Optimizing energy distribution efficiency in wireless sensor networks using the hybrid LEACH-DECAR algorithm

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ABSTRACT

Wireless sensor network (WSN) is a network system consisting of various supporting components that integrate information to the base station. In its operation, delivery is greatly influenced by energy usage because limited battery supply causes variability in energy consumption on node activity factors, communication distance, and environmental conditions. So, in order to increase performance and energy efficiency, a routing protocol is required by selecting the best path through cluster head. The technique of determining the cluster head (CH) based on energy is used to avoid irregularity (randomness). In this study, the hybrid routing protocol selects CH based on the remaining energy, considering distance, coverage radius, and energy metrics. The system test evaluation compares the implementation of low-energy adaptive clustering hierarchy (LEACH) and hybrid LEACH- Distributed, energy and coverage-aware routing (DECAR). The results of 300 rounds show that the hybrid achieves a packet delivery ratio close to 100% and a throughput of 78.22 Kbps, while LEACH achieves a packet delivery ratio of 92.18% and a throughput of 247.15 Kbps. The average energy consumption of LEACH is 99.27%, while the hybrid shows much greater efficiency at 30.55%. This study emphasizes the significance of maintaining equilibrium performance and energy consumption in the development of future routing protocols.

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1. INTRODUCTION

Technology has developed very rapidly, advances in sensor technology in wireless communication network systems have resulted in further development [1]. A sensor-based wireless network system or known as a wireless sensor networks (WSNs) represent a significant technological innovation that supports a vast array of contemporary uses, such as medical care, surveillance systems, security apparatus, and manufacturing processes [2], [3]. WSN has several parts of small sensor nodes that are integrated and transfer information wirelessly or wirelessly through several stages until the data information reaches the control center or base station. This system is operated without physical cables, where these sensors are able to receive data information, unite, and communicate between devices directly or through intermediary nodes, one of which is by using a module as a data communication medium between nodes. The sensor node will be active by supplying a battery as a receiver and transmitter until the information is distributed, but the limitations of coverage and energy contained in the sensor node are a challenge [4]. This condition can be caused by several factors, including the distance between node points that are far apart, consumption at the sensor node. Factors that are not immediately addressed will result in decreased data transmission performance and high energy consumption [5]. This condition has the potential to shorten the life of the WSN network [6].

To overcome energy and network performance problems, the development strategy applied is an energy-efficient routing protocol [7], [8]. The implementation of the routing protocol by selecting the appropriate path for sending data from the network system by determining certain criteria on the way from the source of delivery to the destination. This process aims to maintain the stability of energy consumption and data communication delivery so that it reaches its destination, so that the network usage period can be more optimal [9]. In the implementation of the routing protocol, Its effectiveness has been demonstrated that sensor nodes can be grouped into different areas, each overseen by a specific leader node referred to as a cluster head (CH). Every CH gathers information from its associated nodes, analyzes the data, and transmits it to the primary base station [10]. Similar research related to the development of an energy-efficient low energy adaptive cluster hierarchy (LEACH) routing that can extend network life by using an adaptive CH selection mechanism shows that battery life usage has increased, and the system can be more optimal [11], [12]. The development of the LEACH routing protocol by combining both algorithms, shows that the hybrid scheme can reduce average energy consumption compared to using the LEACH configuration, not only stabilizing packet delivery, but also improving overall network performance [13]. The hybrid schemes are able to enhance effectiveness of energy by reducing transmission frequency inside the network and streamlining the message delivery process [14].

In addition, the application of algorithms to overcome the problem of energy consumption effectiveness in delivery, requires the application of routing protocol optimization with grid-shaped cluster grouping on each sensor node [15]. In this case, the grouping can be structured based on a predetermined distance radius [16]. The implementation was tested using parameters based on average energy consumption, throughput, and delivery ratio so that performance and energy usage are more optimal so that it can increase network usability. This research focuses on the execution of routing protocols a combined approach, through the selection of cluster heads combines with LEACH method with adaptive randomization and the distributed, energy and coverage-aware routing (DECAR) technique based on residual energy and coverage. An even node distribution using a grid pattern can serve as an effective strategy for organizing clusters within wireless sensor network systems. The protocol implementation uses three routing metrics including distance between points, coverage radius, and energy. Therefore, the findings of this study have a contribution to providing feasible solutions to the identified problems, how much influence the hybrid scheme has on the energy and performance of the single-hop wireless sensor network so that the hybrid technique is able to enhance energy efficiency and performance obtained.

2. METHOD

In this study, we develop a routing protocol using a hybrid algorithm in WSNs. A hybrid strategy is achieved by merging the LEACH protocol along with DECAR. This integration focuses on selecting nodes as efficient CH in each round. The process includes parameter setting, area calculation, node coverage assessment, CH selection, and data analysis, as visually represented in Figure 1. The CH selection cycle takes into account the leftover energy levels and the distance of the nodes. Every node calculates its coverage based on its energy levels and distance i to base station (BS), subsequently forwarding information from the cluster nodes to the BS. This methodology ensures an efficient classification system regarding energy distribution in WSNs.

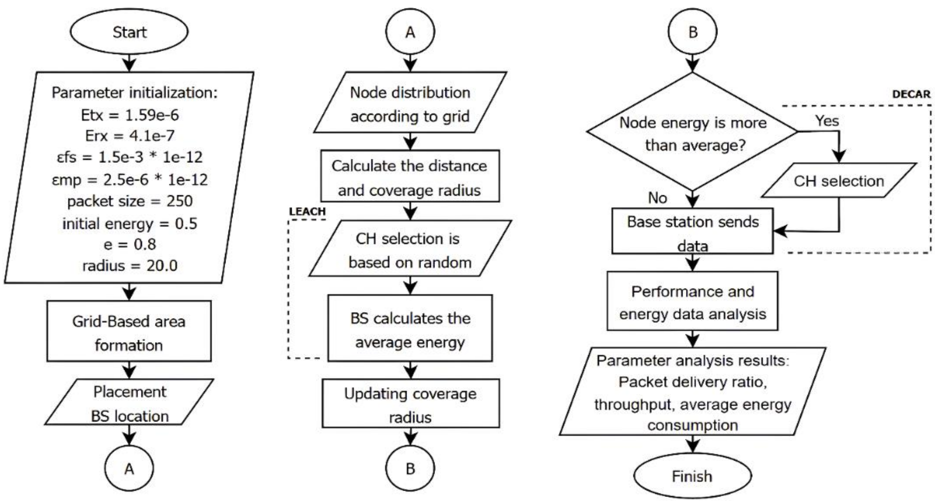


Figure 1. Research framework

2.1. System classification

In the formation of the system, the classification of research parameters was established to determine the performance of the LEACH-DECAR hybrid routing protocol. Parameter initialization was used as an estimate for testing in the wireless sensor network system, as shown in Table 1. In this study, various experiments were conducted to test different numbers of nodes distributed in the network area, with five tests involving 100, 150, 200, 250, and 300 nodes [17]. The nodes were distributed randomly and provided with equal energy for classification purposes.

Table 1. Research parameters

Parameter	Nilai
Size area	100×100 m
BS location	50×50
Initial energy	0.5
E_{tx} (Transmission energy)	1.59 μJ/bit
E_{rx} (Receiver energy)	0.41 μJ/bit
ϵ_{fs}	1.5×10^{-3} pJ/bit
ϵ_{fmp}	2.5×10^{-6} pJ/bit
Packet size	250
e	0.8
Sensor radius	20.0

2.2. Network model

The formation of this wireless sensor network system was conducted in an area measuring 100×100 m, with the base station center point positioned at coordinates (50, 50). The network was organized based on a network model by applying the grid-based technique, as illustrated in Figure 2.

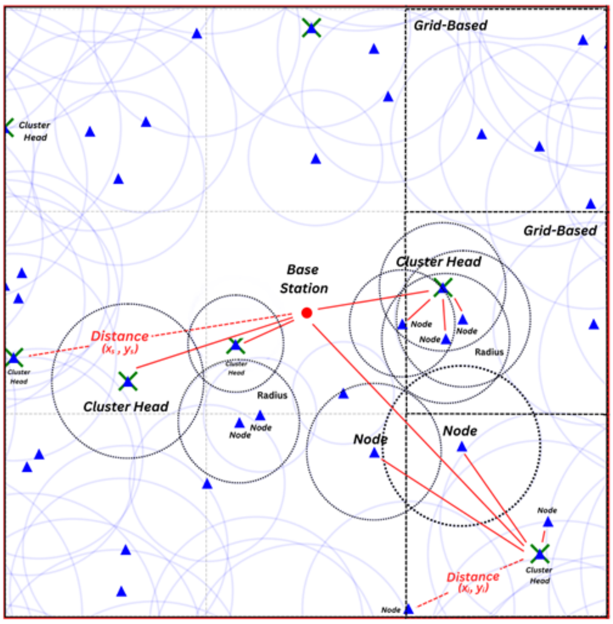


Figure 2. Wireless sensor network scheme

The concept of decentralized grid-based networking involved organizing resources in a grid format, which was structured as small boxes or nested loops by randomly and evenly allocating nodes throughout the area [18]. This approach facilitated efficient distribution and access processes. The coordinates (x, y) of each box were represented as cells, and each node had a fixed cell location (x_i, y_i) within the box. The initialization of the coordinate cell location x_i was accomplished by,

$$x_i = (g_x \times grid\_size)\ np.random(0, grid\_size)$$

And at the y_i coordinate with,

$$y_i = (g_Y \times grid\_size) + np.random(0, grid\_size) \quad (1)$$

Where g(x, y) is the grid index for the (x, y)coordinates; grid_size indicates the size of each grid cell in its initial vertical or horizontal position; and np.random represents the random offset to adjust the grid cell, creating variation within the cell.

In random deployment, each node in the grid will have x, y coordinates. These coordinates ensure that each area is reachable, thereby minimizing dead zones. The distance measurement model between the CH and the base station can be represented by,

$$d_{to}CH = \frac{M}{\sqrt{2\pi k}}$$

$$d_{to}BS = 0.765\frac{M}{2} \quad (2)$$

Where $d_{to}CH$ represents the distance among fellow node and the cluster head; $d_{to}BS$ indicates the distance between the CH and the base station; and k is the number of clusters.

2.3. Energy consumption model

All sensor nodes are considered to start with equal initial energy. The amount of energy each node consumes is determined by a radio energy model, which takes into account the transmission distance between transmitter and receiver. Based on this distance, either a free space propagation model or a multipath fading model is applied. Consequently, the transmission energy $E_{Tx}(l, d)$ consumed when transmitting a message (in bits) over a distance (d) will decrease [17], [18],

$$E_{Tx}(l,d) = lE_{elec} + l \in d^2 \quad (3)$$

$$\begin{aligned} &lE_{elec} + l \in_{fs} d^2 \qquad d < d_0 \\ &lE_{elec} + l \in_{fmp} d^4 \qquad d \geq d_0 \end{aligned} \quad (4)$$

Where E_{elec} indicates the amount of energy consumed system, including both the sender and receiver, measured in bits; $\in_{fs}$ [J/bit/m²] and $\in_{fmp}$ [J/bit/m⁴] they respectively represent the energy consumption under free space and multipath models. Parameter of d_0 indicates the distance limit where the energy model transitions from open space to multiple path transmission, indicating a change in energy consumption characteristics.

$$d_0 = \sqrt{\frac{\in_{fs}}{\in_{fmp}}} \quad (5)$$

When a node receives a message (in bits), the energy consumption is represented as E_{Rx}, which indicates the energy dissipation per unit time. The process of receiving a message can be described using the following [19], [20],

$$E_{Rx}(l) = lE_{elec} \quad (6)$$

The network will conserve energy during the rotation process. With each rotation, the network updates the coverage radius to ensure that the entire observed area remains covered.

$$r_c' = \left(1 - e \, . \frac{d_{max} - d_{sink}}{d_{max} - d_{min}}\right). r_c \quad (7)$$

Here, r_c represents the initial reference radius used as a benchmark for calculating the efficiency constant factor, denoted by the symbol e; The variables d_{max}, d_{min}, and d_{sink} describe the maximum and minimum distances within the network, along with the distance from a particular node to the central station. In a balanced radio communication link, an equal quantity of energy is necessary to transmit and receive information (in bits) among different nodes. In the LEACH protocol, ideal data aggregation is achieved by collecting packets from various cluster members, which are then integrated by the CH and transmitted as one complete bundle to the base station (BS). In addition, the overall energy used in every cycle is dictated by [21].

$$E_{round} = L(2NE_{elec} + NE_{DA} + k \in_{fmp} d_{to}^4 BS + N \in_{fs} d_{to}^2 CH) \quad (8)$$

Then, in the next round, the energy consumption rotation model is repeated for each node until the energy reaches the specified limit.

2.4. Hybrid LEACH-DECAR routing protocol

The combination of LEACH and DECAR routing protocol principles is the topic of this research. The selection of CH responsibilities will be carried out by implementing LEACH, which selects randomly while DECAR will determine based on residual energy [16], [22]. Hybrid LEACH-DECAR employs a distinct CH selection mechanism, combining elements from both the LEACH and DECAR protocols.

It begins with the initialization of each node, taking into account its available energy and geographical position. During the first round, each node makes a random choice about whether or not to transform into a CH, using a likelihood set by a random figure between 0 and 1. The initial round is governed by time division multiple access (TDMA), which includes a setup phase for determining the CH and a steady-state phase for the message transmission process (sending and receiving) [23]. An illustration of the LEACH phase is shown in Figure 3.

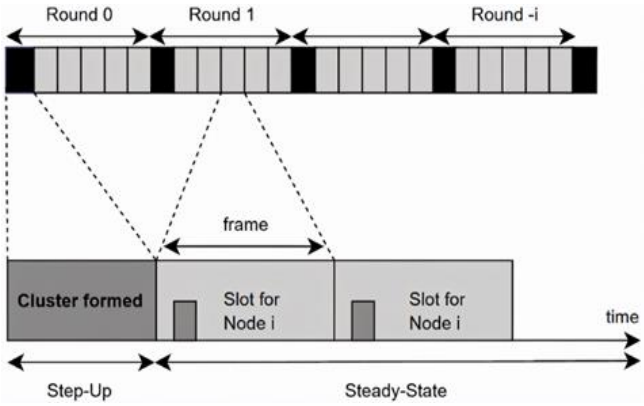


Figure 3. Illustration of LEACH phase

The CH selection phase takes place within the process of forming clusters, where an evaluation is conducted to determine if node-i's count falls below a certain limit. If that is the case, node-i satisfies the requirements to assume the role of a CH [24]. Other nodes will join the nearest cluster based on their geographical positions, as described in (2).

Each member that joins will send a message to the CH according to the predetermined delivery schedule. The process for selecting CH is carried out by assessing the remaining energy, making certain it is above the established limit. The energy evaluation at each node can be determined using the equation,

$$w_i = \frac{E_i}{d_i + \epsilon} \quad (9)$$

The leftover energy capacity of every node is denoted as w_i; where E_i signifies the energy still available at each node and d_i indicates the distance for communication from node i. The communication distance is calculated using the following equation [25],

$$d_i = \sqrt{(x_i - x_s)^2 - (y_i - y_s)^2} \quad (10)$$

where (x_i , y_i) represent the position of the i node, while (x_s , y_s) denote the location of the sink.
ϵ = distance stability value (avoids division by zero).

Nodes with higher energy levels exhibit greater polarity in the routing process, increasing their chances of becoming CH. This criterion helps prevent the overloading of low-energy nodes and allows CHs to remain active longer compared to random selection. The Hybrid LEACH-DECAR protocol implements CH rotation and radius coverage. After several rounds, the node designated as CH will be replaced based on the same criteria, with updates to the coverage radius as described in (7), optimizing energy usage and extending network lifetime. Thus, the Hybrid LEACH-DECAR mechanism can achieve more efficient and sustainable CH selection.

2.5. System measurement parameter

Measurement of the performance and energy levels of a network can be classified using parameters in determining the level of success in sending data, displaying consistency, and others. The study of simulated system testing scenarios incorporates a variety of factors for assessing network performance. These factors include the packets delivery ratio, overall throughput, and evaluations of average energy consumption.

2.5.1. Packet delivery ratio

This evaluation of parameters is conducted by determining the proportion of data packets that have reached the intended destination in relation to the overall data produced by the node. The ratio can consider the performance of reliability in data delivery. The parameter calculation uses the following equation [26].

$$Packet\ Delivery\ Ratio = \frac{Packet\ received}{Packet\ sent}\ x\ 100\% \tag{11}$$

2.5.2. Throughput

The parameter shows the result of the average volume of data that crosses the network in a certain period of time. In the process of data transmission, there exists both the count of data packets successfully dispatched to the endpoint and those datas that fail to arrive (lost). The calculation of the throughput parameter uses the following [27],

$$Throughput = \frac{Output\ data\ received\ (bit)\ x\ packet\ size}{Data\ delivery\ time} \tag{12}$$

2.5.3. Average consumption energy

The parameter shows the results of the average volume of overall energy usage used by the system. The measurement is obtained according to the sum of each node's consumption per round to obtain the overall results of energy usage in the system.

$$E_a = \frac{\sum_{k=1}^{n}[E_{ik} - E_{fk}]}{N} x100\% \tag{13}$$

3. RESULTS AND DISCUSSION

After the software configuration on the wireless sensor network system is complete. The next stage to validate the performance and energy efficiency of hybrid LEACH-DECAR routing analysis is carried out on the LEACH routing protocol. Analysis testing is based on test parameters, where nodes are randomly distributed and over time there is a reduction in residual energy in the level of energy consumption per node.

This study provides a discussion and comparative analysis of two routing protocols under identical scenarios, focusing on system performance indicators, including packet delivery ratio, data flow rate throughput, and also average energy consumption. Various tests of the number of nodes 100, 150, 200, 250, 300. Based on the calculation equation for the test parameters above, we can create a network model based on the parameters in Table 1. The system design is tested as a classification of performance and energy efficiency on the network.

3.1. Network performance

Network performance testing is carried out as a measure of system performance in the process of sending packets to the destination point. The test was carried out for 300 rounds with an initial energy per node of 0.5 joules and a data packet sent with a size of 250 bits. During the test, the number of packets from each round was analyzed to measure the performance of sending and receiving data in units of time. The outcomes of the through put examination are illustrated in Figure 4.

Data delivery rate of the LEACH routing protocol is far superior to using a hybrid routing protocol. Figure 4 shows that testing a hybrid routing protocol with 100 nodes only gets 12.5%, 150 nodes get 17.5%, 200 nodes get 22.4%, 250 nodes get 26.9%, and 300 nodes get 31.6% of the LEACH routing protocol. The data that is distributed will experience a significant increase at the beginning of the delivery, but there is some data that is not sent when the system energy is insufficient, resulting in data loss and data not being received by the base station.

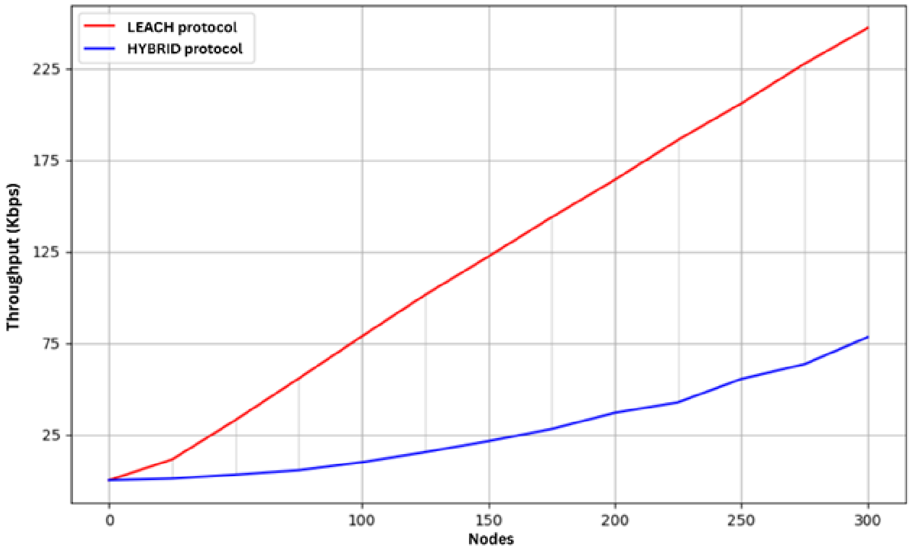


Figure 4. Throughput results

Packet delivery ratio from the test results is shown in Figure 5, from several node variation experiments, the hybrid routing protocol did not experience a decrease from testing 100 to 300 nodes, so the entire packet sent did not experience any problems when the packet went to the base station (all packets were delivered to the main station). Nonetheless, result from the LEACH routing protocol assessment revealed a reduction in the packet ratio during the 100 node evaluation by 0.21% and by 2.27% in the 150 node evaluation, the 200 node test of 3.53%, the 250 test of 6.13%, and the 300 node test of 7.82%, This shows that there are several packets that experience problems when sending to the base station (packets are lost).

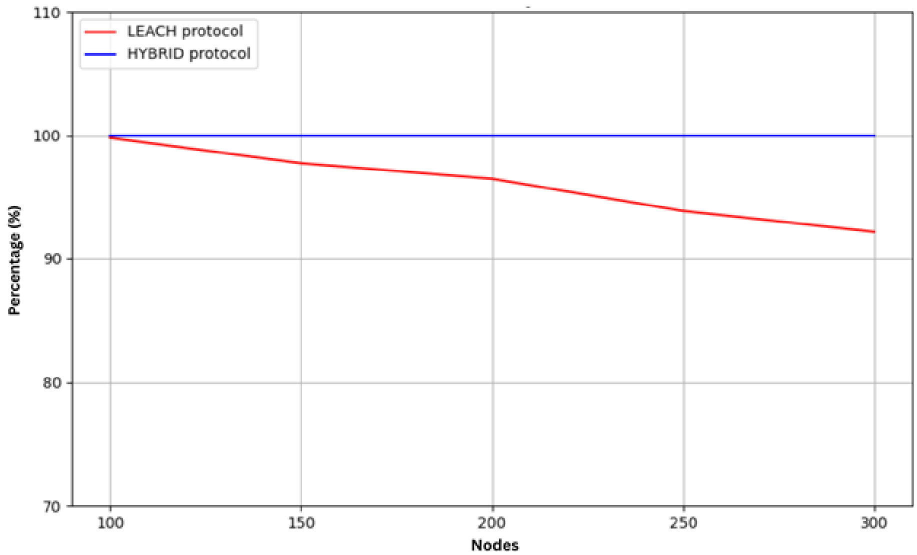
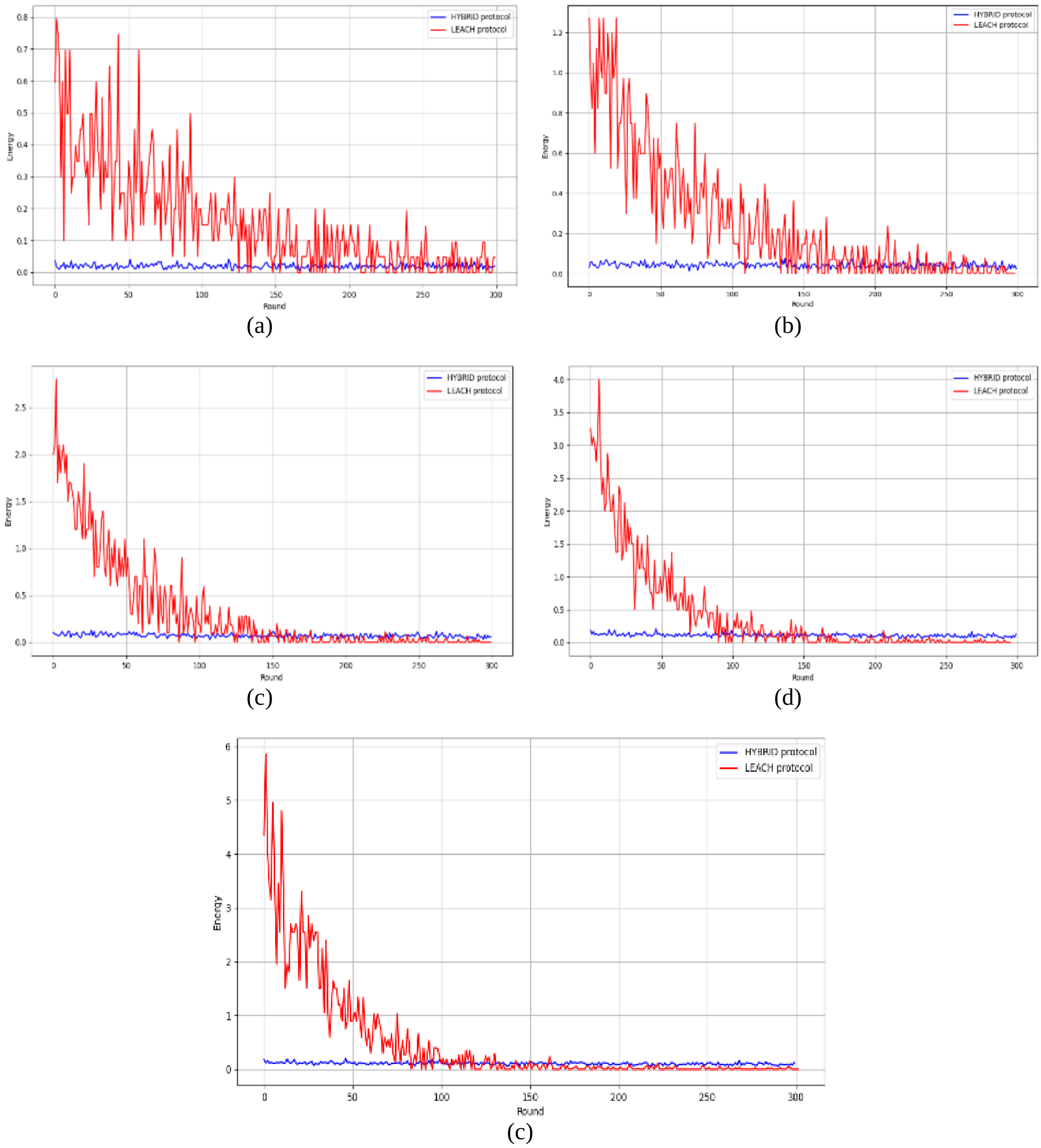


Figure 5. Packet delivery ratio result

3.2. Network energy consumption

Network energy consumption testing is carried out as a measure of how much consumption is on system performance. In energy consumption testing, the comparison between the total overall energy consumption and the energy consumption per node from several test classifications for each different number of nodes [28]. Testing is carried out for 300 rounds with an initial energy per node of 0.5. Energy consumption results obtained are presented in Figure 6.

Furthermore, from the test results using a hybrid routing protocol with several variations of node testing, the resulting energy consumption remains stable up to ≥300 rounds and there is no spike at the beginning of the test, while the LEACH protocol indicates an increase in data delivery in the early rounds. Figure 6(a) shows the comparison of energy consumption with 100 nodes, where the hybrid routing protocol remains stable while the LEACH protocol fluctuates significantly before gradually decreasing. Figure 6(b) shows that the 150 nodes LEACH routing protocol test has started to run out of energy before 300 rounds. Then, Figures 6(c) and 6(d) show that the LEACH routing protocol is slowly running out of energy testing 200 nodes at 170 rounds and 250 nodes at 155 rounds. Figure 6(e) shows that the LEACH routing protocol is starting to run out of energy <150 rounds. This indicates that an increased delivery rate correlates with greater energy use, if the starting condition has already seen a surge in energy usage, it may lead to the node depleting its energy reserves, resulting in suboptimal performance in the subsequent rounds of operation.



(a) (b) (c) (d) (c)

Figure 6. Energy consumption in a round (a) 100 nodes, (b) 150 nodes, (c) 200 nodes, (d) 250 nodes, and (e) 300 nodes

The results of the packet delivery ratio test show variations between some data that is sent and not sent (up to the Base Station). Table 2 shows the percentage ratio of hybrid protocol testing at 100-300 nodes, the packet delivery performance is very good, without any packet delivery ratio (PDR) value decreasing until the 300-round test. With the growth in the total of network nodes, the span lies between 100 and 300 nodes, the hybrid protocol can still send all packets compared to the LEACH protocol which experiences a gradual decrease. This is because the number of nodes is too dense, causing a decrease in PDR and packet loss, the larger the node in a range, the slower the delivery communication will be [29]. Moreover, packet loss may occur if a node depletes its energy during the communication process, resulting in the packet failing to reach the base station directly. In this case, the hybrid LEACH-DECAR protocol considers energy management strategies more in continuous packet delivery, thereby reducing the loss of packets sent during the delivery process [30].

Table 2. Performance of throughput and packet delivery ratio

Nodes	Throughput (Kbps)		Packet delivery ratio (%)	
	LEACH	HYBRID	LEACH	HYBRID
100	78.62	9.83	99.7874	100
150	122.19	21.35	97.72798	100
200	164.14	36.84	96.47164	100
250	205.88	55.34	93.86876	100
300	247.15	78.22	92.18398	100

Table 3 shows the comparison of energy consumption between LEACH and hybrid routing protocols on different numbers of nodes in operation for 300 rounds. From the data obtained, it can be observed that the LEACH routing protocol exhibits an increasing trend in energy consumption during each cycle as the quantity of nodes increases, starting from 0.1579 joules at 100 nodes to 0.4964 joules at 300 nodes. In contrast, the hybrid routing protocol also shows an increasing trend, but with a much lower value, namely from 0.0194 joules to 0.1527 joules. The average energy consumption for LEACH is also quite significant, with a value reaching 99.27% at 300 nodes, indicating high efficiency in energy management. On the other hand, hybrid shows a lower average energy consumption, namely 30.55% at 300 nodes, indicating that the protocol is more energy efficient, the overall performance is still inferior to LEACH in terms of efficiency. This suggests that although hybrid is more efficient in energy consumption.

Table 3. Network energy consumption

Nodes	Energy consumption of round (Joule)		Energy consumption 300 rounds (Joule)		Average consumption energy (%)	
	LEACH	HYBRID	LEACH	HYBRID	LEACH	HYBRID
100	0.157898528	0.019395404	47.36956	5.818621	94.74	11.64
150	0.245377634	0.041858979	73.61329	12.55769	98.15	16.74
200	0.329668936	0.072203225	98.90681	21.66097	98.91	21.66
250	0.413501491	0.108421614	124.0504	32.52648	99.24	26.02
300	0.496379161	0.152748387	148.9137	45.82452	99.27	30.55

Table 4 provided a brief overview of the comparative results of the review of four aspects, demonstrating that LEACH saved energy consumption efficiency by reducing the number of messages delivered at one time, which resulted in an unstable packet loss ratio. In contrast, hybrid LEACH-DECAR offered advantages in energy management, with messages delivered at one time being relatively low, thereby ensuring that the stability of the packet loss ratio was minimal or more stable. When compared to similar advanced routing protocols that focus on energy efficiency for instance the directing for weak energy in unreliable networks (RPL), hybrid LEACH-DECAR exhibited advantages in energy consumption management, although RPL maintained a better packet delivery ratio stability in unstable network conditions [7]. Thus, hybrid LEACH-DECAR presented an attractive alternative in the scope of efficient energy management.

Table 4. Comparison of LEACH vs Hybrid LEACH-DECAR

Aspect	Protocol routing	
	LEACH	Hybrid LEACH-DECAR
Throughput scalability	High	Low
Energy efficiency	Low	High
Stability of PDR	Less stable	Stable
Balance between performance and energy	Suboptimal	Optimal

4. CONCLUSION

This study proposes the design of a hybrid LEACH-DECAR routing protocol scheme in WSNs that will be compared with the LEACH routing protocol during testing. The hybrid LEACH-DECAR scheme involved selecting the CH based on random selection with residual energy, allowing for maintained routing selection during delivery to the base station. The performance and energy efficiency were determined based on testing parameters criteria including data transmission efficiency ratio, throughput, and average energy consumption, with experiments conducted on 100, 150, 200, 250, and 300 nodes. The evaluated performance of both routing protocols with 300 rounds clearly shows that the proposed hybrid LEACH-DECAR routing protocol provides quite good delivery ratio performance, reaching 100% in the system, but the data flow throughput performance is lower than the LEACH protocol, which is 247.15 Kbps for LEACH and 78.22 Kbps for hybrid. The energy consumption of the hybrid routing protocol is relatively more efficient, with an average energy consumption of 30.55% compared to the LEACH protocol which reaches 99.27%, which is caused by a spike in data delivery at the beginning of the round. The test results show an inverse relationship between performance improvement and energy consumption. The LEACH protocol excels in data flow delivery performance, while the hybrid protocol is superior in stabilizing the packet transmission success possesses a lower average energy consumption than the LEACH protocol. Routing protocols were developed sustainably by exploring other protocol algorithms. The Hybrid LEACH-DECAR technique in this study performed well in regulating the level of energy efficiency. However, this did not cover the effectiveness of the message delivery flow level in the network. This could be overcome through a density approach and intelligent data aggregation to balance performance results and network energy efficiency, or through other methods.

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This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Author state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article [and/or its supplementary materials].

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