Design and Implementation of Energy-Efficient Delay-Aware FCM Clustering Protocol for WSNs

Ms. Monali Chinchamalatpure1 Dr. Somdattaroy Choudhary2
PhD scholar, DY Patil College of Engineering,
DY Patil University, Ambi, Pune, India

Abstract

Wireless Sensor Network (WSN) clustering plays a crucial role in enhancing network lifespan, scalability, and efficiency. The Fuzzy C-Means (FCM) algorithm is employed for clustering in WSN, enabling flexible and efficient formation of clusters by assigning sensor nodes to multiple clusters with varying degrees of membership. FCM enhances clustering accuracy and reduces energy consumption by optimizing the placement of cluster heads (CHs) based on sensor node proximity and energy levels. The use of FCM-based clustering contributes to improving WSN performance in terms of balanced energy distribution and better intra-cluster communication.

Keywords: Fuzzy C-Means, Clustering, Wireless Sensor Network, Energy Efficiency, Intra-cluster Communication.

Introduction

In research work main focuses on improving Wireless Sensor Networks (WSNs) by using soft computing algorithms to achieve energy-efficient, secure, and cluster-based data aggregation.

Wireless Sensor Networks (WSN):

A WSN is a collection of spatially distributed sensors that gather environmental or physical data (e.g., temperature, humidity, vibration) and transmit it wirelessly. WSNs are classified into static WSNs (fixed sensor nodes) and mobile WSNs (nodes with mobility).
Static WSNs: Nodes are fixed in specific locations. Suitable for applications like environmental monitoring or structural health monitoring.
Mobile WSNs: Nodes have mobility and can adapt to dynamic environments. Suitable for scenarios like tracking moving targets, healthcare monitoring, or disaster recovery.
Key challenges in WSNs include energy consumption, data security, and efficient data management due to the limited power and resources of sensor nodes.

Data Aggregation in WSNs:

Data aggregation involves combining and summarizing data from multiple sensors to reduce redundancy, save energy, and minimize the number of transmissions to a central sink or base station.

Cluster-Based Data Aggregation:

To optimize energy and resource usage, WSNs are often divided into clusters. Each cluster has a Cluster Head (CH) responsible for collecting data from the sensors in its cluster. The CH performs local aggregation and sends the processed data to the base station. Cluster-Based Data Aggregation reduces the number of transmissions. It helps to saves energy by limiting the communication range for individual sensors. It also helps to balances the network load across clusters.

Energy Efficiency:

In WSNs, sensor nodes operate on batteries with limited capacity. Prolonging the network's lifetime depends on minimizing energy consumption. There are different Energy-efficient approaches

-Optimizing the selection of cluster heads.
-Reducing the frequency of data transmissions.
-Using lightweight computation to process data.

Soft Computing Algorithms:

Soft computing refers to techniques inspired by biological and natural systems that are flexible and can handle uncertainty and imprecision. There are common methods mentioned below
Fuzzy Logic: Handles uncertainty by mimicking human reasoning.
Genetic Algorithms: Optimizes solutions by simulating natural selection.
Artificial Neural Networks (ANNs): Learns patterns for decision-making.
Swarm Intelligence: Inspired by collective behaviour in nature (e.g., ants, bees) to solve optimization problems.

Why soft computing for WSNs?

Soft computing can optimize energy usage, secure data aggregation, and determine the best cluster structures dynamically. To enhance energy efficiency and delay awareness, soft computing techniques can be integrated. Fuzzy Logic helps to determine CH selection based on fuzzy parameters like energy, distance, and mobility. Genetic Algorithms allows to optimize cluster configurations for energy and delay. Particle Swarm Optimization (PSO)helps to dynamically adapt cluster boundaries and CH locations in mobile WSNs.

Objective

- To develop a clustering algorithm that prioritizes energy efficiency and minimizes delays for both static and mobile wireless sensor networks.

Key Goals:

1. Energy Efficiency: Use algorithms to minimize power consumption and extend the network lifetime.
2. Secure Data Transmission: Implement mechanisms to ensure the data's security during collection and transmission.
3. Optimized Clustering: Dynamically select the best cluster heads and organize sensors to balance the network load.

Implementation details-

Energy-Efficient and Delay-Aware Clustering Theory:
The proposed clustering algorithm combines energy efficiency and delay awareness to enhance WSN performance. Key theoretical principles include:

a. Energy Efficiency:

1. Residual Energy Optimization: Cluster Head selection considers the remaining energy of nodes to prevent premature depletion. Periodic re-clustering ensures balanced energy consumption across the network.
2. Intra-Cluster Communication: Use low-power transmission within clusters to minimize energy usage. Nodes close to the CH transmit directly, while distant nodes use multi-hop communication.
3. Load Balancing: Distribute the workload across all nodes to prevent energy hotspots near the CH or base station.

b. Delay Awareness:

1. Minimizing Communication Delay: Prioritize CHs that are closer to the base station to reduce transmission delays. Ensure CHs maintain optimal distances from member nodes to minimize data collection time.
2. Mobility Management (for mobile WSNs): Use predictive models to estimate node mobility patterns and adjust cluster configurations dynamically. Incorporate algorithms like Kalman filters or fuzzy logic to predict node positions and prevent communication disruptions.
3. Time Synchronization: Synchronize data transmission schedules to avoid delays caused by collisions or idle periods.

c. Algorithmic Framework:

1. Initialization Phase: Nodes broadcast their location, energy level, and mobility status. The network identifies candidate CHs based on predefined criteria (e.g., energy, proximity, mobility).
2. Cluster Formation Phase: Nodes join the nearest CH based on signal strength or distance. For mobile WSNs, dynamic clustering ensures that nodes join new CHs as they move out of range.
3. Data Transmission Phase: CHs aggregate data and forward it to the base station using multi-hop communication. Delay-aware mechanisms prioritize data from high-latency nodes.
4. Re-Clustering Phase: Periodic re-clustering ensures energy balance and adapts to topology changes.
5. Performance Metrics:

d. Cluster Head Selection Criteria:

Residual Energy: Nodes with higher energy levels should be prioritized.

1. Node Proximity: Minimize distance between sensors and the CH to save energy.
2. Mobility Awareness: In mobile WSNs, CHs should adapt to node movement.
3. Delay Awareness: Minimize latency during data collection and transmission.

The effectiveness of the proposed algorithm can be evaluated using:

- Energy Consumption: Measure the total energy used during clustering and communication.
- Network Lifetime: Time until the first node exhausts its energy.
- Average Delay: Time taken for data to reach the base station.
- Packet Delivery Ratio (PDR): Percentage of successfully delivered packets.
- Cluster Stability: Frequency of re-clustering due to mobility.

Fuzzy C-Mean Clustering Algorithm

Fuzzy c-means (FCM) is a data clustering technique in which a dataset is grouped into n clusters with every datapoint in the dataset belonging to every cluster to a certain degree. For example, a certain datapoint that lies close to the center of a cluster will have a high degree of belonging or membership to that cluster and another datapoint that lies far away from the center of a cluster will have a low degree of belonging or membership to that cluster.

Main objective of fuzzy c-means algorithm is to minimize:

$$J(U,V) = \sum_{i=1}^{n}\sum_{j=1}^{c}(\mu_{ij})^m \left\|x_i - v_j\right\|^2 c$$

Algorithm Steps:

et $X = \{x_1, x_2, x_3 ..., x_n\}$ be the set of data points and $V = \{v_1, v_2, v_3 ..., v_c\}$ be the set of centers.

'n' is the number of data points.

'vj' represents the j^{th} cluster center.

'm' is the fuzziness index $m \in [1, \infty]$.

'c' represents the number of cluster center.

'µij' represents the membership of i^{th} data to j^{th} cluster center.

'dij' represents the Euclidean distance between i^{th} data and j^{th} cluster center.

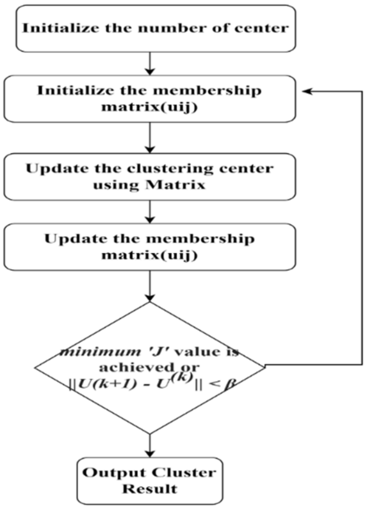
- Step 1: Randomly select *'c'* cluster centers.
- Step 2: Calculate the fuzzy membership uij using

$$\mu_{ij} = 1 / \sum_{k=1}^{c} (d_{ij} / d_{ik})^{(2/m-1)}$$

- Step 3: Compute the fuzzy centers 'v_j' using ;

$$v_j = (\sum_{i=1}^{n} (\mu_{ij})^m x_i) / (\sum_{i=1}^{n} (\mu_{ij})^m), \quad j = 1, 2, \ldots, c$$

- Step 4: Repeat step 2) and 3) until the minimum '*J*' value is achieved . $||U(k+1) - U(k)|| < \beta$.
  where,
  k' is the iteration step.
  'β' is the termination criterion between [0, 1].
  *'U = (μij)n*c' is the fuzzy membership matrix.*
  'J' is the objective function.



Flow Chart: Fuzzy C-Mean Clustering Algorithm

Result-

Initially we did random sensor deployment then forming clusters & defining cluster head are the next staps & with multiple iteration we have defined the optimized clustering result.

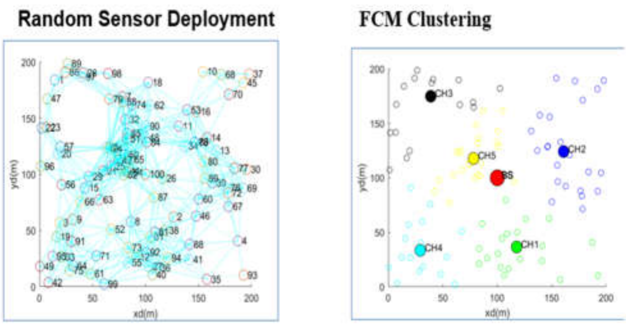


Fig1. Result for FCM clustering

Clustering Optimization Results

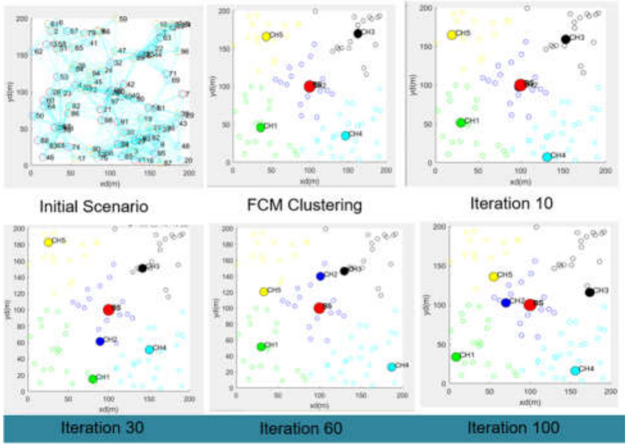


Fig2. Result for Clustering Optimization

Conclusion:

The proposed energy-efficient and delay-aware clustering algorithm aims to enhance the performance of both static and mobile WSNs by addressing critical challenges of energy consumption, delay minimization, and dynamic topology management. Incorporating adaptive clustering mechanisms ensures prolonged network lifetime and reliable data delivery in diverse application scenarios.

References:

1. *Int. J. Sensor Networks, "Distributed data aggregation algorithm based on lifting wavelet compression in wireless sensor networks", Vol. 27, No. 4, 2018, Copyright © 2018 Inderscience Enterprises Ltd.*
2. *International Journal of Computer Networks & Communications (IJCNC) Vol.11, No.5, September 2019," A LOW-ENERGY DATA AGGREGATION PROTOCOL USING AN EMERGENCY EFFICIENT HYBRID MEDIUM ACCESS CONTROL PROTOCOL IN HIERARCHAL WIRELESS SENSOR NETWORKS", Rana Adel1 and Tamer Barakat2, pp.79-91*
3. *Haseeb, Khalid, Naveed Islam, Tanzila Saba, Amjad Rehman, and Zahid Mehmood. "LSDAR: A light-weight structure based data aggregation routing protocol with secure internet of things integrated next-generation sensor networks." Sustainable Cities and Society 54 (2020): 101995.*
4. *Roslin, S. Emalda. "Data validation and integrity verification for trust based data aggregation protocol in WSN." Microprocessors and Microsystems 80 (2021): 103354.*
5. *Shobana, M., R. Sabitha, and S. Karthik. "An enhanced soft computing-based formulation for secure data aggregation and efficient data processing in large-scale wireless sensor network." Soft Computing (2020): 1-12.*
6. *Liu, Xiaozhu, Rongbo Zhu, Ashiq Anjum, Jun Wang, Hao Zhang, and Maode Ma. "Intelligent data fusion algorithm based on hybrid delay-aware adaptive clustering in wireless sensor networks." Future Generation Computer Systems 104 (2020): 1-14.*
7. *W. Heinzelman, J. Kulik, and H. Balakrishnan, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks," Proc. 5th ACM/IEEE Mobicom Conference (MobiCom '99), Seattle, WA, August, 1999, pp. 174-85.*
8. *C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed diffusion: a scalable and robust communication paradigm for sensor networks," Proceedings of ACM MobiCom, Boston, MA, 2000, pp. 56-67.*

9. D. Braginsky and D. Estrin, "Rumor Routing Algorithm for Sensor Networks," in the Proceedings of the First Workshop on Sensor Networks and Applications (WSNA), Atlanta, GA, October 2002.

10. Chithik Raja, Mohamed Sinnaiya, "The Minimum Cost Forwarding Using MAC Protocol for Wireless Sensor Networks," International Journal of Modern Engineering Research. Vol. 2, 2012, pp. 4122-4127.

11. C. Schurgers and M.B. Srivastava, "Energy efficient routing in wireless sensor networks," in the MILCOM Proceedings on Communications for Network-Centric Operations: Creating the Information Force, McLean, VA, 2001.

12. M. Chu, H. Haussecker, and F. Zhao, "Scalable Information-Driven Sensor Querying and Routing for ad hoc Heterogeneous Sensor Networks," The International Journal of High Performance Computing Applications, Vol. 16, No. 3, August 2002.

13. Y. Yao and J. Gehrke, "The Cougar Approach On In-Network Query Processing In Sensor Networks," in SIGMOD Record, September 2002.

14. N. Sadagopan, B. Krishnamachari, A. Helmy, "THE ACQUIRE MECHANISM FOR EFFICIENT QURYING IN SENSOR NETWORKS," Proceedings of the First International Workshop on Sensor Network Protocol and Applications, Anchorage, Alaska, May 2003.

15. R. C. Shah and J. Rabaey, "Energy Aware Routing for Low Energy Ad Hoc Sensor Networks," IEEE Wireless Communications and Networking Conference (WCNC), March 17-21, 2002, Orlando, FL.

16. S. Servetto and G. Barrenechea, "Constrained Random Walks on Random Graphs: Routing Algorithms for Large Scale Wireless Sensor Networks," proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications, Atlanta, Georgia, USA, 2002.

17. W. Heinzelman, A. Chandrakasan and H. Balakrishnan,"Energy-Efficient Communication Protocol for Wireless Microsensor Networks," Proceedings of the 33rd Hawaii International Conference on System Sciences (HICSS '00), January 2000.

18. S. Lindsey, C. Raghavendra, "PEGASIS: Power-Efficient Gathering in Sensor Information Systems," IEEE Aerospace Conference Proceedings, 2002, Vol. 3, 9-16 pp. 1125-1130.

19. A. Manjeshwar and D. P. Agarwal, "TEEN: A Routing Protocol for Enhanced Efficiency in Wireless Sensor Networks," In 1st International Workshop on Parallel and Distributed Computing Issues inWireless Networks and Mobile Computing, April 2001.

20. A. Manjeshwar and D. P. Agarwal, "APTEEN: A Hybrid Protocol for Efficient Routing and Comprehensive Information Retrieval in Wireless Sensor Networks," Parallel and Distributed Processing Symposium, Proceedings International, IPDPS 2002, pp. 195-202.

21. V. Rodoplu and T. H. Meng, "Minimum Energy Mobile Wireless Networks," IEEE Journal Selected Areas in Communications, vol. 17, no. 8, Aug. 1999, pp. 1-17

22. L. Subramanian and R. H. Katz, "An Architecture for Building Self Configurable Systems," in the Proceedings of IEEE/ACM Workshop on Mobile Ad Hoc Networking and Computing, Boston, MA, August 2000.

23. W. Khan, A. H. Abdullah, M. A. Razzaque and J. I. Bangash, "VGDRA: A Virtual Grid-Based Dynamic Routes Adjustment Scheme for Mobile Sink-Based Wireless Sensor Networks," in IEEE Sensors Journal, vol. 15, no. 1, pp. 526-534, Jan. 2015.

24. Q. Li and J. Aslam and D. Rus, "Hierarchical Power-aware Routing in Sensor Networks," In Proceedings of the DIMACS Workshop on Pervasive Networking, May, 2001.

25. Y. Xu, J. Heidemann, D. Estrin, "Geography-informed Energy Conservation for Ad-hoc Routing," In Proceedings of the Seventh Annual ACM/IEEE International Conference on Mobile Computing and Networking 2001, pp. 70-84.

26. Y. Yu, D. Estrin, and R. Govindan, D. Estrin, "Geographical and Energy Aware Routing: a recursive data dissemination protocol for wireless sensor networks," UCLA Computer Science Department Technical Report, UCLA-CSD TR-01-0023, May 2001.

27. F. Kuhn, R. Wattenhofer, A. Zollinger, "Worst-Case Optimal and Average-Case Efficient Geometric Ad-hoc Routing," Proceedings of the 4th ACM International Conference on Mobile Computing and Networking, Pages: 267-278, 2003.