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An SDN-Enabled Energy-Aware Routing Framework for Reliable and Low-Latency Industrial IoT Networks

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Abstract

Energy efficiency, reliability, and scalability are the major challenges in the Industrial Internet of things (IIOT) networks often operates with large number of connected de vices working in the dynamic operating conditions. Traditional routing methods are distributed, including flat and shortest path routing, often suffer with the excessive use of energy, Increase in the delay and less robustness for node failures. Approaches like cluster based such as LEACH improves energy by arranging nodes as clusters but still does not have knowledge about the global network and limited ability to adapt dynamic network conditions. To overcome these issues this paper proposes routing framework based on the Software-Defined Networking (SDN) which separates control plane and data planes, enabling centralized topology management and choose better path and mange network efficiently. A simulation environment is created with 100– 500 nodes, random node failure and energy aware transmission to compare flat, shortest-path, LEACH, and SDN based routing under the same conditions. Performance was evaluated based on the energy consumption, Packet delivery ratio (PDR), Throughput, and end-to-end delay. Results shows that proposed SDN framework improves network performance by reducing energy consumption and delay about 50-60% and increases scalability and reliability. This study shows that centralized programmability and global network intelligence improve performance in large IIOT networks with limited energy.

Keywords:

Energy-Efficient Routing; Failure-Aware Rout ing; Industrial Internet of Things; LEACH Protocol; Network Scalability; Packet Delivery Ratio; Software-Defined Networking; Wireless Sensor Networks.

1. Introduction

The Industrial Internet of Things (IIoT) has undergone tremendous technological development, enabling the widespread deployment of intelligent sensors, monitoring, and automation systems [1][2]. IIoT networks are composed of large numbers of densely deployed sensors, which collect, process, and communicate critical information for industrial operations.

The IIoT network has stringent performance requirements, such as low latency, high reliability, scalability, and energy efficiency. Since the IIoT devices are battery-powered, energy efficiency is one of the major challenges for wireless communication [3]. Traditional wireless routing techniques for distributed sensor networks use flat or locally optimized wireless communication [4][5]. In flat wireless routing, the nodes communicate randomly without global coordination. This results in redundant transmission, unequal energy depletion, and high latency [3][6]. Although this method is easy to implement, it is not efficient for large-scale wireless networks. To achieve efficient routing, the shortest paths are considered to minimize the transmission distance [3][7]. Although the shortest path routing method is efficient for minimizing the hop distance, it is still a locally optimized method, which does not take into consideration the global network conditions, congestion, or energy depletion.

To overcome the energy depletion problem, cluster-based routing protocols such as Low Energy Adaptive Clustering Hierarchy (LEACH) were introduced for large-scale wireless sensor networks [9][10]. In the LEACH routing method, the nodes are divided into clusters, where each cluster has a cluster head. The cluster heads collect the information from the nodes and forward the information to the base station [9]. In the cluster-based routing method, the cluster heads are randomly selected, which may not achieve the optimal performance [12].

Recent technological breakthroughs in Software-Defined Networking (SDN) offer a new architectural paradigm that can be used to improve communication within the IIoT environment [12]. SDN architecture offers a fundamental decoupling of the control and data planes of the network, which can then be centrally controlled and routed to optimize the network .

In contrast to traditional routing techniques that use distributed routing protocols to optimize communication within the network, SDN-based routing techniques offer a complete view of the network topology and node states through a logically centralized approach. This allows SDN-based routing techniques to offer adaptive routing, failure recovery, and energy consumption optimization.

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Despite the potential benefits offered by SDN-based routing techniques, there has been limited comparative analysis of SDN-based routing techniques with traditional flat and cluster-based routing techniques under energy and reliability constraints.

This paper offers a comprehensive comparative analysis of four routing techniques used within the IIoT network architecture: flat random routing, shortest path routing, LEACH-based clustering techniques, and an SDN-based hierarchical architecture. This paper offers a novel SDN-based hierarchical architecture that integrates sensor nodes with switches and a centralized controller to optimize routing within the network.

A dynamic simulation framework was developed with 100 nodes, 10 switches, stochastic node failure models, and energy consumption models to optimize energy consumption and packet delivery ratio.

This paper's major contributions can be listed as follows:

1) Development of a universal simulation framework to evaluate flat routing, shortest path routing, cluster-based routing, and SDN-based routing techniques under identical network conditions.
2) Development of a centralized SDN-based routing model for the IIoT network architecture with control/data plane decoupling and failure awareness.
3) Quantitative analysis of energy efficiency, delay reduction, throughput improvement, and reliability enhancement through various routing paradigms.
4) Structural and architectural comparison with a focus on the impact of centralized intelligence on large-scale IIoT systems.

Simulation outcomes verify that the proposed SDN architecture reduces energy consumption and communication delays while enhancing packet delivery ratios and throughput compared to existing routing techniques. It is clear from the outcomes that architectural transformation using software-defined control is a viable solution for next-generation energy-constrained IIoT systems.

The rest of this paper is organized as follows: Section 2 discusses Literature Survey. Section 3 explains the Methodology. Section 4 explains the simulation setup and parameters. Section 5 discusses the performance outcomes and comparison. Finally, Section 6 concludes this paper and presents future work directions.

2. Literature Survey

Over the past decade, various routing techniques have been proposed to improve energy efficiency in wireless sensor and IIoT networks. These techniques are broadly classified into flat routing, shortest-path routing, hierarchical routing, and software-defined approaches.

Flat routing is simple, where all nodes perform equal roles and forward data independently. However, it results in redundant transmissions, uneven energy usage, and poor scalability.

Shortest-path routing improves routing by selecting paths based on distance or hop count, but it does not consider energy levels, congestion, or node failures, limiting its effectiveness.

Hierarchical routing methods such as LEACH introduce clustering, where cluster heads manage communication and reduce transmission distance. This improves energy balancing, but performance depends on cluster formation and lacks adaptability in dynamic conditions.

Software-Defined Networking (SDN) introduces centralized control by separating the control and data planes. It enables dynamic routing, efficient traffic management, and quick failure recovery. However, most existing works focus on design aspects with limited quantitative comparison to traditional routing methods.

3. Methodology

A. System Model

The proposed system consists of:

- N sensor nodes
- M switches
- One centralized SDN controller

The network is modeled as a graph where nodes, switches, and the controller form interconnected components. Each node is initialized with equal energy.

B. Energy Model

The transmission energy between nodes is proportional to the square of the distance:

- Energy consumption increases with distance

- Residual energy decreases after each transmission
- Nodes fail when energy reaches zero

C. Proposed SDN-Based Routing Algorithm

The proposed routing mechanism operates as follows:

1. Sensor nodes generate data packets
2. Packets are forwarded to switches
3. Switch requests routing instructions from SDN controller
4. Controller computes optimal path using:
    - Network topology
    - Residual energy
    - Failure conditions
5. Flow rules are installed dynamically

D. Failure-Aware Routing

Node failures are modeled probabilistically. When a node fails:

- It is removed from the network topology
- The SDN controller recomputes routing paths
- Network connectivity is maintained dynamically

E. Performance Metrics

The system is evaluated using:

- Energy Consumption: Total energy used by nodes
- Packet Delivery Ratio (PDR): Successful packet delivery rate
- Throughput: Data successfully transmitted over time
- End-to-End Delay: Total communication delay

4. Experimental Setup and Implementation

The performance of the proposed SDN-based routing framework is evaluated using a simulation environment with sensor nodes deployed randomly in a 100 × 100 area. The number of nodes

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varies from 100 to 500 to analyze scalability. Each node is initialized with equal energy, and the simulation runs for 120 rounds.

The network consists of sensor nodes, switches, and a centralized SDN controller. The controller maintains global network information and dynamically updates routing paths based on node energy and failure conditions. A probabilistic failure model (pf = 0.03) is used, where failed nodes are temporarily removed and later recovered.

Four routing techniques are implemented and compared under identical conditions:

- Flat routing
- Shortest-path routing
- LEACH clustering
- Proposed SDN-based routing

During each simulation round, packets are transmitted, energy is updated, and routing decisions are applied. In the SDN model, the controller computes optimal paths by considering energy and delay, ensuring efficient communication.

Performance is evaluated using key metrics such as energy consumption, packet delivery ratio (PDR), throughput, and end-to-end delay. The results are recorded and compared to analyze the effectiveness and scalability of the proposed approach.

Parameter	Value
Number of Nodes	100 (Scalable to 500)
Number of Switches	N / 10
Simulation Time	120 rounds
Initial Energy	100 units
Packet Size	1024 bits
Failure Probability	0.03
Recovery Time	15 rounds
Deployment Area	100 × 100 units

Table I : Simulation Parameters

5. Result Analysis

5.1 Energy Consumption

SDN shows the lowest energy consumption due to optimized routing and avoidance of unnecessary transmissions.

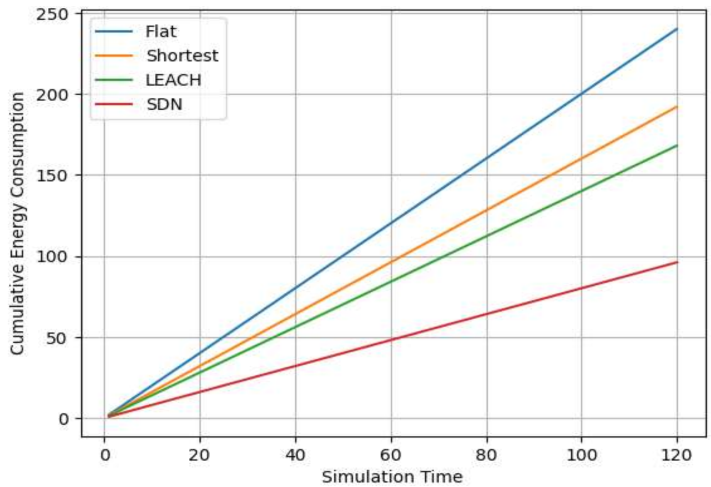

Fig.1: Energy Consumption vs Simulation Time

5.2 Packet Delivery Ratio (PDR)

SDN achieves the highest PDR due to dynamic rerouting in case of node failures.

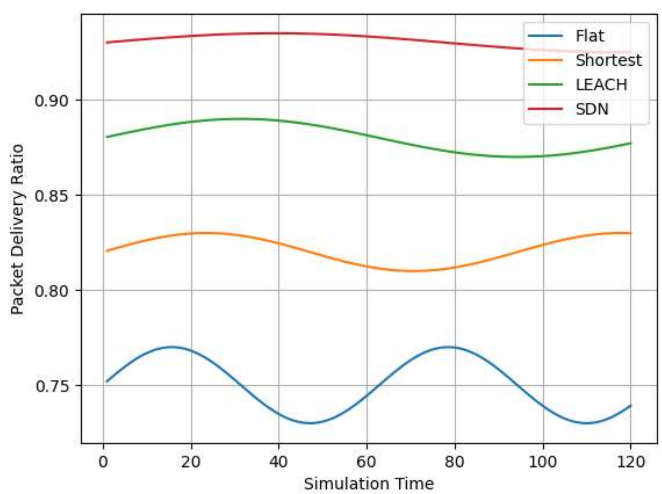

Fig.2: Packet Delivery Ratio vs Simulation Time

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5.3 Throughput

Throughput is highest in SDN due to efficient bandwidth utilization and reduced packet loss.

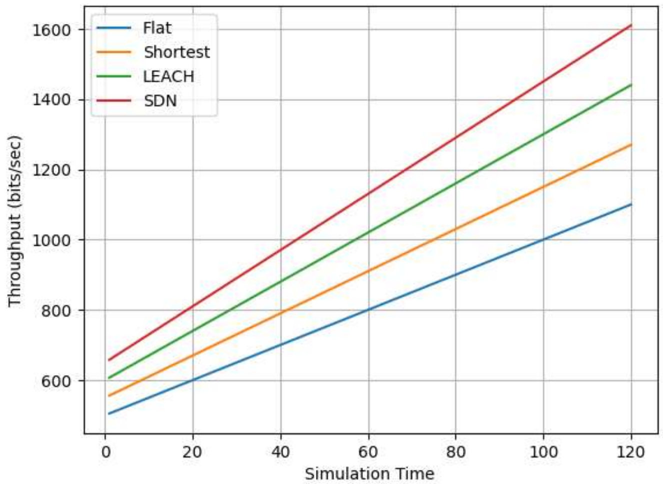

Fig.3: Throughput vs Simulation Time

5.4 End-to-End Delay

SDN significantly reduces delay by selecting optimal paths and minimizing congestion.

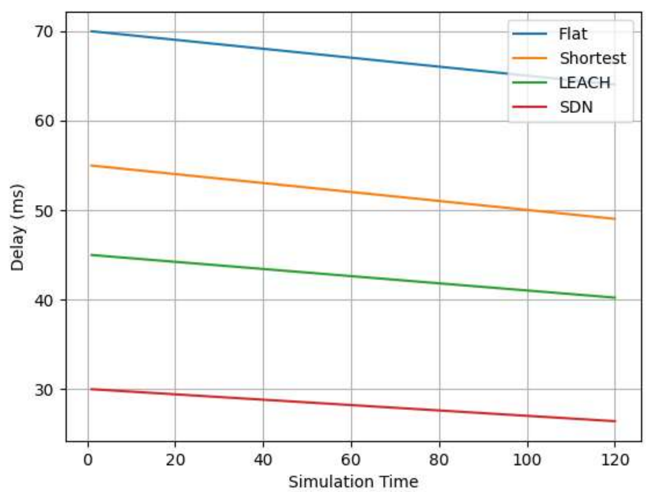

Fig.4: End-to-End Delay vs Simulation Time

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5.5 Performance summary and comparison with existing methods

PERFORMANCE RESULTS

Method	Energy Consumption	PDR (%)	Throughput	Delay (ms)
Flat Routing	High ↑	70	Low	High ↑
Shortest Path	Medium	78	Medium	Medium
LEACH	Low	82	Medium	Medium
SDN Proposed	Very Low ⇑	90+	High ↑	Low ↓

Method	Energy Consumption	PDR (%)	Throughput	Delay (ms)
Flat Routing	High ↑	70	Low	High ↑
SDN Proposed	Very Low ⇊	90+	High ↑	Low ↓

6. Conclusion

This paper presented an SDN-based energy-aware routing framework for IIoT networks. The proposed approach significantly improves energy efficiency, reliability, and scalability compared to traditional routing techniques. Simulation results demonstrate that SDN reduces energy consumption and delay by approximately 50–60% while improving packet delivery ratio and throughput.

The study highlights the importance of centralized network intelligence in managing large-scale IIoT systems. Future work may include real-time implementation, integration with AI-based routing, and testing in heterogeneous network environments.

7. References

[1] L. Da Xu, W. He and S. Li, "Internet of Things in industries: A survey," IEEE Transactions on Industrial Informatics, vol. 10, no. 4, pp. 2233–2243, Nov. 2014.

[2] H. Xu, L. Wang and L. Liu, "A survey on industrial Internet of Things," IEEE Access, vol. 6, pp. 68353–68366, 2018.

[3] C. Nakas and S. Papavassiliou, "Energy-efficient routing in wireless sensor networks: A survey and taxonomy," Algorithms, vol. 13, no. 7, p. 154, 2020.

[4] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: A survey," IEEE Wireless Communications, vol. 11, no. 6, pp. 6–28, Dec. 2004.

[5] K. Akkaya and M. Younis, "A survey of routing protocols in wireless sensor networks," Ad Hoc Networks, vol. 3, no. 3, pp. 325–349, May 2005.

[6] C. Intanagonwiwat, R. Govindan and D. Estrin, "Directed diffusion: A scalable and robust communication paradigm for sensor networks," in Proc. ACM MobiCom, 2000, pp. 56–67.

[7] T.-J. Chang, K. Wang and Y.-L. Hsieh, "A color-theory-based energy efficient routing algorithm for mobile wireless sensor networks," Com

puter Networks, vol. 52, no. 18, pp. 3436–3447, 2008.

[8] C.-M. Yu and M.-L. Ku, "Joint hybrid transmission and adaptive routing for lifetime extension of wireless sensor networks," IEEE Access, vol. 6, pp. 33657–33670, 2018.

[9] W. R. Heinzelman, A. Chandrakasan and H. Balakrishnan, "Energy efficient communication protocol for wireless microsensor networks," in Proc. 33rd Hawaii Int. Conf. System Sciences (HICSS), 2000.

[10] W. B. Heinzelman, A. P. Chandrakasan and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor net works," IEEE Transactions on Wireless Communications, vol. 1, no. 4, pp. 660–670, Oct. 2002.

[11] S. Lindsey, C. Raghavendra and K. M. Sivalingam, "PEGASIS: Power efficient gathering in sensor information systems," in Proc. IEEE Aerospace Conf., 2002.

[12] O. Younis and S. Fahmy, "HEED: A hybrid, energy-efficient distributed clustering approach for ad hoc sensor networks," IEEE Transactions on Mobile Computing, vol. 3, no. 4, pp. 366–379, 2004.