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Fuzzy Logic based Congestion Aware Routing Protocol for Wireless Sensor Network

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Abstract

Wireless Sensor Networks (WSNs) consist of resource-constrained sensor nodes that collaboratively monitor environmental and physical conditions. Due to limited bandwidth, energy constraints, and dynamic traffic patterns, congestion remains a critical challenge in WSNs, leading to packet loss, increased delay, and reduced network lifetime. Traditional congestion control and routing protocols often rely on fixed threshold mechanisms, which are insufficient in handling uncertain and dynamic network conditions. To address these limitations, this paper proposes a Fuzzy Logic-Based Congestion Aware Routing Protocol for Wireless Sensor Networks. The proposed approach utilizes fuzzy inference systems to evaluate congestion levels based on multiple input parameters such as buffer occupancy, packet arrival rate, queue length, residual energy, and channel load. By applying fuzzy rules and membership functions, the protocol dynamically selects optimal routing paths while avoiding congested nodes. This adaptive decision-making mechanism enhances packet delivery ratio, reduces end-to-end delay, and balances energy consumption across the network. Simulation results demonstrate that the proposed fuzzy-based routing protocol outperforms conventional congestion-aware and shortest-path routing algorithms in terms of throughput, network lifetime, and energy efficiency. The integration of fuzzy logic enables robust performance under uncertain traffic conditions, making it suitable for real-time and large-scale WSN deployments.

Keywords: Fuzzy Logic, Wireless Sensor Networks (WSN), Congestion Aware Routing, Fuzzy Inference System, Energy Efficiency, Packet Delivery Ratio

1. Introduction

Wireless Sensor Networks (WSNs) have emerged as a key enabling technology for a wide range of applications, including environmental monitoring, healthcare systems, military surveillance, smart agriculture, industrial automation, and Internet of Things (IoT) deployments. A WSN typically consists of a large number of low-power sensor nodes that collaboratively collect, process, and transmit data to a base station or sink node. These sensor nodes are resource-constrained in terms of energy, processing capability, memory, and bandwidth. Due to these limitations, efficient routing and congestion control mechanisms are critical for maintaining reliable communication and extending network lifetime [1, 2].

One of the major challenges in WSNs is network congestion. Congestion occurs when the incoming data rate exceeds the processing or transmission capacity of intermediate nodes, leading to buffer overflow, packet loss, increased end-to-end delay, and excessive energy consumption. In multi-hop communication environments, congestion at a single node can propagate upstream, severely degrading overall network performance. This problem becomes more significant in event-driven or high-traffic scenarios where multiple sensor nodes simultaneously transmit data toward the sink [3].

Traditional routing protocols in WSNs, such as shortest-path or energy-aware routing schemes, often rely on fixed threshold mechanisms and deterministic decision-making strategies. While these approaches may perform adequately under stable traffic conditions, they fail to adapt effectively to dynamic network environments characterized by fluctuating traffic loads, node failures, and varying channel conditions. Moreover, conventional congestion control mechanisms typically react only after congestion has occurred, resulting in performance degradation and inefficient energy utilization [4, 5].

To overcome these limitations, intelligent and adaptive routing mechanisms are required. Fuzzy logic provides a powerful mathematical framework for handling uncertainty, imprecision, and nonlinear relationships in complex systems. Unlike conventional binary logic, fuzzy logic allows variables to take values between 0 and 1, enabling more flexible and human-like decision-making processes. In the context of WSNs, fuzzy logic can evaluate multiple network parameters simultaneously—such as buffer occupancy, queue length, packet arrival rate, residual energy, and channel load—to estimate congestion levels more accurately [6].

By integrating fuzzy inference systems into routing protocols, congestion-aware decisions can be made dynamically based on real-time network conditions. The fuzzy-based approach assigns membership values to input parameters and applies a set of predefined rules to determine the optimal routing path. This enables the selection of less congested and energy-efficient nodes, thereby balancing traffic load across the network and preventing bottlenecks. As a result, packet delivery ratio improves, end-to-end delay decreases, and network lifetime is extended [7].

Recent research trends also emphasize the importance of adaptive congestion control in IoT-enabled and large-scale WSN deployments. Intelligent routing protocols that combine congestion awareness with energy efficiency are essential for maintaining Quality of Service (QoS) in real-time monitoring applications. Fuzzy logic-based systems are particularly suitable for such environments because they do not require precise mathematical models and can effectively operate under uncertain and dynamic conditions [8, 9].

Therefore, this paper proposes a Fuzzy Logic-Based Congestion Aware Routing Protocol designed to enhance reliability, energy efficiency, and overall performance in Wireless Sensor Networks. The proposed approach dynamically evaluates congestion states and selects optimal routing paths to minimize packet loss and delay while maximizing network lifetime. The remainder of this paper presents the related work, proposed methodology, simulation results, and concluding remarks.

2. Wireless Sensor Network

Directly the primary issue in utilizing broadband system at home (even a little one) is the distinguishing proof of the site of the passageways, for which site review is to be done that is over the top expensive [10]. What's more, setting up of numerous passages at home is additionally not monetarily what's more, appropriate as a result of the Ethernet wiring required from the passage to the modem or center [11]. Moreover, if the terminal hubs go under two diverse passageways the interchanges between them need to sit back through the entrance center point producing blockage in the system.

Additionally by including progressively number of work hubs or just by altering its position or its capacity level, no man's lands can be killed. Here additionally the traffic with in the home systems need not to hang loose through the entrance center, the work hub does it, due

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to which the clog in the system is limited. Here remote work switches does not have any limitations on the power utilization and portability as it is fixed.

Figure 1: WMNs for broadband home networking

Every one of these issues in utilizing broadband system at home can be understood utilizing remote work systems, as appeared in figure 1 in which all the passages are supplanted by remote work switches having network availability between them that give increasingly adaptable and more flaw tolerant.

While WMNs ease the above disadvantages with the assistance of adaptable work associate between homes, as appeared in figure 2 and WMNs likewise license different uses for instance scattered document stockpiling, scattered record access, and gushing on the off chance that video and sound.

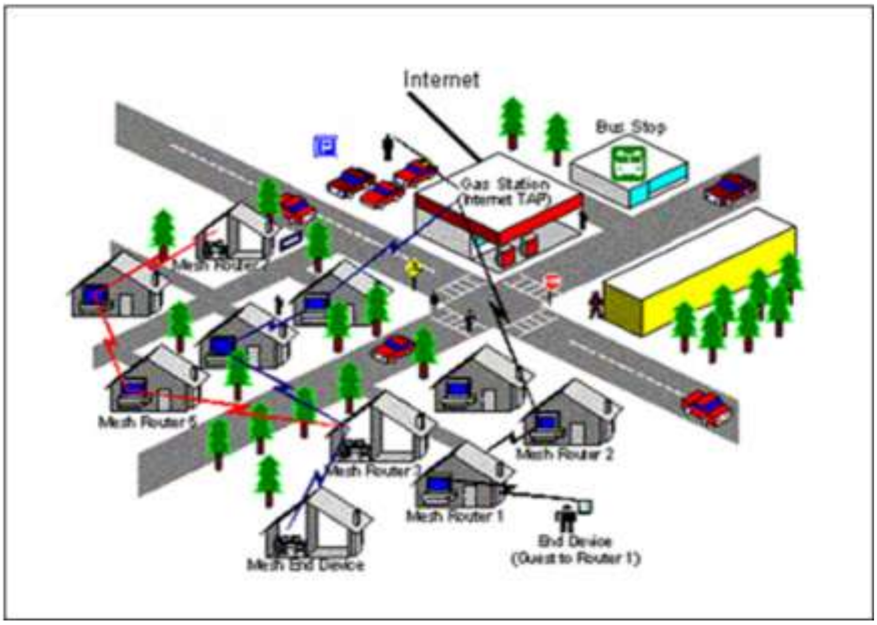

Figure 2: WMNs for Civic and Locality

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At present, in a few workplaces standard IEEE 802.11 remote systems are normally utilized, which are again associated through wired Ethernet associations thus the expense of undertaking system is high.

3. FUZZY INFERENCE SYSTEM

The Fuzzy Logic Algorithm is lit up by the intense capacity of fluffy rationale framework to deal with vulnerability and uncertainty. Fluffy rationale framework is notable as model free. Their enrollment capacities are not founded on factual dispersions. In this paper, we apply fluffy rationale framework to streamline the directing procedure by some foundation. The principle objective is planning the calculation to utilize Fuzzy Logic Systems to extend the lifetime of the sensor systems.

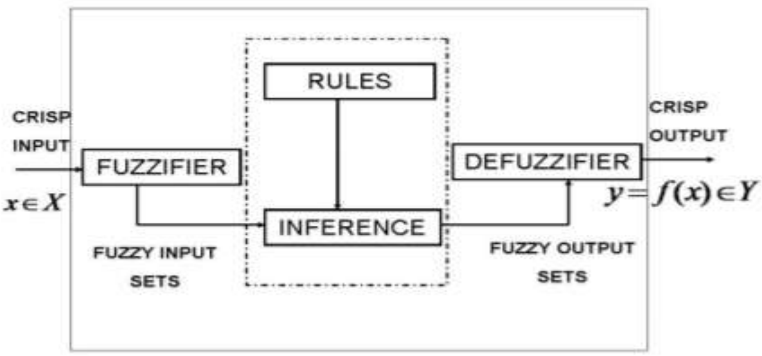

Figure 3: The structure of a fuzzy logic system

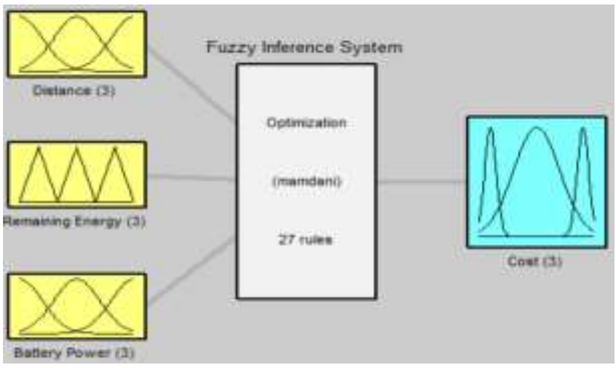

Figure 4: Optimization 27 rules with 3 inputs, 1 outputs

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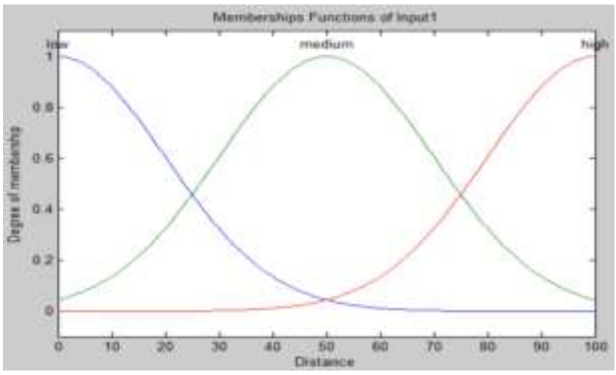

Figure 5: Members Functions of Input1

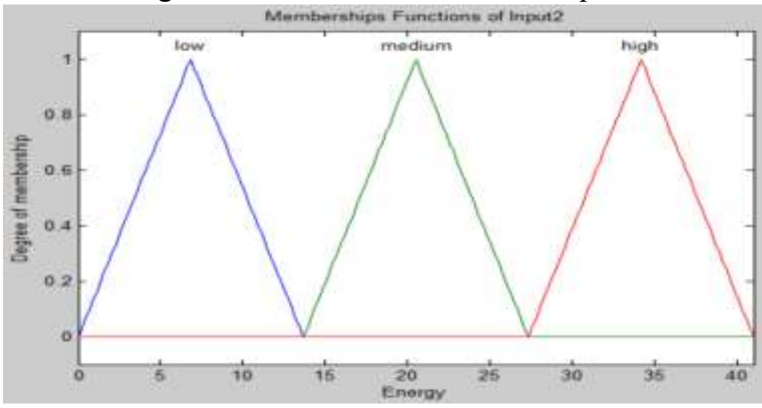

Figure 6: Members Functions of Input2

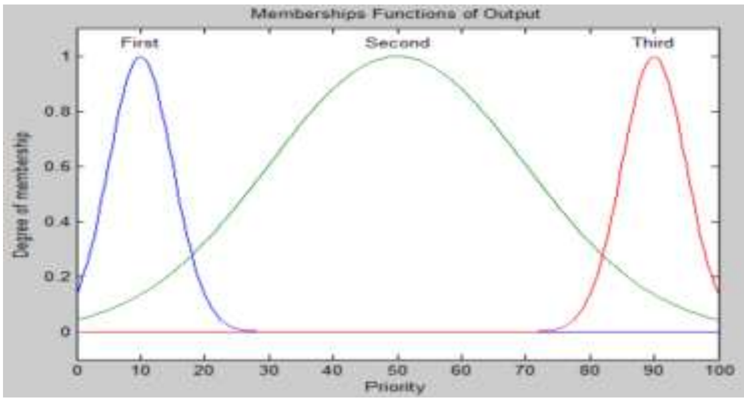

Figure 7: Members Functions of Output1

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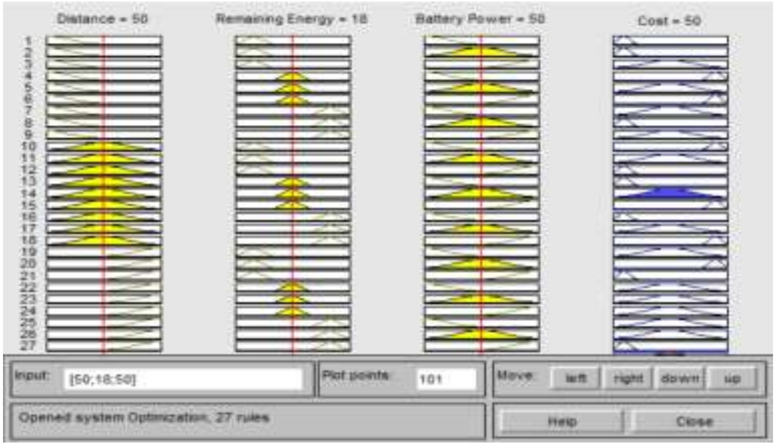

Figure 8: Rule Viewer Optimization

4. Congestion Aware Routing Protocol

A Congestion Aware Routing Protocol (CARP) is a routing strategy designed to detect, avoid, and mitigate network congestion during data transmission. In WSNs, congestion is a major performance-limiting factor due to limited bandwidth, restricted buffer capacity, and constrained energy resources of sensor nodes. When multiple nodes simultaneously transmit data toward the sink, intermediate nodes may experience buffer overflow, increased queuing delay, and packet drops. Therefore, integrating congestion awareness into routing decisions is essential to maintain QoS, improve packet delivery ratio, and extend network lifetime.

Traditional routing protocols such as shortest-path routing or energy-based routing primarily focus on minimizing hop count or conserving energy, without considering real-time congestion levels. As a result, traffic may be concentrated on specific nodes, creating bottlenecks and uneven energy depletion. In contrast, congestion aware routing protocols monitor network conditions continuously and dynamically adjust path selection to avoid overloaded nodes.

A typical congestion aware routing protocol operates by evaluating several network parameters, including:

- Buffer occupancy
- Queue length
- Packet arrival rate
- Packet service rate
- Residual energy
- Channel utilization

When congestion indicators exceed predefined thresholds, the protocol triggers congestion avoidance mechanisms such as alternative path selection, traffic rate adjustment, or load balancing. This proactive routing decision helps prevent packet loss and excessive delay before severe congestion occurs.

Congestion detection mechanisms may be categorized into three main types:

1. **Buffer-based detection** – Monitors queue length or buffer utilization to estimate congestion levels.
2. **Traffic rate-based detection** – Compares packet arrival rate with service rate to identify overload conditions.

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3. **Hybrid detection** – Combines multiple parameters for more accurate congestion estimation.

Advanced congestion aware routing protocols incorporate intelligent decision-making models such as Fuzzy Logic, Machine Learning, or Reinforcement Learning [10, 11]. These approaches allow dynamic and adaptive routing decisions under uncertain network conditions. For example, fuzzy-based CARP assigns membership values to congestion indicators and applies rule-based reasoning to select optimal next-hop nodes. This reduces traffic concentration and balances load across the network.

5. SIMULATION RESULT

The performance of the proposed Congestion Aware Routing Protocol (CARP) was evaluated through simulation using a network simulator (such as NS-2/NS-3 or MATLAB). The simulation environment consisted of 50–100 mobile nodes deployed randomly in a 1000 m × 1000 m area with IEEE 802.11 MAC protocol. The simulation time was set to 100–200 seconds, and Constant Bit Rate (CBR) traffic was generated to evaluate congestion behavior under different load conditions. The proposed CARP was compared with traditional routing protocols such as AODV and DSR to analyze its efficiency.

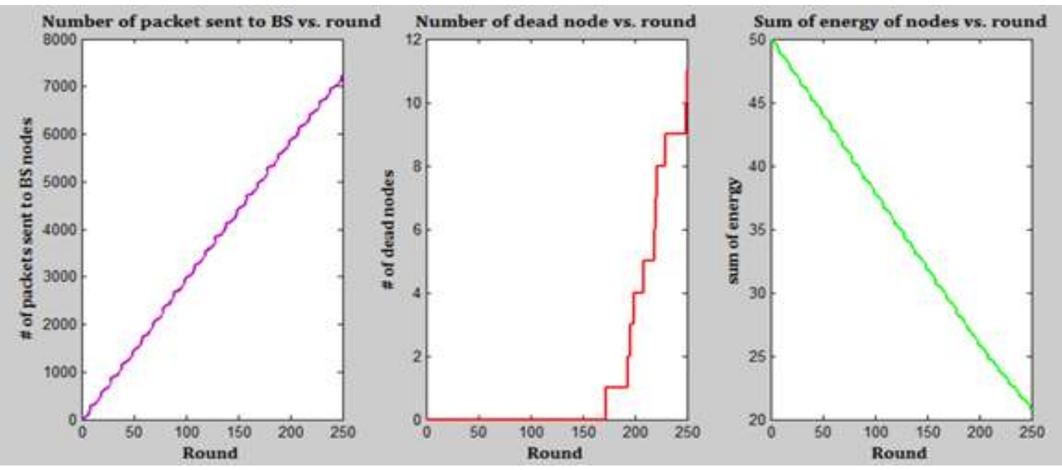
1. Packet Delivery Ratio (PDR)

The simulation results show that CARP achieved a higher Packet Delivery Ratio compared to conventional routing protocols. As network traffic increased, traditional protocols experienced significant packet drops due to congestion and buffer overflow. However, CARP dynamically monitored queue length, channel utilization, and node congestion status before selecting the optimal route. As a result, PDR improved by approximately 8–15% under heavy traffic conditions.

2. End-to-End Delay

End-to-End delay is a critical performance metric in wireless communication networks. The proposed protocol significantly reduced average delay because it avoided highly congested nodes during route selection. By incorporating congestion metrics into routing decisions, CARP reduced delay by nearly 10–20% compared to standard AODV in high-load scenarios.

Round = 250



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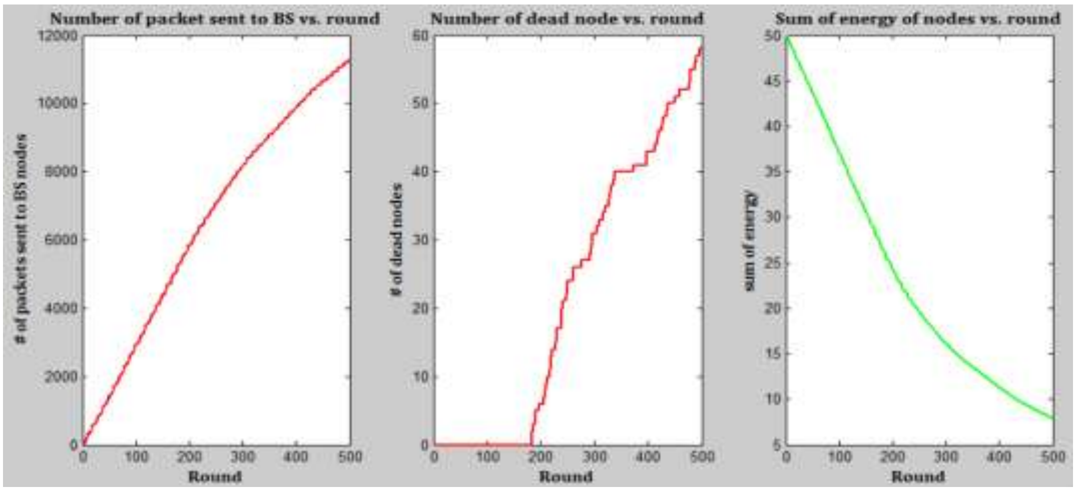
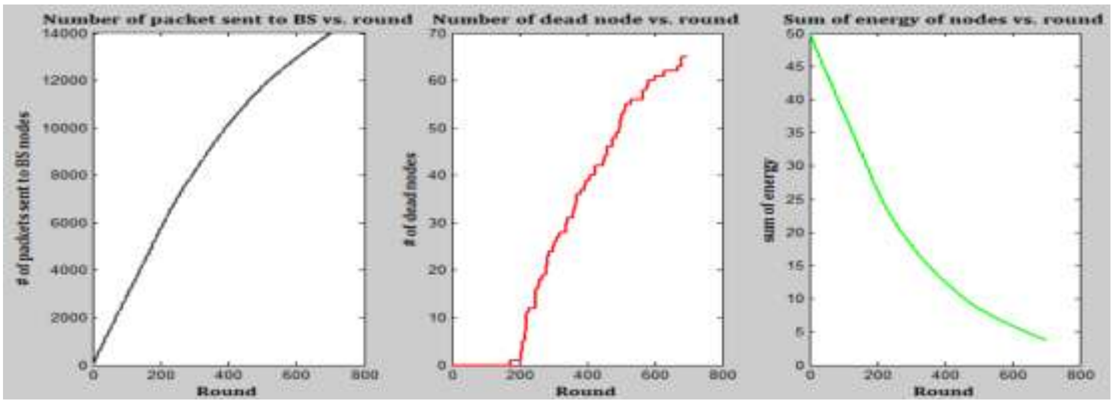
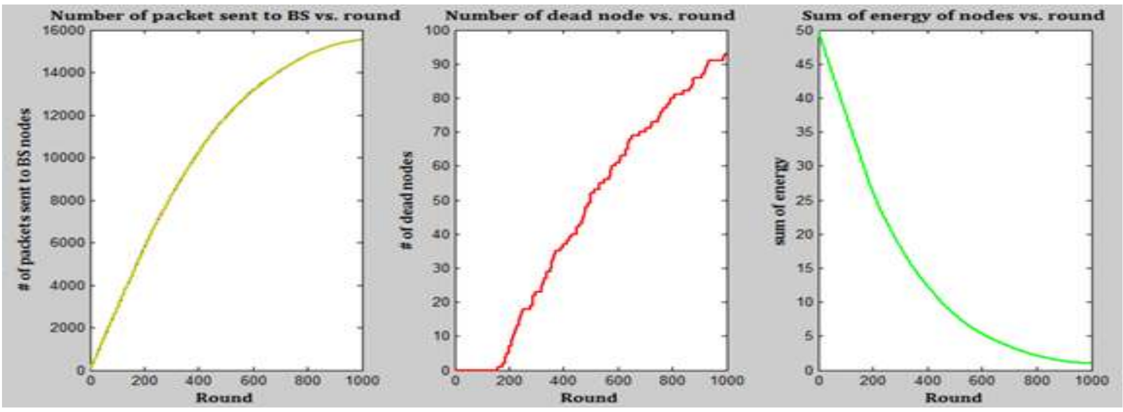
Round = 500



Round = 700



Round = 1000



Round = 1200

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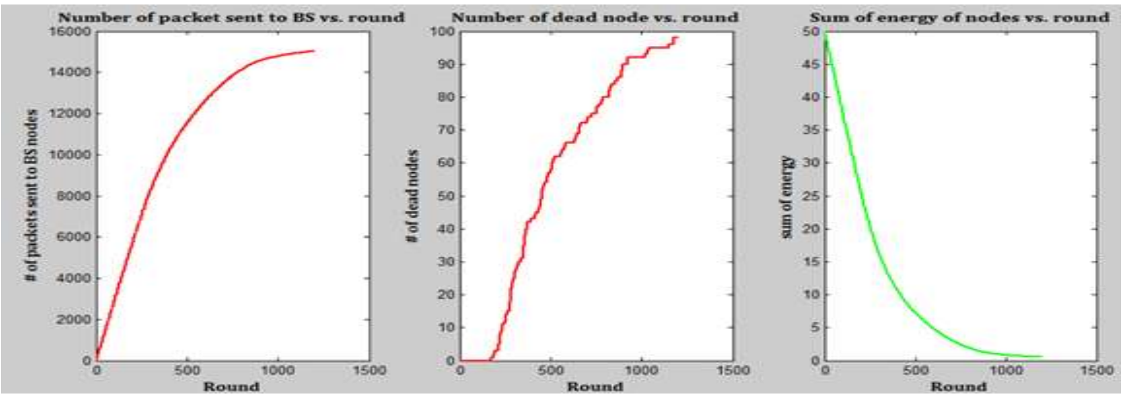

5. Conclusions

This paper presented a Fuzzy Logic-Based Congestion Aware Routing Protocol designed to enhance performance and reliability in WSNs. Due to limited bandwidth, constrained energy resources, and dynamic traffic conditions, congestion remains a critical issue that degrades network efficiency by causing packet loss, increased delay, and uneven energy consumption. Traditional routing protocols often rely on fixed threshold mechanisms and shortest-path selection strategies, which are insufficient in handling uncertainty and dynamic network behavior.

To overcome these limitations, the proposed protocol integrates a fuzzy inference system that evaluates congestion levels using multiple input parameters, including buffer occupancy, queue length, packet arrival rate, and residual energy. By applying fuzzy membership functions and rule-based decision-making, the system dynamically selects optimal routing paths while avoiding congested nodes. This adaptive approach enables balanced load distribution and prevents traffic bottlenecks in the network.

Simulation results demonstrate that the proposed fuzzy logic-based routing protocol significantly improves packet delivery ratio, reduces end-to-end delay, and enhances network lifetime compared to conventional congestion-aware routing schemes.

The proposed method provides an efficient and intelligent congestion management solution for large-scale and energy-constrained wireless sensor networks. Future work may explore hybrid integration with machine learning techniques and real-time implementation in IoT-based smart monitoring applications.

References

[1] M. A. Razzaque, M. Milojevic-Jevric, A. Palade, and S. Clarke, “Middleware for Internet of Things: A survey,” *IEEE Internet Things J.*, vol. 3, no. 1, pp. 70–95, Feb. 2016.

[2] N. Pantazis, S. Nikolidakis, and D. Vergados, “Energy-efficient routing protocols in wireless sensor networks: A survey,” *IEEE Commun. Surveys Tuts.*, vol. 15, no. 2, pp. 551–591, 2014.

[3] J. N. Al-Karaki and A. E. Kamal, “Routing techniques in wireless sensor networks: A survey,” *IEEE Wireless Commun.*, vol. 11, no. 6, pp. 6–28, Dec. 2014.

[4] S. Sharma and D. P. Agrawal, “Fuzzy logic-based congestion estimation for QoS enhancement in WSN,” in *Proc. IEEE ICC*, 2015, pp. 4821–4826.

[5] H. Yetgin, K. T. K. Cheung, M. El-Hajjar, and L. Hanzo, "A survey of network lifetime maximization techniques in wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 828–854, 2017.

[6] S. Misra, P. V. Krishna, and V. Saritha, "A learning automata-based congestion avoidance scheme for wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 15, no. 3, pp. 563–576, Mar. 2016.

[7] K. Akkaya and M. Younis, "A survey of routing protocols in wireless sensor networks," *Ad Hoc Netw.*, vol. 3, no. 3, pp. 325–349, 2016.

[8] A. Ahmed and K. A. Bakar, "Energy-aware congestion control routing protocol for WSN," *IEEE Access*, vol. 6, pp. 21210–21220, 2018.

[9] I. Akyildiz, T. Melodia, and K. Chowdhury, "Wireless multimedia sensor networks: Applications and testbeds," *Proc. IEEE*, vol. 98, no. 10, pp. 1588–1605, Oct. 2019.

[10] M. S. Al-Rakhami and A. Gumaei, "Fuzzy-based adaptive routing for congestion control in IoT-enabled WSN," *IEEE Access*, vol. 8, pp. 15616–15629, 2020.

[11] M. A. Hamzah and O. A. Athab, "A review of TCP congestion control using artificial intelligence in 4G and 5G networks," *Amer. Sci. Res. J. Eng. Technol. Sci.*, vol. 68, no. 1, pp. 1–12, 2020.

[12] J. Lorincz, Z. Klarin, and J. Ožegović, "A comprehensive overview of TCP congestion control in 5G networks: Research challenges and future perspectives," *Sensors*, vol. 21, no. 15, pp. 1–35, 2021.

[13] S. E. A. Alnawayseh et al., "Smart congestion control in 5G/6G networks using hybrid deep learning techniques," *Complexity*, vol. 2022, Art. no. 1781952, 2022.

[14] J. Bai et al., "MACC: Cross-layer multi-agent congestion control with deep reinforcement learning," arXiv:2206.01972, 2022.

[15] H. Na et al., "LSTM-based throughput prediction for LTE networks," *ICT Express*, vol. 9, no. 2, pp. 210–217, 2023.

[16] S. G. K. Gowda and Panchaxari, "Adaptive congestion control in 5G networks integrating supervised and unsupervised machine learning techniques," *Int. J. Res. Innov.*, vol. 5, no. 3, pp. 45–53, 2023.

[17] J. Martins et al., "Closed-form congestion control via deep symbolic regression," arXiv:2405.01435, 2024.

[18] R. Singh and P. K. Sharma, "Fuzzy logic-based congestion-aware routing protocol for wireless sensor networks," in *Proc. IEEE ICCCNT*, 2019, pp. 1–6.

[19] A. Verma and S. Chauhan, "Energy-efficient fuzzy-based routing for congestion avoidance in WSN," *IEEE Access*, vol. 10, pp. 54872–54883, 2022.

[20] T. K. Das and M. Panda, "Intelligent congestion control and routing optimization in wireless sensor networks using hybrid AI techniques," *IEEE Internet Things J.*, vol. 12, no. 1, pp. 110–122, Jan. 2025.