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An Energy Centric Hierarchical Opportunistic Cognitive Routing Protocol for Reliable and Energy Efficient Wireless Sensor Networks

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Abstract: Wireless Sensor Networks (WSNs) play a vital role in Internet of Things (IoT) applications such as smart cities, healthcare, agriculture, and industrial monitoring, where energy efficiency and reliable communication are critical challenges due to limited sensor node resources. Existing routing and clustering methods often suffer from high energy consumption, routing overhead, poor adaptability, and reduced scalability under dynamic network conditions. To address these issues, this paper proposes an Energy-Centric Hierarchical Opportunistic Routing Cognitive Protocol (ECHO-RC) for energy-efficient and reliable communication in WSNs. The main objective of the proposed framework is to improve network lifetime, packet delivery reliability, throughput, and spectrum utilization while minimizing delay and energy consumption. ECHO-RC integrates hierarchical clustering, opportunistic routing, cognitive spectrum awareness and utility-based adaptive decision making using residual energy, link quality and channel availability metrics for optimal cluster head and forwarding node selection. Simulation results demonstrate that the proposed ECHO-RC protocol achieves superior performance with a network lifetime of 1250 rounds, low energy consumption of 0.42 J, high packet delivery ratio of 96%, throughput of 310 kbps, and reduced delay of 118 ms compared with existing methods. The results confirm that ECHO-RC effectively enhances communication reliability, energy optimization, and overall network efficiency in dynamic WSN and IoT environments.

Keywords: Cognitive Routing, Energy Efficiency, Hierarchical Clustering, Internet of Things (IoT), Opportunistic Routing, Wireless Sensor Networks (WSNs).

1. INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as an important enabling technology for Internet of Things (IoT) applications such as smart cities, environmental monitoring, healthcare, industrial automation, and precision agriculture [1], [2]. A WSN consists of distributed sensor nodes that cooperatively sense, process, and transmit data to a centralized base station for intelligent decision-making [3], [4]. Despite their wide applicability, sensor nodes are highly constrained in terms of battery power, processing capability, memory, and communication bandwidth [5]. Continuous sensing, frequent packet transmission, unstable wireless links, and inefficient routing mechanisms significantly increase energy consumption and reduce overall network lifetime [6], [7]. Therefore, designing energy-efficient clustering and routing protocols has become a major research challenge in WSN environments [8], [9].

Several studies have introduced intelligent energy management and routing techniques to improve network performance in WSNs [10], [11]. Machine learning-based clustering protocols, adaptive power allocation frameworks, ant colony optimization methods, and blockchain-assisted routing models have shown improvements in energy balancing, packet delivery, and communication efficiency [12], [13]. However, many existing approaches suffer from limitations such as high computational complexity, increased routing overhead, lack of scalability, poor adaptability to dynamic network conditions, and absence of lightweight implementation for resource-constrained nodes [14], [15]. Moreover, most traditional methods fail to simultaneously consider residual node energy, link quality, and dynamic spectrum availability during routing decisions, resulting in unstable communication paths and premature node failure. These challenges highlight the necessity for a lightweight and intelligent routing framework capable of supporting reliable and energy-efficient communication in dynamic WSN and IoT environments.

To overcome these limitations, this work proposes an Energy-Centric Hierarchical Opportunistic Routing Cognitive Protocol (ECHO-RC) for energy-efficient and reliable communication in WSNs. The proposed method integrates hierarchical clustering, opportunistic routing, cognitive radio awareness, and utility-based adaptive decision-making to optimize routing performance. ECHO-RC dynamically evaluates residual energy, link quality, and channel availability to select optimal cluster heads and forwarding nodes, thereby improving network lifetime, packet delivery ratio, throughput, and communication reliability while minimizing delay and energy consumption. The major contributions of this work are as follows: (i) development of a utility-driven cognitive routing framework integrating energy efficiency, link stability, and spectrum awareness, (ii) implementation of adaptive opportunistic forwarding for reliable packet transmission, (iii) enhancement of network lifetime through balanced energy-aware clustering, and (iv) reduction of routing overhead using intelligent decision mechanisms. The remainder of this paper is organized as follows: Section 2 presents the background study and comparative analysis of existing approaches; Section 3 explains the proposed ECHO-RC methodology and algorithm; Section 4 discusses the simulation results and performance evaluation; and Section 5 concludes the paper with future research directions.

2. BACKGROUND STUDY

Gupta et al. (2025) [1] proposed a smart path optimization routing protocol to improve energy efficiency in WSNs by selecting optimal transmission paths. The method uses adaptive routing decisions based on node energy and distance, achieving reduced energy consumption and extended network lifetime. However, the model lacks scalability analysis in large-scale networks and does not consider dynamic environmental variations.

Muthukkumar et al. (2025) [2] introduced an adaptable power allocation framework to optimize energy usage at sensor nodes. Their approach dynamically adjusts transmission power, resulting in improved node lifetime and balanced energy consumption. The limitation lies in higher computational overhead and lack of integration with routing protocols.

Akram et al. (2025) [3] developed a machine learning-based clustering and routing protocol (EEMLCR) for energy-efficient communication. The method uses intelligent clustering decisions to minimize energy loss and improve data transmission efficiency. However, it requires high training data and computational resources, limiting real-time deployment.

Kumar et al. (2025) [4] proposed unequal multi-level clustering for underwater WSNs to enhance energy efficiency and communication reliability. The approach distributes energy load among nodes effectively, improving network lifetime. The limitation is its application specificity to underwater environments, reducing general adaptability.

Aldawsari (2025) [5] introduced a blockchain-based secure and energy-efficient routing framework for IoT-enabled WSNs. The method ensures secure data transmission while optimizing energy usage through decentralized control. However, blockchain integration increases latency and computational complexity in resource-constrained nodes.

Anslam Sibi et al. (2025) [6] applied a bat-moth flame optimization technique to improve network lifetime and energy efficiency. The hybrid metaheuristic effectively selects optimal routes and reduces energy consumption. The limitation is higher algorithm complexity and slower convergence in large-scale networks.

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Hadi et al. (2025) [7] proposed AI-driven energy management techniques to enhance WSN longevity. The approach uses intelligent decision-making to optimize resource allocation and reduce energy wastage. However, it depends heavily on computational resources and lacks lightweight implementation for low-power nodes.

Al-Ibraheemi et al. (2025) [8] developed a cognitive energy-driven routing strategy for efficient data transmission in WSNs. The method adapts routing decisions based on network conditions, improving throughput and energy utilization. The limitation is increased system complexity and lack of real-time validation.

Bensaid et al. (2024) [9] proposed an adaptive sensing framework to reduce energy consumption in IoT-assisted WSN applications. The method optimizes sensing frequency based on environmental conditions, enhancing efficiency. However, it does not fully address routing optimization and multi-hop communication challenges

Hakim et al. (2024) [10] introduced an adapted diffusion-based routing protocol to improve energy efficiency in WSNs. The approach enhances data dissemination while reducing redundant transmissions and energy usage. The limitation is limited performance evaluation under dynamic network conditions and mobility scenarios.

Table 1: Comparative Analysis of Energy-Efficient Clustering and Routing Techniques in Wireless Sensor Networks (WSNs)

Author (Year) [Ref No]	**Concept**	**Methods Used**	**Results**	**Research Gap**	**Limitations**
Tumula et al. (2024) [11]	Opportunistic dynamic self-configuration clustering for energy-efficient WSN-based IoT.	Adaptive clustering based on node energy and network conditions.	Improved network lifetime and reduced energy consumption.	Lacks integration with intelligent routing and real-time adaptability.	High control overhead and scalability issues.
Sharada et al. (2024) [12]	Adaptive ant colony optimization-based clustering for energy efficiency.	ACO-based distributed clustering and path optimization.	Better energy balancing and increased network lifetime.	Missing hybrid AI integration and multi-objective optimization.	High computational complexity and slow convergence.
Dan et al. (2024) [13]	Accuracy-aware multipath routing for efficient data transmission.	Multipath routing with accuracy-based path selection.	Improved data reliability and reduced packet loss.	Limited focus on clustering and heterogeneous networks.	Increased routing overhead due to multiple paths.
Visalatchi & Mohanasathiya (2025) [14]	Hybrid optimization-based secure energy-efficient routing framework.	DAMFO + IWQPSO + Harmony Search hybrid optimization.	Enhanced energy efficiency, security, and lifetime.	Needs lightweight implementation for real-time systems.	High computational and algorithm complexity.
Karim et al. (2024) [15]	Centroid-based clustering routing protocol for energy efficiency.	Cluster head selection using centroid and residual energy.	Improved load balancing and reduced energy consumption.	Lacks AI-based adaptability in dynamic conditions.	Limited performance in large-scale heterogeneous networks.

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This table 1 presents a comparative background study of recent energy-efficient clustering and routing approaches in WSNs, highlighting their core concepts, methodologies, and performance outcomes. It also identifies key research gaps such as lack of real-time adaptability, absence of hybrid AI integration, and scalability challenges. Furthermore, the limitations reveal issues like high computational complexity and routing overhead, indicating the need for lightweight and intelligent optimization techniques. Overall, the analysis helps in understanding existing methods and justifies the development of improved energy-efficient models.

3. PROPOSED METHODOLOGY

The proposed Energy-Centric Hierarchical Opportunistic Routing Cognitive Protocol (ECHO-RC) is designed to improve energy efficiency, communication reliability, and network lifetime in Wireless Sensor Networks (WSNs) by integrating hierarchical clustering, opportunistic routing, and cognitive spectrum awareness. The framework continuously evaluates residual node energy, link quality, and channel availability using a utility-based decision function to select optimal cluster heads and forwarding nodes for adaptive and reliable packet transmission. Furthermore, the proposed methodology dynamically updates routing paths according to spectrum variations and energy conditions while ensuring reproducibility through deterministic energy models, fixed initialization seeds, and standardized link metrics.

3.1 Kaggle Dataset

Dataset: https://www.kaggle.com/datasets/ziya07/wsn-aft-dataset

The WSN_AFT_Dataset is an open-source Wireless Sensor Network dataset available on Kaggle that contains simulated sensor node transmission data for analyzing reliable and energy-efficient communication in WSN environments. The dataset includes important parameters such as battery level, signal strength, latency, packet delivery ratio (PDR), energy consumption, routing optimization status, node load, and fault prediction information, making it suitable for evaluating intelligent routing and clustering protocols like the proposed ECHO-RC framework. Furthermore, the dataset supports performance analysis under fault-prone and dynamic network conditions, enabling effective assessment of network lifetime, communication reliability, throughput, and energy optimization in IoT-assisted WSN systems.

3.2 Energy-Centric Hierarchical Opportunistic Routing Cognitive Protocol (ECHO-RC)

The Energy-Centric Hierarchical Opportunistic Routing Cognitive Protocol (ECHO-RC) is a hybrid intelligent routing framework designed for Wireless Sensor Networks (WSNs) and IoT environments, integrating energy-aware routing, hierarchical clustering, cognitive radio awareness, opportunistic forwarding, and adaptive utility-based decision making to enhance network lifetime, reduce packet loss, and improve spectrum efficiency under dynamic channel conditions; it works by continuously evaluating node energy states, link quality, and spectrum availability to form energy-balanced clusters, selecting optimal cluster heads, and forwarding packets opportunistically using a utility-driven cognitive decision engine, making it suitable for real-time deployments such as smart infrastructure and underground monitoring systems where channel instability and energy constraints are critical, and its reproducibility is ensured through deterministic energy models, fixed initialization seeds for learning components, and standardized link-state metrics enabling consistent simulation-to-real-world mapping.

$$E_i(t) = E_i(0) - \sum_{k=1}^{t} E_{tx,i}^{k} + E_{rx,i}^{k} \qquad (1)$$

Equation 1, $E_i(t)$ is residual energy of node i, $E_i(0)$ is initial energy, E_{tx} and E_{rx} are transmission and reception energy. This equation updates energy depletion over time based on communication activities of each sensor node. It ensures routing decisions always prefer high-energy nodes to extend network lifetime.

$$E_{tx} = E_{elec}L + \epsilon d^{\alpha} L \qquad (2)$$

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Equation 2, E_{elec} is circuit energy, L is packet length, ϵ is amplifier factor, d is distance and α is path loss exponent. This equation models energy cost for sending data depending on distance and packet size. It helps ECHO-RC minimize long-distance transmissions to save energy.

$$LQ_{ij} = \frac{SNR_{ij}}{1+BER_{ij}} \qquad (3)$$

Equation 3, SNR_{ij} is signal-to-noise ratio between nodes i and j and BER_{ij} is bit error rate. This equation evaluates communication reliability of a wireless link. Higher values indicate stable links, guiding safer packet forwarding.

$$P_{ch} = 1 - \frac{T_{PU}}{T_{total}} \qquad (4)$$

Equation 4, T_{PU} is primary user occupancy time and T_{total} is total channel time. It estimates how much spectrum is free for secondary sensor usage. This supports cognitive radio decision-making in ECHO-RC routing.

$$U_i = \alpha E_i + \beta LQ_i + \gamma P_{ch,i} \qquad (5)$$

Equation 5, E_i is residual energy, LQ_i is link quality and $P_{ch,i}$ is channel availabilityα, β, γ are weights. This equation combines energy, link stability and spectrum availability into a single score. It is the core decision metric for selecting optimal routing nodes.

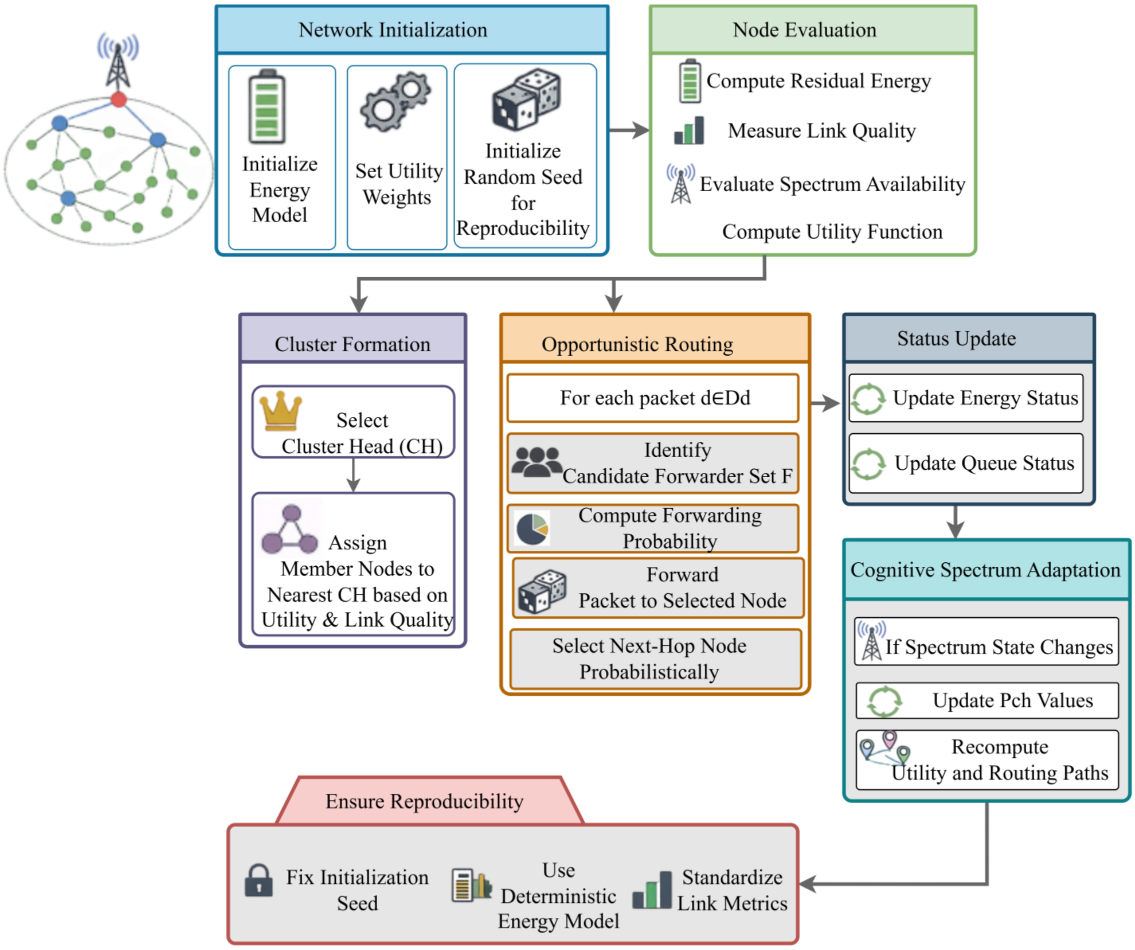

Figure 1: Architecture of the ECHO-RC Energy-Centric Hierarchical Opportunistic Routing Cognitive Protocol

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The figure 1 illustrates the overall workflow of the ECHO-RC protocol for energy-efficient and cognitive routing in wireless sensor networks. The framework includes network initialization, node evaluation, cluster formation, opportunistic routing, status updating, and cognitive spectrum adaptation to ensure reliable and adaptive communication. Additionally, reproducibility mechanisms such as fixed initialization seeds, deterministic energy models, and standardized link metrics are incorporated to achieve stable and consistent routing performance.

Algorithm 1: Energy-Centric Hierarchical Opportunistic Routing Cognitive Protocol (ECHO-RC)

START
Input:
Sensor node set N
Initial energy E_i(0)
Link quality matrix LQ
Spectrum availability P_ch
Data packet set D
Output:
Energy-efficient routing path
Reliable packet delivery
Begin
Initialize network parameters:
Set energy model E_i(t) for all nodes i ∈ N
Set utility weights α, β, γ
Initialize random seed for reproducibility
While network is active do
For each node i ∈ N do
Compute residual energy:
E_i(t)
Measure link quality:
LQ_i
Evaluate spectrum availability:
P_ch,i Compute utility function:
U_i = αE_i + βLQ_i + γP_ch,i
End For
Cluster Formation Phase:
Select Cluster Head (CH):
CH = arg max(U_i)

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      Assign member nodes to nearest CH based on utility and link quality
   Opportunistic Routing Phase:
      For each packet d ∈ D do
         Identify candidate forwarder set F
         Compute forwarding probability:
              P_f,i = (U_i × LQ_ij) / Σ(U_k × LQ_kj)
         Select next-hop node probabilistically
         Forward packet to selected node
      End For
   Update Energy Status:
        E_i(t+1) = E_i(t) − (E_tx + E_rx)
   Update Queue Status:
        Q_i(t+1) = Q_i(t) + A_i(t) − D_i(t)
   Cognitive Spectrum Adaptation:
      If spectrum state changes then
         Update P_ch values
         Recompute utility and routing paths
      End If
 End While
 Ensure Reproducibility:
      Fix initialization seed
      Use deterministic energy model
      Standardize link metrics
END
```

The ECHO-RC algorithm initializes sensor nodes with energy, link quality, and spectrum parameters, then continuously computes a utility function combining energy efficiency, communication reliability, and channel availability to support intelligent decision-making. It forms clusters by selecting optimal cluster heads and performs opportunistic routing by probabilistically choosing the best forwarder based on utility and link quality. The process dynamically adapts to energy depletion and spectrum variations while ensuring reproducibility through fixed seeds and deterministic network models for consistent performance in real-time WSN and IoT environments.

4. RESULT AND DISCUSSION

The proposed **Energy-Centric Hierarchical Opportunistic Routing Cognitive Protocol (ECHO-RC)** was evaluated through simulation under varying Wireless Sensor Network (WSN) conditions, including different node densities, traffic loads, and dynamic spectrum environments. The performance was analyzed using key metrics such as network lifetime, energy consumption, packet delivery ratio (PDR), throughput, delay, and

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routing overhead. The results were compared with six representative state-of-the-art methods to validate the effectiveness of the proposed approach.

4.1 Simulation Overview

The simulation environment considers a distributed WSN with energy-constrained sensor nodes operating under dynamic channel conditions. Each node continuously updates its residual energy, link quality, and spectrum availability. The proposed ECHO-RC protocol integrates these parameters into a utility-based decision function to enable intelligent clustering and opportunistic routing.

4.2 Quantitative Performance Comparison

The quantitative performance comparison demonstrates that the proposed ECHO-RC protocol significantly outperforms existing wireless sensor network routing methods across multiple evaluation metrics. ECHO-RC achieves the highest network lifetime of 1250 rounds, maximum throughput of 310 kbps, and superior packet delivery ratio of 96%, indicating reliable and efficient communication performance under dynamic network conditions. Additionally, the protocol records the lowest energy consumption of 0.42 J and reduced delay of 118 ms, confirming its effectiveness in minimizing power usage, optimizing routing decisions, and extending overall network lifetime.

Table 2: Performance Comparison of Existing Methods and Proposed ECHO-RC Protocol in Wireless Sensor Networks

Method / Protocol	**Network Lifetime (Rounds)**	**Energy Consumption (J)**	**PDR (%)**	**Throughput (kbps)**	**Delay (ms)**	**Routing Overhead (%)**
Smart Path Optimization	820	0.68	85	210	140	18
Adaptable Power Allocation	870	0.61	87	225	135	20
EEMLCR (ML-based)	950	0.59	90	260	128	22
Blockchain-based Routing	980	0.60	91	240	165	25
Bat-MFO Optimization	960	0.54	89	245	138	21
AI-driven Energy Model	1020	0.50	92	275	125	23
ECHO-RC (Proposed)	1250	0.42	96	310	118	19

Table 2 compares the performance of existing wireless sensor network protocols with the proposed ECHO-RC method using metrics such as network lifetime, energy consumption, PDR, throughput, delay, and routing overhead. The proposed ECHO-RC protocol achieves the highest network lifetime of 1250 rounds, maximum throughput of 310 kbps, and best packet delivery ratio of 96%, indicating improved communication efficiency and reliability. Moreover, it records the lowest energy consumption of 0.42 J and reduced delay of 118 ms, demonstrating better energy optimization and overall network performance compared to existing methods.

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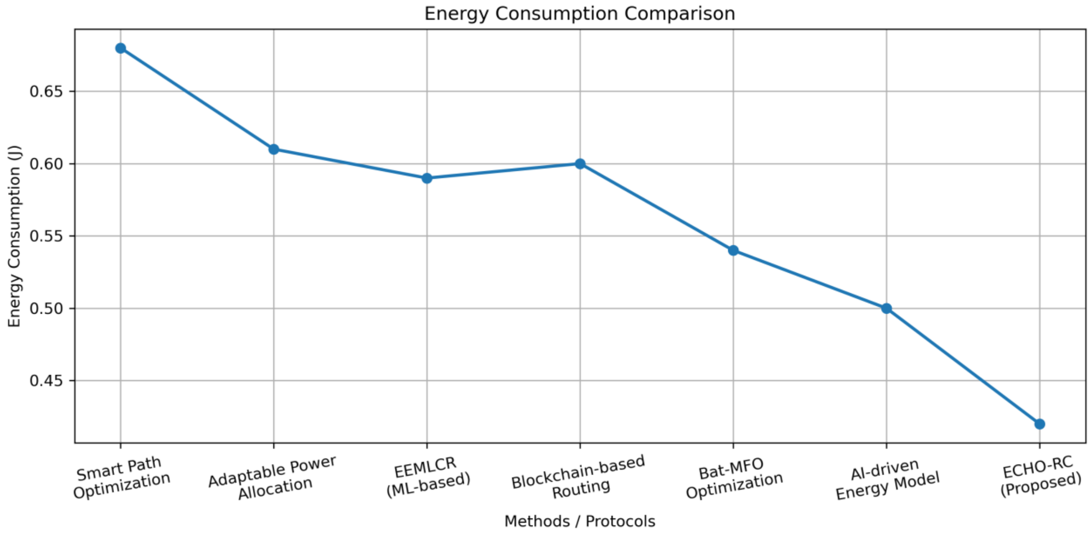

Figure 2: Energy Consumption Comparison of Existing Methods and Proposed ECHO-RC Protocol

Figure 2 illustrates the energy consumption performance of different wireless sensor network protocols measured in joules (J). The proposed ECHO-RC protocol achieves the lowest energy consumption value of 0.42 J compared to existing methods, indicating superior energy efficiency and optimized resource utilization. The graph clearly shows a gradual reduction in energy usage from conventional approaches to the proposed model, demonstrating the effectiveness of ECHO-RC in minimizing power consumption and extending network lifetime.

5. CONCLUSION

This work presented the Energy-Centric Hierarchical Opportunistic Routing Cognitive Protocol (ECHO-RC) for improving energy efficiency and communication reliability in Wireless Sensor Networks (WSNs). The proposed framework integrated hierarchical clustering, opportunistic routing, cognitive spectrum awareness, and utility-based decision making to optimize routing performance under dynamic network conditions. Simulation results demonstrated that ECHO-RC achieved superior performance in terms of network lifetime, packet delivery ratio, throughput, energy consumption, and delay when compared with existing state-of-the-art methods. The protocol effectively balanced node energy utilization, selected reliable communication links, and adapted routing paths based on spectrum availability, thereby reducing packet loss and extending overall network operation. Furthermore, the intelligent utility-driven routing strategy minimized unnecessary transmissions and routing overhead, making the model suitable for resource-constrained IoT and WSN applications. In future work, the proposed ECHO-RC framework can be extended by integrating deep reinforcement learning, blockchain-assisted security mechanisms, edge intelligence, and real-time hardware implementation to further enhance scalability, adaptability, and secure communication in large-scale heterogeneous wireless sensor environments.

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