Original scientific paper

Performance Evaluation of $F_{K-means}RA$ with LEACH Variants in WSNs

Idris Afzal Shah, Mushtaq Ahmed, and Injila Mubarik

***Abstract* — This work evaluates $F_{K-means}RA$ against a broader set of LEACH variants, including LEACH-C, MOD-LEACH, LEACH-B, MULTIHOP-LEACH, and I-LEACH, with a focus on metrics such as average residual energy, number of alive nodes, and throughput. The paper focuses on comparative performance benchmarking across these popular LEACH variants, providing a rigorous validation of $F_{K-means}RA$ efficiency. In this paper, we extend our prior study on the performance of the proposed algorithm, $F_{K-means}RA$, against famous protocols, such as LEACH, etc. Comparative analysis with LEACH variants ensures a fair, relevant, and focused performance assessment of clustering hierarchical protocols in contrast to chain-based or flat routing protocols like PEGASIS or HEED. The simulation results demonstrate that the fuzzy logic-based model outperforms these protocols in terms of network stability and resource utilization. $F_{K-means}RA$ has nearly 450 nodes alive after the end of 1250 rounds, 200% energy more left than multihop LEACH, and a 13.6% throughput improvement over multihop LEACH.**

***Keywords* — Wireless Sensor Networks, Fuzzy Logic, LEACH, Cluster Head Selection.**

I. Introduction

RECENT advances in embedded computing have integrated control systems into both large appliances and small, disposable items. This shift supports the concept of Ambient Intelligence, where devices collect and analyze data to regulate physical processes and interactions. Traditional interaction models are evolving to include person-to-physical world connections, as highlighted in smart environment research [1], [2]. Achieving this requires reliable communication, enabling devices to share data with users or actuators. Wireless Sensor Networks (WSNs) have emerged to support this, comprising nodes with sensing, computing, and control abilities [3]–[5]. These nodes monitor parameters like temperature and pressure and can act on their environment. WSNs use wireless links and collaborative multi-hop communication to transmit data to a base station (BS). Deployed in regions of interest, WSNs are vital in defense, environmental monitoring, and healthcare [6]–[8].

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The key contribution of this paper is that it extends our earlier work of the $F_{K-means}RA$ by offering a detailed comparative analysis against several prominent LEACH-based routing protocols, including LEACH-C, MODLEACH, LEACH- B, MULTIHOP-LEACH, and I-LEACH, in contrast to our prior work in which simulation against LEACH only was carried out. Rationale for carrying out simulation with LEACH variants is that $F_{K-means}RA$ is a clustering-based hierarchical protocol, and comparing it with widely studied LEACH variants ensures a fair, relevant, and focused performance assessment. In this article, we also give a comprehensive explanation of the internal workings of the $F_{K-means}RA$ viz. the clustering of sensor nodes, the cluster head selection process, and the fuzzy logic-based membership function used for decision-making in contrast to our earlier work.

The rest of the paper is as follows: section II discusses issues and challenges in WSNs, section III and IV discusses the related work and energy model. Section V details about the working of $F_{K-means}RA$ with section VI demonstrating simulation with LEACH variants. Conclusion is given in section VII.

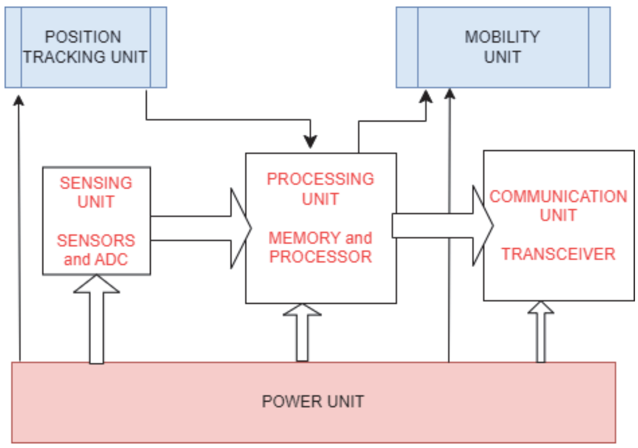

Fig. 1. Wireless Sensor Network Architecture.

II. Issues and Challenges in WSNs

A typical wireless sensor node consists of five key components: a controller for executing code and managing data; memory for storing programs and sensed data; sensors and actuators to interact with the physical environment; a communication interface to enable wireless data exchange, even in mobile deployments; and a power source, usually a battery with occasional support for energy harvesting (e.g., solar). These components must operate efficiently, minimizing energy consumption – especially by keeping the controller and communication module in low-power states when not in use [9] [10].

WSNs have diverse applications across several domains. In the military, they were first used for surveillance tasks through miniaturized sensor nodes, exemplified by the "Smart Dust" concept. In healthcare, WSNs enable remote patient monitoring via wearable devices and real-time biological sensors, including ECG systems and telemedicine solutions like AMON for high-risk patients. In agriculture, systems like the Agricultural Environment Monitoring System (AEMS) utilize WSNs and cameras to monitor environmental parameters such as temperature, humidity, and rainfall. In urban environments, WSNs support smart city applications, including intelligent parking systems, traffic monitoring, and infrastructure management by detecting available parking spaces and tracking vehicle movement through magnetic sensors, offering a low-cost alternative to traditional systems [11] [12] [13] [14].

Despite their great practical value, wireless sensor network systems have many issues and challenges associated with them, as follows.

1) Scalability: Because the number of sensor nodes in a sensor networking system might range from a few to many, there are significant differences in the system's scale. Furthermore, the deployment density can be adjusted accordingly [15].

2) Energy efficiency [16], [17]: Because wireless sensor nodes must operate on a limited power source, hardware and software architecture must be optimized to allow for effective performance of the intended function.

3) Maintenance [18]: WSN has a lot of limitations, including storage, power supply, and a lot of algorithms. As a result, maintaining all of these is quite difficult.

4) Security [19]: WSN has security concerns, much like any other internet-dependent application. To combat data theft in every manner imaginable, proper data transmission management should be implemented.

5) Quality of Service: Timely distribution of data is es-essential for real-time applications, which rely significantly on it.

III. Related Work

The Low Energy Adaptive Clustering Hierarchy (LEACH) protocol, introduced in [20], is a hierarchical routing approach designed to reduce energy consumption in Wireless Sensor Networks (WSNs). It randomly selects Cluster Heads (CHs) in each round based on a probability threshold and rotates this role to balance energy usage. However, the random CH selection does not consider key metrics like residual energy or distance to the sink, which affects performance.

To address this, LEACH-C uses centralized control where nodes share energy and location information with the base station, which then selects CHs with above-average energy for better distribution. MODLEACH retains a CH across rounds if its energy exceeds a set threshold, minimizing re-clustering. LEACH-B selects CHs based on timers inversely related to residual energy to promote balance. Multi-hop LEACH forwards data through multiple CHs, reducing transmission distance but risking uneven CH distribution due to random- ness. I-LEACH improves efficiency by selecting CHs using the ratio of current to initial energy and the number of neighbors [21], [22].

HEED (Hybrid Energy-Efficient Distributed clustering) is another widely studied energy-efficient protocol that selects CHs based on residual energy and communication cost. Although more robust than LEACH, HEED suffers from a high iteration count and overhead due to its probabilistic approach [23].

PEGASIS, a chain-based protocol, focuses on minimizing transmission distances by forming chains of nodes. While energy-efficient, it introduces high delay and is unsuitable for large-scale or high-data-rate applications [24].

$F_{K\text{-}means}RA$ enhances clustering by applying K-means with fuzzy logic, considering residual energy, distance to the base station, and the number of neighbours. If energy and distance are equal among candidates, the node with the least intra-cluster transmission cost is chosen [25]. These variants aim to overcome LEACH's limitations by improving energy efficiency, stability, and CH distribution.

Additionally, $F_{K\text{-}means}RA$ improves upon I-LEACH by integrating fuzzy inference, which offers smoother decision-making and better adaptability to diverse network conditions. It also avoids the overhead of centralized CH selection in LEACH-C and improves energy retention and throughput significantly.

IV. Energy Model

We adopt the radio model given in [26]. The radio energy model is particularly designed for two types of communication channels: (i) free space channel and (ii) multi-path channel, according to the distance (d) between receiver and transmitter. When d is less than the threshold (d_0), the free space model is used; otherwise, the multi-path fading channel is used. Energy dissipation incurred in the transmission and reception of bits is given as (1) and (2)

$$E_{T_x}(l,d) = \begin{cases} l \cdot E_{elec}^{T_x} + l \cdot \varepsilon_{fs} \cdot d^2 & if\ d < d_0 \\ l \cdot E_{elec}^{T_x} + l \cdot \varepsilon_{mp} \cdot d^2 & if\ d \geq d_0 \end{cases} \quad (1)$$

$$E_{R_x}(l) = l \cdot E_{elec}^{R_x}, \quad (2)$$

where $E_{elec}^{T_x}$ and $E_{elec}^{R_x}$ are energy consumption per bit o f the transmitter and receiver. ε_{fs} and ε_{mp} are the amplific ation factors for free space and multi-path, and the t hreshold value d_0, is given (3):

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}. \quad (3)$$

It is obvious from equation (1) that the amount of energy used to transmit data is directly correlated with the distance between the transmitting and receiving nodes. Energy is used for the distance more than d_0 at a rate of 4 times the distance. Therefore, it is necessary to limit long-distance transmission in order to prolong network lifetime. The energy used by the sensor node E_{RA} to acquire and combine the packet of length K bits with its own data packet is displayed as follows:

$$E_{RA} = K \cdot \left(E_{elec} + E_{DA} \right), \quad (4)$$

where E_{DA} is the energy dissipated in aggregating one bit.

V. $F_{K\text{-}MEANS}RA$

In the $F_{K\text{-}means}RA$ algorithm, data communication between the sensor and the sink takes place in a multi-hop fashion. Intra-cluster communication takes place between sensor nodes and Cluster heads (CHs) chosen for that particular round. CHs then aggregate and compress data before transferring it to the base station. Fig. 2. shows the schematic representation of $F_{K\text{-}means}RA$.

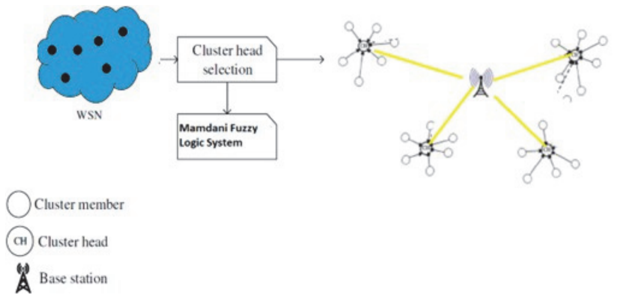

Fig. 2. Schematic representation of $F_{K\text{-}means}RA$.

Three metrics have been chosen keeping in view the impact they have on the network longevity viz. Residual energy of a node, distance from the BS, and number of neighbour nodes in a cluster. We scale the values by performing normalization using the min-max technique given by equation (5):

$$Y_{scaled-value} = \frac{Y_{\max} - Y_{residual}}{Y_{\max} - Y_{\min}}. \quad (5)$$

Eg: if the residual energy of a node is $Y_{residual}$=0.5 J with maximum energy of Y_{max}=5 J and minimum energy of Y_{min}=0 J, then scaled value of node is =(5-0.5)/(5-0)=0.9. These scaled values are then input to the triangular membership function (shown in Fig. 3.) to calculate the membership degree as per the association function given below in equation (6):

$$Membership\_degree(y) = \begin{cases} 0 & if\ y \le y_1, \\ \dfrac{y_2 - y}{y_2 - y_1} & if\ y_1 < y \le y_2, \\ \dfrac{y_3 - y}{y_3 - y_2} & if\ y_2 < y \le y_3, \\ 0 & if\ y > y_3. \end{cases} \quad (6)$$

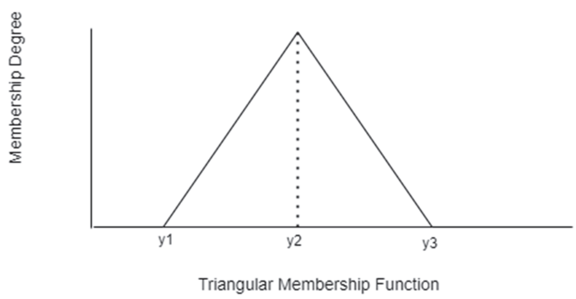

Fig. 3. Triangular Membership Function.

The Triangular Membership Function employed to represent and map the characteristics of the three linguistic variables, along with input fuzzy variables, is given in Table 1.

TABLE 1: INPUT FUZZY VARIABLES.

Linguistic Variable Name	***Linguistic Values***
Distance from BS	Close, Far, Too_Far
Residual Energy	Less, Average, High
Neighbour Nodes in cluster	Few, Medium, Many

The association function for the residual energy metric can be written as:

$$Residual\_Energy_{degree}(y) = \begin{cases} 0 & if\ y \le 0, \\ \dfrac{y_2 - y}{y_2 - y_1} & if\ 0 < y \le 0.66, \\ \dfrac{y_3 - y}{y_3 - y_2} & if\ 0.66 < y \le 1, \\ 0 & if\ y > 0. \end{cases} \quad (7)$$

Now, for the above case where the scaled value of residual energy = 0.9, the membership degree can be calculated by equation (8):

$$Residual\_Energy_{high} = \frac{(1-0.9)}{1-0.66} = 0.30. \quad (8)$$

Similarly, we calculate the membership_degree for other two metrics, viz distance from BS, number of neighbour nodes. Thus for a node with scaled values of 0.15 from BS, 0.30 for neighbour nodes, the membership degree can be calculated by equation (9) and (10):

$$Distance\_BS_{close} = \frac{0.33-0.15}{0.33-0} = 0.54, \quad (9)$$

$$Neighbor\_Nodes_{few} = \frac{0.33-0.3}{0.33-0} = 0.09. \quad (10)$$

The Mamdani Fuzzy Inference System (MFIS) is utilized to determine the probability of a node being selected as a Cluster Head (CH), denoted as (*Pr_CH_Selection*). To achieve this, a set of 27 manually crafted IF-THEN rules has been devised, with a subset of tuples outlined in Table 2 for conciseness. These rules govern the behavior of the MFIS when provided with input variables, ultimately producing the probability output (*Pr_CH_Selection*). The concept of representing *Pr_CH_Selection* using a Triangular Membership Function (MF) involves assigning membership values to different degrees of probability for selecting a Cluster Head (CH) within a Wireless Sensor Network (WSN). This function typically takes into account factors such as residual energy, distance from the base station, and the number of neighboring nodes.

TABLE 2: IF−THEN FUZZY RULES FOR PR_CH_SELECTION.

Rule	***Distance from BS***	***Residual Energy***	***Neighbor nodes***	***Pr_CH_Selection***
1	Close	High	Few	Extremely high
2	Far	Average	Few	Mediocre
3	Too_Far	Less	Few	Less

Output Variable Name	*Linguistic Values*
Pr_CH_Selection	Less, Mediocre, High, Very High, Extremely High

In a Triangular MF, Fig. 4., the membership value increases linearly from the lower bound to the peak value, and then decreases linearly towards the upper bound. This shape mimics the gradual transition of the probability from being low to high and then back to low again.

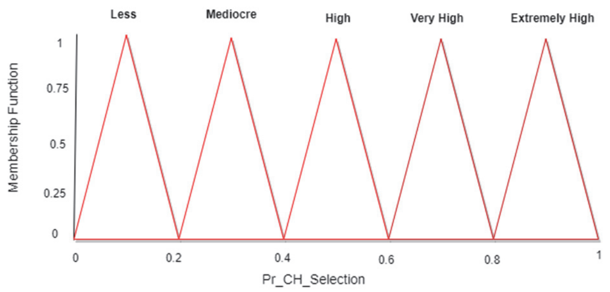

Fig. 4. MF for Pr_CH_Selection.

After obtaining the membership values using the Triangular MF, the centroid method is employed for defuzzification. This method calculates the center of mass or centroid of the fuzzy set defined by the MF. In the context of *Pr_CH_Selection*, the centroid method provides a precise numerical value representing the most likely probability for selecting a Cluster Head. This defuzzified value aids in making decisions or performing further computations based on the probability of CH selection within the WSN. In the context described, RULE 1 is activated, and the Mamdani system selects the minimum value (using an AND operation), which in this case is 0.09. The defuzzified value is then calculated using the centroid of the area method, specifically the centroid of the trapezoid under the curve, as shown in Equation (11):

$$Pr\_CH\_Selection = \frac{(0.18 + 2 \cdot 0.2) \cdot 0.09}{3 \cdot (0.2 + 0.18)} = 0.087 . \quad (11)$$

This value represents the probability of a node becoming a CH in the current round. Analogously, similar computations are performed for other nodes, with the node possessing the highest probability (*Pr_CH_Selection*) being designated as the cluster head for the present round. All sensor nodes within the system are equipped with GPS systems, enabling them to determine their distance from the Base Station (BS) and identify their neighboring nodes. Moreover, in the event of a node failure, each node within the cluster adjusts its distance to the failed node to infinity, rendering it unreachable. Consequently, the deceased node ceases to participate in the communication process.

A detailed flowchart of the $F_{K\text{-}means}RA$ algorithm is given in Fig. 5.

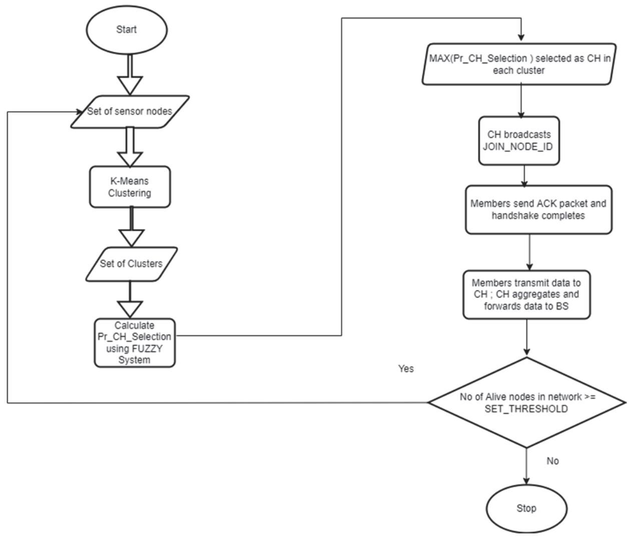

Fig. 5. Flowchart of $F_{K\text{-}means}RA$.

VI. Simulation and Results

We have taken a scenario of 500 randomly placed sensor nodes with a sink in the centre of the area and carried out a comparative analysis against the LEACH protocol and its variants in terms of metrics as discussed below. MATLAB R2018 has been used to perform simulations.

Table 3: Simulation Metrics.

Parameter	*Value*
Area size	300x300
No of sensor nodes	500
Initial Energy	1 J
E_{elec}	50 nJ/bit/m^2
Data Packet Size	375 bytes
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
d_0	87 m

A. Alive Nodes

Fig. 6. illustrates that the number of active nodes remains at 450 after 1250 rounds, surpassing the performance of the LEACH variants viz. MULTIHOP LEACH, LEACH- B, MODLEACH, I-LEACH and LEACH-C with values of 200, 150, 130, 125, 20. The observed improvement in maintaining active nodes in the fuzzy model compared to LEACH variants is due to an optimized selection method for cluster heads using fuzzy variables, as opposed to LEACH's random selection approach.

B. Average Residual Energy

The ratio of total energy to total alive nodes is significantly higher in the fuzzy model compared to, particularly, MultiHop LEACH, as depicted in Fig. 7. Specifically, at the end of 1250 rounds, the fuzzy model retains nearly 200% more energy than MultiHop LEACH, which emerges as the second-best performer.

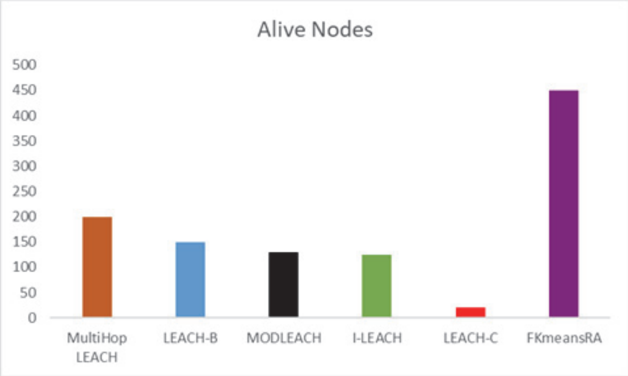

Fig. 6. Alive Nodes in Network.

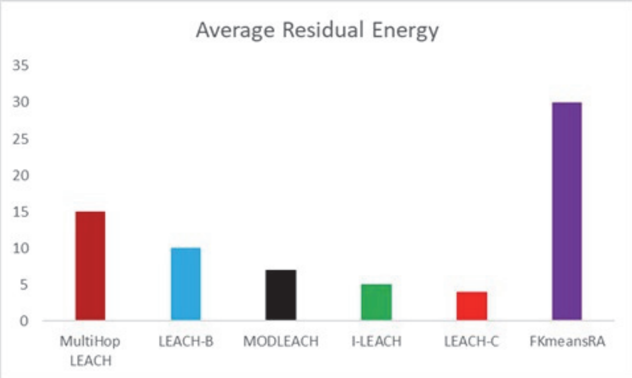

Fig. 7. Average Residual Energy of Network.

C. Throughput

The metric being analyzed here is the number of packets successfully transmitted to the Base Station (BS), Fig. 8. Comparing the fuzzy model with LEACH variants, it is observed that the model achieves a 13.6% increase over multi-hop LEACH in this metric, indicating improved data delivery efficiency. This enhancement is attributed to the higher number of active nodes in the fuzzy model, allowing for more data collection and transmission opportunities, ultimately resulting in better throughput compared to LEACH variants.

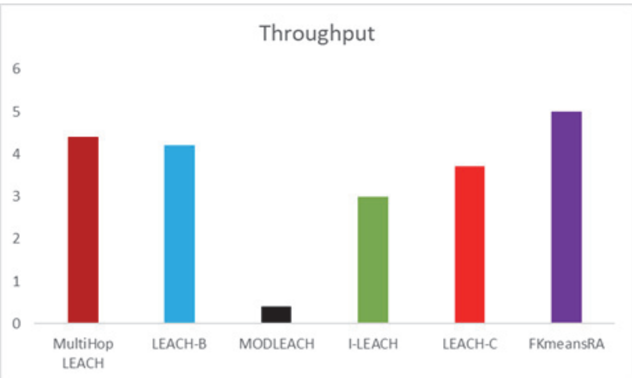

Fig. 8. Throughput of Network.

VII. Conclusion

$F_{K\text{-}means}RA$ is compared with LEACH variants viz. MULTIHOP LEACH, LEACH-B, MODLEACH, I-LEACH, and LEACH-C methods based on the criteria of packets received, residual energy, alive, and dead nodes. The results also clearly show that the residual energy in the fuzzy approach is more efficiently balanced than LEACH variants. For future work, performance can be analysed and evaluated based on mobile sink. Last but not least, quality of service (QoS) parameters such as reliability, fault tolerance, and delay should be further optimized.

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