Improving Energy Efficiency in Wireless Sensor Networks using Fuzzy Logic Technique

Arun Panwar[1],Awadhesh Kumar Maurya[2],Rajnish Pandey[3]
[1,2,3]Department of Information Technology ,
Institute of Engineering and Technology, Dr. Rammanohar Lohia Avadh University, Ayodhya, India

Abstract : Modern communication approaches have been transformed by the growth of sensor networks, with Wireless Sensor Networks (WSNs) being essential in gathering and relaying critical environmental data to Base Stations (BS). However, network efficiency is hampered by problems including complicated node placement, poor connection, and low battery life, especially in data-intensive applications like data monitoring and analysis. Tailored sensor node topologies and routing protocols suited for data analysis activities are necessary to address these problems. In-depth study of WSN architecture, design constraints for video traffic data processing, pertinent applications, and important research issues are presented in this work. To enhance traffic data transfer from Cluster Heads (CH) to BS, we present an intelligent route selection strategy using a Fuzzy Technique based on Artificial Intelligence (AI). The proposed approach uses fuzzy triangular functions for input range representation to incorporate three important factors: cluster traffic status, distance to the sink, and CH residual energy. By ensuring effective and efficient data transfer, this method improves WSN efficiency for applications involving the data collection and monitoring task. The research work provides several benefits, including increased network performance, longer network operating lifespans, and more network durability.

Keywords: WSN, Base Station, Fuzzy, Cluster Head, AI

1. Introduction

The development of sensor networks has played a significant role in modern times in changing communication approaches. Micro-electronic developments have aided in the creation of wireless micro-sensors and hastened the growth of Wireless Sensor Networks (WSNs)[1]. In order to gather relevant environmental data and transmit it to a selected Base Station (BS), these networks play a crucial role. Dispersed strategically in an arbitrary manner across many locations, sensor nodes find applications in a variety of fields, including urban traffic anomaly detection, healthcare diagnostics, military surveillance, and AI-powered analytics. However, difficulties with node deployment occur, which exacerbates problems with overlapping coverage, connection, and battery power limitations. These network-wide difficulties are made worse by the demands of data analysis. Reducing packet sizes is necessary to improve energy usage and meet memory restrictions due to insufficient transmission capacity. An further major obstacle that causes energy dissipation during data transmission and reception is the geographical distance between the sink and sensor nodes[2][3]. As a result, energy efficiency becomes a crucial issue that has an immediate impact on how long the network can continue to operate[4]. It is crucial to overcome these challenges, which has led to a concentrated effort to create robust and effective sensor nodes and routing protocols designed especially for data analysis applications. Sensor nodes are multipurpose devices that may be used for data sensing, processing, and transmission, which emphasizes the need for an advanced method. Moreover, creating configurations tailored to individual applications for wireless sensor networks is essential to fulfilling the particular requirements of data analysis jobs on the network[5]. This paper will be divided into sections that will investigate in detail a number of different aspects, including sensor node architecture, particular design constraints related to video traffic data analysis within WSNs, applications related to video analytics, important research challenges, a thorough review of the literature, discovered research gaps, underneath motivations, problems identified, research objectives, technique, and expected outcomes.

2. Literature Review

In [6], authors proposed the PR-LEACH routing method, a novel approach designed to address energy optimization challenges in Internet of Things (IoT) networks. The PR-LEACH method focuses on enhancing energy efficiency through the computation of local thresholds. By dynamically adjusting these thresholds based on local conditions, PR-LEACH aims to minimize energy consumption while maintaining effective communication within the IoT network. This approach offers potential benefits in terms of prolonging network lifetime and improving overall performance.

In [7], researchers developed a sophisticated route-planning system tailored for Software-Defined Vehicular Networks (SDVNs). Leveraging fuzzy logic and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) algorithm, this system aims to optimize route selection in SDVNs. By incorporating fuzzy logic to handle uncertainty and TOPSIS for decision-making, the route-planning system offers a robust solution for efficiently navigating the complex and dynamic environments encountered in vehicular networks. This approach holds promise for enhancing traffic management, improving safety, and optimizing resource utilization in SDVNs.

In [8], researchers unveiled the LEACH-SF cluster-based routing protocol, marking a significant milestone in Wireless Sensor Networks (WSNs) advancement. This protocol, characterized by its ability to form balanced clusters and prolong network lifetime, employs fuzzy clustering techniques alongside the careful selection of cluster heads. By leveraging fuzzy logic, LEACH-SF facilitates optimized cluster formation, ensuring equitable energy distribution and efficient data transmission throughout the network. Through the strategic assignment of cluster heads, this protocol not only enhances network stability but also contributes to the overall sustainability of WSN operations.

In [9], authors delved into the intricate dynamics of sensor network optimization, specifically focusing on determining the minimum number of sensor nodes required for active sensing and quality of service evaluation. This research endeavor sheds light on the fundamental principles underlying sensor network deployment and operation, offering valuable insights into the scalability and performance considerations crucial for achieving desired levels of service quality. By elucidating the relationship between sensor node density and network performance, this study serves as a cornerstone for future sensor network design and deployment strategies.

In [10], the exploration into energy-efficient sensor network operation continued as nodes were clustered and systematically evaluated for cluster head (CH) selection. Notably, this research introduced the innovative use of mobile sinks to conserve node energy, further extending the operational lifespan of sensor networks. By adopting a proactive approach to CH selection and integrating mobile sinks into network management strategies, this study represents a paradigm shift in energy optimization techniques within WSNs, offering promising avenues for achieving sustainable and resilient network operation in diverse deployment scenarios.

In [11], researchers proposed a sophisticated two-level clustering and content-based routing method, leveraging fuzzy logic principles to optimize network performance. By considering key factors such as energy availability, node capacity, and neighborhood density in the clustering process, this method ensures efficient resource utilization and robust data transmission. Through the integration of content-based routing mechanisms, the proposed approach enhances data delivery efficiency while minimizing energy consumption, thereby addressing the dual imperatives of network longevity and performance optimization. This research lays the groundwork for the development of adaptive and resilient sensor network architectures capable of meeting the evolving demands of diverse application domains.

In [12], authors introduced an upgraded iteration of the SEP protocol known as MR-SEP, marking a significant advancement in Wireless Sensor Network (WSN) protocols. The MR-SEP protocol revolutionizes network organization by dividing the network area into multiple cluster levels, with each level featuring a designated Cluster Head (CH). A key innovation of MR-SEP lies in its utilization of minimum Base Station (BS) distance as a criterion for member Sensor Nodes (SN) to join CHs, ensuring optimal cluster formation and resource allocation. In the context of data transmission, MR-SEP orchestrates an efficient data gathering process whereby the CH aggregates data from both member SNs and neighboring layer CHs, thereby streamlining the data transmission task and enhancing overall network performance. This protocol represents a significant stride towards achieving scalability, efficiency, and reliability in WSNs, offering promising avenues for addressing the evolving challenges of modern sensor network deployments.

3. Problem Statement

The principal aim of this work is to design robust and energy-efficient protocols designed for data analysis in wireless sensor networks (WSNs)[13][14]. This work seeks to greatly improve the energy efficiency of WSNs in data analysis applications by addressing the issues related to energy consumption, data volume management, and real-time processing. The ultimate goal is to further the development of energy-efficient solutions in a variety of fields, such as industrial automation, smart surveillance, and environmental monitoring. This project aims to address important issues in WSN deployment and operation by means of focused research and creative protocol design, opening the door for the long-term and efficient use of sensor networks in data analysis situations[15].

4. Methodology Of Proposed Approach

In order to improve traffic data transmission from the Cluster Head (CH) to the Base Station (BS), the technique involves using a Fuzzy Technique powered by Artificial Intelligence (AI) for optimal route selection. The CH, in its capacity as the origin, gathers traffic information from nodes inside its cluster. The goal is to find the best path using an AI-powered search mechanism so that data may be sent to the BS for further processing and analysis in an efficient and effective manner.

Trapezoidal MF

$Trap(x: a, b, c, d) =$

$$\begin{array}{ll} 0 & if\ x \leq a, \\ \frac{(x-a)}{(b-a)} & if\ a \leq x \leq b, \\ 1 & if\ b \leq x \leq c, \\ 0 & if\ d \leq x \end{array}$$

$$\mu_{trapezoid} = \max(\left(min\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0)$$

In our analysis of the Fuzzy-based technique, we've identified three key parameters, each with its corresponding Fuzzy membership function, pivotal in determining the selection of the next best hop. The first parameter is:

a. Cluster Traffic (α1)

Energy-efficient communication in Wireless Sensor Networks (WSNs) is greatly aided by the traffic condition in Cluster Heads (CH). Since sensor nodes use a lot of energy when sending data, one of the most important aspects of energy optimization is the amount of traffic data that is tracked. Reducing energy usage and maintaining dependable and efficient network connectivity depend on efficient traffic data management[16].

$$\sigma_1 = \sum_{s=1}^{v} \left(\frac{1}{h_s} \sum_{w=1}^{h_s} traff(SN_w, CH_s) \right)$$

b. Average Distance from the Sink (α2)

In Wireless Sensor Networks (WSNs), determining the average distance between Cluster Heads (CH) and the sink is crucial for guaranteeing energy efficiency. Energy consumption can be minimized by minimizing this distance, which is essential for lowering energy consumption during data transmission and enhancing the network's overall performance.

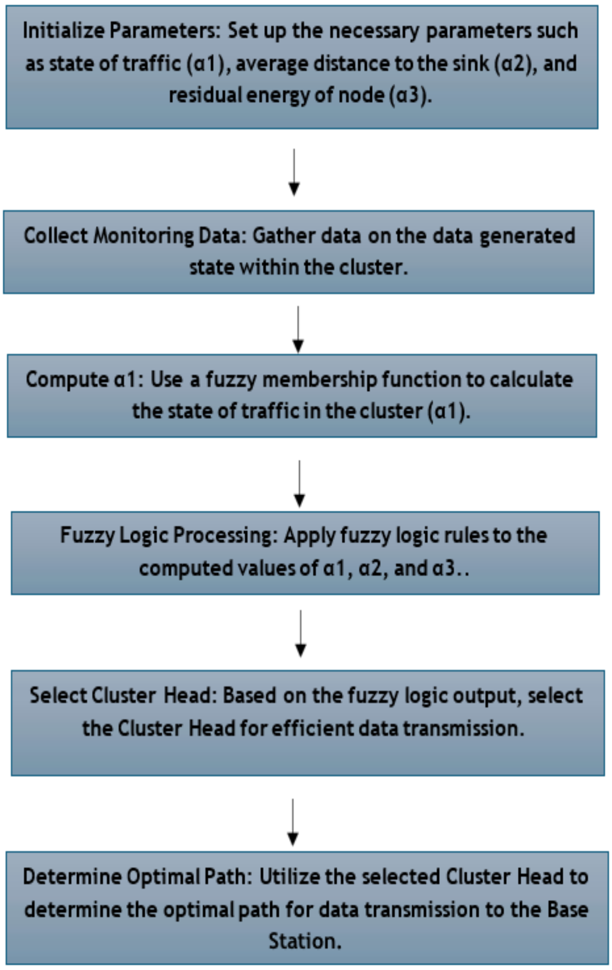
$$\sigma_1 = \sum_{s=1}^{v} \left(\frac{1}{h_s} \sum_{w=1}^{h_s} dis(SN_w, CH_s) \right)$$

c. Residual Energy of Node (α3)

In Wireless Sensor Networks (WSNs), determining the average distance between Cluster Heads (CH) and the sink is crucial for guaranteeing energy efficiency. Energy consumption can be minimized by minimizing this distance, which is essential for lowering energy consumption during data transmission and enhancing the network's overall performance[17][18].

$$\sigma_3 = \sum_{s=1}^{v} \left(\frac{1}{\sum_{s=1}^{v} CE_{CHs_s}} \right)$$

The work flow of the suggested fuzzy-based protocol is shown in Figure 3, which incorporates important variables[19] including cluster traffic, average distance from the sink, and node residual energy.



FIS is used where fuzzy rules are defined. The selected input membership the corresponding fuzzy rules table is defined in table 1.

Table1. Fuzzy rules if Fuzzy Inference System

Rule	CT	RE	ADS	Probability
1	H	L	H	L
2	H	H	L	M
3	L	H	L	V
4	L	L	H	H
5	H	M	M	M
6	M	H	H	H
7	L	L	L	M

Where, CT =Cluster Traffic, RE= Residual Energy, ADS=Average Distance from Sink.

L=Low, M=Medium, H=High, V=Very High

Example: **Rule3:** If CT is L and RE is H and ADS is L , then Probability of selection is H

Proposed Algorithm:

```
InitParams:
    α1 , α2, α3 = 0
CollectData:
    traffic_data = GatherTrafficData()
    distance_data = GatherDistanceData()
    energy_data = GatherEnergyData()
ComputeAlpha1:
    α1 = CalcTrafficState(traffic_data)
ComputeAlpha2:
    α2 = CalcAverageDistance(distance_data)
ComputeAlpha3:
    α3 = CalcResidualEnergy(energy_data)
FuzzyProcess:
    fuzzy_output = FuzzyLogic(α1, α2, α3)
SelectHead:
    head_node = ChooseClusterHead(fuzzy_output)
DeterminePath:
If head_node:
        path = CalcOptimalPathToBaseStation()
Else:
        path = CalcOptimalPathToClusterHead(head_node)
```

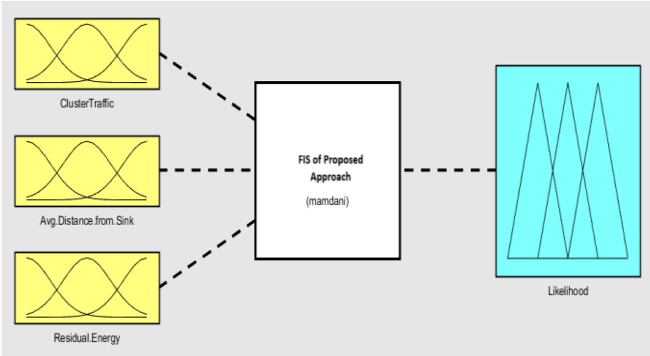
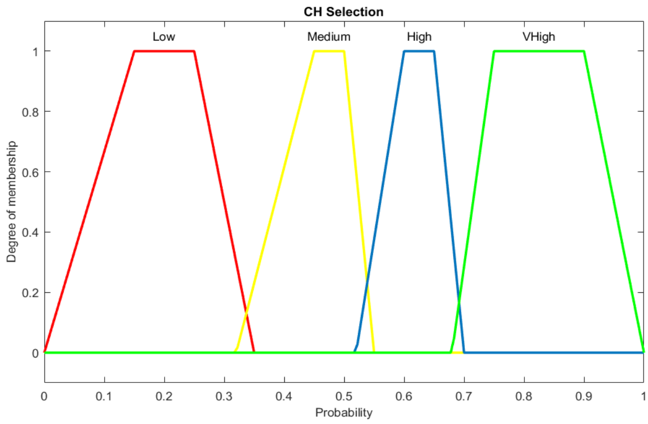


Figure 3. Proposed Fuzzy FIS model



Three crucial Input Membership Functions (IMFs) are used in the Fuzzy-based model to choose which Cluster Heads to choose: cluster traffic, residual energy of the Cluster Heads ,and average distance to the sink. Fuzzy triangle functions are used to represent the input range values.

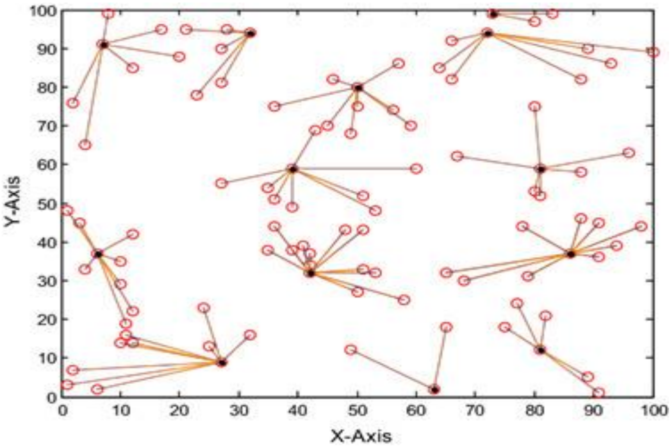
5. Simulation and Results

The simulation activities are carried out with Matlab's Fuzzy Toolbox, which provides an adaptable framework appropriate for a variety of uses, such as the creation of algorithms, data processing, visualization, and numerical calculations. These simulations randomly distribute a heterogeneous set of sensor nodes (SN) to illustrate the behavior of the Fuzzy-based Protocol.

Parameter	**Values**
Number of Sensor Nodes	100
Network Region	(100,100) m^2
Electronic Circuitry (ERX)	50 nJ/bit
Data Aggregation (EDA)	10 nJ/bit
Initial Battery Level (E0)	0.5 J
Free Space Model (Efs)	10 pJ/bit/m^2

Assumptions for network designing

The suggested protocol's spatial organization of these Sensor Nodes (SN) is depicted in Figure 2. During 3500 packet transmission rounds, 100 SN are dispersed throughout a 100x100 m^2 region in the scenario. The Base Station (BS) is situated outside of the network boundaries, which is noteworthy. It is noteworthy to emphasize that in this network, the likelihood of choosing a Cluster Head (CH) is fixed at 10%. In addition, 10 percent of the total SN are Advanced Nodes (AN), while the remaining SN are Normal Nodes (NN).



The simulation was conducted over a span of 3000 rounds, meticulously capturing the dynamics of the system. Throughout this extensive simulation, the occurrence of dead nodes was meticulously recorded at regular time intervals, as illustrated in Figure 3. The results unveiled a significant enhancement in the rates of FND (First Node Death), HND (Half Node Death), and LND (Last Node Death) with the implementation of the proposed protocol. This improvement underscores the efficacy and robustness of the protocol in prolonging the network's lifespan and mitigating the occurrence of node failures.

Table 1:Dead Nodes at various intervals

	LEACH	DEEC	SEEC	SEP	Proposed Approach
First Node Dead	700	950	1200	1400	1480
Half Node Dead	1200	1350	1700	1800	2000
Last Node Dead	2400	2550	2640	2700	2850

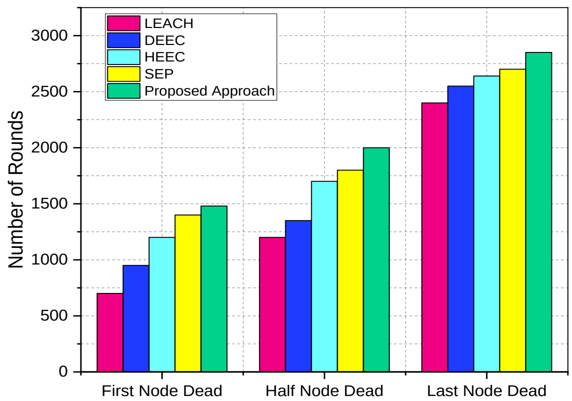


Figure 3. Energy consumption at various intervals

Figure 4 depicts the fluctuations in the number of active nodes across various time intervals. Notably, the utilization of the proposed protocols demonstrated a marked enhancement in the count of active nodes compared to conventional approaches. By the 2500th round, for instance, the LEACH protocol sustained merely 6 nodes, DEEC managed to retain 9 nodes, HEEC preserved 12 nodes, and SEP maintained 15 nodes. In stark contrast, the proposed protocol exhibited a remarkable resilience, sustaining a total of 18 nodes at the same juncture.

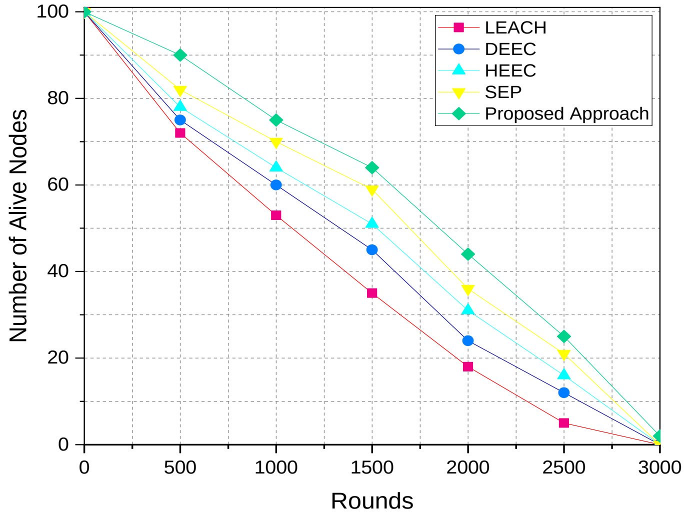


Figure 4. Alive nodes in the Network

This notable increase in the number of active nodes exemplifies the efficacy and superiority of the proposed protocol in fostering a more robust and enduring network infrastructure.

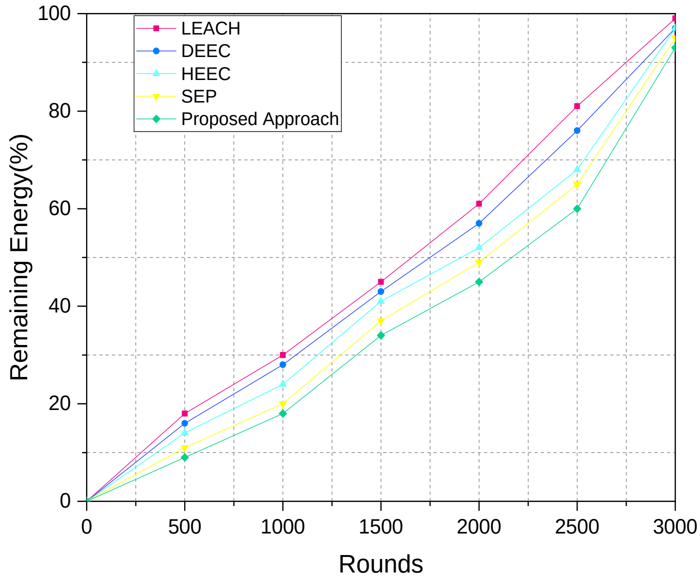


Figure 5. Remaining energy in network

Figure 5 provides insights into the remaining energy levels of nodes across various time intervals throughout the simulation. Notably, the proposed protocol demonstrates a superior retention of residual energy per node when juxtaposed with the SEP protocol. Specifically, the LEACH protocol exhibited a mere 1% residual energy in the network after the culmination of 3000 rounds, while DEEC and HEEC managed to persist with 3% energy each. In comparison, the SEP protocol exhibited a relatively higher resilience with 5% energy remaining. However, the proposed protocol surpassed them all by sustaining a remarkable 7% remaining energy. This substantial margin underscores the efficacy and efficiency of the proposed protocol in maximizing energy utilization and prolonging the operational lifespan of the network nodes, thereby enhancing overall network performance and sustainability.

6. Conclusion

This The research presents a novel solution harnessing fuzzy logic, which integrates critical factors including distance to the Base Station (BS), remaining energy levels, and the density of neighbouring nodes. By leveraging this comprehensive approach, the proposed protocol achieves enhanced load distribution, thereby significantly extending the lifespan of individual nodes within the network. Distinguished from conventional algorithms like LEACH, DEEC, SEP, and HEED, the proposed Fuzzy-based protocol emerges as a frontrunner in performance metrics. Notably, it surpasses these existing protocols by demonstrating superior efficiency and effectiveness in network management. One of the key advantages lies in the improvement of average energy consumption. In comparative analyses, the proposed method showcases substantial enhancements, with energy consumption reductions of 2%, 4%, 4%, and 6% respectively when benchmarked against traditional algorithms. This highlights the robustness and efficacy of the fuzzy-based approach in optimizing energy utilization across the network, thereby enhancing its overall sustainability and performance.

Reference

[1] R. Elavarasan K. Chitra, An efficient fuzziness based contiguous node refining scheme with cross-layer routing path in WSN, *Peer Peer Netw. Appl.*, **13** (2020), 2099–2111. https://doi.org/10.1007/s12083-019-00825-0

[2] R. K. Poluru, M. P. K. Reddy, S. M. Basha, R. Patan, S. Kallam, Enhanced adaptive distributed energy-efficient clustering (EADEEC) for wireless sensor networks, *Recent Adv. Comput. Sci. Commun.*, **13** (2020), 168–172. https://doi.org/10.2174/2213275912666190404162447

[3] M. Sohrabi, M. Zandieh, M. Shokouhifar, Sustainable inventory management in blood banks considering health equity using a combined metaheuristic-based robust fuzzy stochastic programming, Socio-Econ. Plan. Sci., 2022, In press. https://doi.org/10.1016/j.seps.2022.101462

[4] Pandey, Rajnish, and Jyoti Prakash Singh. "BERT-LSTM model for sarcasm detection in code-mixed social media post." Journal of Intelligent Information Systems 60.1 (2023): 235-254.

[5] Tiwari, Shashank Shekher, et al. "An ensemble approach to detect depression from social media platform: E-CLS." Multimedia Tools and Applications (2024): 1-33.

[6] H. Li, J. Liu, Double cluster-based energy efficient routing protocol for wireless sensor network, *Int. J. Wireless Inf. Netw.*, **23** (2016), 40–48. https://doi.org/10.1007/s10776-016-0300-9

[7] B. Balakrishnan, S. Balachandran, FLECH: Fuzzy logic-based energy efficient clustering hierarchy for non-uniform wireless sensor networks, *Wirel. Commun. Mob. Comput.*, **2017** (2017), 1214720. http://doi.org/10.1155/2017/1214720

[8] T. Y. Kord, M. U. Bokhari, SEPFL routing protocol based on fuzzy logic control to extend thelifetime and throughput of the wireless sensor network, *Wireless Netw.*, **22** (2016), 647–653. https://doi.org/10.1007/s11276-015-0997-x

[9] F. A. Khan, A. Ahmad, M. Imran, Energy optimization of PR-LEACH routing scheme using distance awareness in internet of things networks, *Int. J. Parallel Prog.*, **48** (2018), 244–263. https://doi.org/10.1007/s10766-018-0586-6

[10] M. M. Shurman, Z. Alomari, K. Mhaidat, K. An efficient billing scheme for trusted nodes using fuzzy logic in wireless sensor networks, *J. Wirel. Eng. Technol.*, **5** (2014), 62–73. https://doi.org/10.4236/wet.2014.53008

[11] A. Jain, A. K. Goel, Energy efficient fuzzy routing protocol for wireless sensor networks, *Wireless Pers. Commun.*, **110** (2020), 1459–1474. https://doi.org/10.1007/s11277-019-06795-z

[12] L. Zhao, Z. G. Bi, A. Hawbani, K. P. Yu, Y. Zhang, Y. Guizani, ELITE: An intelligent digital twin-based hierarchical routing scheme for softwarized vehicular networks, *IEEE T. Mobile Comput.*, 2022. https://doi.org/10.1109/TMC.2022.3179254

[13] G. Sun, Y. H. Liu, S. Liang, Z. Y. Chen, A. M. Wang, Q.A. Ju, et al., A sidelobe and energy optimization array node selection algorithm collaborative beamforming in wireless sensor networks, *IEEE Access*, **6** (2018), 2515–2530. https://doi.org/10.1109/ACCESS.2017.2783969

[14] L. Zhao, Z. H. Yin, K. P. Yu, X. Y. Tang, L. X. Xu, Z. Z. Guo, et al., A fuzzy logic based intelligentmulti-attribute routing scheme for two-layered SDVNs, *IEEE T. Netw. Serv. Man.*, 2022. https://doi.org/10.1109/TNSM.2022.3202741
[15] Faiz, Mohammad, and A. K. Daniel. "FCSM: fuzzy cloud selection model using QoS parameters." 2021 First International Conference on Advances in Computing and Future Communication Technologies (ICACFCT). IEEE, 2021.
[16] Sandhu, Ramandeep, et al. "Enhancement in performance of cloud computing task scheduling using optimization strategies." *Cluster Computing* (2024): 1-24.
[17] Faiz, Mohammad, Nausheen Fatima, and Ramandeep Sandhu. "A Vaccine Slot Tracker Model Using Fuzzy Logic for Providing Quality of Service." Multimodal Biometric and Machine Learning Technologies: Applications for Computer Vision (2023): 31-52.
[18] M. Sohrabi, M. Zandieh, M. Shokouhifar, Sustainable inventory management in blood banks considering health equity using a combined metaheuristic-based robust fuzzy stochastic programming, *Socio-Econ. Plan. Sci.*, 2022, In press. https://doi.org/10.1016/j.seps.2022.101462
[19] Prakash, Sudhir, et al. "A Study of Chemical Compound of Graph with help of Computer Coding." Turkish Journal of Computer and Mathematics Education (TURCOMAT) 10.3 (2019): 1553-1564.