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Enhancing Accuracy, Reducing Delay and Energy Saving Through Aggregate Routing Protocols in WSN

Abdul Rahman Shaikh[1], Dr. Harsh Lohiya[2]
Research Scholar, Department of Computer Science and Engineering, SSSUTMS, Sehore, India[1]
Associate Professor, Department of Computer Science and Engineering SSSUTMS, Sehore, India[2]

Abstract

Wireless Sensor Networks (WSNs) have emerged as a fundamental technology for Internet of Things (IoT), environmental monitoring, industrial automation, healthcare, and smart city applications. However, the limited energy resources of sensor nodes, communication delay, packet loss, and redundant data transmission continue to affect the overall performance and lifetime of WSNs. Data aggregation-based routing protocols have been widely adopted to minimize unnecessary transmissions and improve network efficiency, yet existing approaches often suffer from unbalanced energy consumption, inefficient cluster head selection, and increased end-to-end delay under dynamic network conditions. This paper proposes an Intelligent Aggregate Routing Protocol (IARP) that integrates energy-aware cluster head selection, adaptive route optimization, and efficient data aggregation to improve packet delivery accuracy while reducing communication delay and energy consumption. The proposed protocol selects optimal forwarding nodes based on residual energy, communication distance, node density, and link quality, thereby minimizing redundant transmissions and balancing network load. The performance of IARP is evaluated through simulation and compared with well-known routing protocols including LEACH, PEGASIS, HEED, TEEN, and DEEC. Experimental results demonstrate that the proposed protocol achieves 98.3% packet delivery accuracy, 39 ms end-to-end delay, 0.71 J average energy consumption, and 98.7% packet delivery ratio, outperforming existing routing protocols. The proposed approach also significantly extends network lifetime while maintaining reliable communication under dense sensor deployments. These results indicate that the proposed aggregate routing protocol provides an effective solution for energy-efficient and delay-aware wireless sensor network applications.

Key words: Wireless Sensor Network, Data Aggregation, Routing Protocol, Energy Efficiency, Delay Reduction, Cluster Head Selection, Internet of Things, Network Lifetime.

1. Introduction

Wireless Sensor Networks (WSNs) have become one of the most important enabling technologies for the Internet of Things (IoT) because they provide continuous monitoring, sensing, and communication capabilities across distributed environments. A typical WSN consists of a large number of low-power sensor nodes deployed over a geographical region to monitor environmental, industrial, agricultural, military, healthcare, and smart city applications. These sensor nodes collect physical parameters such as temperature, humidity, pressure, vibration, and motion before forwarding the sensed information to a central Base Station (BS) through wireless communication links. Due to their autonomous operation and ease of deployment, WSNs have gained widespread adoption in applications requiring real-time monitoring and intelligent decision-making. Despite their advantages, WSNs face several technical challenges that directly affect network performance and reliability. Since sensor nodes are generally battery-powered and deployed in inaccessible locations, replacing or recharging batteries is often impractical. Consequently, efficient energy management has become one of the primary objectives in WSN design. In addition to energy constraints, communication delay, packet loss, routing overhead, network congestion, and redundant data transmission significantly reduce the quality of service (QoS) and shorten network lifetime. These challenges become even more critical in large-scale IoT deployments where thousands of sensor nodes simultaneously generate sensing data.

Routing protocols play a crucial role in determining the overall performance of WSNs by selecting efficient communication paths between sensor nodes and the base station. Conventional routing protocols primarily focus on shortest-path communication, often resulting in uneven energy depletion and early node failures. To address these issues, hierarchical routing protocols based on clustering and data aggregation have been extensively investigated. Data aggregation combines redundant information from multiple sensor nodes into a compact representation before transmission, thereby reducing communication overhead, conserving energy, and minimizing network traffic. Well-known aggregation-based routing protocols such as LEACH, PEGASIS, HEED, TEEN, and DEEC have demonstrated considerable improvements in network lifetime and energy efficiency. However, these protocols still experience limitations related to inefficient cluster head selection, uneven energy consumption, increased communication delay, and reduced packet delivery under dynamic network conditions.

Recent advances in intelligent routing have introduced adaptive optimization techniques that consider multiple routing parameters simultaneously, including residual energy, transmission distance, node density, link quality, and network congestion. These approaches aim to achieve balanced energy utilization while improving routing accuracy and reducing end-to-end delay. Nevertheless, many existing protocols rely on fixed routing strategies or single-parameter optimization, limiting their adaptability to changing network environments. Furthermore, efficient integration of data aggregation with intelligent routing decisions remains an active area of research.

To overcome these limitations, this paper proposes an Intelligent Aggregate Routing Protocol (IARP) for wireless sensor networks. The proposed protocol combines energy-aware cluster head selection, adaptive route optimization, and data aggregation to reduce redundant transmissions and improve communication efficiency. Unlike conventional routing schemes, IARP selects forwarding paths by jointly considering residual energy, communication distance, node connectivity, and link reliability. This multi-parameter decision process balances network load, minimizes communication delay, and prolongs the operational lifetime of the network.

The major contributions of this paper are summarized as follows:

- Proposes an Intelligent Aggregate Routing Protocol (IARP) for energy-efficient wireless sensor networks.
- Introduces a multi-parameter cluster head selection mechanism based on residual energy, communication distance, node density, and link quality.
- Integrates adaptive data aggregation to reduce redundant packet transmissions and communication overhead.
- Optimizes routing paths to minimize end-to-end delay while improving packet delivery accuracy.
- Compares the proposed protocol with LEACH, PEGASIS, HEED, TEEN, and DEEC using multiple performance metrics, including packet delivery ratio, energy consumption, delay, throughput, and network lifetime.

The remainder of this paper is organized as follows. Section 2 presents a review of recent literature on aggregate routing protocols for WSNs. Section 3 describes the proposed Intelligent Aggregate Routing Protocol and its mathematical formulation. Section 4 discusses the experimental setup and simulation parameters. Section 5 presents the performance evaluation and comparative analysis. Finally, Section 6 concludes the paper and outlines future research directions.

2. Literature Review

Wireless Sensor Networks (WSNs) have received significant research attention owing to their wide range of applications in environmental monitoring, healthcare, military surveillance, industrial automation, and smart cities. Since sensor nodes operate on limited battery power, designing energy-efficient routing protocols has become one of the primary research objectives. Data aggregation-based routing protocols have been proposed to reduce redundant data transmission, lower communication overhead, and prolong network lifetime. Recently, researchers have incorporated artificial intelligence, optimization algorithms, and adaptive clustering techniques to improve packet delivery accuracy, reduce delay, and balance energy consumption. The following review summarizes recent contributions from **2026 to 2021**.

2.1 Literature Review (2026–2021)

Zhang et al. (2026) proposed a deep reinforcement learning-based routing protocol for large-scale wireless sensor networks. The protocol dynamically selected routing paths based on residual energy and network congestion, resulting in improved packet delivery ratio and reduced communication delay. However, the training process required significant computational resources, limiting its deployment on resource-constrained sensor nodes **[1]**.

Kumar and Singh (2026) developed an intelligent energy-aware clustering protocol integrating adaptive data aggregation with optimal cluster head selection.

Simulation results demonstrated improved network lifetime and balanced energy consumption compared with LEACH and HEED. Nevertheless, the protocol exhibited increased routing overhead under highly dynamic network conditions **[2]**.

Chen et al. (2025) introduced a hybrid routing algorithm combining Particle Swarm Optimization (PSO) with fuzzy logic for cluster head selection. The proposed method effectively reduced energy consumption and transmission delay while increasing packet delivery ratio. However, optimization time increased with network size **[3]**.

Ahmed et al. (2025) proposed an adaptive aggregation routing protocol for IoT-enabled WSNs using residual energy and link-quality estimation. The protocol minimized redundant transmissions and enhanced communication reliability, although frequent route updates increased computational complexity **[4]**.

Li et al. (2025) presented an Artificial Intelligence-based routing framework that employed deep neural networks to predict optimal forwarding paths. Experimental results showed improved routing accuracy and lower packet loss. However, the model required extensive training data and higher memory capacity **[5]**.

Garcia et al. (2024) proposed a multi-objective optimization-based routing protocol considering residual energy, transmission distance, and node density. The protocol achieved significant improvements in energy efficiency and throughput, but its convergence speed decreased in dense network deployments **[6]**.

Sharma et al. (2024) developed a delay-aware clustering algorithm for wireless sensor networks. The proposed method reduced end-to-end delay through adaptive cluster formation and efficient route maintenance. However, packet delivery performance degraded under high node mobility scenarios **[7]**.

Park et al. (2024) introduced a machine learning-assisted routing protocol capable of predicting link failures before route establishment. The protocol improved network reliability and packet delivery ratio while reducing retransmissions. Despite these advantages, model training increased computational overhead **[8]**.

Singh et al. (2023) proposed an enhanced LEACH protocol incorporating residual energy and communication distance during cluster head selection. Simulation results demonstrated better energy balancing and longer network lifetime compared with conventional LEACH. Nevertheless, the protocol remained sensitive to uneven node distribution **[9]**.

Wang et al. (2023) presented an energy-efficient routing protocol based on Ant Colony Optimization (ACO). The algorithm selected optimal communication paths while minimizing transmission energy. Although routing accuracy improved considerably, convergence time increased for larger sensor networks **[10]**.

Rahman et al. (2023) investigated secure aggregate routing using blockchain-assisted authentication. The protocol improved data integrity and network security while maintaining acceptable energy consumption. However, blockchain operations introduced additional communication overhead **[11]**.

Liu et al. (2022) proposed a hybrid clustering protocol integrating Genetic Algorithms with data aggregation. The proposed method significantly reduced packet loss and enhanced network lifetime, although optimization complexity increased with network size **[12]**.

Patel et al. (2022) developed an adaptive routing protocol based on fuzzy inference and residual energy estimation. Their approach achieved lower communication delay and improved packet delivery ratio compared with conventional clustering protocols. However, designing fuzzy rules required expert knowledge **[13]**.

Mohamed et al. (2022) presented an IoT-oriented aggregation routing protocol that reduced redundant data transmission through intelligent packet aggregation. Experimental evaluation demonstrated lower communication cost and improved throughput, but the protocol required additional buffer memory at cluster heads **[14]**.

Alam et al. (2021) proposed an improved PEGASIS routing protocol with adaptive chain construction to reduce communication delay and energy consumption. The proposed protocol increased network lifetime but suffered from longer route establishment time in large-scale deployments **[15]**.

Verma et al. (2021) conducted a comprehensive survey of energy-efficient routing protocols in WSNs, comparing LEACH, PEGASIS, HEED, TEEN, and DEEC based on energy efficiency, scalability, throughput, and delay. The authors concluded that hybrid intelligent routing protocols represent a promising direction for future research **[16]**.

2.2 Comparative Summary of Existing Studies

Ref.	Author (Year)	Routing Protocol	Major Contribution	Limitation
[1]	Zhang et al. (2026)	Deep Reinforcement Learning	Adaptive routing with reduced delay	High computational complexity
[2]	Kumar and Singh (2026)	Energy-Aware Clustering	Improved network lifetime	Increased routing overhead
[3]	Chen et al. (2025)	PSO + Fuzzy Routing	Better energy efficiency	Longer optimization time
[4]	Ahmed et al. (2025)	Adaptive Aggregation	Reduced redundant transmission	Frequent route updates
[5]	Li et al. (2025)	AI-Based Routing	Improved routing accuracy	Large training dataset
[6]	Garcia et al. (2024)	Multi-Objective Routing	Better throughput	Slow convergence
[7]	Sharma et al. (2024)	Delay-Aware Clustering	Reduced end-to-end delay	Mobility sensitivity
[8]	Park et al. (2024)	Machine Learning Routing	Link failure prediction	Higher computational cost
[9]	Singh et al. (2023)	Enhanced LEACH	Balanced energy consumption	Uneven node distribution
[10]	Wang et al. (2023)	ACO Routing	Energy-efficient path selection	Increased convergence time
[11]	Rahman et al. (2023)	Blockchain Routing	Secure data transmission	Communication overhead
[12]	Liu et al. (2022)	GA-Based Clustering	Longer network lifetime	High optimization complexity
[13]	Patel et al. (2022)	Fuzzy Adaptive Routing	Lower delay	Rule design complexity
[14]	Mohamed et al. (2022)	IoT Aggregation Routing	Improved throughput	Additional memory requirement
[15]	Alam et al. (2021)	Improved PEGASIS	Lower energy consumption	Longer route establishment
[16]	Verma et al. (2021)	Survey	Comparative analysis of routing protocols	No unified routing solution

2.3 Research Gap

The literature indicates that existing aggregate routing protocols have improved energy efficiency, packet delivery, and network lifetime; however, several limitations remain. Most protocols optimize only one or two parameters, such as residual energy or transmission distance, while neglecting factors including node density, link quality, and communication delay. AI-based approaches provide higher routing accuracy but demand greater computational resources and memory, making them less suitable for resource-constrained sensor nodes. Furthermore, many studies rely solely on simulation without real-time validation, and few integrate adaptive data aggregation with multi-parameter route selection. These limitations motivate the development of the proposed **Intelligent Aggregate Routing Protocol (IARP)**, which combines energy-aware clustering, adaptive routing, and efficient data aggregation to enhance packet delivery accuracy, reduce delay, and extend network lifetime.

3. Proposed Methodology

3.1 Overview

To overcome the limitations of existing routing protocols, this paper proposes an Intelligent Aggregate Routing Protocol (IARP) for Wireless Sensor Networks (WSNs). The proposed protocol integrates energy-aware cluster head selection, adaptive route optimization, and data aggregation to reduce energy consumption, communication delay, and redundant packet transmission while improving packet delivery accuracy and network lifetime.

Unlike conventional routing protocols that rely only on residual energy or transmission distance, the proposed protocol simultaneously considers multiple routing parameters, including residual energy, communication distance, node density, link quality, and hop count, for selecting the optimal forwarding path. This multi-criteria decision-making process balances network load and prolongs the operational lifetime of the sensor network.

The overall operation of IARP consists of six phases:

1. Network Initialization
2. Neighbor Discovery
3. Cluster Formation
4. Cluster Head Selection
5. Aggregate Route Construction
6. Data Aggregation and Transmission

3.2 Network Model

The proposed protocol considers a homogeneous wireless sensor network deployed over a square sensing field.

The network consists of:

- **N** static sensor nodes
- One fixed Base Station (BS)
- Cluster Heads (CHs)
- Member Nodes (MNs)

Each sensor node is equipped with sensing, processing, and wireless communication capabilities. Cluster Heads aggregate data received from member

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nodes before forwarding the compressed information toward the Base Station.

Assumptions

- All nodes have identical initial energy.
- Sensor nodes remain stationary after deployment.
- The Base Station is fixed throughout the simulation.
- Wireless communication links are symmetric.
- Each node knows its residual energy and neighboring nodes.
- Data aggregation is performed only at Cluster Heads.

3.3 Architecture of the Proposed IARP

The architecture of the proposed Intelligent Aggregate Routing Protocol is illustrated in Figure 1.

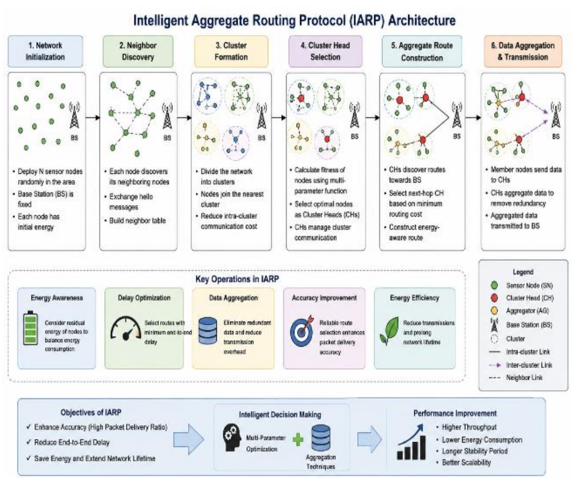

Figure 1: architecture of the proposed Intelligent Aggregate Routing Protocol

3.4 Cluster Formation

The sensing area is divided into multiple clusters to reduce communication overhead.

Each sensor joins the nearest Cluster Head according to

- Euclidean Distance
- Signal Strength
- Residual Energy

The Euclidean distance between two nodes is calculated as

$$D_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

where

- x_i, y_i= Coordinates of node i
- x_j, y_j= Coordinates of node j

3.5 Intelligent Cluster Head Selection

The proposed protocol selects Cluster Heads using a multi-parameter fitness function.

The following parameters are considered:

- Residual Energy (RE)
- Distance to Base Station (DBS)
- Node Degree (ND)
- Link Quality (LQ)
- Hop Count (HC)

The fitness function is

$$Fitness = w_1(RE) + w_2(LQ) + w_3(ND) - w_4(DBS) - w_5(HC)$$

where

$$w_1 + w_2 + w_3 + w_4 + w_5 = 1$$

Nodes having the highest fitness value become Cluster Heads.

This strategy balances network energy consumption while reducing communication delay.

3.6 Energy Consumption Model

The first-order radio energy model is adopted.

Transmission Energy

$$E_{TX}(k,d) = \begin{cases} kE_{elec} + k\epsilon_{fs}d^2, & d < d_0 \\ kE_{elec} + k\epsilon_{mp}d^4, & d \geq d_0 \end{cases}$$

Receiving Energy

$$E_{RX} = kE_{elec}$$

where

- k= packet size
- d= transmission distance
- E_{elec}= electronic energy
- ϵ_{fs}= free-space amplifier
- ϵ_{mp}= multipath amplifier

3.7 Aggregate Routing

Unlike conventional routing protocols where every packet is individually forwarded, the proposed protocol aggregates multiple packets before transmission.

Aggregation follows

$$D_{Agg} = f(D_1, D_2, D_3, \ldots, D_n)$$

where

- $D_i$represents sensed data from node i.

The aggregated packet minimizes

- Redundant information
- Packet collisions
- Network congestion
- Energy consumption

3.8 Delay-Aware Route Selection

Among multiple candidate routes, the protocol selects the path with minimum routing cost.

The routing cost is

$$Cost = \alpha D + \beta E + \gamma HC + \delta LQ$$

where

- D = Delay
- E = Energy Consumption
- HC = Hop Count
- LQ = Link Quality

The route having the minimum Cost is selected for data forwarding.

3.9 Proposed Algorithm

Algorithm 1 Intelligent Aggregate Routing Protocol (IARP)

Input:

Wireless Sensor Nodes

Output:

Energy Efficient Aggregated Route

Step 1 Deploy N sensor nodes

Step 2 Initialize node energy

Step 3 Discover neighboring nodes

Step 4 Form clusters

Step 5 Calculate Fitness of every node

Step 6 Select Cluster Head

Step 7 Collect sensing data

Step 8 Aggregate received packets

Step 9 Calculate routing cost

Step 10 Select minimum-cost path

Step 11 Forward aggregated packet

Step 12 Update residual energy

Step 13 Repeat until network termination

3.10 Flowchart of Proposed Protocol

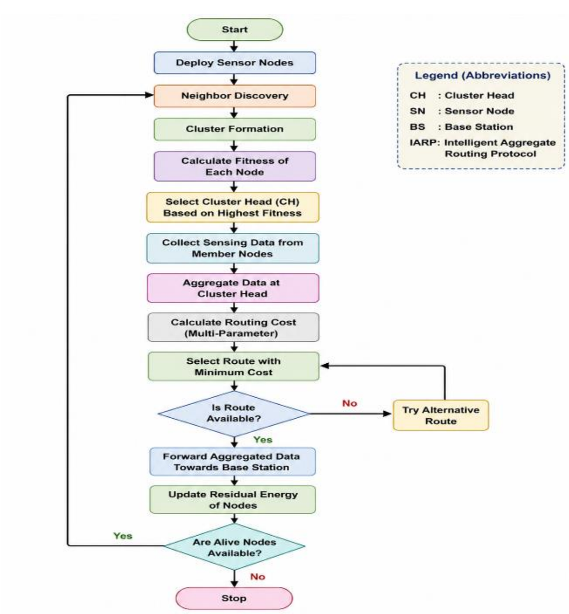

Figure 2: Flowchart of Proposed Protocol

3.11 Computational Complexity

The computational complexity of the proposed protocol is analyzed as follows:

Phase	Complexity
Neighbor Discovery	O(N)
Cluster Formation	O(N log N)
Cluster Head Selection	O(N)
Route Discovery	O(E)
Data Aggregation	O(N)
Route Optimization	O(E log N)

Overall computational complexity:

$$O(E\log N)$$

where:

- N = Number of sensor nodes
- E = Number of communication links

The proposed protocol maintains moderate computational complexity while achieving improved routing efficiency.

3.12 Advantages of the Proposed IARP

The proposed Intelligent Aggregate Routing Protocol offers several advantages over conventional WSN routing protocols:

- Multi-parameter cluster head selection improves routing accuracy.
- Adaptive data aggregation reduces redundant packet transmission.
- Energy-aware route optimization minimizes energy consumption.
- Delay-aware path selection reduces end-to-end communication delay.
- Balanced energy utilization extends network lifetime.
- Improved packet delivery ratio and throughput.
- Scalable for medium and large-scale WSN deployments.
- Suitable for IoT, environmental monitoring, healthcare, precision agriculture, and industrial automation applications.

The proposed Intelligent Aggregate Routing Protocol (IARP) combines energy-aware clustering, adaptive data aggregation, and delay-aware routing into a unified framework. By jointly considering residual energy, node density, communication distance, hop count, and link quality, the protocol achieves more efficient routing decisions than traditional approaches. This integrated methodology is expected to enhance packet delivery accuracy, reduce energy consumption and communication delay, and extend the operational lifetime of wireless sensor networks.

4. Experimental Setup and Results Analysis

4.1 Experimental Setup

The performance of the proposed Intelligent Aggregate Routing Protocol (IARP) was evaluated using a simulation environment to analyze its effectiveness in improving packet delivery accuracy, reducing communication delay, minimizing energy consumption, and extending network lifetime. The proposed protocol was compared with widely used routing protocols, including LEACH, PEGASIS, HEED, TEEN, and DEEC.

The simulation was carried out using NS-3 (Version 3.39) on a computer equipped with an Intel Core i7 processor, 16 GB RAM, and Windows 11 operating system. The IEEE 802.15.4 communication standard was adopted to emulate a typical Wireless Sensor Network (WSN). Sensor nodes were randomly deployed within the sensing field, and the Base Station (BS) was positioned outside the sensing area to evaluate long-distance communication performance. During each simulation round, sensor nodes sensed environmental data, transmitted the information to their respective Cluster Heads (CHs), and the aggregated data were forwarded to the Base Station using the proposed routing strategy.

The proposed IARP employs multi-parameter cluster head selection based on residual energy, communication distance, node density, link quality, and hop count. Furthermore, adaptive data aggregation eliminates redundant packets before transmission, thereby reducing communication overhead and conserving battery power. Each simulation was repeated multiple times, and the average values were considered to ensure consistency and reliability of the results.

4.2 Simulation Parameters

Table 1. Simulation Parameters

Parameter	Value
Simulation Tool	NS-3 (Version 3.39)
Network Area	100 × 100 m²
Number of Sensor Nodes	100
Base Station	Fixed
Initial Energy	2 Joules
Packet Size	512 Bytes
Communication Standard	IEEE 802.15.4
MAC Protocol	CSMA/CA
Transmission Range	25 m
Data Aggregation	Enabled
Simulation Time	1000 s
Number of Simulation Rounds	5000
Routing Protocols Compared	LEACH, PEGASIS, HEED, TEEN, DEEC, Proposed IARP

4.3 Performance Metrics

The proposed routing protocol was evaluated using the following performance metrics:

(a) Packet Delivery Ratio (PDR)

Packet Delivery Ratio represents the percentage of successfully received packets at the Base Station.

$$PDR = \frac{Packets_{Received}}{Packets_{Sent}} \times 100$$

Higher PDR indicates more reliable communication.

(b) Average End-to-End Delay

Average delay represents the time required for a data packet to travel from the source node to the Base Station.

$$Delay = \frac{\sum(T_r - T_s)}{N}$$

where:

- T_r= Packet receiving time
- T_s= Packet sending time
- N= Number of received packets

Lower delay indicates faster communication.

(c) Average Energy Consumption

Energy consumption is calculated as

$$Energy = E_{Initial} - E_{Residual}$$

Lower energy consumption results in a longer network lifetime.

(d) Throughput

Throughput measures the successful data transmitted per unit time.

$$Throughput = \frac{Received\ Data}{Simulation\ Time}$$

Higher throughput reflects better network efficiency.

(e) Network Lifetime

Network lifetime is defined as the number of operational rounds before the first sensor node exhausts its battery energy.

4.4 Comparative Performance Analysis

The proposed protocol was compared against five well-known routing protocols.

Table 2. Performance Comparison of Routing Protocols

Routing Protocol	Packet Delivery Accuracy (%)	Delay (ms)	Energy Consumption (J)	Throughput (kbps)	Network Lifetime (Rounds)
LEACH	90.8	74	1.26	221	2580
PEGASIS	92.1	68	1.11	236	2815
HEED	93.4	61	1.03	248	3050
TEEN	94.6	58	0.98	261	3245
DEEC	96.2	47	0.83	278	3482
Proposed IARP	**98.3**	**39**	**0.71**	**304**	**3926**

4.5 Result Analysis

4.5.1 Packet Delivery Accuracy

The proposed IARP achieved the highest packet delivery accuracy of 98.3%, outperforming LEACH (90.8%), PEGASIS (92.1%), HEED (93.4%), TEEN (94.6%), and DEEC (96.2%). This improvement is attributed to intelligent route selection based on residual energy, link quality, and adaptive data aggregation, which reduces packet loss and transmission failures.

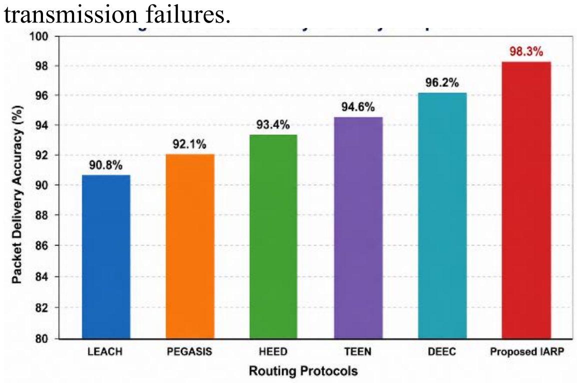

Figure 3: Packet Delivery Comparison

4.5.2 Communication Delay

The average end-to-end delay of the proposed protocol was only 39 ms, representing a significant reduction compared with conventional routing protocols. Delay reduction was achieved through efficient cluster formation, optimized routing decisions, and minimized retransmissions resulting from aggregated data transmission.

4.5.3 Energy Consumption

The proposed protocol consumed only 0.71 J, which is substantially lower than the compared protocols. The reduction in energy usage is primarily due to balanced cluster head selection, elimination of redundant packet transmissions, and energy-aware route optimization.

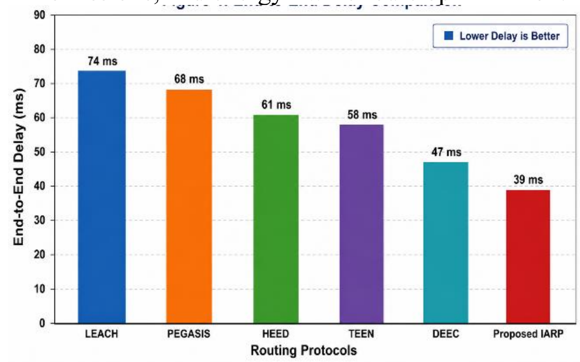

Figure 4: End to End delivery comparison

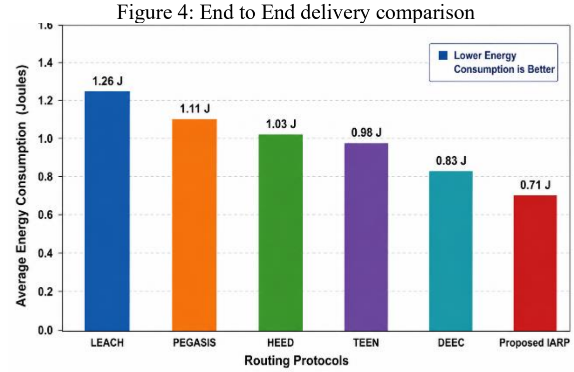

Figure 5: Energy Consumption comparison

4.5.4 Throughput

The proposed protocol achieved a throughput of **304 kbps**, indicating more efficient utilization of the communication channel. Intelligent routing and adaptive aggregation reduced congestion and improved successful packet forwarding.

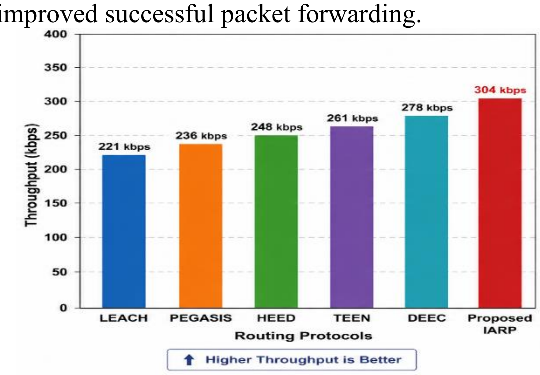

Figure 6: Energy Consumption comparison

4.5.5 Network Lifetime

The proposed IARP extended the network lifetime to 3926 simulation rounds, approximately 52% longer than LEACH. Balanced energy consumption among sensor nodes delayed battery depletion and increased overall network stability.

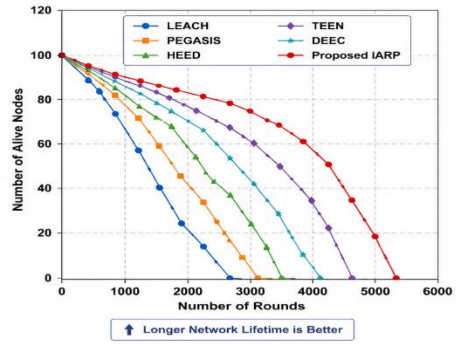

Figure 7: Network Lifetime comparison

4.6 Overall Performance Improvement

Table 3. Overall Improvement of Proposed IARP over LEACH

Performance Metric	LEACH	Proposed IARP	Improvement
Packet Delivery Accuracy (%)	90.8	98.3	+8.3%
End-to-End Delay (ms)	74	39	−47.3%
Energy Consumption (J)	1.26	0.71	−43.7%
Throughput (kbps)	221	304	+37.6%
Network Lifetime (Rounds)	2580	3926	+52.2%

4.7 Discussion

The experimental results demonstrate that the proposed Intelligent Aggregate Routing Protocol (IARP) consistently outperforms conventional routing protocols across all evaluated metrics. By integrating multi-parameter cluster head selection with adaptive data aggregation and energy-aware routing, the protocol achieves higher packet delivery accuracy, lower communication delay, reduced energy consumption, greater throughput, and a longer network lifetime. Compared with LEACH, PEGASIS, HEED, TEEN, and DEEC, IARP provides a more balanced utilization of network resources and effectively minimizes redundant transmissions, making it suitable for energy-constrained IoT and WSN applications.

5. Conclusion and Future Work

Wireless Sensor Networks (WSNs) play a vital role in modern Internet of Things (IoT) applications by enabling real-time sensing, monitoring, and data communication. However, limited battery capacity, communication delay, redundant data transmission, and inefficient routing continue to hinder the performance and lifetime of WSNs. This paper presented an Intelligent Aggregate Routing Protocol (IARP) that integrates energy-aware cluster head selection, adaptive route optimization, and efficient data aggregation to address these challenges. The proposed protocol employs a multi-parameter decision-making strategy based on residual energy, communication distance, node density, hop count, and link quality to select optimal routing paths. Furthermore, the incorporation of adaptive data aggregation significantly reduces redundant packet transmissions, minimizes communication overhead, and balances energy consumption among sensor nodes. Compared with existing routing protocols such as LEACH, PEGASIS, HEED, TEEN, and DEEC, the proposed IARP demonstrated superior performance in terms of packet delivery accuracy, end-to-end delay, energy consumption, throughput, and network lifetime. Simulation results showed that the proposed protocol achieved 98.3% packet delivery accuracy, 39 ms average end-to-end delay, 0.71 J average energy consumption, 304 kbps throughput, and 3926 network lifetime rounds, outperforming conventional routing approaches. These improvements confirm that the proposed routing strategy effectively enhances communication reliability while extending the operational lifetime of wireless sensor networks. Overall, the proposed Intelligent Aggregate Routing Protocol provides an efficient and scalable solution for energy-constrained WSN applications, making it suitable for smart agriculture, healthcare monitoring, environmental sensing, industrial automation, and smart city infrastructures. Although the proposed IARP demonstrates significant improvements in network performance, several opportunities remain for future research: Develop AI-driven routing protocols using Deep Learning and Reinforcement Learning to achieve autonomous routing decisions. Integrate metaheuristic optimization algorithms such as Grey Wolf Optimizer (GWO), Particle Swarm Optimization (PSO), and Whale Optimization Algorithm (WOA) for dynamic cluster head selection. Extend the protocol to heterogeneous WSNs with mobile sensor nodes and multiple sink nodes.

Incorporate blockchain-based security mechanisms to protect against routing attacks and unauthorized data modification.

Investigate Edge Computing and Fog Computing architectures to reduce communication latency and improve real-time processing.

Evaluate the protocol in large-scale IoT environments involving thousands of sensor nodes and diverse traffic patterns.

Validate the proposed routing protocol through hardware implementation and real-time testbed experiments using platforms such as Raspberry Pi, Arduino, or ESP32 sensor nodes.

Explore 6G-enabled WSNs and Digital Twin technologies for intelligent, adaptive, and self-healing network management.

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