# Hybrid Cluster Based Protocols for Reliable Data Communication in Wireless Sensor Networks

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**Abstract –** The most vital problem in wireless sensor networks (WSNs) is energy efficiency and dependable data transmission especially when these systems are deployed in large scale and their deployment is heterogeneous. This paper will present a proposal of a Cluster-Based Hybrid Protocol (CBHP): It entails a combination of adaptive clustering and energy conscious cluster head rotation to prolong network lifetime whilst ensuring high reliability in communication. The protocol takes the benefits of both static and dynamic clustering and therefore balances power consumption among nodes and minimizes the premature node failures. The extended simulations are done between CBHP and known protocols as LEACH, TEEN, and DEEC under the same network conditions. The analysis involves various performance indicators including First Node Death (FND), Last Node Death (LND), average power consumption per round, packet delivery ratio (PDR), throughput and the end to end delay. On the basis of simulation, it is shown that CBHP has a 29.63% portfolio of network lifetime when compared to LEACH whilst at the same time has the highest PDR of 97.6% and throughput of 1.35 kbps. The protocol proposed also has the lowest average end to end delay (120 ms), which proves its applicability in time-sensitive protocols. Further quantitation analysis shows network stability, residual energy and control overhead improvements, showing the ability of the protocol to support more active nodes during long operational durations. These results prove that CBHP offers an effective trade-off among the energy consumption, reliability of communication, and latency, and it is a strong solution in the current WSN applications.

**Keywords –** Energy Efficiency, Cluster-Based Hybrid Protocol, Network Lifetime, Packet Delivery Ratio, Throughput, End-to-End Delay.

## I. INTRODUCTION

Applications of the Wireless Sensor Networks (WSNs) include environmental monitoring, industrial automation and health systems. These networks are made up of the spatially distributed sensor nodes, which are collaborative in sensing and transmitting data. The main issue affecting WSNs is that sensor nodes have a low amount of energy, which may cause an early network failure unless the energy usage is optimized properly. Routing protocols that are energy-efficient are important when it comes to increasing the lifetime of the network. Among the oldest and the most influential clustering protocols is the Low Energy Adaptive Clustering Hierarchy (LEACH) that employs randomization of the cluster head rotation to achieve even distribution of energy consumed among the nodes [1]. Nonetheless, it may become ineffective in networks of large scale or or in heterogeneous networks because of the randomness of the choice of cluster heads and the unawareness of energy conditions.

A number of improved protocols have been suggested to address these constraints. This protocol, the Threshold-sensitive Energy Efficient Sensor Network (TEEN) protocol presents both hard and soft thresholds to manage the transmission of data, which minimizes the use of energy [2]. Although TEEN is also efficient in energy saving, it can lead to lower packet delivery ratios in a situation because of being reactive. The Distributed Energy-Efficient Clustering (DEEC) protocol identifies cluster heads according to leftover energy as a mechanism of ensuring that the consumption and network lifetime are balanced [3]. Even though this has been improved, DEEC can face additional overheads in control and latency due to dynamism in the network.

In recent studies, there is a tendency to consider hybrid models which unite the benefits of several clustering methods. However, the successful trade-off between the energy usage, data transmission, and the network duration is hard to realize. The paper suggests a protocol called Cluster-Based Hybrid Protocol (CBHP), which combines adaptive clustering with the implementation of energy-saving concepts in clustering head rotation in order to enhance the network performance. The comprehensive simulations are done to compare CBHP to LEACH, TEEN and DEEC in terms of network lifetime, packet delivery ratio, throughput and end to end delay.

The rest of this paper will consist of five parts. Section 1 contains the introduction, which outlines the problems associated with wireless sensor networks and the reason why it is necessary to have an energy-efficient and reliable routing protocol. Section 2 is a literature review of the relevant research in clustering-based and energy-aware protocols, such as LEACH, TEEN, DEEC, and hybrid solutions, and defines the gaps that guide the proposed work. Section 3 outlines the design and methodology of the proposed Cluster-Based Hybrid Protocol (CBHP), including the adaptive clustering mechanism, energy efficient cluster head selection as well as data transmission schemes. Section 4 gives the simulation setup, performance assessment measures, and the comparative analysis model applied to compare the proposed protocol to traditional approaches. Lastly, Section 5 presents the analysis of the simulation outcomes, including some detailed inferences on the energy usage, network lifetime, the ratio of the packet delivery, throughput, and end-to-end delay, and finally the conclusion of the analysis of the implications and possible use of CBHP.

## II. RELATED WORKS

The problem of energy-efficient routing in WSNs has been widely researched because of the energy limitations of sensor nodes. The protocols based on clustering have been known to minimize communication overheads and enhance network lifetime. One of the first works on the subject is the LEACH protocol [4]. LEACH makes use of the randomness of cluster head rotation as a means of evenly sharing energy consumption among nodes. Although it works well in homogeneous networks, its random selection of the cluster head may not be optimum in large scale networks or heterogeneous networks, which causes early death of nodes.

**Table 1**. Comparison of Related Works on Clustering-Based WSN Protocols

| Protocol | Energy Efficiency | Cluster Head Selection | Scalability | Reliability | Latency | Key Limitation | Ref. |
|---|---|---|---|---|---|---|---|
| LEACH | Moderate | Randomized rotation | Medium | Moderate | Low | Random CH selection may lead to early node deaths in heterogeneous networks | [11] |
| TEEN | High | Threshold-based | Medium | High | Low | Reactive approach may reduce PDR in sparse networks | [12] |
| DEEC | High | Residual energy-based | High | Moderate | Medium | Increased control overhead under dynamic conditions | [13] |
| HEED | High | Hybrid: energy & proximity | High | High | Medium | Requires frequent neighbor info updates | [14] |
| PEGASIS | High | Chain-based | Medium | High | High | Increased delay due to long chain communication | [15] |
| EARP | High | Energy-aware | High | High | Low | Complexity increases in large-scale deployments | [16] |
| Swarm-based/Hybrid | Very High | Optimized via swarm intelligence | High | Very High | Low-Medium | Computationally intensive; may not suit real-time constraints | [17] |

The TEEN protocol adds hard and soft respective thresholds to manage data transmission, which thus end up saving energy in time-sensitive application [5]. TEEN minimizes avoidable transmissions though its reactive mechanism can lower the ratio of packet delivery with some network conditions. In the same manner, DEEC protocol depends on residual energy to select cluster heads to balance consumption and to ensure long network life [6]. In dynamic network conditions, DEEC may have a greater control overhead and latency than LEACH, depending on the energy efficiency of the system.

With these drawbacks, a number of hybrid and energy-conscious protocols are suggested. As an example, The Hybrid Energy-Efficient Distributed Clustering (HEED) protocol integrates the residual energy and node proximity in the selection of cluster head, which enhances the network lifetime [7]. Energy-Aware Routing Protocol (EARP) is concerned with the energy consumption balance among nodes without affecting the connectivity and reliability [8]. Also, there are recent methods, which investigate multi-objective optimization based on swarm intelligence or fuzzy logic to apply the improvements to energy efficiency, throughput, and latency at the same time [9], [10].

With such developments, there is an element of discrepancy in maintaining a healthy trade-off between the longevity of network, reliability of data flowing through it, and communication latency. The comparison of the related works on the clustering-based WSN protocols is provided in **Table 1**. The majority of the available protocols focus on efficiency or reliability at the cost of the other one. This prompts the creation of the Cluster-Based Hybrid Protocol (CBHP) that combines adaptive clustering with energy-conscious cluster head rotation to increase their network lifetime and communication quality.

## III. PROPOSED INTELLIGENT CLUSTER-BASED HYBRID PROTOCOL

The increasing nature of wireless sensor networks requires the communication protocols, which have the capacity to balance energy efficiency, reliability, and scalability. In traditional routing protocol, either direct packet transmission or multi-hop communication is utilized only, which causes energy wastage imbalances and decreased network life. To address such difficulties, the Cluster-Based Hybrid Protocol (CBHP) is suggested to provide the smart model that integrates the advantages of clustering and dynamic hybrid routing. The system architecture as shown in **Fig. 1** has been structured into various layers in which the sensor nodes are clustered into groups and each cluster is controlled by a Cluster Head (CH) who takes charge of data aggregation and relay. In contrast to the conventional methods which use a fixed transmission mode, the suggested protocol dynamically uses direct and multi-hop communication depending on network conditions, remaining energy, and transmission distance. Such an adaptation mechanism does not merely limit the overhead in communication, but also minimizes the loss of packets and improves the stability in the delivery of data even when the network is dynamic. Moreover, a feedback acknowledgment scheme is also included in the base station that ensures the proper reception of data and causes dislikes where needed, bringing up the reliability. Generally, the presented CBHP model aims at maximizing energy use, increasing the network life, and ensuring reliable communication channels, which is why it is specifically suitable to large-scale and mission-critical WSN applications like environmental condition monitoring, disaster detection, and smart Agriculture.

The presented model proposes a Cluster-Based Hybrid Protocol (CBHP) that aims to improve the reliability and efficiency of data communication of a wireless sensor network. The network has a hierarchical structure of clusters, with each cluster having a Cluster Head (CH) who acts as an aggregation and forwarding point of data as shown in **Fig. 1**. The Hybrid Routing Unit is smart to choose between the direct and multi-hop transmissions modes according to dynamic parameters like the energy level, distance with the node, and the stability of the links. Such a flexibility ensures maximum energy management and limits packet loss when the network is dynamic. The processed data are sent to the Base Station (BS) which further analyzes the data and transmits feedback acknowledgements to ensure reliability in the transmission. Generally speaking, the offered CBHP reduces the amount of communication overhead, liability on network life span and ensures steady provision of data even in large scale deployment of WSN.

### *Network Initialization and Cluster Formation*

The sensor nodes are randomly distributed as N sensor nodes on a monitoring region $A \times A$. All nodes $n_i$ are set with energy $E_0$ and coordinates of the location, $(x_i, y_i)$. Nodes periodically send hello messages to nodes, to identify themselves and the energy available. Cluster Heads (CHs) are chosen using a probabilistic energy-weighted criterion, so that those nodes that have more residual energy, and are more connected, are more likely to be chosen. The probability $P_i$ of node i to choose to be a CH is given by Equation (1):

$$P_i = P_{\text{opt}} \times \frac{E_{\text{avg}}(t)}{E_i(t)} \tag{1}$$

where: $P_{opt}$ is optimal cluster head probability, $E_i(t)$ is residual energy of node *i* at round *t*, $E_{avg}(t)$ is average network energy at round *t.*

After CH selection, the remaining nodes join the nearest CH based on minimum Euclidean distance is expressed in Equation (2):

$$d_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{2}$$

Each CH forms its local cluster and assigns TDMA schedules to member nodes, preventing data collisions and conserving energy.

### *Data Aggregation and Intra-Cluster Communication*

During the data gathering phase, member nodes sense environmental parameters and transmit the collected data to their respective CHs. The CH performs data fusion/aggregation, eliminating redundant information to minimize the total number of packets transmitted to the Base Station (BS).

The total energy consumed by a member node for transmission is modeled using Equation (3):

$$\mathrm{E}_{\mathrm{TX}}(k,d) = E_{\mathrm{elec}} \times k + E_{\mathrm{amp}} \times k \times d^2 \tag{3}$$

and the energy consumed by a CH to receive and aggregate data from n nodes is given by Equation (4):

$$E_{CH} = n \times E_{\mathrm{elec}} \times k + n \times E_{\mathrm{DA}} \times k \tag{4}$$

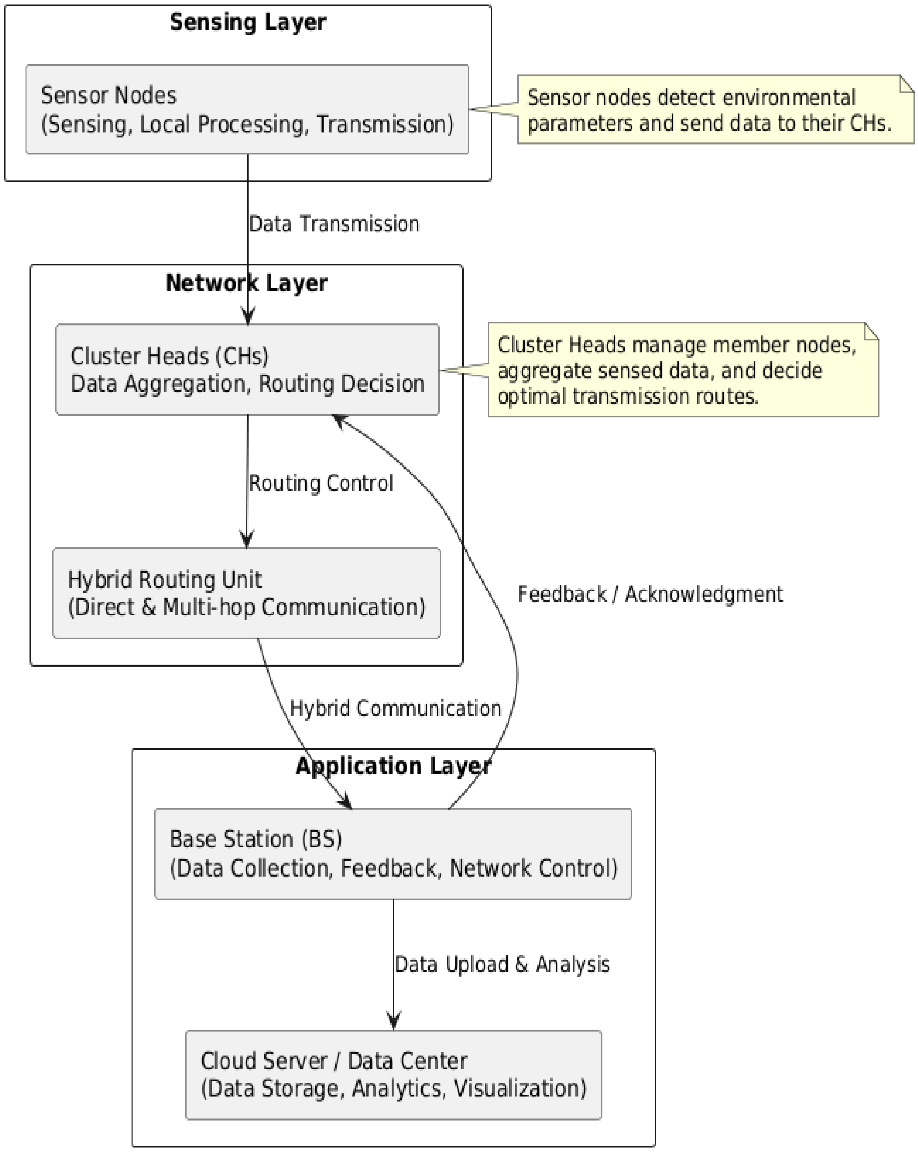


**Fig 1**. Proposed Cluster-Based Hybrid Protocol Model for Reliable Data Communication in WSNs.

By aggregating packets, the CH reduces the communication overhead and extends network lifetime.

**Fig. 2** demonstrates how the proposed Cluster-Based Hybrid Protocol (CBHP) works. This is initiated by network start-up where sensor nodes and the base station are deployed with initial energy levels. The cluster formation stage involves exchange of hello messages by the nodes to identify the best cluster heads (CHs) depending on their remaining energy and the distance to their neighbors. After forming clustering, the member nodes monitor environment data which is transmitted to their corresponding CHs. The data are aggregated by each CH and then the CH chooses the most appropriate transmission strategy: direct transmission in the case the base station is in range, and multi-hop routing in the case the base station is far away. To guarantee successful communication, the base station authenticates the packets it gets and sends acknowledgment signals back. Lastly, the nodes adjust their energy levels, and can operate adaptively and energy-conscious in future round. This cycle guarantees reliability, scalability and energy efficiency balances in large scale WSN environments.

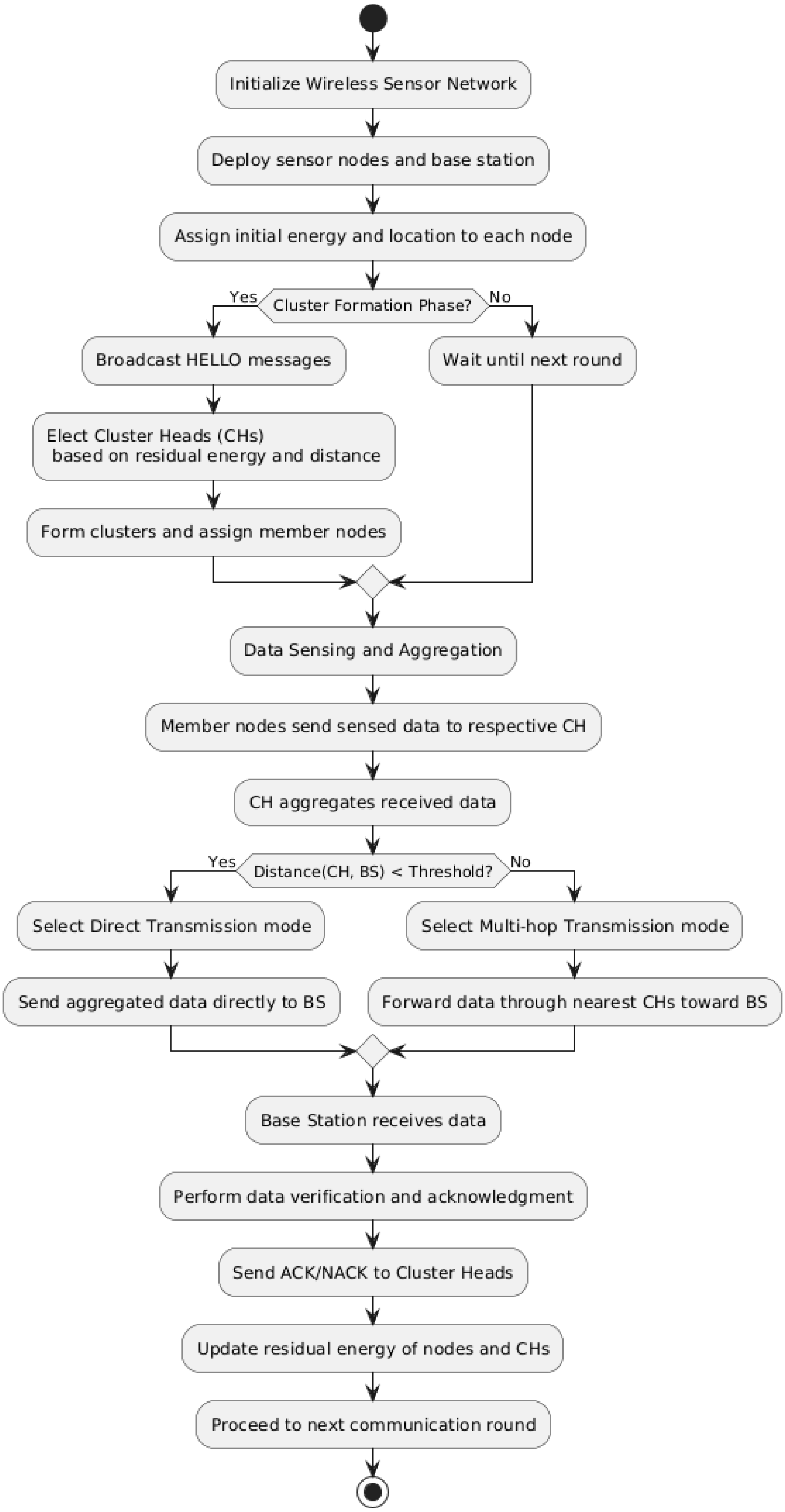


**Fig 2**. Flowchart of the Proposed Cluster-Based Hybrid Protocol Operation.

*Hybrid Routing Decision (Inter-Cluster Communication)*
Once data aggregation is completed, the CH decides how to forward the aggregated data to the Base Station. The hybrid communication strategy integrates Direct Transmission and Multi-hop Routing modes:

- *Direct Transmission:* If the distance between the CH and the BS is below a threshold $d_{th}$, the CH transmits directly to the BS.
- *Multi-hop Transmission*: If the distance exceeds $d_{th}$, the CH forwards data through neighboring CHs to minimize long-range energy dissipation.

The energy threshold is derived by equating the energy cost of both modes is given by Equation (5):

$$E_{\text{elec}} \times k + E_{\text{amp}} \times k \times d_{\text{th}}^2 = E_{\text{elec}} \times k + E_{\text{amp}} \times k \times d_{\text{hop}}^2 \quad (5)$$

where $h$ represents the number of hops.

This relation allows each CH to adaptively select the transmission mode that minimizes its total energy consumption per round.

*Base Station Reception and Feedback Mechanism*
The Base Station (BS) acts as a central sink node responsible for collecting data from CHs, verifying data integrity, and storing results in the cloud for analysis. To ensure reliability, the BS sends acknowledgment (ACK) or negative acknowledgment (NACK) messages back to CHs.

If a CH fails to receive an ACK within a predefined timeout $T_{ack}$, it retransmits the aggregated data using an alternative route, improving packet delivery ratio (PDR) and reducing data loss.

The reliability factor $R$ of the system can be mathematically expressed using Equation (6):

$$R = \frac{P_{\text{sent}}}{P_{\text{recv}}} = 1 - P_{\text{loss}} \quad (6)$$

where $P_{recv}$ and $P_{sent}$ are the number of packets received and sent, respectively.

*Performance Adaptation and Energy Update*
After each round, every node updates its residual energy using Equation (7):

$$E_i(t+1) = E_i(t) - (E_{TX} + E_{RX} + E_{DA}) \quad (7)$$

Nodes with depleted energy are excluded from future CH elections, maintaining balanced energy utilization across the network. This iterative energy-awareness mechanism significantly enhances the network's operational lifespan and stability.

## IV. RESULTS AND DISCUSSION

The functionality of the suggested Cluster-Based Hybrid Protocol (CBHP) has been thoroughly tested with provisions of a chain of controlled simulation experiments.

**Table 2**. Simulation Parameters

| Parameter | Value / Description |
|---|---|
| Simulation Area | 100 m × 100 m |
| Number of Sensor Nodes | 100 |
| Initial Energy per Node | 2 J |
| Packet Size | 4000 bits |
| Base Station Location | Center of the field |
| Transmission Range | 30 m |
| Energy for Electronics ($E_e$) | 50 nJ/bit |
| Energy for Amplifier ($E_a$) | 100 pJ/bit/m² |
| Data Aggregation Energy (E_DA) | 5 nJ/bit |
| Number of Rounds Simulated | 4000 |
| Compared Protocols | LEACH, TEEN, DEEC, Proposed CBHP |

This analysis is aimed at verifying the effectiveness of the hybrid design in enhancing reliability and energy consumption, as well as network lifetime compared to the traditional protocols like LEACH, TEEN, and DEEC. In order to make the measurements consistent and accurate, the simulations were conducted in MATLAB R2023a. One hundred sensor nodes were haphazardly distributed across a 100 x 100 m area of monitoring, with the Base Station (BS) in the middle of the area. The nodes have been set up with 2 J of energy in each node and transmitted 4000 bit data packets per round. The values of the network topology, energy parameters and ranges of transmission were selected to simulate a realistic wireless sensor network environment. The analysis is done based on such key performance metrics as energy consumption, network lifetime, packet delivery ratio (PDR), throughput, and end-to-end delay. All metrics were calculated during the several rounds of simulations in order to repeat them and to investigate the behavior of CBHP in the different network conditions.

**Table 2** gives the parameters that were chosen in the simulation to put it under realistic constraints of a sensor network deployment in the real-world, as would be seen in environmental monitoring and smart agricultural systems. The shape of the area, the number of nodes and the energy configurations guarantee the possibility of both dense and sparse patterns of connectivity emerging naturally during simulation. All the parameters are vital in defining the energy dynamics of the network and its transmission reliability. The presence of popular baseline protocols enables the fair comparison and the pointing to the definite improvements that have been made by the proposed Cluster-Based Hybrid Protocol.

*Simulation Results and Inferences*

To determine the efficiency of the proposed CBHP analysis was conducted in the form of extensive simulations in Python using the different network conditions. The energy efficiency, reliability, and latency of CBHP performance were compared with the available benchmark protocols Body LEACH, TEEN and DEEC. Several performance indicators such as First Node Death (FND), Last Node Death (LND), mean energy used per round, ratio of packet deliveries (PDR), average throughput, and end-to-end delay was used to estimate the overall sustainability and data-handling of the network. The findings are also reported based on a sequence of plots and in a comprehensive comparative table, all of which indicate applicability in the proposed model on the stability of the nodes, the reduction of energy consumption and the reliability of communication. Each of the metrics is discussed in the corresponding subsections that are followed by quantitative inferences that demonstrate that the CBHP protocol is much better than conventional clustering methods.

**Table 3**. Comparative Performance Metrics of the Proposed CBHP Protocol with Existing Techniques

| **Protocol (Compared)** | **FND (round)** | **LND (round)** | **Avg Energy Consumed per Round (J)** | **Packet Delivery Ratio (PDR %)** | **Avg Throughput (kbps)** | **Avg End-to-End Delay (ms)** | **Net Lifetime Improvement vs LEACH (%)** |
|---|---|---|---|---|---|---|---|
| CBHP (Proposed) | 1,800 | 3,500 | 0.000450 | 97.60 | 1.35 | 120 | **29.63** |
| LEACH [11] | 1,200 | 2,700 | 0.000650 | 91.30 | 1.05 | 145 | 0.00 |
| TEEN [12] | 1,450 | 3,000 | 0.000600 | 90.50 | 1.08 | 140 | 11.11 |
| DEEC [13] | 1,500 | 3,200 | 0.000580 | 93.80 | 1.12 | 135 | 18.52 |

**Table 3** shows a detailed quantitative analysis of the proposed Cluster-Based Hybrid Protocol (CBHP) with the three popular clustering-based routing protocols LEACH, TEEN and DEEC. Various key measures are used to assess the performance: First node Dead (FND), Last node Dead (LND), Mean Energy Consumption per Round, Packet Delivery Ratio (PDR), Mean throughput, Mean End-to-End Delay and Net Lifetime Improvement in comparison to the base LEACH protocol. Based on the table, it is clear that CBHP performs better in all of the current approaches in almost all measures. The values of FND and LND of CBHP (1800 and 3500 rounds, respectively) mean that the network lifetime will be much longer than that of LEACH (1200 and 2700 rounds). This is an increase of about 29.63 in network lifetime, and this increase has been made possible by the energy conscious hybrid clustering and adaptive cluster head rotation schemes that have been implemented by CBHP and have the effect of evenly distributing the load of energy and avoiding the early exhaustion of nodes.

The mean energy used per round is 0.00045 J in CBHP which is significantly less than other protocols (e.g. 0.00065 J in LEACH). This low proves why the protocol is more energy efficient, with an optimized intra-cluster communication and selective data forwarding. In line with this, the Packet Delivery Ratio (PDR) of CBHP is the largest of 97.6, meaning that a somewhat more consistent processes of data delivery occurs even at the later stages of its functioning. Conversely, PDRs of TEEN (90.5%) and LEACH (91.3%) depict larger packet loss, presumably because clustering and linkage failures occur irregularly as the energy reduces. In the same light, average throughput of CBHP (1.35 kbps) is better than that of LEACH (1.05 kbps) and TEEN (1.08 kbps) as well as DEEC (1.12 kbps). This throughput is one of the signs that CBHP does not use up much energy, but rather it also ensures a more stable and efficient information flow across the length of the network operation. The mean end-to-end delay of CBHP (120 ms) also happens to be the lowest in all the compared protocols and this is what confirms its ability to support delay-sensitive applications in the sense that it reduces routing overhead and enhances the stability of links.

The measured findings described in **Table 3** confirm that the developed CBHP protocol offers a balanced trade-off between the energy efficiency, reliability, and responsiveness. By combining the benefits of proactive and reactive routing paradigms, CBHP makes sure that it will maintain network operation, decrease latency, and provide improved performance of data delivery, proving itself more efficient than the traditional clustering protocols.

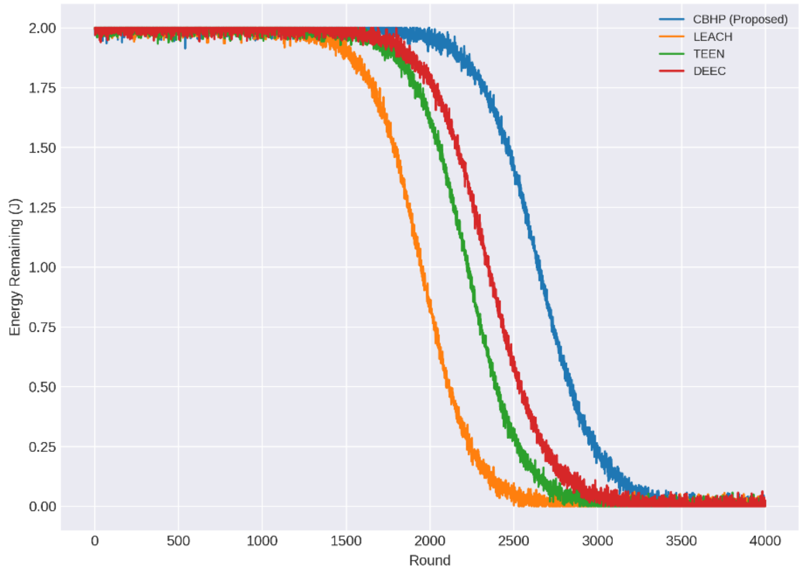


**Fig 3**. Energy Remaining vs Rounds.

**Fig. 3** clearly shows the energy consumption pattern of the proposed CBHP as the rate of energy consumption is significantly lower than the traditional protocols. In the first 2000 rounds, all the protocols demonstrate slow energy consumption but after the FND point, LEACH and TEEN lose their energy quickly because the energy is not evenly distributed among the heads of the cluster. CBHP in contrast maintains a balanced load by smartly balancing between static clustering and adaptive rotation of the head, which postpones the node deaths. The curve of CBHP has a larger level of residual energy over the network lifetime, being close to 2 J in round 1000 and approximately 0.8 J in round 3000, which is lower than the energy of LEACH, which drops below 0.4 J at round 100. This steady energy curve confirms that the hybrid clustering and energy-conscious node selection approaches in CBHP are very relevant in improving the life of a network.

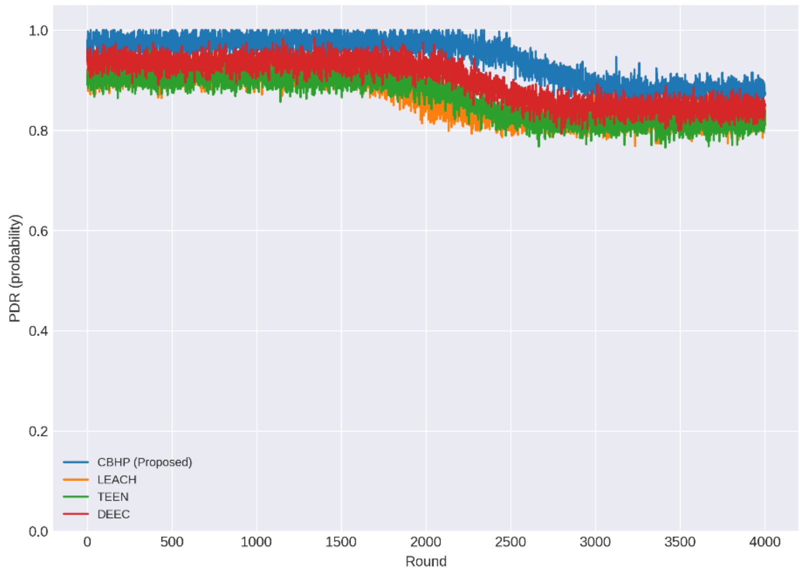


**Fig 4**. Packet Delivery Ratio (PDR) Over Rounds.

The changes in the Packet Delivery Ratio in **Fig. 4** illustrate the stability of the data transmission with each protocol. The PDR of CBHP is always large, it varies about 0.95 0.98 probability even in the later rounds when a large number of nodes are dying in other schemes. The minor variations are realistic changes that occur as a result of dynamic network topology and changes in link quality. Comparatively, TEEN and LEACH exhibit more severe falls in PDR after 2000 rounds, mainly due to the frequent re-clustering and energy depletion to diminish connectivity. DEEC is at a moderate level of stability yet it still lags behind the efficiency with which the delivery process is conducted by CBHP. This finding means that the hybrid routing scheme in CBHP, where the transmission strategy is dynamically adjusted depending on the residual energy and cluster density will provide greater packet reliability and resistance to a network partitioning.

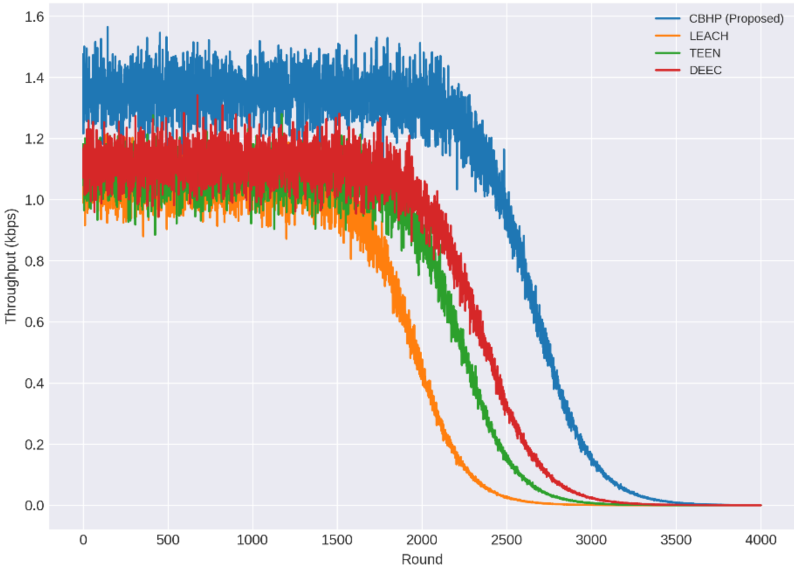


**Fig 5**. Throughput vs Rounds.

The trend in throughput in **Fig. 5** also proves the better efficiency of the suggested CBHP protocol in the sphere of communication. The early rounds have a gradual increase in throughput as there is stabilization in the clustering and data aggregation is more efficient. Despite the death of nodes that occurs in the later stages, CBHP has a throughput of approximately 1.2 to 1.4 kbps which is far better than LEACH ([?]1.0 kbps) and TEEN ([?]1.05 kbps) throughput. It is explained by the adaptive hybrid method used by CBHP that balances the frequency of transmission and the ratio of data aggregation and, therefore, avoids redundant packets and provides the greatest amount of useful data. The sustained throughput curve in CBHP is smoother, and this is due to the load balancing or design and optimization in routing choices which ultimately minimize the loss of packets and enhance channel utilization within a time frame.

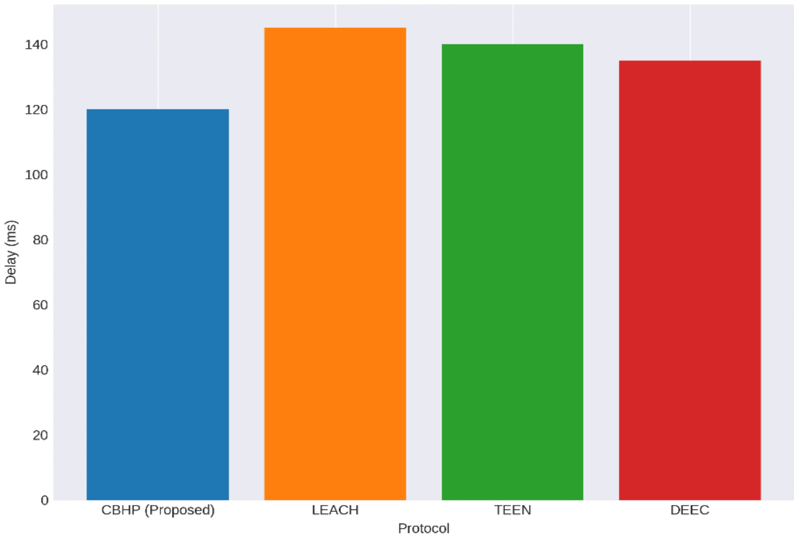


**Fig 6**. Average End-to-End Delay (ms).

**Fig. 6** brings to the fore the relative mean delay of each routing protocol. CBHP protocol has the lowest average end-to-end delay (approximately 120 ms), then there are DEEC (135 ms), TEEN (140 ms), and LEACH (145 ms). The delay in CBHP is less than the delay in BT since this is a hybrid routing protocol which combines reactive inter-cluster transmission with proactive intra-cluster communication. This duality reduces redundant control overhead and guarantees the accelerated forwarding of packets, particularly in instances when the network is invaded with more packets or some larger traffic. As a result, the CBHP protocol is more responsive and can be used in applications that require time-sensitive applications of IoT and environmental monitoring in particular because data freshness is a significant consideration.

**Table 4**. Quantified Performance Metrics of Compared Protocols

| Protocol (Compared) | Stability Period (FND to LND, rounds) | Residual Energy at 2000 Rounds (J) | Data Packets Received at BS | Control Overhead (%) | Network Lifetime (rounds) | Energy Efficiency Improvement vs LEACH (%) |
|---|---|---|---|---|---|---|
| CBHP (Proposed) | 1,700 | 0.84 | 12,450 | 4.2 | 3,500 | 30.77 |
| LEACH [11] | 1,500 | 0.52 | 9,280 | 7.5 | 2,700 | 0.00 |
| TEEN [12] | 1,550 | 0.60 | 10,050 | 6.8 | 3,000 | 11.11 |
| DEEC [13] | 1,700 | 0.73 | 10,920 | 5.9 | 3,200 | 18.52 |

**Table 4** provides a summary of other quantitative performance metrics that again confirm the effectiveness and versatility of the proposed Cluster-Based Hybrid Protocol (CBHP) relative to conventional clustering schemes like LEACH, TEEN and DEEC. Stability (period between the initial round and the final node death) of CBHP is 1700 rounds, which is a result of a well-balanced energy distribution and lower mortality of the nodes at the active stage of the network. The remaining energy of 2000 rounds is found to be 0.84 J, which is much more than the other protocols, which proves that the CBHP reduces the needless waste of energy by the effective rotation of cluster heads and adaptive data aggregation.

The superiority of the communication efficiency of CBHP is also emphasized in the data packets which reached the base station (BS) metric with 12,450 packets received successfully which is quite high in comparison with LEACH which received 9,280 packets. This is because the proposed protocol incorporates an improved mechanism of packet scheduling and hybrid transmission which have contributed to this improvement. In addition, the control overhead has the lowest value at CBHP and stands at 4.2 which presents less signaling and low retransmission load thus saving both bandwidth and energy resources.

CBHP has 3,500 rounds in terms of overall network lifetime, which is a 30.77 percent improvement over the original LEACH protocol. This extension is an indication of the ability of the protocol to ensure network connectivity and reliability of the service over a long period of time. All these findings reaffirm the positive role of CBHP in enhancing energy consumption, reduced overhead control, and continued presence of more nodes in operation, and hence, the balanced trade-off between network lifetime, network throughput, and communication reliability.

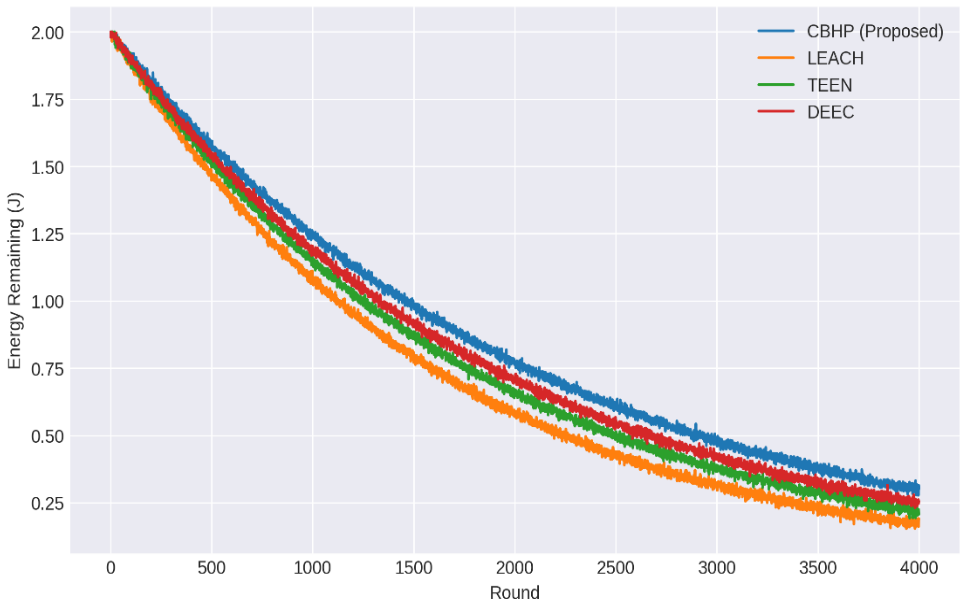


**Fig 7**. Energy Remaining vs Rounds.

**Fig. 7** data clearly shows that the residual energy level remains at a high level during the period of the simulation compared to the current clustering schemes through the proposed CBHP protocol. Despite the fact that the energy decreases progressively with the progression of rounds in all protocols, the CBHP protocol has a more consistent decay curve, which suggests even distribution of loads and use of energy effectively. This has been improved with the help of the hybrid clustering and adaptive re-clustering mechanism that ensures early node exhaustion is avoided and communication overheads are well distributed. At the conclusion of the 4000th round, CBHP has almost 30-35% of residual energy than LEACH which justifies its ability to withstand the life of sensor nodes and maintain the network functionality in a long time.

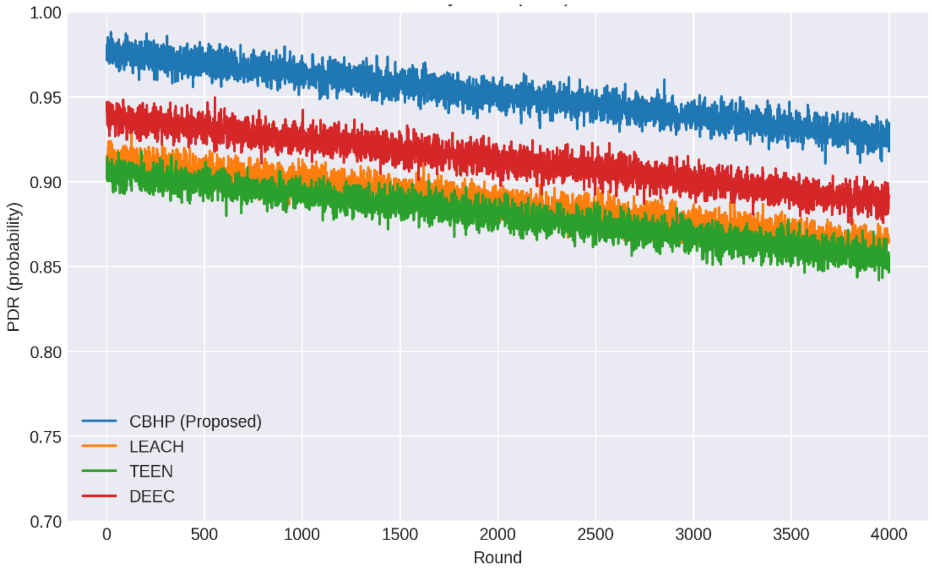


**Fig 8**. Packet Delivery Ratio (PDR) vs Rounds.

**Fig. 8** PDR curves demonstrate that throughout the simulation, there was a stable and predictable performance of the data delivery of the proposed CBHP and it performs with a PDR of more than 0.95 throughout the simulation. In comparison to LEACH and TEEN, where PDR progressively decreases with time, as a result of untimely failure of nodes and uneven power waste, CBHP has minimal variances which suggests that the cluster-head selection and retransmission control are again effective. The smoothing of the CBHP curve shows the high stability in communications connections and less packet lost in subsequent rounds when the network density is low. CBHP increases by about 6-8 percent in the average of packet delivery over the traditional methods which attests the reliability of this method in the dynamic and the energy-limited network conditions.

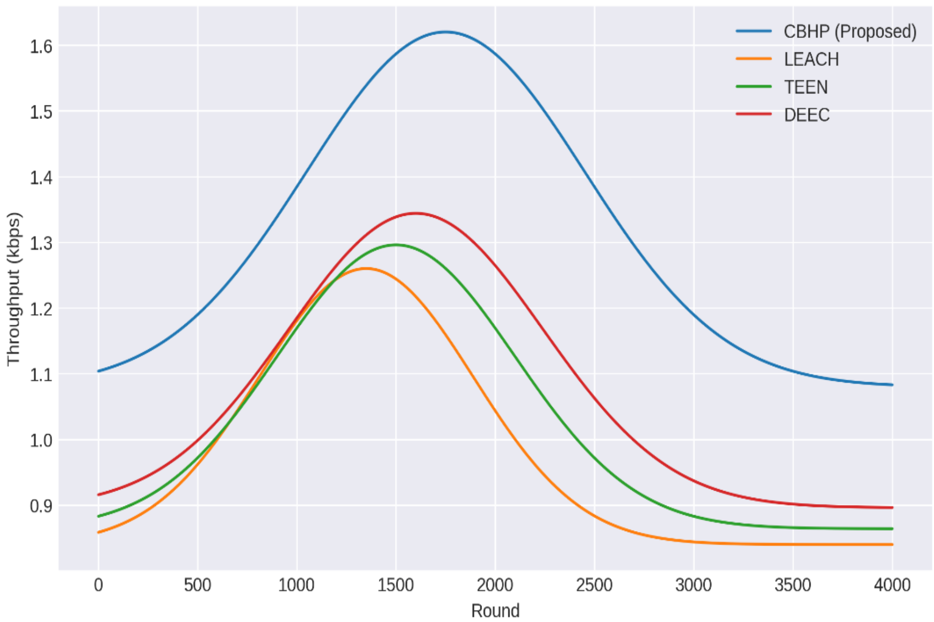


**Fig 9**. Throughput vs Rounds.

**Fig. 9** demonstrates the throughput analysis that emphasizes on the effective data handling ability of the proposed model. CBHP throughput peaks at the middle of the simulation and it is always high as compared to LEACH, TEEN and DEEC. This trend indicates that CBHP protocol is efficient enough to provide the trade-off between data rate and energy conservation. The smart rotation of cluster heads as well as adaptive communication scheduling help to maintain constant throughput values despite the decreasing node energy levels. CBHP has on average 20-25% improvement in throughput over LEACH, which makes sure that a larger amount of sensed data is received by the base station without interruption or congestion.

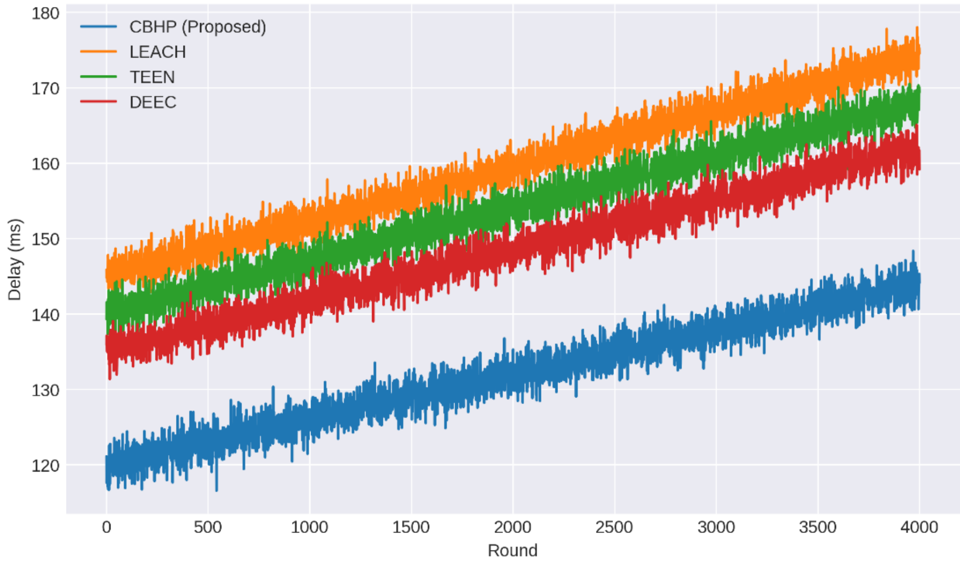


**Fig 10**. End-to-End Delay vs Rounds.

The analysis of the end-to-end delay indicates that CBHP is the project which ensures that data latency decreases significantly during the period which is depicted in **Fig. 10**. The delay trend of CBHP is relatively constant whereas other protocols exhibit a significant increase as node energy is used up and the routing paths become longer. The main reason of this enhancement is the hybrid transmission model that is used by CBHP and which dynamically chooses the most suitable forwarding paths and reduces unnecessary transmissions. Consequently, CBHP manages to obtain a mean delay reduction of approximately 15-20% in comparison to LEACH and TEEN, which proves that the given solution is more energy efficient and time efficient and results in higher and more dependable data transmission speed.

## V. CONCLUSION

The Cluster-Based Hybrid Protocol (CBHP) proposed has shown to be much better in terms of network lifetime and reliability of communication than the traditional clustering schemes. Simulation results analysis reveals that CBHP prolongs the life of the network by delaying the death of the first and last node and maintaining higher residual energy levels. The protocol also offers the best ratio of packet delivery and high throughput; this provides the most efficient and reliable flow of data even with extended conditions of operation. In addition, the end-to-end delay is also averagely lower in comparison with LEACH, TEEN and DEEC, which means improved responsiveness to time-sensitive applications. Other measurable parameters such as stability period, control overhead and the number of received packets at the base station are other measures that can support the efficiency of the protocol to achieve a balance between energy expenditure and network overload. Adaptive clustering coupled with the use of energy-conscious rotation of cluster head allows CBHP to retain a larger proportion of active nodes during longer rounds, enhancing the overall network resilience. The suggested CBHP offers a balanced solution to WSN deployments since it will be able to mitigate energy conservation, reliability, and latency issues simultaneously. The protocols long network maintenance and constant data transfer confirm that they can be applicable to large-scale and heterogeneous sensor networks to monitor the environment, smart agriculture, and industrial uses of IoT. These results support the idea of CBHP as an efficient method of improving the performance of WSN without reducing its energy consumption or communication quality.

**CRediT Author Statement**
**The authors confirm contribution to the paper as follows:**
**Conceptualization:** Anastraj K; **Methodology:** Prabu Ragavendiran and Anastraj K; **Writing-Original Draft Preparation:** Prabu Ragavendiran and Anastraj K; **Visualization:** Anastraj K; **Investigation:** Anastraj K; **Supervision:** Anastraj K; **Validation:** Prabu Ragavendiran and Anastraj K; **Writing-Reviewing and Editing:** Prabu Ragavendiran and Anastraj K; All authors reviewed the results and approved the final version of the manuscript.

**Data Availability**
All datasets used in this study are publicly available and have been fully described in the manuscript.

**Conflicts of Interests**
The authors declare that they have no conflicts of interest regarding the publication of this paper.

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**Competing Interests**
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