Maximizando la Vida Útil de Nodos en Redes de Sensores Inalámbricas: Una aplicación innovadora del problema de Optimización P-Median al Protocolo LEACH-C

Maximizing Nodes' Service Lives In Wireless Sensor Networks: An Innovative Application Of The P-Median Optimization Problem To The Leach-C Protocol

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Abtract

This study explores an innovative focus for optimizing clusters in the LEACH-C protocol via applying the P-Median model. Using a fixed number of sensors, the method is centered on improving energy efficiency for Wireless Sensor Networks (WSN). Applying the P-Median model managed to delay the death of the first node, reducing both the number of clusters and the number of packets sent to the cluster heads, increasing packets sent to the sink, and increasing average network energy. These advances represent a significant improvement in energy efficiency, a central aspect of WSN, also contributing to long-term sustainability and lowering operating and maintenance costs. The relevance of this study reaches beyond improvements in energy efficiency, presenting the potential to revolutionize resource and infrastructure management, especially in remote areas. The results of this study open a promising path towards optimization in the field of WSN and highlight the usefulness of the P-Median model in improving performance and energy efficiency within these networks.

Keywords

Clusters, Energy efficiency, LEACH-C protocol, P-Median, Wireless Sensor Networks, WSN, Clústeres, Eficiencia Energética, Protocolo LEACH-C, P-Mediana, Redes de Sensores Inalámbricos.

Resumen

En esta investigación, se explora un enfoque innovador para la optimización de clústeres en el protocolo LEACH-C a través de la aplicación del modelo P-Median en Redes de Sensores Inalámbricos (WSN). Utilizando un número fijo de sensores, el método se centra en mejorar la eficiencia energética, crucial para la sostenibilidad y reducción de costos en WSN. La implementación del modelo P-Median demostró ser eficaz en retrasar la muerte del primer nodo y reducir el número de clústeres y paquetes enviados a las cabezas de clúster (CH), al tiempo que aumentó los paquetes enviados al sumidero y la energía promedio de la red.

Estos avances significan una mejora considerable en la eficiencia energética, contribuyendo a la sostenibilidad a largo plazo y disminuyendo los costes operativos y de mantenimiento. Más allá de las mejoras energéticas, este estudio tiene el potencial de revolucionar la gestión de recursos e infraestructuras, especialmente en áreas remotas, al ofrecer una metodología adaptable a diferentes configuraciones de WSN. Los resultados abren un camino prometedor hacia la optimización en el campo de las WSN, destacando la utilidad del modelo P-Median para mejorar tanto el rendimiento como la eficiencia energética en estas redes, lo que representa un avance significativo con aplicaciones potenciales amplias para futuras investigaciones y desarrollos tecnológicos.

Palabras clave

Clusters, Eficiencia Energética, Protocolo LEACH-C, P-Median, Redes Inalámbricas de Sensores, WSN, Clusters, Eficiencia Energética, Protocolo LEACH-C, P-Median, Redes Inalámbricas de Sensores.

I. Introduction

The development of wireless sensor networks (WSN) has drawn interest in recent years, particularly for energy management. In [1], an exhaustive review was done regarding energy-efficient hierarchical routing protocols and their impact on the energy sustainability of WSN, noting that the LEACH protocol is one of the first and best-known energy-efficient hierarchical routing protocols in WSN, The LEACH protocol (Low-energy adaptive clustering hierarchy), was proposed by [2] and combines cluster-based routing, access to energy-efficient means, and aggregation of specific application data to achieve excellent performance in terms of system lifespan, latency, and perceived application quality. However, the use of a central control algorithm to form the clusters can produce better clusters after dispersing the principal cluster nodes across the network. This is the basis for LEACH-Centralized (LEACH-C), a protocol which uses a centralized grouping algorithm and the same stationary status protocol as in LEACH, thus laying the basis for developing WSN. However, other ways of handling the challenge of energy efficiency in WSN have been proposed; in [3], there is an energy assignment strategy for detecting stochastic events in rechargeable sensor networks. Algorithm 1 demonstrates its optimality by improving event detection due to efficiently assigning energy in scenarios without energy restrictions, and Algorithm 2 provides a Pareto-optimal solution in scenarios where energy is limited, allowing for efficient energy assignment to maximize detection of important events. In [4] the proposal is an energy cooperation method based on partially-observable Markov decision processes (POMDP). A POMDP is used to optimize energy assignment and improve data transmission efficiency to approach problems such as unequal energy distribution, hot points, and energy holes in WSN. Similarly, in [5] an optimal intra-inter cluster data aggregation technique is proposed which is conscious of the quality of IoT-assisted WSN, using hybridized optimization techniques. For grouping, they use a modified version of the Bowerbird optimization algorithm, and to estimate the cluster head (CH), a multi-objective seagull optimization decision-making algorithm (MSO-DM) algorithm is used. Similarly, [6] proposed using genetic algorithms to optimize task assignment and data transmission on the network, which select data transmission routes with minimal energy consumption. The idea is that each network node becomes an individual within the genetic algorithm, and their status represents the genes of the individual. Afterwards, the selection, crossing, and mutation mechanism is used to generate new solutions for the problem. The process repeats several times to find an optimal solution. In turn, [7] presents three different focuses to increase longevity for a WSN. These focuses include cluster-based multipath routing, static relocation of the data gathering point, and multiple gathering points. Their conclusion is that static relocation of the data gathering point can increase network longevity, Similarly, [8] also proposes using genetic algorithms for energy management, and they identified 21 important attributes for efficient energy consumption and network service life. By contrast, in [9] the proposal is the combination of two advanced optimization techniques: Grey Wolf Optimization (GWO) and Dragonfly Optimization (DFO) to find the optimal data transference path between the objective node and the control center within WSN. Table 1 summarizes the studies related with our proposal; however, to our knowledge, the P-Median model has never been used in the LEACH or LEACH-C protocol for handling network energy efficiency. Finally, the objective of the research is to improve the energy efficiency of Wireless Sensor Networks (WSN) through the integration of the P-Median model in the LEACH-C protocol.

Table 1 Related works

Cite	Protocol Name	Method
[10]	ECO-LEACH	Energy-aware Clustering Optimization
[11]	-	Hybrid Energy-Efficient Distributed
[12]	Q-Leach	Time Division Multiple Access (TDMA)
[13]	EACR-LEACH	Energy Aware Cluster-based Routing
[14]	IBRE-LEACH	Improved Balanced Energy Consumption
[15]	-	Independent Recurrent Neural Network (IndRNN) called DFAIRNN
[16]	EE-LEACH	Fuzzy Logic
[17]	EAMMH	Energy Aware Multi-hop Multi-path Hierarchical
[18]	-	Residual energy of the sensor nodes
[19]	E-LEACH	Time Division Multiple Access (TDMA)
[20]	O-LEACH	Genetic algorithm (GA) together with an artificial neural network (ANN)
[21]	LEACH-K	K-Means
[22]	EECR	Based on efficient clustering, includes cluster building stage and stable data transmission stage
[23]	FTBA-TC-LEACH	Triangle-flipping strategy bat algorithm (FTBA)
[24]	LEACH-VA	Voronoi Algorithm
[25]	SC-LEACH	The CH selection is designed to be dependent on energy

II. Methodology

The P-Median model is not new. In [26] it is defined as a problem related with the minimization of the total distance weighted by the demand between demand nodes in the set *I* and the installations in set *J*. It has been used in different areas; for example, in [27], it is used to determine the location of installations intended for humanitarian emergencies. The P-Median model is defined as:

Indices and set of indices

I Set of demand nodes; $i \in I$ *J* Set of facilities sites; $j \in J$
Decision variables:

X_j = 1 if a facility is located at chosen site *j*, 0 otherwise.

Y_{ij} = 1 if facility *j* handles the demand of point *i*, 0 otherwise.

Entry parameters:

d_{ij} distance between demand point *i* and candidate facility *j*

cap_{ij} capacity of facility *j*

P maximum number of installations which can be placed, w_i weight associated with each demand point (demand or number of clients/people)

$$Minimize\ \sum_i \sum_j w_i d_{ij} Y_{ij}, \quad (1)$$

$$Subject\ to\ \sum_j X_j = P, \quad (2)$$

$$\sum_j Y_{ij} = 1 \quad \forall j \quad (3)$$

$$\sum_j w_i Y_{ij} \le cap_j X_j \quad \forall j \quad (4)$$

$$X_j, Y_{ij} \in \{0,1\} \quad \forall i, \forall j \quad (5)$$

The objective function in (1) seeks to minimize the distance between the demand points and the candidate installations. Equation (2) establishes that there will be exactly P facilities which will be located at site j. Equation (3) ensures that each demand point i is assigned to installation j. Equation (4) only allows assignment to installations which can cover demand, and (5) establishes the binary conditions for the model. In turn, the LEACH-C protocol is an improvement on LEACH designed for WSN. LEACH-C presents a constant phase similar to the LEACH protocol, in which nodes re-send their detected data to their Cluster Heads (CHs) during the assigned time interval. The CHs then add and process the data to improve the quality of the signals received and filter the noise before sending them to the sink. However, the configuration phase in LEACH-C is different, since CHs are selected by the sink as a function of the nodes' location and the energy levels. The sink processes the data received to form more efficient clusters which require less energy during transmission. CH choice is based on the nodes' average energy, calculated by the sink, and those with remaining energy below this average cannot be selected as CHs. The sink then sends a message containing information about the ID of the selected CHs. In general, the LEACH-C protocol achieves better grouping than LEACH, but it requires a positioning system for each node. However, the premature death of CHs with low energy remains a problem in LEACH-C, since there is a possibility of selecting nodes with less energy as CHs instead of those with greater energy reserves [1]. The transmitter node also consumes energy to operate the radio electronics with an amplifying strength, and only the receptor node consumes energy to operate the radio electronics. In the present study, we will consider both the free space channel model and the multiple route model. These models also depend on the distance between the transmitter and the receiver; if the transmission distance is less than d0, which is the threshold distance, a free space route will be used; otherwise, a multipe-route model will be used [16]. This is the proposal in [8], which establishes that if l bit packets are sent across a distance d, then the energy required for transmission is:

$$E_{TRi} = E_{(TR_i-ele)} + E_{(TR_i-mp)},$$
$$E_{TRi} = \begin{cases} l * E_{ele} + l * \varepsilon_{fs} d^2 & if\ d < d_0 \\ l * E_{ele} + l * \varepsilon_{fs} d^4 & if\ d \ge d_0 \end{cases} \quad (6)$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \quad (7)$$

Where Equation (6) represents the energy use model for data transmission, and (7) is to determine the threshold distance and determine whether the transmission is over free space or multiple routes. In turn, Equation (8) models energy consumption for receiving the message on the end of the receptor.

$$E_{REi} = E_{(REi-ele)}(l) = l E_{ele} \quad (8)$$

Electronic energy, denoted as E_{ele}, is based on some factors such as filtering, signal diffusion, modulation, and signal coding. The energy of the amplifier is determined as a function of the distance of the receptor, together with the bits' error rate, and is defined as $\varepsilon_{fd} d^2$ or $\varepsilon_{mp} d^4$, as warranted. Energy for data aggregation (EDA) has also been considered. The summary of the values used in the study simulations appears in Table 2, as described in [8].

Table 2 Parameters used in energy dissipation [6]

Parameters	Value and unit
Initial energy for every node	0.5 [*J*]
ε_{fs}	10×10^{-12} [*J*]
ε_{mp}	0.0013×10^{-12} [*J*]
E_{TRi}	50×10^{-9} [*J*]

E_{REi}	50×10^{-9} [J]
EDA	5×10^{-9} [J]
Data package length	4.000 [*bits*]

The integration of the P-Median model with the LEACH-C protocol is done in order to optimize CH selection in each round. During normal LEACH-C protocol function, CH candidate nodes are generated based upon diverse criteria. However, upon applying the P-Median model in this stage, the selection is adjusted in order to always use one candidate node less than in traditional selection. This focus intends to minimize the total weighted distance, following the P-Median model principle.

The demand nodes are treated as clients, and the CH as facilities, aligning the logic of optimal installation location with the formation of WSN clusters. Applying the P-Median model in each round ensures a balanced energy distribution across the network, leading to substantial improvements in energy efficiency and network lifespan. Thus, the PM-LEACH-C protocol (P-Median - Low Energy Adaptive Clustering Hierarchy - Central) is an advanced proposal fusing both methods' advantages. The flowchart appears in Fig. 1.

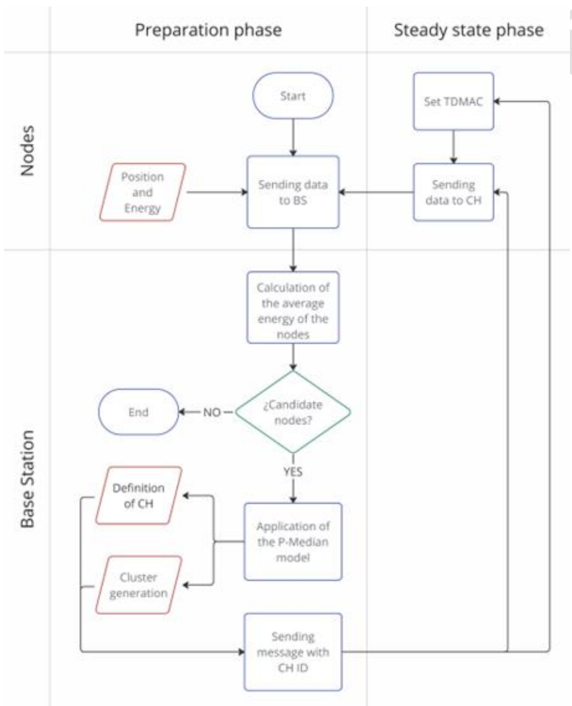

Figure 1 Flowchart of new PM-LEACH-C protocol.
Source: Author(s)

For the simulations, some recommended assumptions were taken from [8], namely: (i) Sensor nodes send data from the clusters' heads into the sink. (ii) Sensor nodes are homogenous. (iii) Random sensor node distribution is assumed. (iv) The sink knows the location of the sensor. (v) The sink can communicate and compute without any energy consumption restrictions. (vi) Sensor nodes can transmit data at the fluctuating energy level as a function of the distance from the sensor nodes to the sink or CHs. (vii) Sensor nodes are static. According to [7], static relocation of the data gathering point can increase network lifespan, which is why we will analyze the behavior of the protocol in various scenarios, as summarized in Table 3. MatLab2023a was used to simulate the protocols on the same basis as the findings from [28]. To resolve the P-Median model in each simulation round, we used the intlinprog solver with a maximum solver execution time configuration of 30 seconds; for graphic analysis, R was used [29].

Table 3 Simulation data

Scenario	Value	
Area	100x100[m2]	
# of Sensor Nodes	200	
# of simulations	3	
Scenario type	Sink position	Name
Base scenario	(50;150) [m]	Far
Comparative scenario 1	(50;75) [m]	Near
Comparative scenario 2	(50;50) [m]	Center

III. Results

III.A. Base scenario

Figure 2 shows the base scenario network.

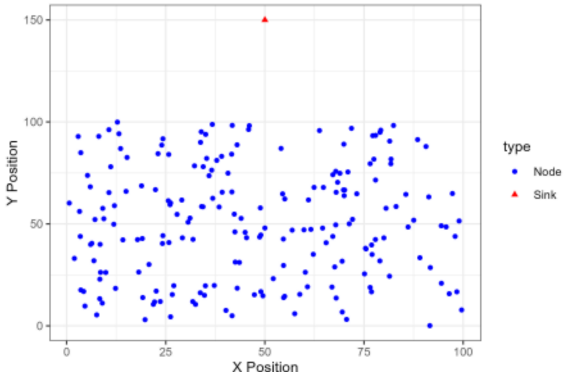

Figure 2 Base Scenario Sensor Network. Source: Author(s)

Fig. 3 presents the results of the three simulations with the distant sink, where we can observe that the proposed protocol presents better performance with the death of both the first and last node after the rest of the analyzed protocols.

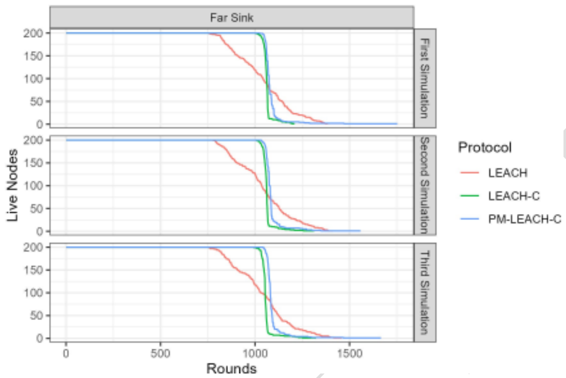

Figure 3 Evolution of live nodes per round. Source: Author(s)

Fig. 4 uses a violin graph to compare the live nodes considering the three simulations. While the proposed protocol presents a lower average live node number than the rest, this is because it has the largest number of rounds with the operational network, with more than 500 rounds compared to LEACH and over 1.000 rounds compared with LEACH-C.

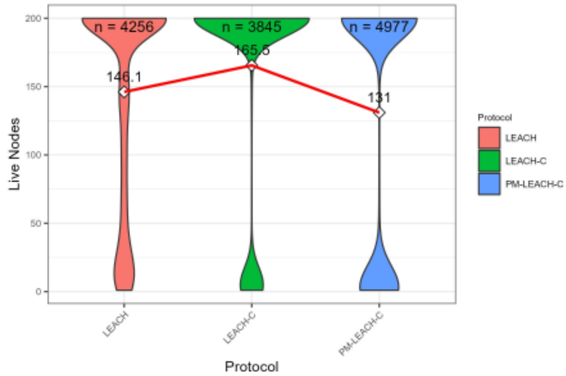

Figure 4 Live node comparison. Source: Author(s)

For the total network energy, Fig. 5 presents This behavior by protocol, indicating that the proposed protocol exceeds the rest.

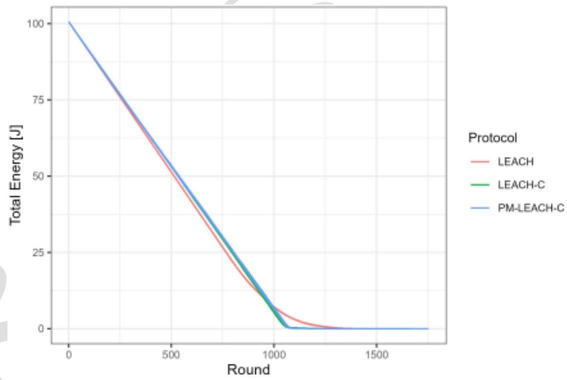

Figure 5 Total energy per round. Source: Author(s)

Fig. 6 compares the rounds where the first sensor node dies. Note that the proposed protocol outdoes the rest of the protocols, exceeding the LEACH-C protocol by 33 rounds and the LEACH protocol by almost 300 rounds.

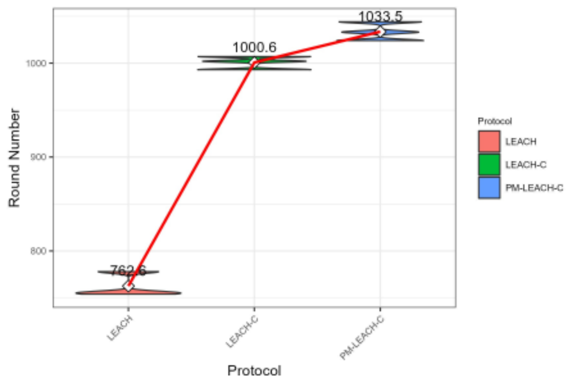

Figure 6 Comparison of rounds in which the first node died. Source: Author(s)

For the total number of rounds with the entire network in operation, Fig. 7 compares the three protocols; the proposed protocol easily surpasses the others.

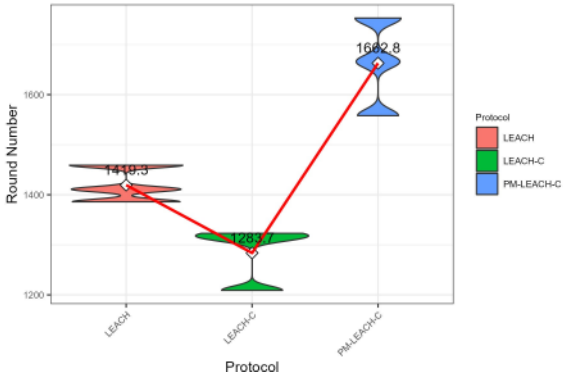

Figure 7 Comparison of rounds in which all nodes died. Source: Author(s)

For the packets sent into the sink, the proposed protocol exceeds the others in the number of packets sent, as well as in the number of rounds with packets sent. Fig. 8 shows these results.

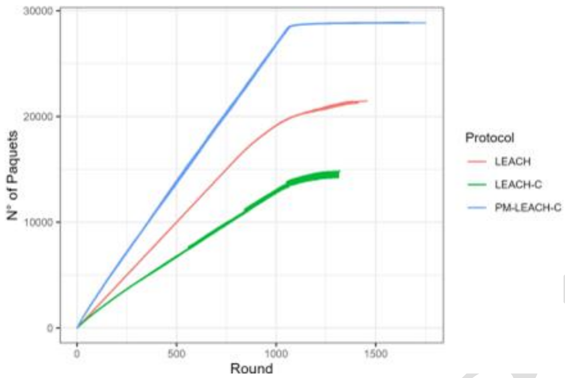

Figure 8 Packets sent to sink per round. Source: Author(s)

For the packets sent to CHs, Fig. 9 shows that the number of packets sent is lower in the proposed protocol, which aligns with the proposal given that the P-Median model was integrated to use one CH node less in each round whenever possible.

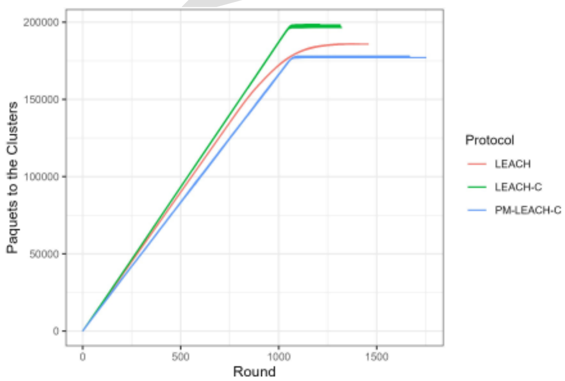

Figure 9 Packets sent to Cluster Heads per round. Source: Author(s)

Finally, Fig. 10 shows the average simulation times for each protocol, where the proposed protocol easily exceeds the rest, given the computational complexity of solving the P-Median model in each simulation round.

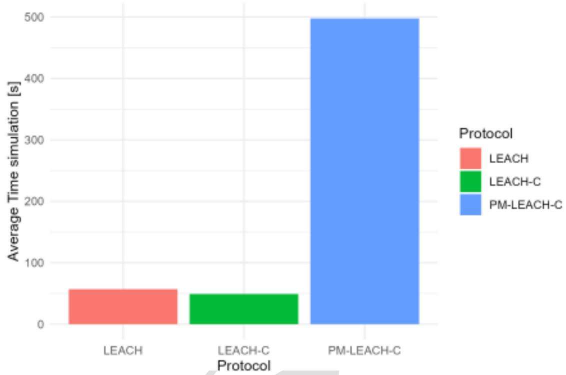

Figure 10 Average simulation time in seconds for each protocol. Source: Author(s)

Table 4 provides a comprehensive view of the performance of the LEACH, LEACH-C, and PM-LEACH-C protocols under two different scenarios: when the sink is nearby and when it is in the center of the network. These scenarios are crucial to understanding how the location of the sink influences the performance of different protocols. It is observed that, in both scenarios, the PM-LEACH-C protocol shows a decrease in the number of active nodes, but this is accompanied by increased longevity of the network, as indicated by the number of rounds until the last dead node. This suggests that although the protocol may have fewer operational nodes at any given time, it maintains network functionality for longer. Another aspect highlighted in the Table 4 is the energy efficiency of PM-LEACH-C, which has the lowest total remaining energy in both scenarios. This supports the premise that the integration of the P-Median model helps optimize energy allocation within the network, given that, despite having lower remaining energy on average, the proposed protocol achieves a greater number of total rounds of operation. The number of packets sent to the sink and CHs is also indicative of the trade-off between data collection and energy efficiency. The PM-LEACH-C shows a significant reduction in the number of packets sent to the CHs in the "Center" scenario, which is consistent with the strategy of using fewer CHs and still maintains a competitive number of packets sent to the sink. suggesting that data collection is not compromised. However, the simulation time is noticeably higher for PM-LEACH-C, underscoring the computational cost of implementing a more complex model. This is an important factor to consider, especially for real-time applications or for nodes with limited processing capabilities.

Table 4 summarizes comparative scenario 1 (Near) and comparative scenario 2 (Center) for the sink.

Table 4 The recommended fonts

Average	LEACH		LEACH-C		PM-LEACH-C	
Parameter	Near	Center	Near	Center	Near	Center
Nodes alive	161,2	164,6	161,2	174,4	158,1	138,3
Rounds to first dead node	999,1	1.016,6	1.189,6	1.220	1.131	1.132,9
Rounds to last node dead	1.500,1	1.473,4	1.546,8	1.439	1.508,5	1.744,7
Total energy [J]	49,9	41,8	40,3	43,8	39,2	34,2
Packets sent to Sink	14.384,2	14.241,8	25.915,7	23.461,4	20.645,6	22.019,3
Packets sent to CH	129.025,5	127.918	122.869,5	118.052	119.489	129.726,1
Simulation time [s]	57,6	57,6	48,9	48,9	479,7	479,7

IV. Conclusions

The development of the PM-LEACH-C protocol represents a significant advance in life extension and energy efficiency in wireless sensor networks. This study demonstrated that, especially when the sink is distant, PM-LEACH-C not only extends the life of the first and last node but also improves network-level energy management beyond what the LEACH and LEACH-C can offer. The strategic incorporation of the P-Median model in LEACH-C has revealed an innovative path towards energy optimization in WSN, establishing a framework for applied research and practical implementation in the field. Although the location close to the sink does not prevent the early death of the first node and the improvement in average energy is not drastic, it is important to note that the overall network lifetime experiences a considerable improvement. These results highlight the relevance of sink positioning and its influence on network topology and energy load distribution. Looking ahead, expanding the number of sensor nodes and refining simulation algorithms, particularly through metaheuristic techniques, are presented as critical steps to advance the practicality of PM-LEACH-C. These approaches promise not only to improve simulation efficiency but also to adapt the protocol to the demands of a diversity of application scenarios, from congested urban environments to vast rural or remote areas. In conclusion, the PM-LEACH-C stands out as a robust and adaptable model with the potential to significantly influence the future design of sustainable and efficient WSNs. This work lays the foundation for an interdisciplinary approach that could unlock new possibilities in network communication and resource management, guiding the development of smart sensor solutions that are energy-efficient and technically viable.

V. CRediT AUTHORSHIP CONTRIBUTION STATEMENT

César Eugenio Sandoval Navarrete: Research, Supervision, Writing - revision and editing, **Pablo Adasme Soto:** validation of results and interpretation of conclusions, **Ali Dehghan Firoozabadi:** validation of results and interpretation of conclusions.

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