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Fuzzy logic–enhanced LEACH protocol for scalable wireless sensor networks

Hayet Termeche[1], Taous Lechani[2], Fayçal Rahmoune[1]
[1]LIST System Engineering and Telecommunication Laboratory, Faculty of Technology, University M'Hamed Bougara of Boumerdes, Boumerdès, Algeria
[2]LEEI Electrification of Industrial Enterprises Laboratory, Faculty of Technology, University M'Hamed Bougara of Boumerdes, Boumerdès, Algeria

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ABSTRACT

This study aims to enhance the LEACH protocol by mitigating its intrinsic stochasticity through the use of fuzzy c-means (FCM) clustering. This approach enables the design of WSN protocols with improved energy efficiency, stability, and scalability. To this end, two fuzzy logic–based protocols are proposed: CFFC-LEACH for small-scale deployments and VGFC-LEACH for large-scale environments. CFFC-LEACH employs artificial intelligence to generate optimal clusters by determining the appropriate number of clusters and efficiently partitioning the sensing area. VGFC-LEACH addresses wide-area monitoring challenges by dividing the network field into virtual zones of 100 x 100 m² to reduce communication distances. Within each zone, a leader is selected in every round based on residual energy and distance to the base station (BS). Clustering is performed using FCM, while cluster heads (CH) are selected through an objective function. Compared to LEACH and EDK-LEACH, network lifetime (NL) is extended by 61.26% and 46.59% with CFFC-LEACH, and by 245.81% and 657.44% with VGFC-LEACH, respectively. Which demonstrate that the proposed protocols significantly outperform LEACH and EDK-LEACH.

Corresponding Author:

Taous Lechani
LEEI Electrification of Industrial Enterprises Laboratory, Faculty of Technology
University M'Hamed Bougara of Boumerdes
35000 Boumerdes, Algeria
Email: t.lechani@univ-boumerdes.dz

1. INTRODUCTION

Recently, efforts have largely concentrated on designing routing protocols to extend the operational lifetime of WSNs [1]. These protocols are developed to facilitate reliable transmission of data from source nodes to BS while accounting for the network's physical limitations and striving to reduce energy consumption [2]. Hierarchical routing protocols have emerged as particularly effective due to their ability to organize sensor nodes into layered structures, which significantly reduces energy usage. Among these, clustering-based approaches are widely adopted [3]. One example is the LEACH protocol, introduced by Heinzelman *et al.* [4], Liu [5].

Despite its advantages, LEACH presents several limitations. The number of clusters per round often varies significantly from the optimal value, and neither the placement nor the number of CHs can be guaranteed because of the stochastic CH selection process. Additionally, the LEACH application in large-scale networks is limited. Collectively, these shortcomings result in unbalanced energy consumption and a reduced network lifetime (NL). Existing solutions fail to simultaneously address the requirements of both small- and large-scale networks using a robust clustering approach. With advancements in artificial intelligence, the fuzzy c-means (FCM) clustering algorithm has been used for classifying data into distinct clusters [6].

In this paper, we propose two novel protocols that outperform the conventional LEACH protocol. Both protocols combine LEACH with the FCM clustering algorithm. The first protocol, cluster formation fuzzy c-means LEACH (CFFC-LEACH), eliminates the randomness in CH selection by fixing the clusters and CHs to their optimal values. The second protocol, virtual grid fuzzy c-means LEACH (VGFC-LEACH), adapts LEACH for large-scale networks by dividing the monitored area into equal-sized squares, electing a leader for each square, and then applying FCM. The essential contributions are:

- The first proposed CFFC-LEACH for small-scale networks, leveraging artificial intelligence to mitigate randomness, thereby enhancing NL.
- The second proposed VGFC-LEACH for large-scale networks, which combines fuzzy logic with the division of the sensing area into virtual grids, thereby adapting LEACH for extensive deployments and ensuring an extended NL.
- The performance assessment is done through simulations and compared with results reported in the literature.

2. LITERATURE REVIEW

Although the LEACH protocol contributes to extending the network's lifetime [7], it suffers from several inherent limitations. To overcome these shortcomings, many improvements have been introduced. The LEACH-centralized (LEACH-C) protocol proposed a centralized control mechanism [8]. Mu and Tang [9] introduced an improved version, referred to as LEACH-B. Another enhancement, RECH-LEACH, introduces a more dynamic cluster head election mechanism based on additional parameters [10], [11]. LEACH-DT is another proposed variant that focuses on balancing energy usage by assigning different cluster head election probabilities to nodes [12]. Finally, the Improved-LEACH protocol integrates both energy levels and node distance into the cluster head selection criteria to outperform the traditional LEACH protocol [13].

The virtual square grid LEACH (VSG-LEACH) protocol [14] was developed to address the inefficiencies of arbitrary CH selection [15]. Bouakkaz and Derdour [16] proposed the "Power Efficient Grid-Chain Routing Protocol in WSN," aiming to extend NL. The multiple mobile sinks coverage maximization (MMSCM protocol) [17] targets mobile wireless sensor networks by supporting concurrent mobility of both sensor nodes and sinks. Tang [18] introduced an energy-aware routing scheme utilizing adaptive dual CHs and non-uniform segmentation. Arghavani *et al.* [19] presented the optimal clustering in circular networks (OCCN) method, aimed at reducing energy usage around a central sink. S-LEACH modifies LEACH protocol by segmenting the monitored area into angular sectors centered on the BS to prolonge node lifetimes [20]. Tarawneh *et al.* [21] proposed an improved version of LEACH, by introducing a circular clustering layout.

LEACH-R enhances LEACH protocol through the incorporation of relay nodes [22]. Similarly, RED-LEACH follows the fundamental structure of LEACH. However, it differentiates itself by enhancing the cluster head election mechanism [23]. E-LEACH further optimizes the clustering process by placing greater emphasis on residual energy as the key selection metric [24]. The extended E-LEACH and extended DE-LEACH protocols introduce a two-tiered approach to CH selection [25]. Enhanced multi-hop LEACH (EM-LEACH) was proposed to optimize energy usage and achieve a more balanced distribution of workload among nodes, thereby improving packet delivery rates and extending the overall lifetime of the WSN [26]. LPLL-LEACH enhances the traditional LEACH protocol by using analytical methods to determine the optimal number of CHs. To address latency, LPLL-LEACH introduces an hybrid communication model combining carrier sense multiple access (CSMA) with time division multiple access (TDMA), effectively reducing transmission delays [27], [28]. The TTRC algorithm [29] aims to minimize energy consumption during packet transmission. Yadav [30], the authors investigate alternative routing strategies for energy efficiency and node longevity in multi-hop WSNs.

While all of the aforementioned algorithms rely on traditional methods to improve the LEACH protocol, this work explores the integration of artificial intelligence (AI). Recently, AI techniques have been increasingly applied to improve the performance of LEACH-based protocols. For example, EDK-LEACH [31] employs a new strategy based on AI to enhance cluster formation and improve network stability within the LEACH protocol. Another algorithm is the CHEF algorithm, which employs fuzzy logic to determine CH selection [32]. Another notable application is the EADCR protocol, which incorporates the FCM clustering technique [33]. Similarly, Bouyer *et al.* [6] employ FCM to determine the optimal number and placement of

CHs. The EHCR-FCM protocol also adopts the FCM technique, utilizing a three-tiered architecture which enhances energy efficiency through adaptive routing strategies [34]. Ghosh *et al.* [35], propose a hierarchical routing protocol (HRP) that combines FCM clustering with ant colony optimization (ACO). Another promising method is the PSO-DAFCA algorithm, which integrates particle swarm optimization (PSO) with FCM to refine both CH selection and cluster member assignment [36].

Jain *et al.* [37], the authors propose a novel "Relay Selection scheme based on Fuzzy Logic" (RSFL). Jain *et al.* [38], an "Adaptive Neuro-Fuzzy Inference System-based Relay Selection" (ANFISRS) scheme is introduced. Similarly, in [39] "Fuzzy and Neuro-fuzzy Based Relay Selection" schemes is presented. Simulation results demonstrate that these approaches outperform existing relay selection strategies in terms of both BER reduction and network longevity.

3. PROPOSED PROTOCOLS

In this section, we introduce two novel protocols: CFFC-LEACH and VGFC-LEACH. These approaches are developed with the primary goal of extending the operational lifetime of WSNs by reducing overall energy consumption. To achieve this, our protocols address the inherent randomness in cluster formation and CH selection. By integrating the FCM clustering algorithm, we are able to determine and maintain an optimal number of clusters and cluster heads, ensuring more structured and energy-efficient network organization. All notations used are shown in Table 1.

Table 1. Notations

Parameter	Notation
N	Number of sensor nodes
C	Number of clusters
X	The i-th sensor node
V	Centroid of the j-th cluster
U	Membership value of sensor node in a cluster
M	Fuzziness parameter (m > 1)
$E_{res}(i)$	Residual energy of node i
$D(i)$	Distance of node i from the cluster centroid
Energy (i, j)	Residual energy of node i within area j
$Distance_{BS}(i)$	Distance of each node from the base station
Etx, ERx	Energy required to transmit or receive a single bit
E_{amp}	Parameter for the free space model
E_{two_ray}	Parameter for the multi-path model
E_{agg}	Energy required per bit for data aggregation
D	Distance between transmitter and receiver
d_0	Threshold distance

3.1. CFFC-LEACH protocol

The proposed algorithm is initiated by organizing sensor nodes into static clusters using the FCM clustering technique. While the cluster structure remains fixed, the selection of CHs is dynamic and updated periodically. The protocol functions in a round-based manner, with each round divided into two main phases: the setup phase and the steady-state phase. During the first phase, CHs are selected based on predefined criteria. Once this phase concludes, the steady-state phase begins, during which nodes perform tasks such as sensing, forwarding data to their respective CHs, and enabling CHs to aggregate and transmit the collected information to the BS.

3.1.1. Cluster formation

Among the various clustering techniques, FCM allows each sensor node to belong to multiple clusters with different degrees of membership, thereby capturing the inherent uncertainty and fuzziness in cluster assignments. The algorithm initializes by randomly selecting cluster centroids and defining a fuzziness parameter m, which controls the degree of overlap among clusters. Membership values for each sensor node are then computed based on their distances to the cluster centroids. Subsequently, cluster centers are updated as weighted averages of the sensor nodes. This iterative process continues until convergence is achieved, that is, when successive updates of the centroids become negligible [40]. The clustering quality is evaluated using an objective function that accounts for the distances between nodes and their corresponding cluster centers, which is mathematically defined as [41]:

$$J_m = \sum_{i=1}^{n} \sum_{j=1}^{c} u_{ij}^m \left\| x_i - v_j \right\|^2 \quad (1)$$

where:

$$\sum_{i=1}^{c} u_{ij} = 1 \quad \forall j = 1, \dots, n \quad (2)$$

Subsequently, the algorithm updates the membership values and cluster centroids using in (3) and (4), and iteratively repeats this process until convergence is reached, i.e., when changes become negligible. In the final stage, each sensor node is assigned to one or more clusters according to its highest membership degree. Through the appropriate selection of fuzzy distance functions, sensor nodes can be clustered in an optimal and efficient manner.

$$u_{ij} = \frac{1}{\sum_{k=1}^{c} \left(\frac{\| x_i - v_j \|}{\| x_i - v_k \|} \right)^{\frac{2}{m-1}}} \quad (3)$$

$$v_j = \frac{\sum_{i=1}^{n} u_{ij}^m . x_i}{\sum_{i=1}^{n} u_{ij}^m} \quad (4)$$

3.1.2. Setup phase

After the clusters are formed, the setup phase begins, where the main goal is to select a CH for each cluster. The optimal number of CHs is typically established at 5% of the total nodes within the coverage area [31]. The setup phase is based on two important factors: the node's available energy and its proximity to the cluster center. To determine the CH, each node is assigned a weight, and the node with the highest weight within the cluster is selected as the CH. The Weight(i) of node (i) depends on its remaining energy and is inversely proportional to its distance from the cluster center. During the first round, since all nodes start with equal energy, the node closest to the cluster center is chosen as the CH. In the following rounds, the selection process also takes into account the residual energy of the nodes. In small areas, residual energy is favored over distance, which justifies the allocation of a higher coefficient to it. The calculation of the weight is guided by the following objective function:

$$Weight\,(i) \; = 0.6\, E_{res}(i) \; + \frac{0.4}{D(i)} \quad (5)$$

The values 0.6 and 0.4 were selected through a parameter tuning process.

The calculation of the node's distance (*D(i)*) from the cluster center follows the Euclidean distance as follows:

$$D(i) = \sqrt{(X(i) - Cx)^2 + (Y(i) - Cy)^2} \quad (6)$$

In this context, X(i) and Y(i) represent the coordinates of a node along the x and y axes, respectively, while Cx and Cy correspond to the cluster center's position on those same axes.

After CHs are elected, they broadcast a message to inform all nodes within the clusters of their status. However, when a CH exhausts its energy, all nodes linked to it lose connectivity with the rest of the network. To overcome this limitation, our proposed approach incorporates a strategy of periodically and randomly rotating the CH role among the cluster members, inspired by the LEACH protocol.

3.1.3. Steady state phase

It is divided into multiple time frames, during which each CH establishes a TDMA schedule that allocates specific time slots to each node, ensuring that data is transmitted in an orderly and collision-free manner. By following this synchronized communication scheme, nodes can avoid unnecessary energy consumption [42]. Once data is collected, the CHs send the information to the BS for further processing.

3.2. VGFC-LEACH protocol

The proposed protocol is tailored for large-scale WSNs. After the random deployment of sensor nodes across the monitoring region, the process begins with dividing the entire area into uniform square zones. This partitioning is intended to minimize communication distances between nodes. Each square is defined using five reference points: the center and its four corners. The coordinates and boundaries of these zones are determined using in (7) and (8):

$$X\ (i)\ = X_0(j)\ + \frac{50.2}{\sqrt{2}}\ .\cos\left(i.\frac{\pi}{2}+\frac{\pi}{4}\right) \tag{7}$$

$$Y\ (i)\ = Y_0(j)\ +\ \frac{50.2}{\sqrt{2}}.\ \sin\left(i.\frac{\pi}{2}+\frac{\pi}{4}\right) \tag{8}$$

Where X(i) and Y(i) denote the coordinates of the corner points used to outline each square within the target monitoring area. The variable i corresponds to the index of the points required to form a square. Initially, the values of X_0 and Y_0 are set to 50 meters along both the x and y axes, representing the center of the very first square. The variable j indicates the total number of divisions along the x and y directions. The coordinates X_0 and Y_0 for each square are computed using in (9) and (10):

$$X_0(j+1) = X_0(j) + 100 \tag{9}$$

$$Y_0(j+1) = Y_0(j) + 100 \tag{10}$$

After dividing the overall network area into uniform square regions, each region is further segmented into clusters. Since sensor nodes are deployed randomly, it becomes essential to establish a database (DB) for each square in order to identify the specific region in which each node resides. Leveraging this database, the FCM clustering algorithm is applied within each square to form local clusters. Figure 1 illustrates the partitioning of the network area.

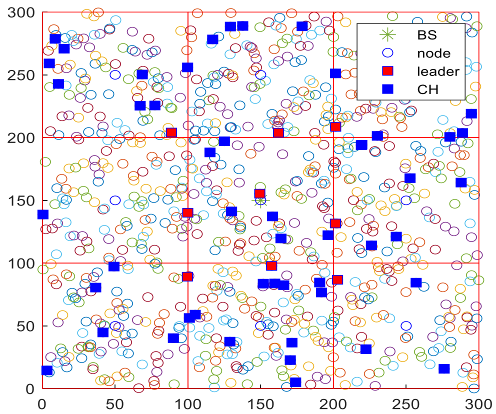


Figure 1. VGFC-LEACH scheme applied to 300×300 m² network area

In the subsequent step, a leader node is selected for each square Sk using a defined objective function. This stage involves the identification of a surface-level leader, chosen based on two critical factors: the node's residual energy and its proximity to the BS. Given that the protocol is designed for large-scale WSNs, minimizing the distance to the BS is considered as important as energy efficiency, so we affect them the same coefficient. Consequently, equal weight is assigned to both criteria in the objective function used to determine the leader node for each surface, as described in (11):

$$L\ (i,j)\ = 0.5\ .Energy(i,j)\ + 0.5\ .\frac{1}{Distance_{BS}(i)} \tag{11}$$

where the weighting coefficient 0.5 is determined through parameter tuning.

The node with the highest computed level L(i) is designated as the leader of the surface Sk. For selecting CHs within each square, the same objective function used in CFFC-LEACH protocol is applied. The final stage involves the transmission of data to BS. In this phase, each CH employs the TDMA scheme to allocate distinct time slots for member nodes within its cluster, thereby avoiding data collisions. The nodes transmit their data to the respective CH during their assigned slots. The CHs then perform data aggregation and remove redundancies before forwarding the compressed data to the surface leader. The leader, in turn, sends the consolidated information directly to the BS via a single-hop transmission. The CFFC-LEACH and VGFC-LEACH protocol's organizational structure is shown in Figure 2 and Figure 3 respectively.

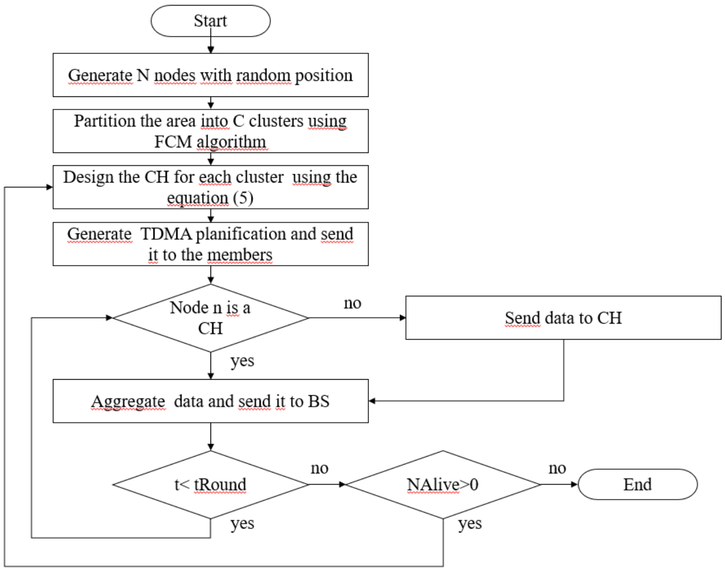


Figure 2. The CFFC-LEACH protocol's operational program

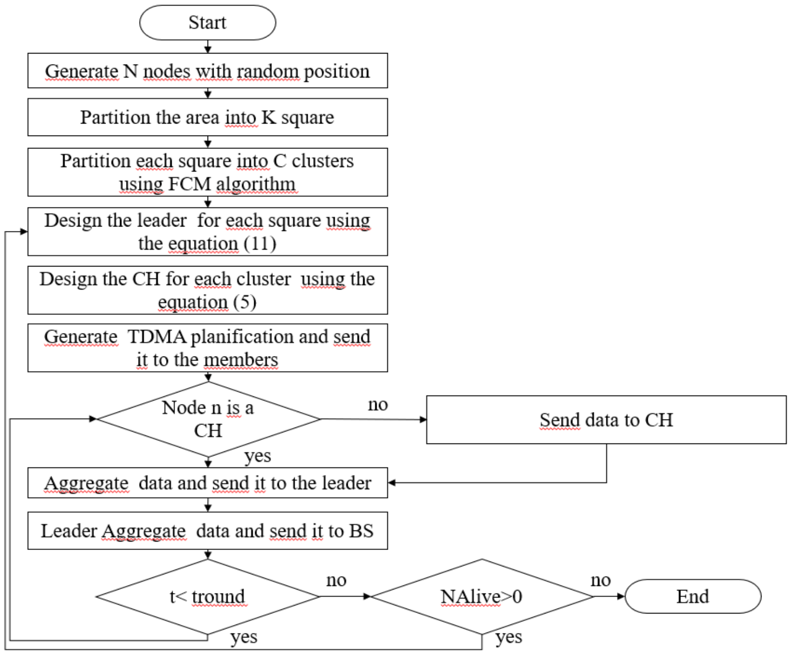


Figure 3. The VGFC-LEACH protocol's operational program

3.3. Energy consumption model

In this work, we adopted Heinzelman's energy model to evaluate the energy consumption involved in both data transmission and reception. Specifically, the energy required to transmit a data packet of k bits is calculated using the following expression [43]:

$$Etx(k,d) = \begin{cases} kE_{elec} + kE_{amp}d^2 & if \quad d < d_0 \\ kE_{elec} + kE_{two-ray}d^4 & if \quad d \geq d_0 \end{cases} \quad (12)$$

Similarly, the energy utilized in receiving k bits of data is expressed as:

$$ERx = kE_{elec} + kE_{agg} \quad (13)$$

The threshold distance (d_0) is calculated using the formula:

$$d_0 = \sqrt{\frac{E_{amp}}{E_{two-ray}}} \quad (14)$$

4. RESULTS AND DISCUSSION

4.1. Simulation parameters

A set of simulation experiments are conducted to evaluate the performance of the proposed CFFC-LEACH and VGFC-LEACH protocols in comparison with the conventional LEACH and EDK-LEACH algorithms under various deployment conditions. The evaluation is performed across three distinct scenarios. Simulations are carried out using MATLAB R2020a, considering three different BS locations and three network area sizes.

The following assumptions are adopted in the simulations: (i) the BS is fixed and its location is known to all sensor nodes; (ii) sensor node locations are fixed and known after deployment; (iii) all sensor nodes are initially assigned equal energy levels and are non-rechargeable; and (iv) each node transmits a single data packet per time unit to its designated CH.

To ensure a fair and consistent comparison, identical parameter settings are used for the baseline LEACH and EDK-LEACH protocols as well as for the proposed CFFC-LEACH and VGFC-LEACH schemes. The simulation parameters are summarized in Table 2.

Table 2. Parameter used to test the performance of CFFC-LEACH and VGFC-LEACH

Parameter	Scenario 1	Scenario 2	Scenario 3
Network size	100×100 m^2	200×200 m^2	300×300 m^2
Number of squares	/	4	9
Base station location	(50,50)	(100,100)	(150,150)
Number of nodes	100	400	400
Total number of clusters	5	5 per Square	2 per Square
Frame size	4,000bit	4,000bit	4,000bit
Energy aggregation (E_{agg})	5nJ	5nJ	5nJ
Initial node energy (E_0)	2J	2J	2J
Free-space amplification coefficient (ε_{amp})	10 pJ/bit/m^2	10 pJ/bit/m^2	10 pJ/bit/m^2
Multi-path amplification factor ($\varepsilon_{two\text{-}ray}$)	0.013 pJ/bit/m^4	0.013 pJ/bit/m^4	0.013 pJ/bit/m^4
Crossover distance(d_0)	87 m	87 m	87 m
Energy required to transmit one bit (E_{TX})	0.5 nJ/bit	0.5 nJ/bit	0.5 nJ/bit
Energy required to receive one bit (E_{RX})	0.5 nJ/bit	0.5 nJ/bit	0.5 nJ/bit
Maximum number of rounds	10,000	10,000	10,000

4.2. Analysis

This study evaluates the performance of LEACH protocol and EDK-LEACH in comparison with the two newly proposed algorithms by analyzing two key metrics: network survivability index (NSI) and the residual energy of the nodes.

4.2.1. Network survivability index

The NSI is defined as the ratio of the total number of active nodes to the total number of nodes in the network, providing a comprehensive metric that reflects both node failures and NL. NSI reaches its maximum value of 1 when all nodes are alive, and drops to 0 when all nodes are dead, indicating complete network collapse, where nodes neither transmit nor receive any messages [41]. Figure 4 illustrates the NSI as a function of the number of rounds for CFFC-LEACH, the standard LEACH protocol, and EDK-LEACH in the small-area scenario. Figure 5 presents the NSI for LEACH, EDK-LEACH, and VGFC-LEACH across two large-area scenarios.

In Figure 5, it is clearly depicted that LEACH and EDK-LEACH performs worst our proposed protocols CFFC-LEACH and VGFC-LEACH. From the NSI, we can derive NL, which is defined as the duration from initial deployment until the death of the first node, serving as a key indicator of network stability. This metric is represented as the period during which NSI equals 1.

For small-scale networks, as shown in Figure 2, the proposed CFFC-LEACH significantly extends the NL compared to LEACH and EDK-LEACH. Specifically, the NL for CFFC-LEACH, LEACH, and EDK-LEACH are 2775, 1717, and 1893 rounds, respectively. This corresponds to an improvement of 1058 and 882 rounds over LEACH and EDK-LEACH, respectively. The proposed protocol enhances both the stable and unstable periods of the network. This improvement is primarily attributed to the controlled number of clusters and the clustering mechanism employed by the FCM algorithm. Additionally, the uniform distribution of CHs across the network area contributes to balanced energy consumption. Furthermore, selecting CHs from within their respective clusters reduces the energy overhead associated with cluster formation.

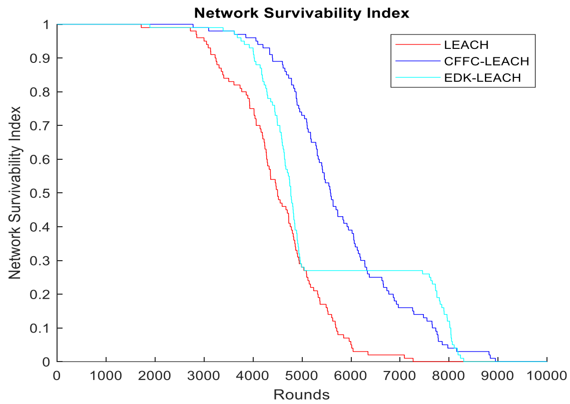
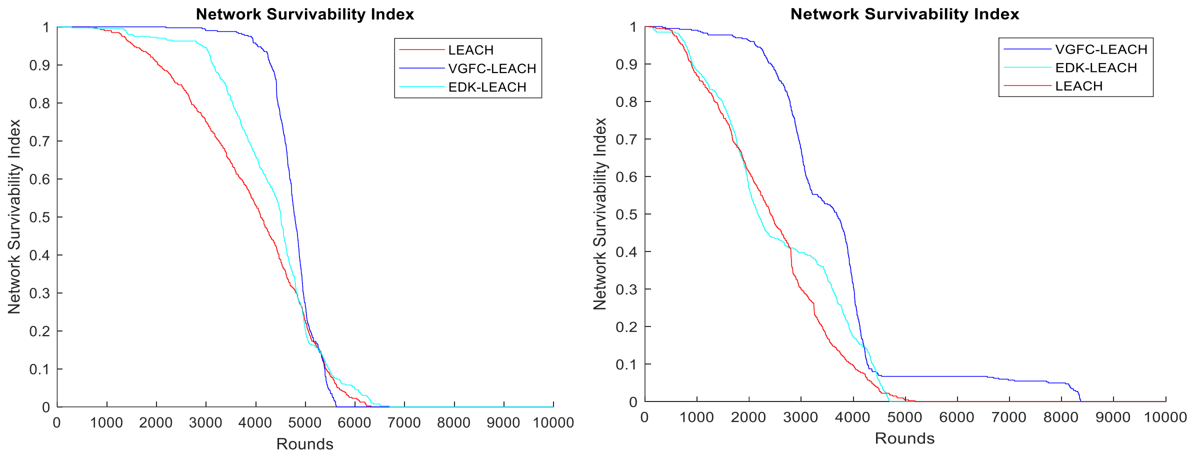


Figure 4. Alive nodes for LEACH, EDK-LEACH, and CFFC-LEACH in scenario 1



(a) (b)

Figure 5. Alive nodes for LEACH, EDK-LEACH, and VGFC-LEACH in (a) scenario 2 and (b) scenario 3

For larger-scale networks, as shown in Figures 3 and 4, the NL in scenario 2 is 4623, 1426, and 112 rounds for VGFC-LEACH, LEACH, and EDK-LEACH, respectively. In scenario 3, the average NL is 4062.7, 3778.4, and 164.7 rounds for VGFC-LEACH, LEACH, and EDK-LEACH, respectively. VGFC-LEACH demonstrates significant improvements, achieving 3132.8 and 3613.7 additional rounds compared to LEACH and EDK-LEACH in scenario 2, and similar gains in scenario 3, highlighting the effectiveness of the proposed protocol in extending NL. It is clear that when the network area increases, sensor nodes tend to consume more energy due to longer transmission distances. However, by partitioning the sensing area into smaller squares, transmission distances are significantly reduced, thereby lowering node energy consumption. In this approach, each square covers an area of 100×100 m², as the LEACH protocol has been demonstrated to achieve optimal performance at this scale. Moreover, the use of a dedicated leader for each square alleviates the workload of the CH, contributing to additional energy savings.

Tables 3 and 4 offer a detailed overview of the results, emphasizing the number of rounds and the percentage of increase for NL corresponding to CFFC-LEACH, and VGFC-LEACH compared to LEACH and EDK-LEACH, across different small and large-scale scenarios. The rate for CFFC-LEACH compared to LEACH was calculated as:

$$\text{Rate}_{\text{CFFC\_LEACH}} = \frac{Nb_{roundLEACH} - Nb_{roundCFFC\_LEACH}}{Nb_{roundLEACH}} . 100 \quad (15)$$

Table 3. Comparison of network lifetime for LEACH, EDK-LEACH and CFFC-LEACH in small areas

Scenario	LEACH	EDK-LEACH	CFFC-LEACH	Rate CFFC-LEACH compared to LEACH	Rate CFFC-LEACH compared to EDK-LEACH
Scenario 1	1717	1893	2775	61,62%	46,59%

Table 4. Comparison of network lifetime for LEACH, EDK-LEACH and VGFC-LEACH in large areas

Scenario	LEACH	EDK-LEACH	VGFC-LEACH	RateVGFC-LEACH compared to LEACH	Rate VGFC-LEACH compared to EDK-LEACH
Scenario 2	633	289	2189	245,81%	657,44%
Scenario 3	154	80	335	117,53%	318,75%

4.2.2 Residual energy

Residual energy is a key indicator when evaluating the performance of WSNs. Figures 6 illustrate the residual energy per round for LEACH, EDK-LEACH, and CFFC-LEACH in scenario 1. Meanwhile, Figures 7 displays the residual energy trends for LEACH, EDK-LEACH, and VGFC-LEACH for large-scale scenarios 2 and 3.

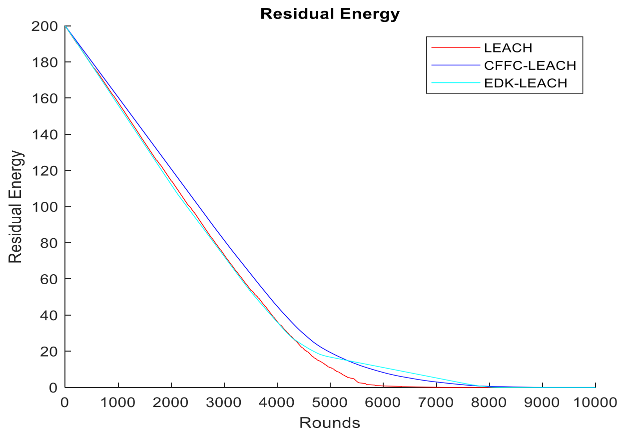
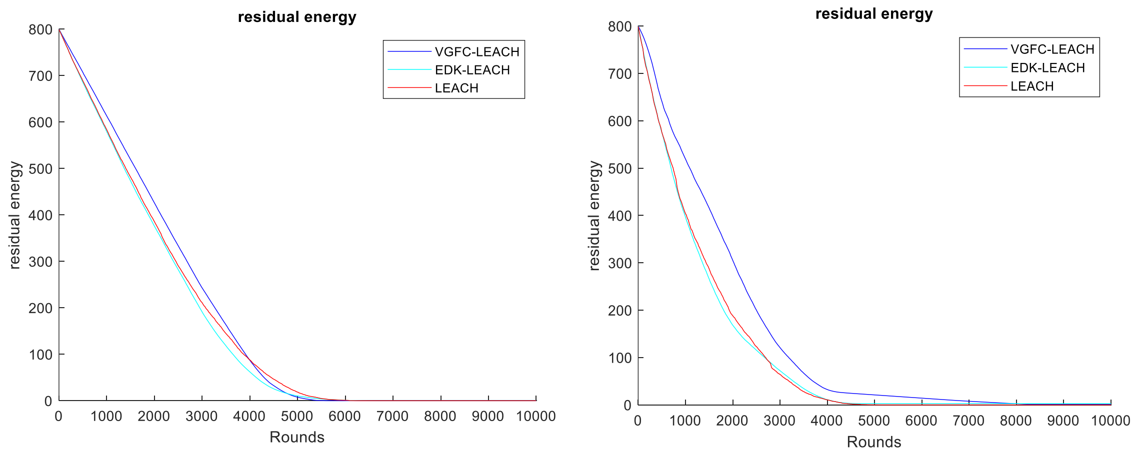


Figure 6. Residual energy for LEACH, EDK-LEACH, and CFFC-LEACH in scenario 1



(a) (b)

Figure 7. Residual energy for LEACH, EDK-LEACH, and VGFC-LEACH; (a) scenario 2 and (b) scenario 3

Tables 5 and 6 provide a detailed comparison of energy consumption among the evaluated protocols under different scenarios. In scenario 1, 25% of the total network energy is consumed after 1173 rounds for LEACH, 1141 rounds for EDK-LEACH, and 1264 rounds for CFFC-LEACH, indicating a slower energy depletion rate for the proposed CFFC-LEACH protocol. In scenario 2, the consumption of 50% of the total energy occurs at 1921 rounds for LEACH, 1873 rounds for EDK-LEACH, and 2138 rounds for VGFC-LEACH, demonstrating the improved energy efficiency of VGFC-LEACH under moderate-scale conditions. In scenario 3, complete energy exhaustion is observed after 5189 rounds for LEACH, 4701 rounds for EDK-LEACH, and 8367 rounds for VGFC-LEACH, highlighting the significant advantage of VGFC-LEACH in large-scale deployments. Furthermore, across all evaluated scenarios, the proposed CFFC-LEACH and VGFC-LEACH protocols consistently maintain higher residual energy levels as the number of rounds increases, reflecting slower energy depletion and extended operational periods. This behavior directly translates into prolonged NL and confirms the enhanced durability achieved by the proposed approaches compared to existing protocols.

Table 5. Comparison of residual energy for LEACH and CFFC-LEACH in small areas

Scenario	% Energy consumption	LEACH	EDK-LEACH	CFFC-LEACH	Rate CFFC-LEACH compared to LEACH	Rate CFFC-LEACH compared to EDK-LEACH
Scenario 1	25%	1173	1141	1264	7,75%	10,78%
	50%	2350	2297	2525	7,44%	9,93%
	75%	3629	3586	3851	6,12%	7,39%
	100%	7267	8202	8948	23,13%	9,10%

Table 6. Comparison of residual energy for LEACH, CFFC-LEACH, and VGFC-LEACH in large areas

Scenario	% Energy consumption	LEACH	EDK-LEACH	VGFC-LEACH	RateVGFC-LEACH compared to LEACH	Rate VGFC-LEACH compared to EDK-LEACH
Scenario 2	25%	920	904	1073	16,63%	18,69%
	50%	1921	1873	2138	11,30%	14,15%
	75%	3074	2949	3268	6,31%	10,82%
	100%	6321	6256	5553	-12,14%	-11,24%
Scenario 3	25%	431	435	650	50,81%	49,43%
	50%	1022	989	1572	53,81%	58,95%
	75%	1927	1807	2502	29,84%	38,46%
	100%	5189	4701	8367	61,24%	77,98%

5. CONCLUSION

Energy efficiency remains a crucial challenge in WSNs, mainly because of limited battery power, especially in large-scale environments. While the LEACH protocol is designed to help save energy within the network, it comes with its own set of limitations. To tackle these challenges, we propose two new protocols: CFFC-LEACH and VGFC-LEACH, each tailored to minimize energy consumption in either small or large areas.

CFFC-LEACH leverages artificial intelligence to form clusters, addressing the randomness of LEACH’s cluster formation process by optimizing area division. It is particularly well-suited for smaller areas. However, VGFC-LEACH is designed for larger-scale networks. It divides the network into small virtual squares to reduce transmission distances. Each square has a leader responsible for relaying aggregated data from the CHs to the BS, taking into account both the remaining energy and the distance to the BS.

Simulation results clearly demonstrate that the proposed protocols outperform LEACH and EDK-LEACH in terms of NL, stability period, and residual energy. This enhanced performance is primarily due to the non-random, energy-aware cluster formation facilitated by the FCM algorithm, which ensures balanced CH load distribution and minimizes long-distance transmissions. Future work will focus on adapting these protocols to heterogeneous sensor networks and scenarios with mobile sink nodes, as well as integrating the strengths of both protocols to optimize performance in dynamic environments.

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BIOGRAPHIES OF AUTHORS

Hayet Termeche was born in Chabet El Ameur, Algeria, in 1993. She received her Master's degree in Distributed Computing Systems from the University of M'Hamed Bougara Boumerdes, Algeria, in 2016. She is currently pursuing her Ph.D. degree in Networks and Telecommunications. She is a member of the research group Methods and Tools for Systems and Telecommunications Engineering at the University of M'Hamed Bougara Boumerdes, Algeria. Her main research interests include the study of intelligent sensor networks for medical applications. She can be contacted at email: h.termeche@univ-boumerdes.dz.

Taous Lechani received her Engineer degree from Mouloud Mammeri university in 1997 and the Ph.D. degree from University M'hamed Bougara of Boumerdes in 2021. She is an assistant professor at M'hamed Bougara University. She is currently member at the research laboratory (LEEI). Her research interests include wireless sensor networks, internet of things, and machine learning. She can be contacted at email: t.lechani@univ-boumerdes.dz.

Fayçal Rahmoune was born in 1972 in Algeria. He received his engineer degree in electrical engineering in 1994 (ex. INELEC, Algeria) and the Ph.D. degree in Electronics from INPG institute, National polytechnic Institute of Grenoble, France in 2004. Dr. Rahmoune Fayçal joined the University of Boumerdès as Associate Professor in Electronics in 2005. Since January 2016, he has been a full professor at the University of Boumerdès, Algeria. The main research interests include Characterization of electronic components, reliability, and optimization in different energy systems, renewable energy systems, and soft computing. He can be contacted at email: faycal.rahmoune@univ-boumerdes.dz.