries drained faster compared to nodes that are located farther away because they have to handle a more significant amount of data traffic that is being transmitted from peripheral nodes to the sink in multi-hop networks. Moreover, their batteries are usually not replaceable since there are many dead nodes, and the process of replacing batteries is both costly and time-consuming [17]. The presence of dead nodes in the network leads to an increased data loss rate and reduces the network's lifespan.

3. Routing Protocols for WSNs

In WSN, routing algorithms ensure that collected data is transmitted from sensor nodes to the BS through different paths efficiently, optimizing energy consumption and network bandwidth. Developing and implementing efficient routing protocols is crucial given the limitations typically associated with WSNs, such as limited battery life and scalability issues. Various factors, such as the limited energy, processing, and storage capabilities of sensor nodes pose challenges in developing and implementing routing algorithms. These factors should be considered when designing WSN routing protocols to be adaptable, scalable, and energy-efficient, ensuring long network lifetimes and reliability [18].

3.1. *Energy-based Routing*

Energy efficiency is essential in designing and operating WSNs regarding energy resources. It aims to extend the sensor's network lifetime by minimizing energy consumption while maintaining satisfactory network performance [19]. These protocols consider factors such as transmission distance, data aggregation, sleep scheduling, and routing path selection to optimize energy usage. Researchers have proposed energy-efficient routing protocols considering node proximity [20,21], data aggregation, and transmission power control to minimize energy consumption while meeting the quality of service requirements. Moreover, energy-aware routing protocols in WSNs often include techniques such as multipath routing, where data is transmitted through multiple paths to balance energy consumption across nodes and increase network reliability. Various energy-efficient routing algorithms have been presented in the literature to address the energy constraints in WSNs. These algorithms optimize routing paths, minimize energy consumption, and improve network performance [22]. These algorithms extend the network lifetime and improve overall performance by selecting optimal paths, minimizing data transmission distances, and reducing unnecessary energy consumption.

4. System Model

Figure 2 depicts a potential WSN configuration [18].

1. The authors assume that data is transferred to the BS via the ESN via a single-source node.
2. All sensor nodes communicate with BS, but the sensor node sends the data it has acquired to BS via ESN.
3. There's one BS on the network.

4. All the ESN communicates with the BS in the area of WSN through a single-hop connection.
5. The BS is connected to the energy supply.
6. There are N sensor nodes in total, and their locations are fixed.
7. The Rayleigh fading model yields the following probability of a successful packet between two nodes [23]:

   $$P_{i,ESN} = \exp\left(-\frac{\theta\sigma^2}{g_i d_{iESN}^{-n}}\right) \tag{1}$$

   where :

   θ: is a threshold parameter that may vary depending on the Signal -to-Noise ratio (SNR) needed to receive a signal.

   σ^2 : power of noise in the channel.

   g_i : gain at node i, possibly including factors like antenna gains.

   $d_{i,ESN}$: distance(m) between node i and node ESN.

   n: path loss exponent, reflecting how the signal power decreases with distance in the propagation environment. $(-n)$ indicates the inverse power law of signal attenuation with $d_{i,ESN}$ distance.
8. To calculate how energy is distributed in the proposed model
9. Energy of Transmission: the transmission energy from node i to ESN node transmite a k-bit based on $d_{i,ESN}$ can be compute as [24], and after modifying equations 2 and 3 in [25] to be suitable with a new method based on ESN. The energy dissipation of the radio in the designated radio model to power the transmitter or receiving circuitry is equal to $E_{T_xelec} = 50nJ/bit$, and equivalent to operating the transmit amplifier $E_{T_xamp} = 100pJ/bit/m^2$:

   $$E_{T_x}(k,d) = E_{T_xelec}(k) + E_{T_xamp}(k,d)$$

   $$E_{i,ESN}(k) = 2 * E_{T_xelec} * k + E_{T_xamp} * k * d_{i,ESN}^2 \tag{2}$$

   Hence,k, representing a $k - bit$ message over a distance d.

   $$E_i'(k) = E_{T_xelec} * k + E_{T_xamp} * k * d_{ESN,b}^2 \tag{3}$$

   Where $E_{i,ESN}$ is energy of transmission between any node i within cluster and ESN the border of cluster, on another hand, E_i' is energy of transmission between node i and the BS, $d_{i,ESN}$ is the distance between node i and border node ESN, and $d_{ESN,b}$ is the distance between node i and the BS. For the duration of the system lifespan, it may be beneficial to increase the number of transmissions to the BS since E_i' is smaller than $E_{i,ESN}$ when the period with E_{T_xamp} is significantly smaller than the term with E_{T_xelec}. The energy consumption for transmitting a message includes both the energy required for the actual transmission of the message and the energy needed for the reception of ACK message. When a node transmits a packet to ESN, it expends energy for its transmission and the potential reception of an ACK packet from the recipient node. Therefore, the energy consumption for the transmission of the packet is effectively doubled to account for both the transmission and reception processes. On the other hand, when a node transmits a packet from ESN to the BS, it does not expect an ACK packet from the BS. Hence, the energy consumption for transmitting a packet to the BS is not doubled as shown in (3).

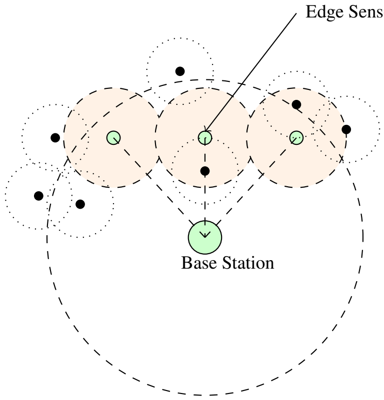

Figure 2: Routing path through ESN communication in WSN

Figure 2 illustrates the routing path through multi-hop communication in a WSN. The diagram shows ESN connected to a BS via dashed lines, indicating the multi-hop nature of the communication path.

4.1. Energy model

The energy dissipation in direct transmission and minimum transmission-energy routing are compared in [24], and it is shown that when the BS is far from the nodes, the optimal system must include a combination of both. The authors suggest a two-level clustering hierarchy-based routing strategy, where all other nodes find the nearest cluster-head to the BS to send their data to, and the number of nodes (cluster heads) that transmit data to the BS is limited to 5% [23]. To increase the system lifetime, the cluster heads are selected at random.

5. Proposed Routing Algorithm based on ESN

Algorithm 1 (EEERP) Pseudocode

```
Data Structures:
ENInfo: Address ($\mathcal{A}$) and Remaining Energy ($\mathcal{E}$) of an edge node
EEERP Class:
  EN: Map storing edge nodes' info
  isEN($\mathcal{A}$): Check if a node is an edge node
  updateENE($\mathcal{A}, \mathcal{C}$): Update energy level of an edge node ($\mathcal{C}$ = energy consumed)
Algorithm Overview:
Initialization:
Initialize EN to store edge node information
Identify edge nodes based on network topology or criteria
Identify the BS
Route Request (RREQ) Handling:
  On RREQ Receive:
1. Check EN Status: Determine if source node is an edge node (isEN($\mathcal{A}$))
2. Select Optimal ESN:
if sensor node is located between two ESNs then
    Dynamically select the most energy-efficient ESN based on:

quad a. Distance to the SN
      b. Remaining energy of each ESN
      c. Signal strength
    Update routing table for the selected ESN
    Adjust path cost based on remaining energy (updateENE($\mathcal{A}, \mathcal{C}$))
end if
  Forwarding RREQ:
if current node is an edge node then
    Forward RREQ to the next hop
else
    Drop RREQ
end if
Route Reply (RREP) Handling:
  On RREP Receive:
1. Check EN Status: Determine if the previous hop is an edge node (isEN($\mathcal{A}$))
2. Update Route Table:
if previous hop is an edge node then
    Update routing table for the edge node
    Adjust path cost based on remaining energy (updateENE($\mathcal{A}, \mathcal{C}$))
end if
  Forwarding RREP:
if current node is an edge node then
    Forward RREP to the next hop towards the source
else
    Drop RREP
end if
Data Transfer:
  On Data Packet Send:
if current node is an edge node then
    if destination is BS then
        Forward data packet to the next edge node towards BS
    else
        Forward the data to the next hop
    end if
else
    Drop data packet and re-initialize the path
end if
```

5.1. Energy Computation in EEERP Protocol

The EEERP protocol integrates principles from both High Quality of Service Routing Algorithm(HQRA) [26] and Ad-Hoc On-Demand Distance Vector (AODV) [27] to optimize energy consumption, however the protocol starts with an initial energy setup similar to HQRA, ensuring all nodes have the same starting energy level. Route Selection: Routes are selected using an entropy-based energy distribution method, which helps in balancing the energy usage across the network. The EEERP protocol adapts HQRA principles by utilizing ESN between clusters. This approach allows for efficient energy computation by dynamically choosing between direct and two-hop paths for data transmission as shown in figure 2. Here's how energy is computed:

5.1.1. Initial Energy Setup

Each node starts with an initial energy level(all nodes have the same energy level, including ESN) G_i.

5.1.2. Energy Distribution and Entropy Calculation

The energy state of the network is characterized using entropy to maximize network lifespan and the network's energy distributions $\mathcal{D}$ will be computed using:

$$\mathcal{D}_i = \frac{G_i}{\sum_{j=1}^{|V|} G_j}, \quad \text{where } |V| \text{ is the total number of nodes.} \tag{4}$$

The entropy-like measure is given by:

$$H = \sum_{i=1}^{|V|} \mathcal{D}_i \log \mathcal{D}_i \tag{5}$$

A higher entropy indicates an evenly distributed energy state [26].

5.1.3. Transmission Energy Consumption via Edge Nodes

In EEERP, energy is consumed differently based on the path chosen:

1. Direct to BS: The energy required to transmit directly to the BS is:

$$g_{direct} = g_0 \cdot d_{i,BS}^{\chi} \tag{6}$$

   where:

   - g_0: Baseline energy consumption.
   - $d_{i,BS}$: Distance between node i and the BS.
   - χ: Path-loss exponent.

2. Through Edge Nodes: Using an edge node to relay data reduces energy consumption:

$$g_{through} = g_0 \cdot d_{i,edge}^{\chi} + g_0 \cdot d_{edge,BS}^{\chi} \tag{7}$$

   where:

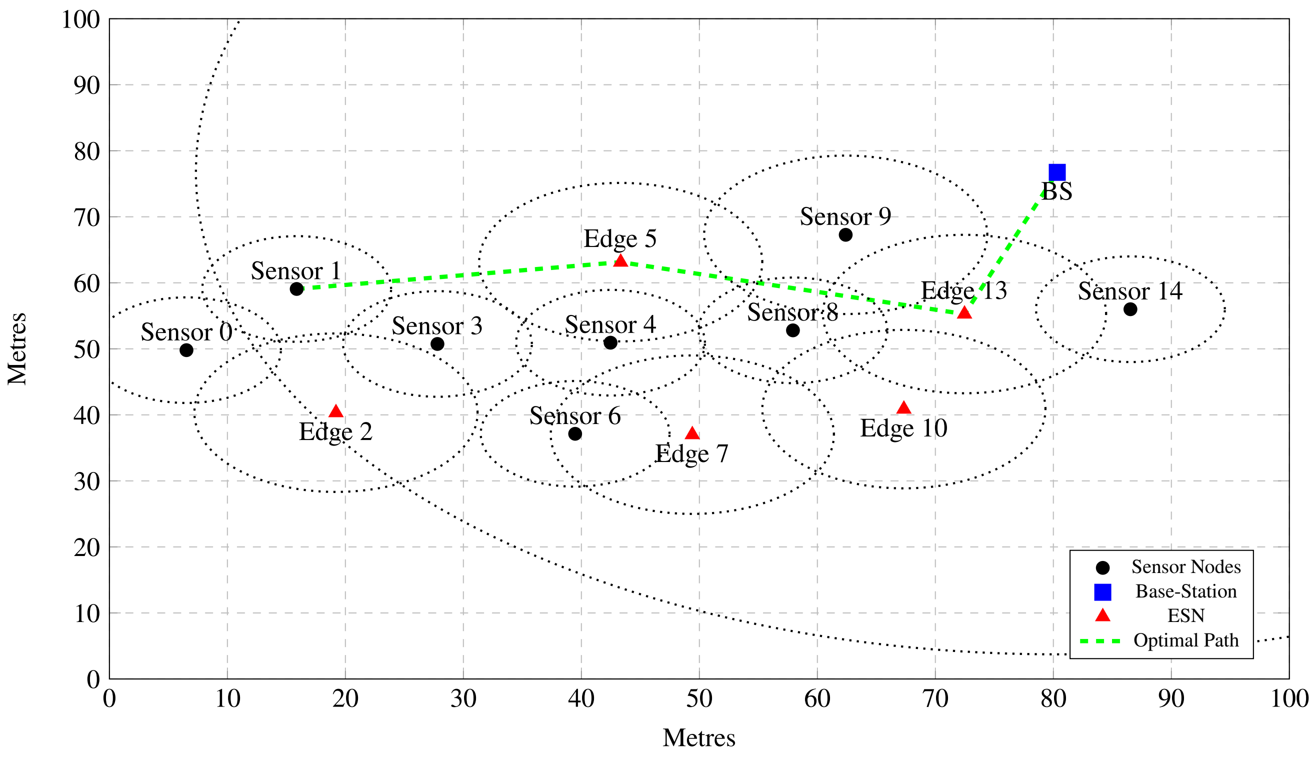

Figure 3: Optimal Path in EEERP with ESN and Cluster Communication

- $d_{i,edge}$: Distance from node *i* to the edge node.
- $d_{edge,BS}$: Distance from the edge node to the BS.

This routing strategy saves energy compared to direct communication as shown in Figure 3.

5.2. Reliability and Fading Model

The Rayleigh fading model [23] calculates the probability of successful delivery via edge nodes:

$$P_{through} = P_{i,edge} \cdot P_{edge,BS} \tag{8}$$

where:

- $P_{i,edge}$ is the probability of successful delivery from node *i* to the edge cluster node using the Rayleigh fading model.
- $P_{edge,BS}$ is the probability of successful delivery from the edge cluster node to the BS, also calculated using the Rayleigh fading model.

In wireless communication, the Rayleigh fading model is used to describe the effect of multipath propagation on the signal. This model is particularly suitable for environments where there are many obstacles, causing multiple scattered paths for the signal to reach the receiver.

The probability of successful delivery $P_{i,edge}$ and $P_{edge,BS}$ can be derived from the signal-to-noise ratio (SNR) and bit error rate (BER) using the Rayleigh fading model. Given that the success of a transmission depends on both the link from node *i* to the edge node and from the edge node to the BS, the overall probability of successful delivery $P_{through}$ is the product of the individual probabilities.

Proof. : Probability of Successful Delivery from Node *i* to Edge Node ($P_{i,edge}$):

$$P_{i,edge} = e^{-\frac{S_{th}}{\bar{S}_{i,edge}}} \tag{9}$$

where S_{th} is the threshold SNR required for successful communication, and $\bar{S}_{i,edge}$ is the average SNR of the link from node *i* to the edge node.

Probability of Successful Delivery from Edge Node to BS ($P_{edge,BS}$):

$$P_{edge,BS} = e^{-\frac{S_{th}}{\bar{S}_{edge,BS}}} \tag{10}$$

where S_{th} is the threshold SNR required for successful communication, and $\bar{S}_{edge,BS}$ is the average SNR of the link from the edge node to the BS.

Overall Probability of Successful Delivery ($P_{through}$): Since the transmissions are independent, the overall probability of successful delivery through the edge node is the product of the individual probabilities:

$$P_{through} = P_{i,edge} \cdot P_{edge,BS} = \left(e^{-\frac{S_{th}}{\bar{S}_{i,edge}}} \right) \cdot \left(e^{-\frac{S_{th}}{\bar{S}_{edge,BS}}} \right)$$

$$P_{through} = e^{-\frac{S_{th}}{\bar{S}_{i,edge}} - \frac{S_{th}}{\bar{S}_{edge,BS}}}$$

□

Therefore, the equation $P_{through} = P_{i,edge} \cdot P_{edge,BS}$ holds under the Rayleigh fading model, demonstrating that the overall probability of successful data transmission through the network is the product of the probabilities of the individual links. This product reflects the cumulative effect of the fading model on the communication links between nodes and from edge nodes to the BS, providing a realistic estimate of network reliability under Rayleigh fading conditions.

Power Efficient Data Collection and Aggregation Protocol (PEDAP) [25] optimizes energy consumption using a minimum spanning tree, which can be robust against fading by minimizing the overall transmission distance. However, it does not explicitly address multipath fading effects like the Rayleigh model. HQRA uses a hierarchical structure to manage fading by limiting the communication range within quadrants but does not explicitly model fading effects like Rayleigh fading. In contrast, EEERP explicitly uses the Rayleigh fading model to calculate the probability of successful delivery, enhancing reliability through edge nodes.

5.3. *Reliability and Fading Model for Multiple Sensors*

The Rayleigh fading model calculates the probability of successful delivery via edge nodes:

$$P_{through} = \prod_{k=1}^{n} \left(P_{k,edge} \cdot P_{edge,BS} \right) \tag{11}$$

where:

- $P_{k,edge}$ is the probability of successful delivery from sensor node k to the edge cluster node using the Rayleigh fading model.
- $P_{edge,BS}$ is the probability of successful delivery from the edge cluster node to the BS , also calculated using the Rayleigh fading model.
- n is the number of sensor nodes sending data to the BS.

In wireless communication, the Rayleigh fading model is used to describe the effect of multipath propagation on the signal. This model is particularly suitable for environments where there are many obstacles, causing multiple scattered paths for the signal to reach the receiver.

The probability of successful delivery $P_{k,edge}$ and $P_{edge,BS}$ can be derived from the SNR and bit error rate (BER) using the Rayleigh fading model. Given that the success of a transmission depends on both the link from node k to the edge node and from the edge node to the BS, the overall probability of successful delivery $P_{through}$ is the product of the individual probabilities.

Proof. Probability of Successful Delivery from Sensor Node as shown in equation 9 and Probability of Successful Delivery from Edge Node to BS as shown in equation 10, Overall Probability of Successful Delivery for Multiple Sensors ($P_{through}$): Since the transmissions are independent, the overall probability of successful delivery through the edge node for multiple sensors is the product of the individual probabilities:

$$\begin{aligned} P_{through} &= \prod_{k=1}^{n} \left(P_{k,edge} \cdot P_{edge,BS} \right) \\ &= \prod_{k=1}^{n} \left(e^{-\frac{S_{th}}{\bar{S}_{k,edge}}} \cdot e^{-\frac{S_{th}}{\bar{S}_{edge,BS}}} \right) \end{aligned} \tag{12}$$

$$P_{through} = \prod_{k=1}^{n} e^{-\frac{S_{th}}{\bar{S}_{k,edge}} - \frac{S_{th}}{\bar{S}_{edge,BS}}}$$

$$P_{through} = e^{-\sum_{k=1}^{n} \left(\frac{\Gamma_{th}}{\bar{\gamma}_{k,edge}} + \frac{\gamma_{th}}{\bar{\gamma}_{edge,BS}} \right)}$$

Therefore, the equation $P_{through} = \prod_{k=1}^{n} \left(P_{k,edge} \cdot P_{edge,BS} \right)$ holds under the Rayleigh fading model, demonstrating that the overall probability of successful data transmission through the network is the product of the probabilities of the individual links. This product reflects the cumulative effect of the fading model on the communication links between nodes and from edge nodes to the BS, providing a realistic estimate of network reliability under Rayleigh fading conditions when multiple sensors are involved.

□

6. Performance Evaluation

1. **Standard AODV [27]** is a reactive routing protocol that discovers routes only when data needs to be sent. It uses RREQ (Route Request) and RREP

Table 1
The simulation parameters. [26]

Parameters name	Value
Network size	100 m × 100 m
Number of sensor nodes N	30
Node distribution	Clustered Distribution
Threshold Reliability of Networks	$1 - \epsilon = 0.92$
Threshold	$\theta = 10^{-2}$
Noise energy	$\sigma = 0.1$
The smallest transmission energy	$\Delta g = 10(\mu J)$
Initial energy in each sensor node	$G_i = G_0 = 10000(\mu J)$
Energy threshold for a dead node	$\eta = 100(\mu J)$
E_{elec}	50 (nJ/bit)
The transmit amplifier E_{amp}	100 (pJ/bit/m^2)
Packet size k	5000 (bits)

(Route Reply) packets for on-demand route discovery and RERR (Route Error) packets for route maintenance.

- Strengths:Simple and efficient for small networks.
- Weaknesses: No explicit energy management, leading to faster depletion of critical nodes.

2. **HQRA Protocol [26]:** is designed to maximize network lifespan by finding the minimum energy paths while meeting reliability constraints.
    - Strengths: Maximizes network lifespan with reliable paths using energy entropy.
    - Weaknesses: Higher computational complexity due to Bellman-Ford iterations.
3. **PEDAP Protocol [25]** PEDAP stands for Power Efficient Data Collection and Aggregation Protocol, a protocol that optimizes data aggregation and routing to extend the life of WSNs.
    - Strengths: It constructs a minimum spanning tree for optimized energy consumption, extends network lifetime through balanced load distribution, and effectively reduces energy expenditure via data aggregation.
    - Weaknesses: Scalability challenges in large networks, assumes a fixed BS location and involves computational complexity in constructing and maintaining the spanning tree.
4. **EEERP Protocol:**[proposed protocol] Energy-Efficient Edge Routing Protocol EEERP improves on standard AODV by optimizing routing paths for energy efficiency while maintaining reliability. It incorporates entropy-based energy management principles from HQRA.
    - Strengths: Combines energy-aware path selection with the simplicity of AODV, utilizing edge nodes for efficient routing, leveraging static nodes to conserve energy, and improving data transmission reliability within clusters.
    - Weaknesses: Requires additional computation and control overhead to monitor energy levels and manage routing paths.

6.1. Numerical Results

This section examines the lifespan of WSNs using the proposed EEERP. The analysis involves studying the energy consumption dynamics and the longevity of WSNs based on different criteria. To better understand EEERP's performance, the results are compared with the PEDAP algorithm and the HQRA Algorithm.

The authors using MATLAB for simulations with different parameters as shown in Table 1 to assess the performance of these protocols under various conditions. The results of these simulations will provide a comprehensive understanding of the performance of the EEERP protocol. Compared with PEDAP and HQRA, EEERP shows notable improvements in energy efficiency and network lifespan. The MATLAB simulations underscore the robustness and efficiency of EEERP under various conditions, demonstrating its potential for practical deployment in WSNs. In this section, the lifespan of WSN is investigated using the proposed EEERP. This investigation involves analyzing the dynamics of energy consumption and the longevity of WSNs based on various criteria. To have a deeper understanding of EEERP's performance , the results are compared with the PEDAP algorithm and HQRA protocol.

The MATLAB tool was developed for simulations to evaluate the performance of these protocols under different conditions. The results of these simulations provide a comprehensive understanding of the EEERP protocol's performance. Compared with PEDAP and HQRA, EEERP significantly improves energy efficiency and network lifespan. The MATLAB simulations highlight the robustness and efficiency of EEERP under various conditions, showcasing its potential for practical deployment in WSNs.

Figure 4 compares the lifespan of the network, measured in rounds before the first node dies, across three protocols: HQRA, PEDAP, and EEERP. The bar chart shows that EEERP has the longest lifespan, followed by HQRA and then PEDAP, indicating the superior energy efficiency and durability of EEERP.

Figure 5 illustrates the total energy consumption (in microjoules, μJ) for each sensor node ID from 1 to 30 for the three protocols. HQRA starts at around 500 μJ and gradually increases to about 4700 μJ , showing a linear increase in energy consumption. PEDAP begins at around 600 μJ and rises more steeply to about 4900 μJ , indicating higher energy consumption per node than HQRA. EEERP

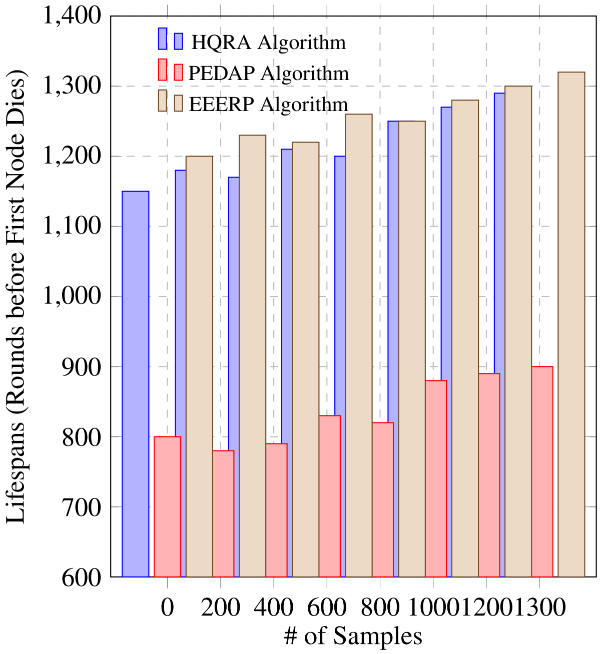

Figure 4: Comparison of Lifespans (Rounds before First Node Dies) Across Protocols

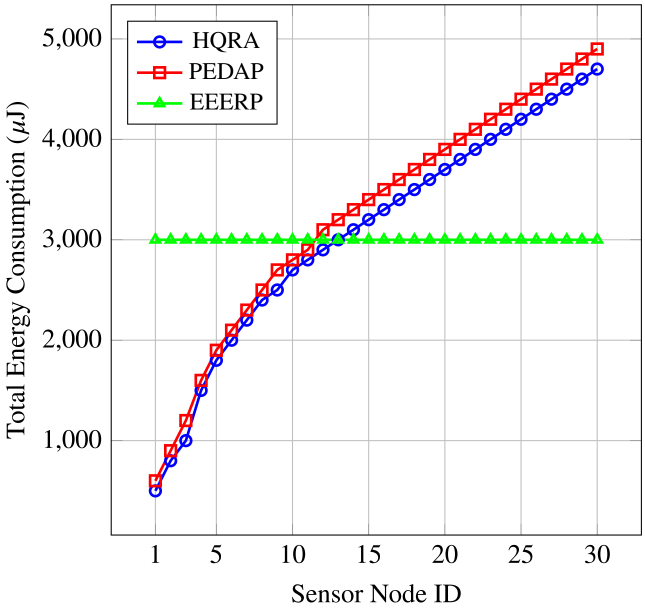

Figure 5: Energy Consumption Across Whole Network for HQRA, PEDAP, and EEERP Protocols

maintains a constant energy consumption of around 3000 μJ across all nodes, suggesting consistent and efficient energy use. EEERP is the most energy-efficient, consuming less energy per node than HQRA and PEDAP, and shows a reliable, uniform pattern that aids in predicting network lifetime and planning maintenance. HQRA is more energy-efficient than PEDAP yet less so than EEERP. Due to its higher energy efficiency, consistency, and scalability performance, EEERP is the best option for WSNs sensitive to energy consumption. It uses edge nodes for data relaying and optimum path selection.

The relationship between energy consumption and transmission power across different nodes is examined. The Figure 7 shows that as transmission power increases, energy consumption rises significantly. This increase in energy consumption is due to the higher power requirements for maintaining a stronger signal and ensuring reliable communication, especially in path loss. Furthermore, the authors observed that nodes closer to the BS consume less energy due to their shorter transmission distance. In contrast, the nodes farther away experience higher energy consumption as they must transmit over longer distances. Finally, the results from Figure 5 demonstrate the trade-offs between transmission power and energy consumption. The data suggests that maintaining lower transmission power is beneficial in terms of energy efficiency, but this must be balanced with ensuring sufficient signal strength to avoid packet loss.

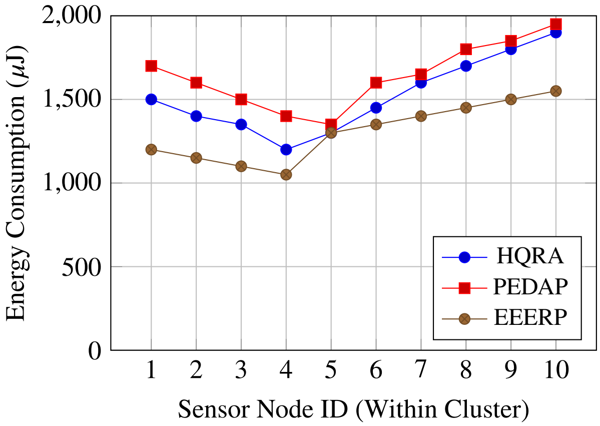

Figure 6: Energy Consumption per Node Within Cluster in HQRA, PEDAP, and EEERP

Figure 6 presents the energy consumption per node within a cluster for HQRA, PEDAP, and EEERP protocols. The plot highlights that EEERP consistently shows lower energy consumption per node within clusters, enhancing its efficiency and effectiveness in cluster-based networks.

Figure 6 depicts the energy consumption versus transmission power and packet loss for nodes 5 to 9. The Figure illustrates the trade−off between transmission power, energy consumption, and the number of packets lost. As transmission power increases, the energy consumed by each node also increases, which is expected due to the higher power required to maintain communication over longer distances or in the presence of interference.

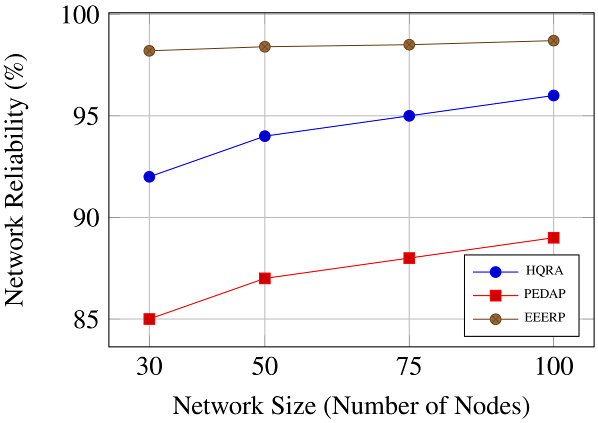

Figure 7: Network Reliability vs. Network Size for HQRA, PEDAP, and EEERP Protocols

Figure 7 shows the EEERP protocol maintains high reliability through several fundamental mechanisms: it employs ESNs to relay data, reducing transmission distance and improving network reliability by decreasing transmission errors. The protocol uses the Rayleigh fading model to account for multipath propagation in environments with obstacles, ensuring accurate reliability predictions. EEERP optimizes energy consumption to prevent premature node failure and network partitioning, balancing the energy load across the network to avoid overburdening any single node. Robust routing strategies adapt to changing network conditions, and multi-hop communication through edge nodes minimizes path loss and signal attenuation, enhancing packet delivery success. These mechanisms collectively ensure EEERP's high reliability across various network sizes and conditions.

Presents the network reliability as a function of network size (number of nodes) for the HQRA, PEDAP, and EEERP protocols. The data demonstrates that EEERP consistently achieves the highest reliability across different network sizes, ranging from 98.2% to 98.7%. The results from Figure 7 indicate that EEERP outperforms HQRA and PEDAP in terms of network reliability, particularly as network size increases. Combining optimized energy consumption, multi-hop communication through edge nodes, and adaptive routing strategies ensures that EEERP maintains consistent packet delivery success, minimizing signal attenuation and path loss.

7. Conclusion

The EEERP protocol represents a significant advancement in WSNs by merging energy-aware path selection with the straightforwardness of the AODV protocol. This integration enhances routing efficiency and data transmission reliability by leveraging edge cluster nodes. The protocol's robustness is further strengthened by incorporating the Rayleigh fading model, which accurately calculates the probability of successful delivery, thereby addressing the multipath propagation effects common in wireless communication environments. EEERP utilizes static nodes to conserve energy, thus extending the operational lifespan of the network.

The protocol requires that all nodes, including edge cluster nodes, have the baseline energy set G_i to begin, helping balance energy consumption across nodes. Of course, this uniformity helps manage energy needs and reduces, correct the phrase, waste out of energy very quickly at a specified set of nodes thereby improving even more the network performance.

An important highlight of the EEERP protocol is the ESN incorporation. ESNs are introduced for the purpose of internal data transmission within the clusters in order to offload energy excess on other nodes improving the network performance. Improved energy management is important for factors such as duration and reliability of WSNs especially in the case of limited energy resources.

In A concise the proposed protocol including the integration of ESNs, the dynamic clustering mechanism, and the improvements in energy efficiency and network reliability.

8. Conflict of Interest

The authors declare no conflict of interest.

9. Author Contributions

All authors contributed to the writing of the paper and approved the final version.

References

[1] A. M. Ahmed, S. A. Majeed, and S. A. Hasan, "Non-terrestrial networks based on non-orthogonal multiple access towards 6g," *Diyala Journal of Engineering Sciences*, pp. 1–26, 2024.

[2] S. Olenik, H. S. Lee, and F. Güder, "The future of near-field communication-based wireless sensing," *Nature Reviews Materials*, vol. 6, no. 4, pp. 286–288, 2021.

[3] W. M. Jassim and A. E. Abdelkareem, "Performance enhancement of sensor network architecture for monitoring underwater oil pipeline," *International Journal of Electrical and Computer Engineering*, vol. 11, no. 2, p. 1414, 2021.

[4] T. A. Abose, V. Tekulapally, K. T. Megersa, D. C. Kejela, S. T. Daka, and K. A. Jember, "Improving wireless sensor network lifespan with optimized clustering probabilities, improved residual energy leach

and energy efficient leach for corner-positioned base stations," *Heliyon*, vol. 10, no. 14, 2024.

[5] S. Daousis, N. Peladarinos, V. Cheimaras, P. Papageorgas, D. D. Piromalis, and R. A. Munteanu, "Overview of protocols and standards for wireless sensor networks in critical infrastructures," *Future Internet*, vol. 16, no. 1, p. 33, 2024.

[6] S. Lazim Qaddoori and Q. I. Ali, "An embedded and intelligent anomaly power consumption detection system based on smart metering," *IET Wireless Sensor Systems*, vol. 13, no. 2, pp. 75–90, 2023.

[7] A. A. Saadi and O. A. Awad, "Lifetime maximization of a mobile wsn using zrp-fuzzy clustering protocol based on ant-lion optimizer," *Iraqi Journal of Information and Communication Technology*, vol. 1, no. 1, pp. 70–82, 2021.

[8] R. Thiagarajan *et al.*, "Energy consumption and network connectivity based on novel-leach-pos protocol networks," *Computer Communications*, vol. 149, pp. 90–98, 2020.

[9] L. Farhan, O. Kaiwartya, L. Alzubaidi, W. Gheth, E. Dimla, and R. Kharel, "Toward interference aware iot framework: energy and geo-location-based-modeling," *IEEE Access*, vol. 7, pp. 56 617–56 630, 2019.

[10] L. Sahoo, S. Sen, K. Tiwary, S. Moslem, and T. Senapati, "Improvement of wireless sensor network lifetime via intelligent clustering under uncertainty," *IEEE Access*, 2024.

[11] C. Zhou, M. Wang, W. Qu, and Z. Lu, "A wireless sensor network model considering energy consumption balance," *Mathematical problems in Engineering*, vol. 2018, no. 1, p. 8592821, 2018.

[12] H. Zhang and X.-Z. Kong, "On k-greedy routing algorithms," *Computational Geometry*, vol. 52, pp. 9–17, 2016.

[13] L. Farhan, R. Kharel, O. Kaiwartya, M. Hammoudeh, and B. Adebisi, "Towards green computing for internet of things: Energy oriented path and message scheduling approach," *Sustainable Cities and Society*, vol. 38, pp. 195–204, 2018.

[14] S. R. Nabavi, N. O. Eraghi, and J. A. Torkestani, "Wsn routing protocol using a multiobjective greedy approach," *Wireless Communications and Mobile Computing*, vol. 2021, no. 1, p. 6664669, 2021.

[15] B. A. Begum and S. V. Nandury, "Data aggregation protocols for wsn and iot applications–a comprehensive survey," *Journal of King Saud University-Computer and Information Sciences*, vol. 35, no. 2, pp. 651–681, 2023.

[16] N. Maryam and B. Hamid, "Egrpm: Energy efficient geographic routing protocol based on mobile sink in wireless sensor networks [j]," *Sustainable Computing: Informatics and Systems*, vol. 25, p. 100377, 2020.

[17] D. A. Guimarães, E. P. Frigieri, and L. J. Sakai, "Influence of node mobility, recharge, and path loss on the optimized lifetime of wireless rechargeable sensor networks," *Ad Hoc Networks*, vol. 97, p. 102025, 2020.

[18] M. Lewandowski and B. Płaczek, "Data transmission reduction in wireless sensor network for spatial event detection," *Sensors*, vol. 21, no. 21, p. 7256, 2021.

[19] Y. Song, S. Zhang, and S. Wang, "An energy efficient fusing data gathering protocol in wireless sensor networks," *Computer Networks*, vol. 243, p. 110305, 2024.

[20] S. Kaviarasan and R. Srinivasan, "Developing a novel energy efficient routing protocol in wsn using adaptive remora optimization algorithm," *Expert Systems with Applications*, vol. 244, p. 122873, 2024.

[21] L. Wang, Y. Luo, and H. Yan, "Optimization analysis of node energy consumption in wireless sensor networks based on improved ant colony algorithm," *Sustainable Energy Technologies and Assessments*, vol. 64, p. 103680, 2024.

[22] I. Diakhate, B. Niang, A. D. Kora, and R. M. Faye, "Optimizing the energy consumption of wsn by using energy efficient routing protocol using dijkstra algorithm," in *2022 2nd International Conference on Electronic and Electrical Engineering and Intelligent System (ICE3IS)*. IEEE, 2022, pp. 147–152.

[23] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. Soong, and J. C. Zhang, "What will 5g be?" *IEEE Journal on selected areas in communications*, vol. 32, no. 6, pp. 1065–1082, 2014.

[24] A. Panchal and R. K. Singh, "Eehchr: Energy efficient hybrid clustering and hierarchical routing for wireless sensor networks," *Ad Hoc Networks*, vol. 123, p. 102692, 2021.

[25] A. Dutta, K. Thakkar, S. Khatua, and R. K. Das, "Power efficient data gathering for sensor network,"

in *Distributed Computing and Internet Technology: 9th International Conference, ICDCIT 2013, Bhubaneswar, India, February 5-8, 2013. Proceedings 9*. Springer, 2013, pp. 232–243.

[26] J. Levendovszky and H. Thai, “Quality-of-service routing protocol for wireless sensor networks,” *J. Inf. Tech. Softw. Eng*, vol. 133, no. 2, p. 37, 2015.

[27] Y. Feng, B. Zhang, S. Chai, L. Cui, and Q. Li, “An optimized aodv protocol based on clustering for wsns,” in *2017 6th International Conference on Computer Science and Network Technology (ICCSNT)*. IEEE, 2017, pp. 410–414.