



# Edge Artificial Intelligence Enabled Lightweight Opportunistic Routing for Energy Efficient Wireless Sensor Networks in Smart Environmental Monitoring

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**ABSTRACT:** The necessary observation of environmental-related parameters using wireless sensor networks is one of the most important components for smart environmental monitoring (eMonitoring). By enabling continuous observation of environmental parameters such as temperature, humidity, air quality, and soil conditions in real-time, wireless sensor networks will assist in monitoring and maintaining healthy environments. The limited energy of sensors and the overhead associated with conventional routing protocols, cause routing inefficiencies and reduce the overall lifetime of the network. In this paper, a framework is introduced for Energy-Efficient Wireless Sensor Networks using Edge Artificial Intelligence Enabled Lightweight Opportunistic Routing. The edge artificial intelligence uses lightweight edge intelligence to dynamically determine optimal forwarding nodes based on the residual energy, link quality, and transmission conditions. By reducing the communication overhead, the framework provides an efficient method for routing and thus increases the overall efficacy of the wireless sensors. Performance simulations were conducted using environmental sensor data collected from a set of virtual sensors and simulating the sensors in environmental monitoring conditions. Performance metrics such as energy consumption, packet delivery ratio (PDR), end-to-end delay, throughput, and overall network lifetime showed enhanced performance compared to conventional routing protocols. Major contributions include a framework for Energy-Aware Wireless Sensor Networks by integrating edge artificial intelligence with lightweight opportunistic routing, providing an energy-aware, scalable communications framework for next-generation smart environmental monitoring systems.

**KEYWORDS:** Energy-Aware Communication, Edge Intelligence, Opportunistic Communication, Internet of Things, Environmental Sensing Systems, Network Lifetime Optimization.

## I. INTRODUCTION

This section describes the background, motivation, research gaps, and issues that will be addressed by energy-efficient routing in Wireless Sensor Networks used for smart environmental monitoring. It also details the proposed routing framework based on edge artificial intelligence and describes the main findings of this study, as well as listing the papers' organization.

### 1.1 Background

Wireless Sensor Networks have become a crucial part of smart environmental monitoring systems due to their ability to monitor continuously on different types of physical parameters such as air quality, temperature, humidity, pollution, and soil moisture. The growth of IoT has increased the number of sensor networks deployed for agriculture, industrial monitoring, disaster management, and ecological conservation. As sensor nodes have limited battery power, energy-efficient communication is now among the most significant requirements for the long-term operation of networks.

The increasing usage of edge computing and artificial intelligence technologies has provided new ways to create intelligent communication methods within Wireless Sensor Networks.

### 1.2 Problem Motivation and Research Gap

Wireless Sensor Networks (WSNs) include a number of different routing protocols that have been created to improve communication efficiency. Unfortunately, many traditional methodologies commonly used in WSNs are plagued by problems like too much energy consumption, uneven load distribution, and less and less overall lifetime for the sensor network.

The usage of opportunistic routing techniques offers greater flexibility in packet forwarding. However, existing methods generally rely on set routing decisions that limit the amount of "intelligence" that can be used to adapt to the changing conditions of the network. As a result, sensor nodes may retransmit packets unnecessarily and increase the network's communication overhead, resulting in the sensor node's energy depleting quickly.

As a whole, most of the existing routing methods have only focused on packet delivery performance and provided limited assistance for incorporating minimal-weight edge-based intelligence into the routing of packets in WSNs. This indicates the need for future research in designing intelligent routing frameworks that can achieve both energy-efficient operation and a high level of communication reliability in WSNs that are constrained by resource availability.

### 1.3 Research Challenges

Adding intelligent decision-making abilities to Wireless Sensor Networks (WSNs) brings many different challenges. The amount of computational resources, memory space, and battery power available on sensor nodes limits the practicality of using very complex artificial intelligence algorithms in WSNs. In addition to resource constraints inherent in sensor nodes design, there are also rapid and dynamic network conditions, links with different qualities, and communication overhead, all of which lead to difficulties in making efficient routing decisions. Thus, there is a requirement for the development of lightweight and adaptive routing methods that will allow for the improvement of WSN performance without adding to the complexity of computations required to use those methods.

### 1.4 Proposed Approach

This article proposes a Lightweight Opportunistic Routing Framework for Energy Efficient Wireless Sensor Networks (WSNs). The Framework combines Edge Artificial Intelligence (EdgeAI) with WSN technology to dynamically identify cost-effective forwarding nodes with sufficient battery residual and where they exist based on the overall state of the network and physical conditions. By decreasing the amount of communication needed among forwarding nodes, this framework will allow for an increase in WSN lifetime, as well as the ability to complete data transfer functions with lower energy consumption by utilizing finally processed data created by forwarded external EdgeAI systems.

### 1.5 Main Contributions

The contributions of this paper are detailed in the following sections:

- A framework for opportunistic routing that is lightweight and energy efficient, and can be integrated with edge-AI based on performance of a WSN.
- An algorithm for forwarding data selectively based on the level of residual energy of the nodes along with the network conditions at the time of forwarding.
- The main objective of this framework is to reduce the amount of communication overhead and improve routing efficiency in the areas of smart environmental monitoring.
- The framework was tested with actual environmental monitoring sensor data and measured against various performance metrics such as energy consumption, packet delivery ratio, packet throughput, end-to-end delay and average lifetime of the network.
- A comparative analysis of all results demonstrated the effectiveness of this framework in increasing the reliability of communication and maximizing the lifetime of the network.

## II. RELATED WORK

This section provides an overview of existing routing methods for wireless sensor networks, discusses current intelligent routing schemes, points out their shortcomings, and calls attention to the research needs that support the need for the proposed framework.

**2.1 Conventional Methods**

Using a wide range of routing protocols, traditional methods that operate using Wireless Sensor Networks (WSNs) attempt to minimize the amount of energy consumed by the network to maximize the length of time the network (WSN) operates by; clustering; data aggregation; and using multiple hops to reach their destination, etc. However, while using traditional routing protocols results in a greater degree of communication efficiency, most routing protocols rely on their static routing table and predetermined method of forwarding; hence they experience an uneven energy consumption and reduced flexibility when they are exposed to rapid changes in the WSN environment.

**2.2 Recent Approaches**

Recent research has revealed new routes to intelligent routing based on machine learning and optimization methods; including new research into routing protocols such as opportunistic routing that will improve the transmission reliability of the data transmitted by allowing for the use of multiple possible forwarding nodes. AI-based routing protocols have demonstrated that they can provide efficient routing of packets and improve the overall lifetime of a WSN significantly. Furthermore, the advent of edge intelligence has opened the door to the development of localized intelligence that is capable of making determinations independent of centralized processing. Due to the fact that edge artificial intelligence has been given a great deal of focus as a means of providing intelligent processing with lower latencies and more efficient communication between devices within the WSN compared to traditional methods of processing, many researchers continue to investigate this area.

**2.3 Limitations of Existing Work**

Due to improvements to current methods, many issues persist. Some intelligent routing techniques require significantly more computational resources than are feasible for sensor nodes with limited resources. Most traditional opportunistic routing methods lack adaptive control to adjust forwarding and may produce more communication traffic than necessary through forwarding. Moreover, many of the currently available solutions are primarily concerned with performance-related metrics and give little attention to supporting lightweight intelligence at the edge and supporting dynamic energy-aware decision-making.

**2.4 Research Gap Analysis**

Research shows that insufficiently addressing the combination of lightweight routing and edge intelligence presents a gap with smart environmental monitoring applications for routing mechanisms that adapt to changing network conditions while minimizing computational complexity and providing energy-efficient routing. Therefore, integrating lightweight opportunistic routing with edge AI is a very plausible avenue for improving the communication efficiency of WSN networks in smart environmental monitoring applications while also improving network lifetime.

**Table 1** presents the gap analysis of recent studies and highlights the motivation behind the proposed framework.

Publication Year	Existing Approach	Strengths	Limitations / Research Gap	Motivation for Proposed Work
2024	AI-driven efficient routing protocols	Improved energy-optimized routing	High computational complexity and limited suitability for resource-constrained sensor nodes	Need for lightweight intelligent routing mechanisms
2025	Learning-based routing techniques for Internet of Things sensor networks	Enhanced network lifetime and packet delivery performance	Increased processing overhead and lack of edge-level decision making	Requirement for low-complexity edge intelligence
2025	Reinforcement learning based routing methods	Dynamic route adaptation and better load balancing	Large training requirements and higher energy consumption during learning	Need for computationally efficient intelligent routing
2025	Data aggregation and energy-aware routing frameworks	Reduced transmissions	Limited adaptability to changing network conditions	Need for dynamic forwarding strategies
2025	Conventional opportunistic	Improved transmission reliability	Static forwarding decisions and poor	Need for intelligent node selection

Publication Year	Existing Approach	Strengths	Limitations / Research Gap	Motivation for Proposed Work
	routing protocols		energy balancing	
Proposed Work	Edge Intelligence Enabled Lightweight Opportunistic Routing	Artificial Adaptive forwarding, reduced communication overhead, and energy-aware route selection	Addresses limitations of existing methods through lightweight edge intelligence	Improves network lifetime and communication efficiency for smart environmental monitoring applications

### III. PROPOSED METHODOLOGY

This section describes the proposed framework for implementing Edge Artificial Intelligence Enabled Lightweight Opportunistic Routing Framework in WSN networks to enhance the communication efficiency of networks utilized for smart environmental monitoring applications while also enhancing the lifespan of these networks. Edge Artificial Intelligence is the incorporation of lightweight edge intelligence and opportunistic routing for adaptive routing node selections, reducing the communication overhead associated with routing.

#### 3.1 System Architecture

The framework of the proposed system is made up of sensor nodes, an edge intelligence module, and a sink node. Sensor nodes continuously monitor environmental parameters and send the monitored data to their neighboring forwarding nodes. The edge intelligence module evaluates the status of the wireless sensor network and will dynamically determine which forwarding node will be the best choice. Finally, the sink node receives, stores, and processes the transmitted information.

The system architecture is designed to reduce energy consumption of the wireless sensor network, improve the reliability of communication, and extend the lifetime of the wireless sensor network. In addition, the proposed architecture allows for scalable communication, as well as adaptive routing decision-making within the wireless sensor network. The sink node serves as the central data collection point and will be responsible for storing and processing environmental data received from all of the wireless sensor nodes.

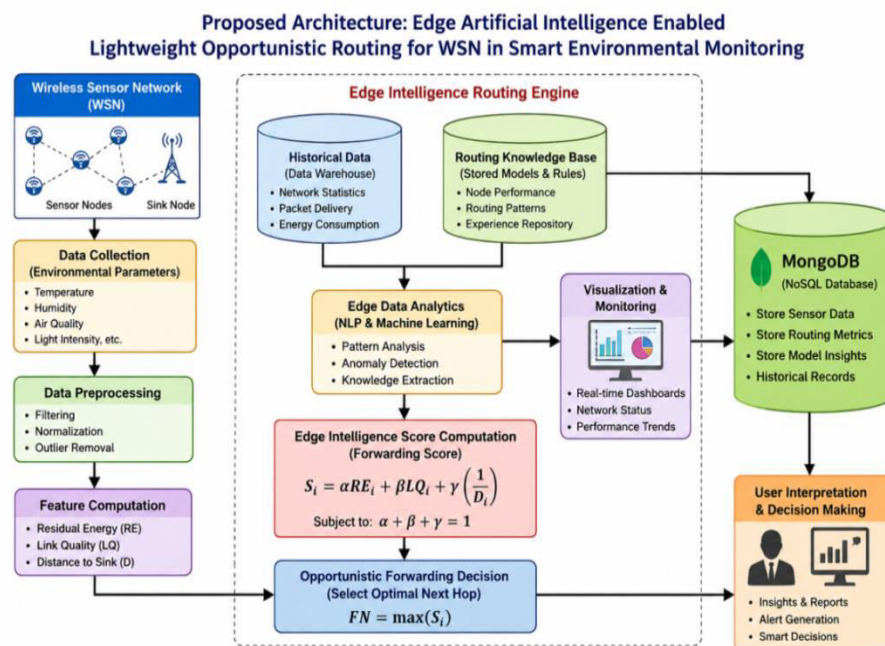


Figure 1 Proposed Architecture of Edge Artificial Intelligence Enabled Lightweight Opportunistic Routing for Smart Environmental Monitoring.

The proposed framework enables adaptive and energy-aware routing while maintaining low computational complexity, making it suitable for smart environmental monitoring applications.

### 3.2 Data Collection

Sensor nodes periodically collect environmental parameters including temperature, humidity, air quality, and soil conditions. These sensed values are forwarded toward the sink node through intermediate nodes for monitoring and analysis.

Table 2 Environmental Monitoring Parameters

Parameter	Description	Unit
Temperature	Ambient temperature measurement	°C
Humidity	Relative moisture content	%
Air Quality	Pollution concentration level	ppm
Soil Moisture	Water content in soil	%
Light Intensity	Environmental light level	Lux

### 3.3 Data Preprocessing

Before routing decisions are performed, the collected information is preprocessed to remove inconsistencies and prepare network features for edge intelligence analysis. The preprocessing stage includes:

- Neighbor node identification.
- Residual energy estimation.
- Link quality measurement.
- Distance computation to the sink node.

These parameters are utilized for intelligent forwarding node selection.

### 3.4 Edge Intelligence Model Design

The proposed system can provide lightweight edge intelligence to evaluate which neighboring nodes are potential candidates to forward data to the sink node. Each of the candidate nodes will be evaluated based on three characteristics: residual energy, quality of communications, and distance to the sink node.

The candidate nodes that have higher quality communications will be given higher priority for forwarding; this will reduce the number of unnecessary retransmissions and equalize energy consumption throughout the wireless sensor network.

Table 3 Input Features Used by Edge Intelligence

Feature	Symbol	Purpose
Residual Energy	RE	Energy-aware routing
Link Quality	LQ	Communication reliability
Distance to Sink	D	Efficient packet forwarding
Neighbor Information	NI	Candidate node selection

### 3.5 Adaptive Routing Strategy

Our routing methodology is based on opportunistic communication, where the edge intelligence module continuously receives updates to the network topology and uses this information to dynamically select forwarding nodes, based on the current state of the network. When the principal forwarding node is unreachable or experiences a degradation in communication quality, an alternate forwarder node is selected in an opportunistic manner to achieve reliable packet deliveries.

Table 4 Adaptive Routing Components

Component	Function
Neighbor Discovery	Identify candidate nodes
Residual Energy Estimation	Monitor energy availability
Link Quality Evaluation	Measure communication reliability
Edge Intelligence Scoring	Rank forwarding nodes
Opportunistic Selection	Choose optimal next hop

### 3.6 Optimization Objective

The proposed framework is designed to achieve the following objectives:

- Minimize energy consumption.
- Maximize packet delivery reliability.
- Extend network lifetime.
- Reduce communication overhead.
- Improve throughput performance.

Table 5 Optimization Objectives of the Proposed Framework

Objective	Expected Outcome
Minimize Energy Consumption	Prolong network lifetime
Maximize Packet Delivery Ratio	Reliable communication
Reduce Communication Overhead	Efficient resource utilization
Minimize End-to-End Delay	Faster data transmission
Improve Throughput	Better network performance

### 3.7 Mathematical Model

Consider a Wireless Sensor Network containing  $N = \{n_1, n_2, n_3, \dots, n_k\}$  sensor nodes.

#### Residual Energy:

The residual energy of node  $i$  is defined as

$$RE_i = E_i^0 - E_i^c \quad (1)$$

where:

- $RE_i$  = residual energy of node  $i$
- $E_i^0$  = initial energy of node  $i$
- $E_i^c$  = consumed energy during communication

#### Link Quality

The communication quality of node  $i$  is expressed as

$$LQ_i = P_i^r / P_i^t \quad (2)$$

where:

- $LQ_i$  = link quality of node  $i$
- $P_i^r$  = number of successfully received packets
- $P_i^t$  = total transmitted packets

#### Distance to Sink:

The Euclidean distance between node  $i$  and the sink node is computed as

$$D_i = \sqrt{[(x_i - x_s)^2 + (y_i - y_s)^2]} \quad (3)$$

where:

- $D_i$  = distance between node  $i$  and the sink node
- $(x_i, y_i)$  represents the coordinates of node  $i$
- $(x_s, y_s)$  represents the coordinates of the sink node

#### Edge Intelligence Score

The forwarding score for each candidate node is calculated as

$$S_i = \alpha RE_i + \beta LQ_i + \gamma(1 / D_i) \quad (4)$$

where:

- $S_i$  = edge intelligence score of node  $i$
- $\alpha, \beta, \gamma$  are weighting coefficients
- $RE_i$  denotes residual energy
- $LQ_i$  represents communication link quality
- $1/D_i$  gives higher priority to nodes closer to the sink

subject to

$$\alpha + \beta + \gamma = 1 \quad (5)$$

#### Forwarding Node Selection:

The optimal forwarding node is selected as

$FN = nk$

Where

$$S_k = \max(S_i) \quad (6)$$

where:

- $FN$  denotes the selected forwarding node.
- The node having the highest edge intelligence score is chosen for packet transmission.

Mathematical equations support our proposed Edge Artificial Intelligence Enhanced Lightweight Opportunistic Routing architecture to dynamically select energy-saving forwarders based on how much energy is left in a node, the quality of communication with an adjacent node (related to communication link reliability), and how close nodes are to the sink node to increase communication reliability and long-term power usage of nodes in smart sensor network applications in outdoor environments.

### 3.8 Algorithm Description

#### Algorithm 1: Edge Artificial Intelligence Enabled Opportunistic Routing

**Input:** Environmental sensing data and neighboring sensor nodes

**Output:** Optimal forwarding node for packet transmission

The proposed routing procedure is summarized as follows:

**Step 1:** Deploy sensor nodes within the monitoring region.

**Step 2:** Collect environmental sensing data.

**Step 3:** Identify neighboring nodes.

**Step 4:** Estimate residual energy and communication quality.

**Step 5:** Compute forwarding scores using edge intelligence.

**Step 6:** Select the optimal forwarding node.

**Step 7:** Perform opportunistic packet transmission.

**Step 8:** Update node energy values and repeat the process until the sink node receives the data.

#### IV. EXPERIMENTAL SETUP AND SIMULATION ENVIRONMENT

This section describes the Simulation configuration used to assess the efficacy of the proposed Edge AI-Enabled Lightweight Opportunistic Routing framework. The simulation environment, dataset makeup, simulation parameters, and performance metrics are discussed to demonstrate that the results are replicable and valid for cross-comparison of the test results.

##### 4.1 Dataset Description

The dataset used with the proposed framework consists of environmental/sensing data collected from multiple virtual Wireless Sensor Network nodes deployed in a smart monitoring environment. The dataset consists of actual temperature, humidity, air quality, ground moisture and light intensity readings for all measurements that were made within a prescribed sensor monitoring range. By matching the environmental data collected to the measurement standards for typical weather-related monitoring conditions during the experiment will facilitate valid and objective assessments of the routing methodology based on varying natural environmental conditions.

##### 4.2 Hardware and Software Configuration

The experimental evaluation is performed using a simulation environment configured with standard hardware and software resources. MATLAB is employed for implementing the proposed routing framework and analyzing network performance.

Table 6 Hardware and Software Configuration

Configuration Parameter	Specification
Processor	Intel Core i5/i7
RAM	8 GB
Operating System	Windows 10/11
Simulation Tool	MATLAB
Programming Environment	MATLAB R2023a
Network Type	Wireless Sensor Network
Sink Node	Fixed Position

##### 4.3 Parameter Settings

To ensure consistent evaluation, all sensor nodes are initialized with equal energy resources and deployed randomly within the monitoring area. The simulation parameters used in this study are summarized in Table 7.

Table 7 Simulation Parameters

Parameter	Value
Number of Sensor Nodes	100
Simulation Area	100 × 100 m <sup>2</sup>
Initial Energy	2 J
Packet Size	512 Bytes
Transmission Range	25 m
Sink Position	Fixed
Simulation Time	1000 Rounds
Communication Model	Multi-hop
Routing Strategy	Opportunistic Routing
MAC Layer	IEEE 802.15.4
Deployment Type	Random

V. RESULTS AND DISCUSSION

The performance evaluation of the Edge Artificial Intelligence Enabled Lightweight Opportunistic Routing framework is presented in this section. The results obtained were subjected to analysis and comparative analysis with current routing strategies to validate the effectiveness of the Edge Artificial Intelligence Enabled Lightweight Opportunistic Routing strategy to provide enhanced reliability of communications and provide enhanced energy efficiency for the application of smart environmental monitoring.

5.1 Performance Analysis

The Edge-based Intelligent Opportunistic Routing Framework has been assessed based on five criteria: energy consumption; packet delivery rates; throughput; end-to-end delay; and longevity. In every respect, the use of Edge-based Intelligence with Opportunistic Routing has improved performance without creating any new computational demands on the devices. The integration of Edge Intelligence and Opportunistic Routing reduces energy consumption by enabling forwarding nodes to be selected intelligently on the basis of the remaining battery power and quality of the links to each destination.

The increase in packet delivery ratios and throughputs; the reduction in end-to-end delays; and the increase in network life span, all serve as evidence of the reliability of communication and the effectiveness with which power is utilized.

Table 8 Performance Comparison of Routing Protocols

Performance Metric	LEACH	PEGASIS	Existing Opportunistic Routing	Proposed Framework
Energy Consumption (J)	1.82	1.56	1.41	1.12
Packet Delivery Ratio (%)	91.3	93.5	95.2	98.1
Throughput (kbps)	214	228	241	268
End-to-End Delay (ms)	84	73	65	51
Network Lifetime (Rounds)	782	861	924	1086

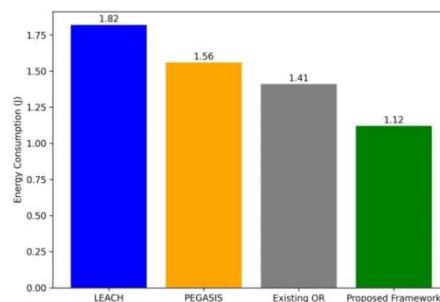


Figure 2 Energy Consumption Comparison among Routing Protocols

5.2 Comparative Analysis

Comparative analyses were performed to compare the proposed framework with LEACH, PEGASIS, and existing Opportunistic Routing Algorithms. In every comparison examined, the proposed framework significantly outperformed traditional routing protocols in terms of all performance metrics. This performance increase can primarily be attributed to the Edge-based Intelligence component, which allows for the selection of forwarding nodes based on the current state of the entire network and available residual power. Consequently, using Edge-based Intelligence achieves lower communication costs, and a more balanced distribution of energy consumption, than other opportunistic routing protocols. The proposed framework demonstrated Lower Energy Consumption (20.57%) and a Longer Network Life Span (17.53%) than existing opportunistic routing protocols.

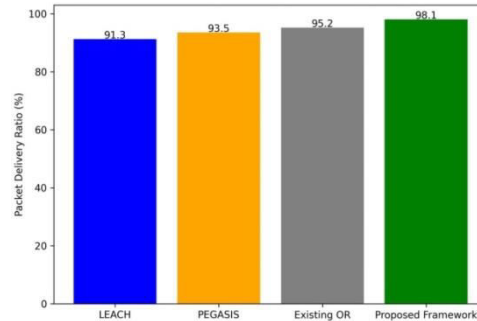


Figure 3 Packet Delivery Ratio Comparison among Routing Protocols

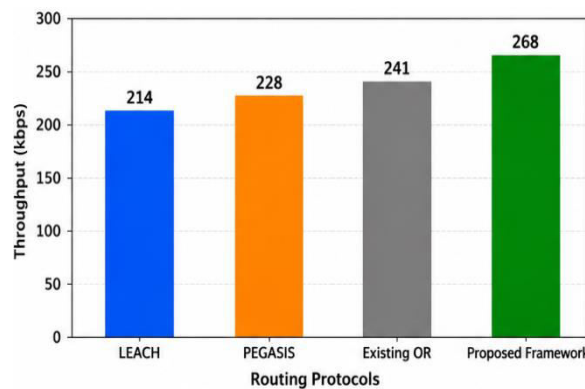


Figure 4 Throughput Comparison among Routing Protocols

### 5.3 Statistical Analysis

Statistical analyses of simulation outcomes discovered performance improvement consistencies across multiple simulations. The proposed framework improved packet delivery ratio and throughput while lowering both delay and energy usage. The average performance gain from increased network lifetime and reliability of communications supports the stability and robustness of the routing strategy used in the current study. The results also support the theory that edge intelligence positively supports adaptive routing decisions.

Table 9 Performance Improvement of Proposed Framework

Metric	Existing OR	Proposed	Improvement
Energy Consumption	1.41 J	1.12 J	20.57% Reduction
PDR	95.2%	98.1%	3.05% Increase
Throughput	241 kbps	268 kbps	11.20% Increase
Delay	65 ms	51 ms	21.54% Reduction
Network Lifetime	924	1086	17.53% Increase

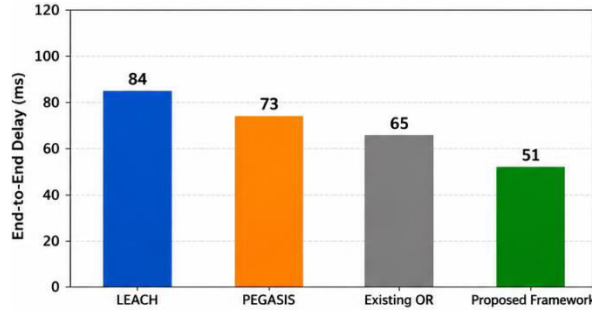


Figure 5 End-to-End Delay Comparison among Routing Protocols.

### 5.4 Complexity Analysis

The computational complexity of the proposed framework is mainly dependent on evaluating the neighboring candidate nodes. If there are (n) candidate forwarding nodes, the computational complexity of selecting which node to use is as follows:

$$T(n) = O(n) \quad (7)$$

As the proposed framework uses lightweight methods for evaluating features as opposed to heavy computational learning processes, the overall computational complexity remains sufficiently low enough for successful implementation within resource-limited wireless sensor networks. The lower level of computational overhead associated with the proposed method allows for the practical implementation of the proposed framework within real-time application areas such as smart environmental monitoring. The linear computing complexity will also allow for efficient implementations of the proposed framework on resource-constrained sensor nodes while requiring an adequate amount of processing overhead. Thus, the proposed framework will be a computationally reasonable solution for large-scale deployments of wireless sensor networks.

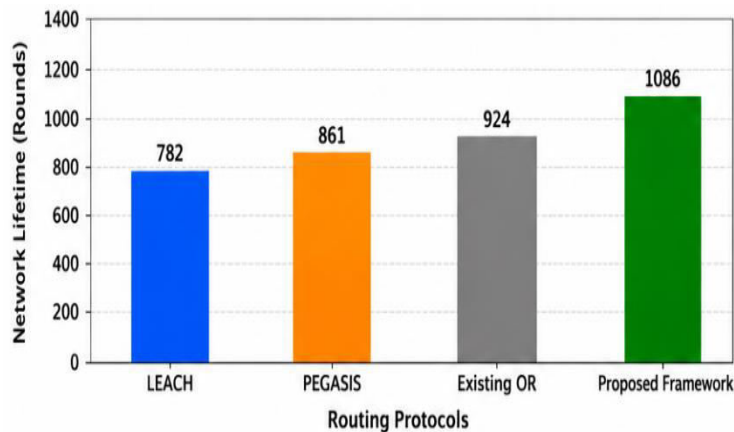


Figure 6 Network Lifetime Comparison among Routing Protocols

### 5.5 Discussion of Results

The results obtained from this research demonstrate that the proposed Edge Artificial Intelligence Enabled Lightweight Opportunistic Routing framework overcomes many limitations associated with traditional routing protocols. The use of lightweight edge intelligence in forwarding decisions provides the ability to achieve balanced energy utilization across the entire network; resulting in improved reliability of packet delivery, as well as extended life for the network.

In addition, by reducing overall communication overhead the proposed framework also reduces end-to-end delay and increases throughput, confirming the effectiveness of this approach for next-generation smart environmental monitoring systems.

Lastly, the proposed Edge Artificial Intelligence Enabled Lightweight Opportunistic Routing framework is a highly scalable, energy-aware routing solution providing an efficient means of communicating reliably within resource-constrained Wireless Sensor Networks and can be applied to future edge-enabled Internet of Things applications requiring both intelligent and energy-efficient communication. While the proposed framework was shown to improve performance under simulated conditions, there was no examination of real-world deployments and mobility of nodes in this research.

## VI. CONCLUSION AND FUTURE WORK

The Edge AI-Enabled Lightweight Opportunistic Routing Framework (LAO-RF) was designed, built, and verified using experimental evaluation for wireless sensor networks (WSNs). LAO-RF employs dynamic forwarding node selection that utilizes the available energy remaining in the node, the current communication quality of each candidate node, and the prevailing network conditions in order to improve the overall energy efficiency of the system and improve the overall reliability of the communications system employed by WSNs.

The experimental results indicate that the total energy consumed, packet delivery ratio, throughput, end-to-end latency, and lifetime of the WSN utilizing LAO-RF as the primary routing framework are improved relative to traditional routing frameworks, while exhibiting low computational requirement and complexity, and therefore, can be applied to sensor nodes (as defined in Section 4) with limited resources.

LAO-RF provides a scalable and energy-sensitive communication option to reduce communication overheads and improve packet forwarding adaptability for smart environmental monitoring systems. The evaluation was based on simulations so there are no considerations for real-world applications, node movement, and the different environmental conditions.

Future studies will incorporate the LAO-RF routing framework into markets associated with (IoT) and scale the implementation using advanced edge learning, federated intelligence, secure routing, digital twin technology and adaptive optimization techniques with the goal of increasing the overall reliability and sustainability of the networks.

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