Journal of Telecommunication Network (Jurnal Jaringan Telekomunikasi) Vol. 16, No.1 (2026)

Implementation of PC-LEACH Protocol on a LoRa-Based Wireless Sensor Network

Krisna Eka Alfiandi[1], **Yoyok Heru Prasetyo Isnomo**[2*], **Muhammad Nanak Zakaria**[3]

[1,2,3]Digital Telecommunication Network Study Program, Department of Electrical Engineering, State Polytechnic of Malang, 65141, Indonesia.

[1]2141160052@student.polinema.ac.id , [2]urehkoyoy@polinema.ac.id, [3]nanakzach@polinema.ac.id

Abstract— **Wireless Sensor Networks (WSNs) face a significant challenge regarding energy efficiency due to the reliance of sensor nodes on limited battery power. The commonly used Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol often overlooks residual energy and distance factors in Cluster Head (CH) selection, which can shorten the network's lifespan. This research aims to implement and analyze the Power-Aware Centralized LEACH (PC-LEACH) protocol on a LoRa-based WSN to optimize energy consumption and extend network lifetime. The method involves implementing the PC-LEACH protocol, where CH selection is adaptively performed based on the nodes residual energy and their distance to the Sink. The system was built using ESP32 microcontrollers, LoRa RA-02 modules, and environmental sensors. Performance was evaluated through physical hardware implementation by comparing the protocol against a non-clustering baseline, with emphasis on energy consumption and system operation. The results show that the PC-LEACH protocol reduced the average current draw by 34% compared with the non-clustering scenario (64 mA vs. 97 mA). In addition, the hardware implementation showed successful data aggregation, dynamic CH rotation, and proper operation of the calibrated sensors.**

***Keywords*— Energy Efficiency, LEACH, LoRa, PC-LEACH, Wireless Sensor Network.**

I. INTRODUCTION

The advancement of wireless communication technologies has created vast opportunities across various sectors, including environmental monitoring, healthcare, agriculture, and industry [1]. A key application in this domain is the Wireless Sensor Network (WSN), which consists of numerous sensor nodes distributed over an area to monitor specific parameters like temperature, humidity, and air quality, transmitting the collected data to a central base station, often called a Sink [2]. However, the primary challenge in WSN deployment is energy efficiency, as sensor nodes are typically powered by batteries with limited capacity, making network lifetime a critical performance metric [3].

Communication protocols play a pivotal role in managing the energy consumption of a WSN. One of the most widely recognized hierarchical routing protocols is the Low-Energy Adaptive Clustering Hierarchy (LEACH). The LEACH protocol organizes sensor nodes into clusters, each led by a Cluster Head (CH). The CH is responsible for gathering data from its cluster members, aggregating it, and forwarding it to the Sink. This reduces the number of long-distance transmissions, thereby conserving energy. However, the conventional LEACH protocol selects CHs based on a probabilistic model that often neglects crucial factors like the residual energy of the nodes and their distance to the Sink [4], [5]. This can lead to an imbalanced workload distribution, causing some nodes to deplete their energy prematurely and shortening the overall network lifespan [6].

To address these limitations, various adaptive versions of LEACH have been proposed [7], alongside other hierarchical models aiming for efficiency, such as the HEED protocol [8]. This research focuses on Power-Aware Centralized LEACH (PC-LEACH), a variant that enhances the CH selection process by incorporating the residual energy of each node and its proximity to the Sink. This ensures that nodes with higher energy reserves and more strategic locations are prioritized for the energy-intensive role of a CH, leading to optimized network-wide energy consumption and an extended operational lifetime [9].

For the implementation of this protocol, LoRa (Long Range) technology was selected as the communication medium. LoRa is ideal for WSN applications due to its ability to transmit data over long distances with minimal power consumption, leveraging Chirp Spread Spectrum (CSS) modulation [10]. This research aims to implement and evaluate the PC-LEACH protocol on a LoRa-based WSN, focusing on its impact on energy efficiency and hardware-based system operation in an environmental monitoring scenario. The implementation is intended to examine whether a clustered communication structure can reduce energy consumption compared with a non-clustering baseline under the tested deployment.

II. METHOD

This research is experimental, focusing on the implementation and evaluation of the PC-LEACH protocol. The methodology involved the development of a physical hardware prototype for validation.

[*] Corresponding Author

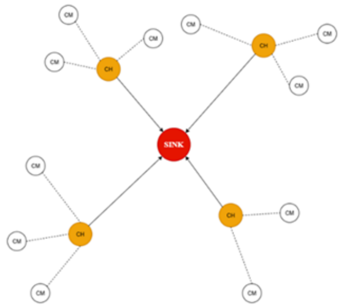


Figure 1. Network Topology

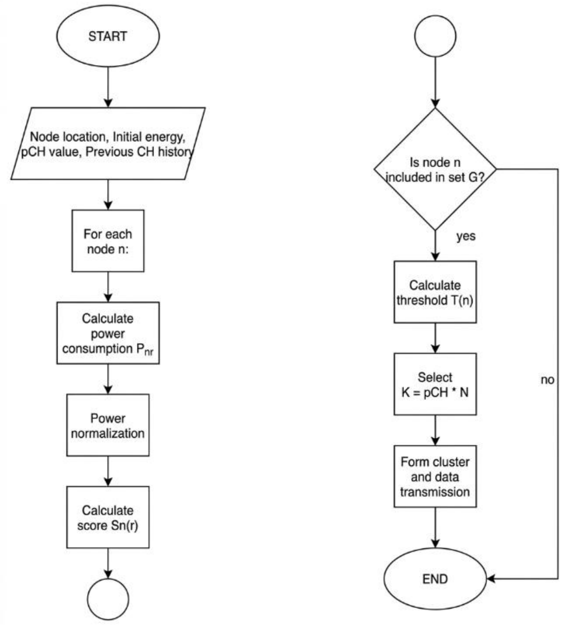


Figure 2. PC-LEACH Flowchart

A. *The PC-LEACH Protocol*

PC-LEACH is an enhancement of LEACH that introduces a centralized and energy-aware mechanism for CH selection, managed by the Sink [11]. Instead of a probabilistic choice, the selection is deterministic and adaptive, considering both the residual energy of each node and its spatial proximity to the Sink. The methodology focused on the development and evaluation of a physical hardware prototype to validate the proposed protocol. The core of PC-LEACH lies in its dynamic CH selection score, calculated for each node n in round r as follows:

$$S_n^{(r)} = \left(\frac{P_n^{(r)}}{P_{max}}\right).\left(1-\frac{d_{ns}}{d_{max}}\right) \qquad (1)$$

Where:

- $S_n(r)$ *is the dynamic CH selection score for node* n *in round* r.
- P_{nr} *is the residual energy of node* n.
- P_{max} *is the maximum residual energy among all nodes.*
- d_{ns} *is the distance from node n to the Sink.*
- d_{max} *is the maximum distance from any node to the Sink in the network.*

The centralized selection process begins with the Sink, acting as the central controller, collecting residual energy data and distance information from all sensor nodes in the network. Based on the collected data, the Sink computes the dynamic score $S_n(r)$ for every eligible node. Based on these scores, the Sink selects the K nodes with the highest scores to act as CHs for the current round, where K is determined by the desired percentage of CHs. Once the CHs are selected, they broadcast their status. Consequently, non-CH nodes then join the nearest CH based on signal strength to finalize the cluster formation[12].

Following the cluster formation, the network enters the *Steady-State Phase*, which is where the primary data transmission occurs. In this phase, all non-CH nodes sense their environment (e.g., temperature, humidity, gas levels) and transmit their data packets to their designated CH. The CHs, upon receiving data from all their cluster members, perform data aggregation. This process combines the data into a single, more comprehensive packet, which significantly reduces redundant transmissions and saves energy. Finally, each CH transmits this single aggregated packet directly to the Sink. Once this phase is complete, the entire process repeats, with the network re-entering the setup phase to select new, energy-capable CHs for the next round, thus supporting continued load balancing.

B. *Hardware Prototype*

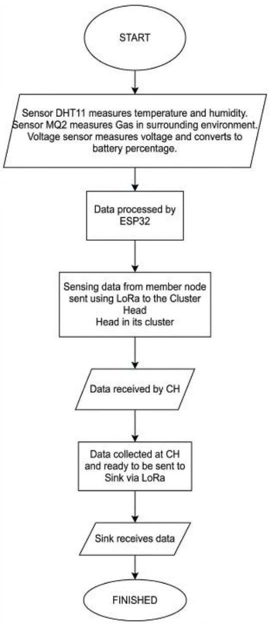


Figure 3 Tool flowchart

A physical WSN was constructed to validate the protocol's performance in a real-world setting. The system comprises multiple sensor nodes and a single Sink. Each sensor node was built using the components listed in table I, which includes an ESP32 microcontroller, a LoRa RA-02 module, and environmental sensors (DHT11 and MQ-2). The Sink node was similarly constructed using an ESP32 and a LoRa RA-02 module, serving as the central controller and data-logging station for the network.

The system was implemented using a sink node and multiple sensor nodes, with communication supported by LoRa modules and sensing functions provided by the attached environmental sensors. For a more detailed implementation, specific circuit schematics were designed for both the Sink and sensor nodes, outlining the precise pin configurations and connections between the microcontroller, LoRa module, sensors, and power supply.

The firmware for all devices was developed using the C++ language within the Arduino IDE. The operational logic for the Sink and the sensor nodes was programmed based on their respective flowcharts The Sink's software handles the centralized PC-LEACH logic for CH selection and data reception, while the node's software manages the sensing, sleeping, and state-transition logic (i.e., operating as a CH or cluster member).

To establish a stable communication link, all LoRa modules were configured with a uniform set of parameters, as detailed in Table I.

TABLE I
LORA PARAMETERS

parameter	Value
Frequency	915 MHz
TX Power	14 dBm
Spreading Factor (SF)	9
Bandwidth (BW)	125 kHz
Coding Rate (CR)	4/5

C. *System Flow and Operation Process*

The overall workflow of the proposed PC-LEACH protocol is detailed in the system flowcharts, which define the distinct operational logic for the Sink (Fig. 2) and the sensor nodes (Fig. 3). The protocol's operation is divided into two main phases: the Setup Phase (for cluster organization) and the Steady-State Phase (for data transmission).

The Setup Phase is initiated and managed by the Sink, which acts as the central controller. The process begins when the Sink broadcasts a 'request packet' to all sensor nodes in the network. Each node, upon receiving this broadcast, calculates its distance to the Sink and retrieves its current residual energy level. It then transmits this information back to the Sink and waits for further instructions. The Sink collects these responses, and once data from all nodes has been received, it calculates the dynamic CH selection score for every node using the formula in (1). Based on these scores, the Sink selects the optimal nodes to act as Cluster Heads (CHs) for the current round.

Once the CHs are selected, the Sink broadcasts a 'CH selection packet' to all nodes, signaling the start of the Steady-State Phase. At this point, each sensor node inspects the packet to determine its role:

1) *If selected as a Cluster Head (CH):* The node enters an active listening state, waiting to receive data packets from all its cluster members. After all data is received, the CH performs data aggregation and transmits the single, compressed packet to the Sink.
2) *If a Member Node:* The node reads its environmental sensors (DHT11 and MQ-2), transmits its data packet to its designated CH, and then immediately enters a deep sleep mode to conserve power until the next round begins.

This approach differs from the traditional LEACH algorithm, which relies on random, distributed CH selection. The centralized and energy-aware decision process in PC-LEACH, combined with the power-saving sleep mode for member nodes, is intended to reduce communication burden and extend the network's operational lifetime through more efficient energy use.

D. *Hardware Configuration and Parameters*

The physical WSN prototype was constructed using the components detailed in Table II. The system consists of multiple sensor nodes and a single Sink, which serves as the central controller.

TABLE II
HARDWARE COMPONENTS

component	function
NodeMCU ESP32	Main microcontroller for sensing and communication.
LoRa RA-02	Enables long-range, low-power wireless communication.
DHT11 Sensor	Measures ambient temperature and humidity.
MQ-2 Gas Sensor	Detect combustible gases and smoke.
Voltage Sensor	Monitors remaining battery voltage.
Li-Ion 18650 Battery	Provides power to each node.

The high-level architecture of the system is depicted in the block diagram (Fig. 4). For detailed implementation, specific circuit schematics were designed for both the Sink and sensor nodes, outlining the precise pin configurations and connections between the ESP32 microcontroller, LoRa module, sensors, and power supply.

The ESP32 microcontroller, programmed using C++ within the Arduino IDE, was responsible for handling all sensor data acquisition, executing the PC-LEACH protocol logic, and managing the LoRa communication routines[13].

For the communication link, the LoRa RA-02 module was configured to operate at a frequency of 915 MHz with a bandwidth of 125 kHz and a spreading factor (SF) of 9 to maintain an optimal balance between range and time-on-air[14]. The transmission power was set to 14 dBm, and a coding rate (CR) of 4/5 was used to maintain link reliability.

The system was powered using 3.7V Li-Ion 18650 batteries, each with a capacity of 2200 mAh. During testing, the data transmission interval was configured to 10 seconds. Power consumption was recorded in both transmission and idle modes, revealing a measured supply current of approximately 97 mA in the baseline non-clustering mode and a significantly reduced 64 mA under PC-LEACH operation, which aligns with standard ESP32 power profiles in IoT applications [15].

III. RESULTS AND DISCUSSION

This section presents the results obtained from the physical hardware implementation to analyze practical power consumption, residual energy behavior, and the operational implementation of the PC-LEACH protocol relative to a non-clustering baseline.

A. Sensor Calibration

Prior to system testing, sensor calibration was performed to ensure data accuracy. The DHT11 sensor for temperature and humidity, and the MQ-2 gas sensor for gas detection, were calibrated against reference instruments.

The average error for DHT11 temperature readings ranged between 0.35% and 1.08%, while humidity error ranged between 2.33% and 4.90%, which are within acceptable tolerance levels for low-cost environmental monitoring networks[16]. The MQ-2 sensor showed a significant change in resistance when exposed to combustible gas, confirming its functionality and responsiveness.

The repeated measurements shown for Node 1 indicate stable sensor output under the tested conditions. This supports the use of the DHT11 readings for prototype-level data acquisition and aggregation. Table III shows the sample calibration data for DHT11 Node 1.

Additionally, the MQ-2 calibration indicated a stable response curve during repeated exposure cycles. The sensor's recovery time after gas exposure was also within the expected range, showing no significant drift in sensitivity. This means that during long-term operation, the gas sensor can maintain accuracy without frequent recalibration.

TABLE III
DHT11 TEMPERATURE AND HUMIDITY SENSOR NODE 1

No.	Sensor Reading (ºC / %)	Reference (ºC / %)	Error Temp (%)	Error Humid (%)
1	28.00 / 44.00	28.2 / 43	0.709	2.326
2	28.00 / 44.00	28.2 / 43	0.709	2.326
3	28.00 / 44.00	28.2 / 43	0.709	2.326
4	28.00 / 44.00	28.2 / 43	0.709	2.326
5	28.00 / 44.00	28.2 / 43	0.709	2.326
6	28.00 / 44.00	28.2 / 43	0.709	2.326
7	28.00 / 44.00	28.2 / 43	0.709	2.326
Avg.			**0.709**	**2.326**

The low error percentages indicate that the acquired temperature and humidity readings were sufficiently consistent for the prototype-level environmental monitoring performed in this study. This calibration supports the use of the DHT11 sensor in the implemented hardware system. Following the DHT11 verification, a similar calibration procedure was conducted for the MQ-2 gas sensor to validate its responsiveness under controlled conditions.

In addition to temperature and humidity calibration, the MQ-2 gas sensor was also tested to evaluate its sensitivity to combustible gases. The calibration process was conducted by exposing the sensor to gas concentrations in a controlled environment and recording the sensor's analog output before and after exposure. The sensor's voltage and resistance values were measured using a multimeter to assess the responsiveness of the sensor under controlled exposure conditions.

Table IV presents the response of the MQ-2 gas sensor under different exposure conditions, including before gas exposure, during gas exposure, after gas dissipation, and repeated exposure. The recorded voltage and sensor resistance values were used to observe the change in sensor output relative to the baseline condition and to assess the consistency of its response to combustible gas.

TABLE IV
MQ-2 GAS SENSOR CALIBRATION SUMMARY

No	Condition	Sensor Voltage (V)	Sensor Resistance (kΩ)	Observation
1.	Before gas Exposure	0.45	12.8	Stable baseline reading
2.	During gas exposure	1.21	5.6	Rapid increase in voltage due to gas presence
3.	After gas dissipates	0.52	11.9	Sensor gradually returns to baseline
4.	Repeated exposure	1.18	5.8	Consistent response, confirming sensitivity

The MQ-2 calibration data indicate that the sensor responds to the presence of combustible gases, producing higher voltage readings during exposure and lower resistance values relative to the baseline condition. This behavior supports the operational use of the MQ-2 sensor in the proposed prototype.

B. Hardware Implementation Results

Figure 4 shows the physical prototype implemented using NodeMCU ESP32, LoRa RA-02, DHT11, MQ-2, and voltage sensors, powered by Li-Ion 18650 batteries. The network architecture consists of one sink node and 15 sensor nodes distributed over a 100 × 100 m area.

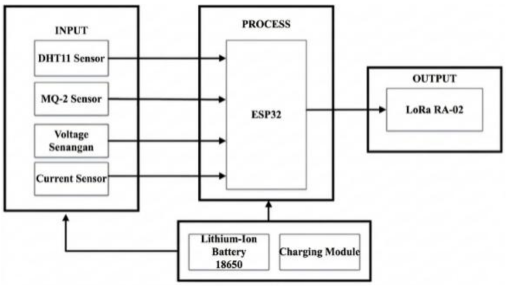


Figure 4. Physical Prototype of the PC-LEACH Hardware System

1) Non-Clustering Scenario

In the baseline scenario, each node was configured to transmit data directly to the sink without any clustering hierarchy. This "all-to-one," ad-hoc communication model serves as the critical benchmark for performance, representing a direct-transmission baseline without clustering hierarchy. Figure 5 presents the residual energy plotted per node over several operational rounds. The results are stark and immediate: the visualization clearly shows severe, unequal energy consumption across the network. Nodes that are physically closer to the sink exhibit a gentler, more gradual energy decline, while those farther away experience a much steeper, more rapid slope.

This disparity indicates uneven energy consumption across the network. Nodes located farther from the sink experienced a steeper decline in residual energy than nodes located closer to the sink, which is consistent with the greater transmission burden associated with direct communication to the sink. As a result, the non-clustering configuration showed less balanced energy usage than the clustered configuration discussed in the following section.

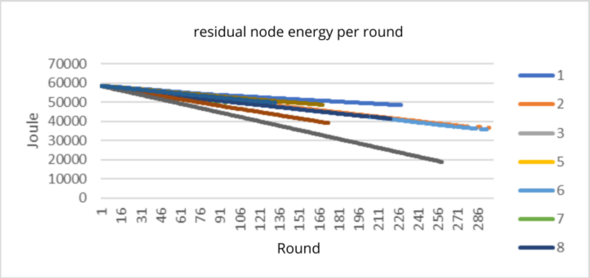


Figure 5. Residual Energy (Non-Clustering)

2) PC-LEACH Scenario

When the PC-LEACH protocol was activated, the network operated under a centralized clustered communication structure, in contrast to the direct-transmission baseline, the network operated under a centralized control system managed by the Sink. The Sink node successfully performed its role as this central controller, executing the adaptive cluster head (CH) selection algorithm based on each node's real-time residual energy and its physical distance. This allowed nodes with more favorable energy and distance conditions to be selected as CHs.

The serial monitor output shows that data aggregation and CH rotation were executed during hardware operation. Figure 6 shows that the residual energy curves under PC-LEACH were more uniform and more gradual than those in the non-clustering scenario. This pattern indicates that the clustered communication structure distributed energy consumption more evenly across the nodes. The observed behavior is consistent with the role of CH rotation and short-range member-to-CH transmission in reducing the burden of direct node-to-sink communication.

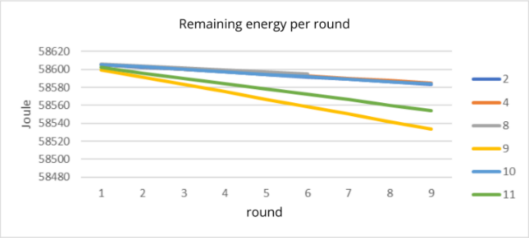


Figure 6. Residual Energy (PC-LEACH)

3) Performance Comparison

Figure 7 presents a direct comparison of residual energy between the non-clustering and PC-LEACH approaches. The PC-LEACH curve shows a smoother and more gradual decrease, whereas the non-clustering curve shows a sharper and less uniform decline. This comparison indicates that PC-LEACH maintained more balanced energy consumption across the nodes under the tested hardware configuration.

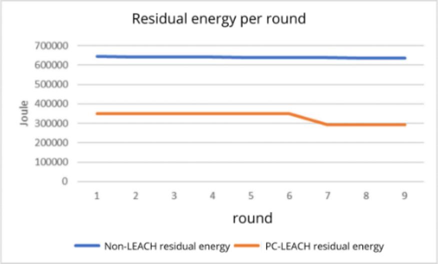


Figure 7. Residual Energy Comparison between Non-Clustering and PC-LEACH

C. Performance Analysis

The hardware implementation results indicate that PC-LEACH achieved lower energy consumption than the non-clustering baseline under the tested configuration.

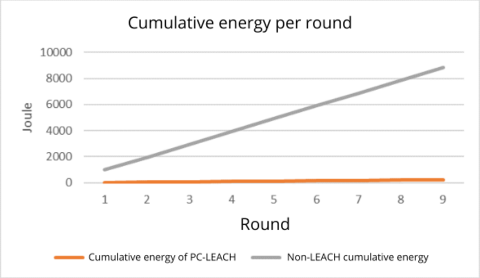


Figure 8. Energy comparison

Figure 8 compares the cumulative energy consumed by the non-clustering and PC-LEACH methods. The steeper, nearly linear slope of the non-clustering curve indicates a higher and more constant energy cost per round, since each node must transmit directly to the sink over longer distances. In contrast, the flatter PC-LEACH curve indicates slower cumulative energy consumption, reflecting the effect of clustered communication in reducing the transmission burden on individual nodes. This pattern is consistent with the measured average current draw, where the non-clustering scenario required 97 mA, whereas the PC-LEACH scenario required 64 mA. Overall, the difference in slope suggests that the PC-LEACH mechanism supports more efficient energy use under the tested hardware configuration.

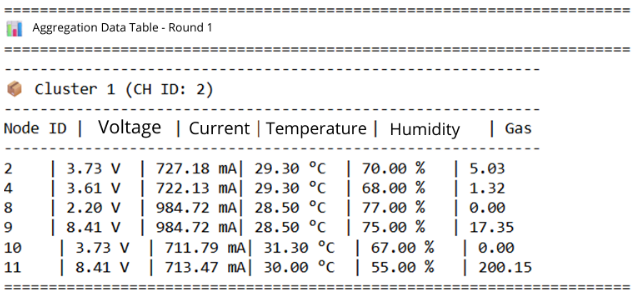
The lower energy consumption observed under PC-LEACH can be associated with two main aspects of the protocol:

1. CH rotation, which changes the coordination role across rounds based on the protocol criteria.
2. Centralized CH selection by the sink, which considers node energy and distance information.

These mechanisms are consistent with the more even energy depletion pattern observed in the hardware results. This tendency is also in line with previous studies reporting the benefit of centralized, energy-aware clustering for WSN energy management [17].

In addition to energy performance, the communication behavior and network stability of the system were also evaluated through hardware implementation. The following results highlight how PC-LEACH maintains reliable data transmission while conserving power.

The network stability and communication performance were evaluated based on the real-time hardware implementation using LoRa. During the experiment, the serial monitor output showed that nodes were able to transmit data to the cluster heads and subsequently to the sink in accordance with the implemented communication sequence.



```
======================================================================
📊 Aggregation Data Table - Round 1
======================================================================
------------------------------------------------------------
📦 Cluster 1 (CH ID: 2)
------------------------------------------------------------
Node ID |  Voltage  | Current | Temperature |  Humidity    | Gas
------------------------------------------------------------
2     | 3.73 V   | 727.18 mA| 29.30 °C   | 70.00 %    | 5.03
4     | 3.61 V   | 722.13 mA| 29.30 °C   | 68.00 %    | 1.32
8     | 2.20 V   | 984.72 mA| 28.50 °C   | 77.00 %    | 0.00
9     | 8.41 V   | 984.72 mA| 28.50 °C   | 75.00 %    | 17.35
10     | 3.73 V   | 711.79 mA| 31.30 °C   | 67.00 %    | 0.00
11     | 8.41 V   | 713.47 mA| 30.00 °C   | 55.00 %    | 200.15
======================================================================
```

Figure 9. Serial monitor results

The serial monitor results show that the PC-LEACH protocol successfully executed cluster formation, CH rotation, and data aggregation during hardware operation. The LoRa RA-02 modules also supported data transmission between nodes and the sink during the tested deployment. Taken together, these results indicate that the proposed hardware prototype operated in accordance with the implemented clustered communication structure.

Overall, the hardware implementation results support the effectiveness of PC-LEACH in reducing energy consumption relative to the non-clustering baseline under the tested setup. The residual energy and cumulative energy plots, together with the measured average current draw, consistently show that the clustered configuration produced a more even energy usage pattern. In addition, the serial monitor output and sensor calibration results support the operational feasibility of the implemented prototype.

IV. CONCLUSION

Based on the hardware implementation and testing, this research concludes that the Power-Aware Centralized LEACH (PC-LEACH) protocol reduced energy consumption compared with the non-clustering baseline in the tested LoRa-based Wireless Sensor Network. The measured average current draw decreased from 97 mA in the non-clustering scenario to 64 mA under PC-LEACH, corresponding to a 34% reduction. The residual energy and cumulative energy results also showed a more gradual and more even energy depletion pattern under the clustered configuration. In addition, the hardware prototype successfully executed CH rotation, data aggregation, and environmental sensing using the calibrated DHT11 and MQ-2 sensors. These results indicate that PC-LEACH was able to improve energy efficiency and support the operational implementation of a clustered LoRa-based WSN under the tested conditions.

REFERENCES

[1] S. Basagni, "Distributed Clustering for Ad-hoc Networks," *ACM Mobile Networks and Applications*, 2002.

[2] D. Kumar, T. C. Aseri, and R. B. Patel, "EEHC: Energy efficient heterogeneous clustered scheme for wireless sensor networks," *IET Communications*, vol. 4, no. 7, pp. 795-805, 2010.

[3] Y. Zhang, et al., "Energy-Efficient Routing in Wireless Sensor Networks," *IEEE Transactions on Wireless Communications*, 2011.

[4] Y. H. Prasetyo Isnomo, M. Muladi, and H. Elmunsyah, “MCACOF: Multi-Criteria Adaptive Clustering and Optimization Framework to Improve WSN Performance,” *IEEE Access*, vol. 14, pp. 4246–4273, 2026, doi: 10.1109/ACCESS.2026.3650923.

[5] Y. H. P. Isnomo, M. Muladi, and H. Elmunsyah, “Systematic Literature Review: Development of the Leach Protocol Algorithm for Efficient Energy Consumption in WSN,” *Przegląd Elektrotechniczny*, vol. 100, no. 7, pp. 148–157, 2024, doi: 10.15199/48.2024.07.31.

[6] A. A. S. H. Al-Dulaimi, M. A. Al-Tameemi, and Z. A. Abd-Al-Hussein, "Improved uplink throughput and energy efficiency of LoRaWAN using 2-hop LEACH protocol," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 24, no. 3, pp. 1557-1563, 2021.

[7] A. B. Santoso, M. N. Zakaria, and Y. H. P. Isnomo, "Implementation of Heed Routing Protocol in LoRa-Based Wireless Sensor Network," *Jurnal Jartel: Jurnal Jaringan Telekomunikasi*, vol. 15, no. 2, pp. 112-120, 2025.

[8] U. Ntabeni, B. Basutli, H. Alves, and J. Chuma, "Improvement of the Low-Energy Adaptive Clustering Hierarchy Protocol in Wireless Sensor Networks Using Mean Field Games (MFG-LEACH)," *Sensors*, vol. 22, no. 19, p. 7496, Oct. 2022.

[9] A. T. Wahyuni, Y. H. P. Isnomo, and M. N. Zakaria, "Implementation of the DE-LEACH Protocol in LoRa Communication Systems to Enhance WSN Lifetime," *Jurnal Jartel: Jurnal Jaringan Telekomunikasi*, vol. 15, no. 4, pp. 417–427, Dec. 2025.

[10] Semtech Corporation, "LoRa Technology Overview." [Online]. Available: https://www.semtech.com.

[11] Q. N. Abdullah and A. H. Ataalla, "Enhancing the lifespan of wireless sensor networks by PDBAC-LEACH protocol using clustering approach as an implementation strategy," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 30, no. 1, pp. 433–443, Apr. 2023.

[12] Cisco, "SNR, RSSI, EIRP and Free Space Path Loss," Dec. 2024. [Online]. Available: https://community.

cisco.com/t5/wireless-mobilityknowledge-base/snr-rssi-eirp-and-free-space-path-loss/ta-p/3128478.

[13] Espressif Systems, "ESP32 Technical Reference Manual," 2019. [Online]. Available: https://www.espressif.com.

[14] J. Haxhibeqiri et al., "A Survey of LoRaWAN for IoT: From Technology to Application," *Sensors*, vol. 18, no. 11, p. 3995, 2018.

[15] M. A. Rahman et al., "Power Consumption Analysis of ESP32 Microcontroller for IoT Applications," *IEEE Internet of Things Journal*, vol. 8, no. 12, pp. 9850-9860, 2021.

[16] D. H. Kim et al., "Calibration and Validation of Low-Cost Environmental Sensors for IoT Air Quality Monitoring," *IEEE Sensors Journal*, vol. 22, no. 5, pp. 4512-4520, 2022.

[17] Salim EL KHEDIRI, et al., "An Optimal Clustering Algorithm-Based Routing Protocol for Wireless Sensor Networks," 2019.