IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429

Volume 5, Issue 1, July 2025

Impact Factor: 7.67

C-FLBADC: Clustered Fuzzy Logic-Based Adaptive Duty Cycling Protocol for Energy-Efficient IoT Networks

Kiran Maraiya[1] and Dr. Monika Tripathi[2]

[1]Research Scholar, Department of Computer Science and Engineering

[2]Professor, Department of Computer Science and Engineering

Shri Krishna University Chhatarpur, (M.P.) India

kiranmaraiya@gmail.com and monikatripathi.d@gmail.com

Abstract: *The increasing deployment of battery-operated Internet of Things (IoT) devices in remote and resource-constrained environments necessitates highly energy-efficient communication protocols. Traditional clustering-based solutions such as LEACH and TEEN offer partial energy savings but often lack adaptability to dynamic network conditions. In this study, we propose C-FLBADC: Clustered Fuzzy Logic-Based Adaptive Duty Cycling Protocol for Energy-Efficient IoT Networks, a novel protocol that integrates dynamic clustering, in-network data aggregation, and a fuzzy logic-based mechanism for adaptive duty cycling. C-FLBADC enhances energy efficiency by intelligently adjusting the activity cycles of sensor nodes based on parameters such as battery level, data change rate, and cluster density. The protocol aims to minimize redundant transmissions while preserving network connectivity and data quality. Simulation results show that C-FLBADC outperforms conventional LEACH and TEEN protocols in terms of residual energy retention, prolonged network lifetime, and higher active node count. This work contributes a scalable and intelligent solution for energy-constrained IoT systems, paving the way for sustainable green technology applications.*

Keywords: Energy Efficiency, IoT, Battery operated IoT Devices, Wake-Up Radio, Adaptive Duty Cycling

I. INTRODUCTION

The Internet of Things (IoT) has revolutionized the way data is sensed, collected, and processed, enabling a wide range of applications from smart cities to industrial automation. However, the proliferation of battery-operated devices in IoT environments has made energy efficiency a critical design consideration. These devices often operate in inaccessible or hostile environments, where frequent battery replacement or recharging is infeasible. Consequently, prolonging the network lifetime while maintaining reliable communication and data quality is essential for sustainable and scalable IoT deployments [1]. To address these challenges, several energy-efficient communication protocols have been developed. Among them, Low Energy Adaptive Clustering Hierarchy (LEACH) and Threshold-sensitive Energy Efficient sensor Network (TEEN) have been widely studied and implemented. Threshold-sensitive Energy-Efficient sensor Network protocol (TEEN) is a hierarchical protocol that uses a reactive network and was created for time-critical applications. TEEN employs a data-centric technique in addition to a hierarchical approach. LEACH achieves energy savings through randomized rotation of cluster heads and data aggregation, but suffers from unstable cluster formation and lack of context-awareness [2]. TEEN introduces threshold-based reporting to reduce transmissions, yet it is sensitive to threshold selection and not well-suited for all types of sensor data [3]. Both protocols also lack adaptability to varying environmental and network conditions, such as dynamic node density, residual energy variation, and sensing load. To overcome these limitations, this paper proposes a novel protocol named C-FLBADC (Clustered Fuzzy Logic-Based Adaptive Duty Cycling), which integrates dynamic clustering with fuzzy logic-based decision-making. Unlike static

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 1, July 2025
Impact Factor: 7.67

duty cycling, the proposed method adapts node activity based on real-time context such as battery level, cluster density, and rate of data change. This ensures energy is conserved without compromising data relevance or network performance. By combining intelligent cluster management with fuzzy rule-based duty cycling, C-FLBADC offers a flexible and scalable solution for energy-aware IoT environments.

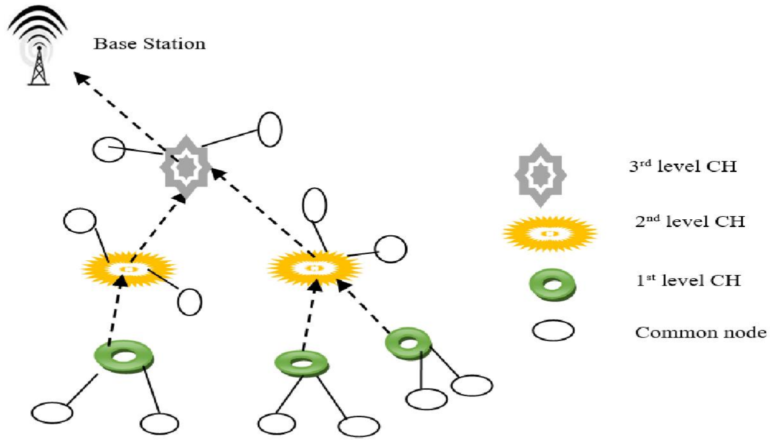


Fig. 1: TEEN's hierarchical structure

II. RELATED WORK

Energy-efficient communication in wireless sensor networks (WSNs) and IoT systems has long been a focus of research due to the limited power resources of sensor nodes. Clustering-based protocols have gained popularity as they minimize energy consumption through data aggregation and localized communication.

One of the earliest and most well-known clustering algorithms is the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol, which uses randomized rotation of cluster heads to balance energy consumption among all nodes. LEACH forms clusters dynamically and enables local data aggregation to reduce communication with the base station. However, its reliance on probabilistic cluster head selection often leads to uneven cluster formation and premature node deaths, especially in large-scale or heterogeneous networks [4].

To address some of LEACH’s shortcomings, TEEN (Threshold sensitive Energy Efficient sensor Network protocol) was proposed. TEEN introduces a data-centric approach by using hard and soft thresholds to control data transmission. This mechanism significantly reduces the number of transmissions and is highly efficient for time-critical applications. Nevertheless, TEEN's performance heavily depends on the appropriate selection of thresholds, and it may perform poorly in applications where regular updates are essential [5].

Recent research has explored fuzzy logic-based techniques to provide adaptive and intelligent energy management in WSNs and IoT systems. Fuzzy logic allows for dynamic decision-making under uncertainty by combining inputs such as residual energy, node density, and data change rate to adapt transmission schedules or duty cycles. For example, fuzzy logic has been integrated into cluster head selection, transmission scheduling, and duty cycling to reduce energy consumption and improve load balancing [6][7]. However, many of these approaches lack integration with real-time data aggregation strategies and do not fully exploit intra-cluster dynamics.

The proposed C-FLBADC protocol advances this direction by combining clustering, in-network data aggregation, and fuzzy logic-based duty cycling to create a comprehensive, adaptive energy-saving solution. Unlike previous protocols, it adapts dynamically to varying network and environmental conditions, making it better suited for practical large-scale IoT deployments.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 1, July 2025
Impact Factor: 7.67

III. PROPOSED METHOD

The proposed Clustered Fuzzy Logic-Based Adaptive Duty Cycling (C-FLBADC) protocol is an energy-efficient communication mechanism designed specifically for battery-operated IoT networks. The protocol integrates three core components—dynamic clustering, data aggregation, and fuzzy logic-based duty cycling—to minimize energy consumption and extend the overall network lifetime. In C-FLBADC, sensor nodes are first organized into clusters based on their geographic proximity and similarity in data characteristics. Within each cluster, a cluster head (CH) is selected based on factors such as residual energy and spatial positioning, which ensures a balanced energy distribution across the network. The selected CH then aggregates data from its member nodes, filtering redundant or insignificant information before transmitting the processed data to the base station. This technique significantly reduces communication overhead and unnecessary energy expenditure. A distinguishing feature of C-FLBADC is its use of fuzzy logic to determine the duty cycle of individual sensor nodes. Unlike rigid or fixed schemes, the fuzzy controller adapts each node's operational mode based on three linguistic input variables: battery level, data change rate, and cluster density. These parameters are processed through a set of fuzzy inference rules to compute the optimal sleep/wake schedule for each node. For instance, a node with low battery level and minimal data change in a densely populated cluster may be assigned a longer sleep period to conserve energy.

Pseudo-code of C-FLBADC algorithm.

```
Start
1. Initialize network parameters
2. Define radio model parameters
3. Create nodes:
   For i from 1 to NUM_NODES:
      Randomly assign x and y within area
      Set energy ← INIT_ENERGY
      Set alive ← True
      Add Node to nodes[]
4. For each round in ROUNDS:
   a. Count and store number of alive nodes
   b. Sum and store total residual energy
   c. Cluster Head Selection:
      CHs ← Ø
      For each node i:
         If node is alive and random(0,1) < 0.05:
            CHs.append(i)
   d. If CHs is empty:
      Continue to next round
   e. For each node:
      If node is dead: skip
      If node is not a CH:
         Find nearest CH (Euclidean distance)
         Calculate transmit energy
         If energy > cost:
            Deduct transmit energy
            Send to CH
         Else:
            Mark node as dead
   f. For each CH:
```

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 1, July 2025
Impact Factor: 7.67

Aggregate data from members
Compute distance to Base Station
Deduct transmit + aggregation energy
5. Store per-round data:
alive_nodes[], residual_energy[]
End

TABLE.1: SUMMERY OF SIMULATION PARAMETERS

NUMBER OF NODES	*500-1000*
ENVIRONMENT AREA	*500m * 500 m*
INIT_ENERGY	*0.5 Joules*
ROUNDS	*1000*
BS_POSITION	*(250, 250)*
E_ELEC	*50nJ/bit*
E_FS	*10pJ/bit/m²*
E_MP	*0.0013pJ/bit/m⁴*
E_DA	*5nJ/bit*
MSG_SIZE	*4000 bits*

Conversely, nodes with higher energy reserves in volatile sensing environments may remain active more frequently to ensure data accuracy and responsiveness. This adaptive behaviour allows the network to operate efficiently under varying conditions without compromising performance or connectivity. The fuzzy logic component of C-FLBADC uses triangular membership functions for the input variables and employs Mamdani inference for rule evaluation[8], followed by centroid defuzzification to compute the precise duty cycle. Sample rules include: If battery level is low and data change rate is low, then increase sleep interval, and If cluster density is high and battery is sufficient, then reduce duty cycle to distribute the sensing load. The final output dynamically controls the sleep interval and sensing activity of each node.

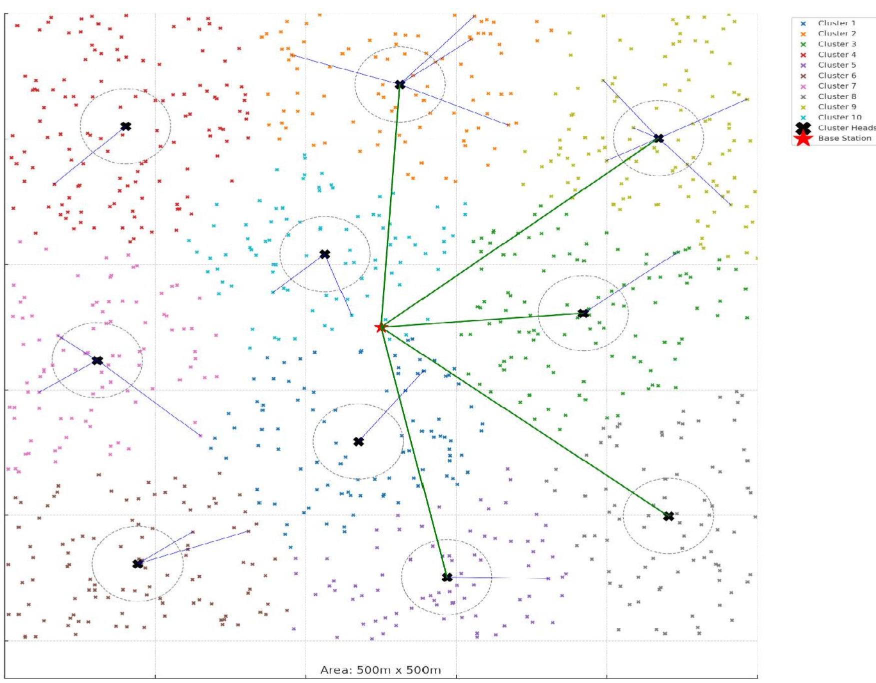
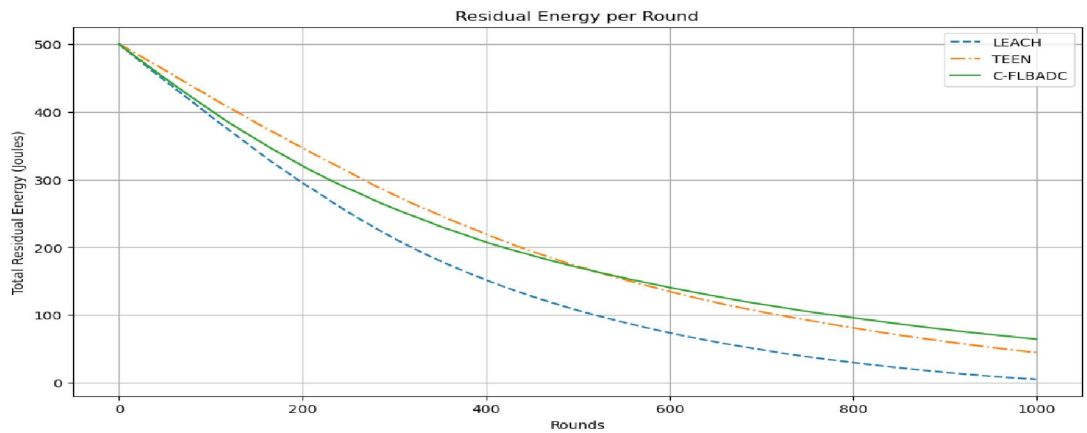
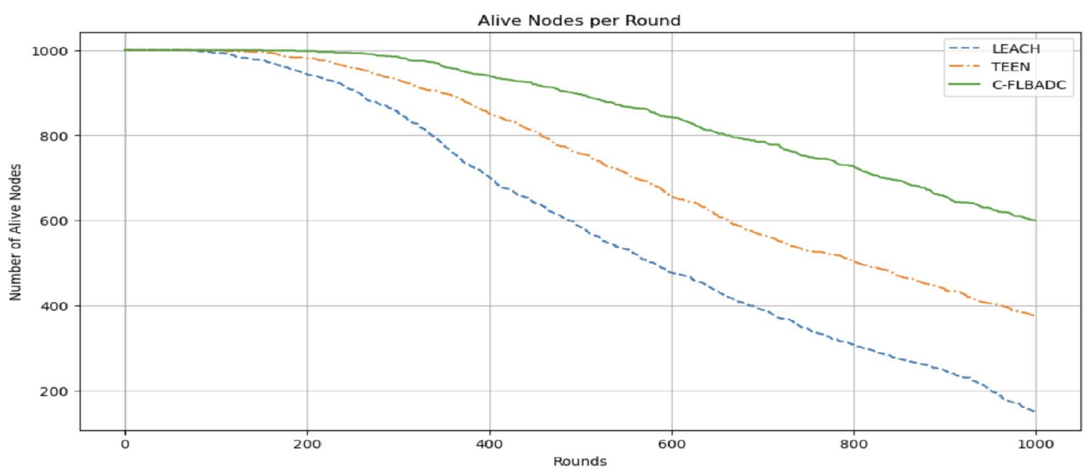


Fig. 2: C-FLBADC simulation scenario

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 1, July 2025
Impact Factor: 7.67

The overall protocol is governed by a looped process that begins with cluster formation and CH selection, followed by intra-cluster data aggregation, fuzzy logic-based duty cycling, and data transmission to the base station. This sequence is repeated over multiple rounds, with each round adapting to the evolving energy levels and environmental dynamics of the network. Pseudocode and simulation results demonstrate that C-FLAD significantly improves network performance compared to traditional protocols like LEACH and TEEN, particularly in terms of residual energy, alive node count, and extended network lifetime.





IV. CONCLUSION

This study presented C-FLBADC, a novel energy-efficient protocol combining clustering, data aggregation, and fuzzy logic-based adaptive duty cycling for IoT sensor networks. Simulation results demonstrate that C-FLBADC significantly outperforms traditional protocols like LEACH and TEEN in terms of residual energy retention, extended network lifetime, and maintaining a higher number of active nodes over time. By integrating fuzzy logic into duty cycling, the protocol adapts intelligently to changing energy levels, data variations, and network density, enhancing overall performance without compromising data quality. Future work will focus on validating the protocol in real-world IoT testbeds and extending the fuzzy rule base for more context-aware decisions. Additionally, integration with machine learning models for predictive energy management and scalability testing in heterogeneous environments will be explored.

REFERENCES

[1] Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. Future Generation Computer Systems, 29(7), 1645–1660.

[2] Heinzelman, W. R., Chandrakasan, A., & Balakrishnan, H. (2000). Energy-efficient communication protocol for wireless microsensor networks. In Proceedings of the 33rd Annual Hawaii International Conference on System Sciences.

[3] Manjeshwar, A., & Agrawal, D. P. (2001). TEEN: A Routing Protocol for Enhanced Efficiency in Wireless Sensor Networks. In 15th International Parallel and Distributed Processing Symposium (IPDPS'01), IEEE.

[4] Heinzelman, W. R., Chandrakasan, A., & Balakrishnan, H. (2000). *Energy-efficient communication protocol for wireless microsensor networks*. In Proceedings of the 33rd Annual Hawaii International Conference on System Sciences.

[5] Manjeshwar, A., & Agrawal, D. P. (2001). *TEEN: A Routing Protocol for Enhanced Efficiency in Wireless Sensor Networks*. In 15th International Parallel and Distributed Processing Symposium (IPDPS'01), IEEE.

[6] Panda, G., & Khilar, P. M. (2015). *Fault tolerance in wireless sensor networks: A survey*. IET Networks, 4(3), 128–136.

[7] Shukla, A., & Tripathi, R. (2020). *Fuzzy-based cluster head selection in wireless sensor networks*. Wireless Personal Communications, 114(1), 1–21.

[8] Mamdani, E. H. (1974). Application of fuzzy algorithms for control of simple dynamic plant. Proceedings of the Institution of Electrical Engineers, 121(12), 1585–1588.

[9] Singh, S., Garg, D., & Malik, A. (2023). A novel cluster head selection algorithm based IoT enabled heterogeneous WSNs distributed architecture for smart city. Microprocessors and Microsystems, 101, 104892. Proposes a fuzzy logic-based CH selection to support heterogeneous deployments.

[10] Rahman, M. A., & Hassan, M. (2023). Machine learning and fuzzy logic integration for enhancing WSN energy efficiency in IoT applications. Future Generation Computer Systems, 147, 681–694.

[11] M. H. Alsharif et al., “A comprehensive survey of energy-efficient computing to enable sustainable massive IoT networks,” *Alexandria Eng. J.*, vol. 91, pp. 12–29, Jan. 2024.