

Improved Energy Optimization Scheme in Wireless Sensor Networks Using Residue Number System and Ant Colony Optimization Approach

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ABSTRACT Wireless Sensor Networks (WSNs) are crucial for environmental monitoring, healthcare, agricultural, and industrial automation; however, their energy efficiency remains a significant challenge. Although the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol improves energy conservation through clustering, it suffers from unbalanced cluster head (CH) distribution and suboptimal routing paths, leading to premature network degradation. To address these limitations, this study proposes CRT-LEACH-ACO, a novel hybrid protocol that integrates: The Chinese Remainder Theorem (CRT) for deterministic and load-balanced clustering and Ant Colony Optimization (ACO) for adaptive, energy-efficient routing. This study evaluates four protocols (LEACH, CRT-LEACH, LEACH-ACO, and CRT LEACH-ACO) through Python-based simulations, analyzing network lifetime, energy consumption, throughput, and Packet Delivery Ratio (PDR). The results of this study demonstrate that CRT-LEACH-ACO outperforms conventional LEACH in all metrics, while also surpassing its variants (CRT-LEACH and LEACH-ACO). The proposed protocol provides a scalable and robust solution for energy-constrained WSNs, making it suitable for long duration monitoring applications. This work advances WSN protocol design by combining mathematical optimization (CRT) with bio-inspired routing.

KEYWORDS: Chinese Remainder Theorem, Ant Colony Optimization, Clustering, Routing, Network Lifetime, Cluster Heads.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) are essential for the Internet of Things (IoTs), comprising distributed sensor nodes that monitor environmental conditions and transmit data to a central base station [13]. Each autonomous sensor node features sensing and communication capabilities for information exchange. WSNs support diverse applications like environmental monitoring, healthcare, industrial automation, and military operations. A significant challenge in Wireless Sensor Networks (WSNs) lies in energy management, as sensor nodes rely on limited, often non-replaceable batteries. Recharging or replacing these batteries can be impractical, especially in remote or inaccessible locations [28][19]. This constraint categorizes WSNs as resource-constrained networks where efficient energy utilization is paramount. Additionally, sensor network design depends on factors such as security, reliability, scalability, power consumption, and task management, which vary based on application requirements [15][12]. The deployment of WSNs can follow either structured or unstructured approaches. Structured deployments strategically position nodes for optimal coverage, reducing maintenance and operational costs. Conversely, unstructured deployments involve randomly distributed nodes that self-organize post-deployment. While cost-effective, unstructured networks face significant challenges, including connectivity issues, failure detection, and security vulnerabilities [21].

To tackle energy efficiency challenges in WSNs, existing protocols such as the Low-Energy Adaptive Clustering Hierarchy (LEACH) have been widely adopted. LEACH reduces energy consumption via cluster-based data aggregation but struggles with scalability and energy balancing in large networks [2][4][5]. Previous research has shown that integrating the Chinese Remainder Theorem (CRT) with the LEACH protocol enhances data aggregation and reduces redundancy; however, several limitations remain. CRT-LEACH encounters scalability issues as the number of sensor nodes increases. In dynamic networks, frequent cluster reformation can introduce latency and reduce overall responsiveness due to routing constraints [19][3]. Similarly, integrating Ant Colony Optimization (ACO) with LEACH enhances routing by finding shorter paths and reducing energy consumption. However, it suffers from premature convergence, sensitivity to parameter tuning, and routing instability in dynamic networks due to poor clustering, random cluster head (CH) selection, and LEACH's uneven energy distribution [11][7]. Despite advances in clustering and routing, no existing protocol combines deterministic CH selection via CRT and dynamic routing via ACO to simultaneously address energy imbalance and path inefficiency.

To address this gap, a novel approach is proposed: integrate the CRT, a modular arithmetic method that enables lightweight, energy-efficient data decomposition and distribution, thereby reducing node burden and balancing traffic. By combining CRT with LEACH and ACO, the proposed approach enables optimal dynamic routing by discovering energy-efficient, low latency paths based on pheromone trails, residual energy, distance, and link quality, thereby ensuring adaptability. This study offers a holistic approach to WSN challenges by simultaneously addressing energy efficiency, Quality of Service (QoS), environmental awareness, and balanced resource utilization within WSNs in IoTs systems, unlike previous solutions that address these aspects in isolation.

This paper is structured as follows: Section2 reviews related research; Section3 details the methods for cluster formation, cluster head selection, and routing; Section4 presents the performance evaluation of the proposed approach using Python simulations; and Section5 concludes with a summary of findings and recommendations for future work.

II. RELATED WORKS

Advancing energy optimization in WSNs is a critical research focus to prolong the network's lifespan and enhance its operational efficiency. Various techniques have been proposed in the literature to achieve energy optimization in WSNs. This section summarizes some related works in the field of WSNs. It can pave the path for further investigation and improvements in the field. Several energy optimization methods have been proposed to improve the efficiency of WSN's radio transmission interface. [18] proposed Rao algorithms to optimize heterogeneous WSN structures, achieving a remarkable enhancement of 71% in the network lifespan of the PEAGSIS protocol. This optimization demonstrated improvements in network lifetime, energy conservation, and routing protocols when evaluated against LEACH, PEAGSIS, PEAGSIS-NN, and PE-LEACH protocols. It also proved to be more efficient than the Jaya optimization algorithm across various performance metrics. Similarly, [12] introduced the squirrel optimization algorithm for routing IoTs networks. This method effectively reduced energy consumption in sensor nodes, leading to a longer network lifespan and surpassing the efficiency of genetic algorithms. Along the same lines, [7] proposed an enhanced ant colony algorithm specifically designed for routing optimization in WSNs within IoT systems. Their experiments validated the algorithm's benefits in reducing energy usage, transmission latency, and inactive nodes while increasing overall network capacity. These enhancements positioned the algorithm as a valuable tool for real-time applications and various network scenarios. However, it does not address LEACH's main shortcoming, which is the random selection of CHs. [5] focused on modifications to the LEACH algorithm to improve network lifetime and energy efficiency. These optimizations enhanced battery performance, network stability, and cluster management while mitigating power failure risks. In contrast, [22] shifted their attention to the security challenges in WSNs,

highlighting the criticality of addressing vulnerabilities in sensitive areas such as commercial, health, and military environments. Addressing another aspect of optimization, [28] introduced a heuristic two-step algorithm for coordinating multiple UAVs in WSNs. This innovative approach, based on graph theory and kernel K-means, successfully optimized data collection and reduced energy consumption per UAV while enhancing the Area of Interest (AoI) performance. In the context of clustering, [11] proposed a fuzzy logic-based model for selecting CHs in WSNs. By employing k-means clustering and using fuzzy logic for CHs selection, this approach increased network stability by 28.57%, contributing significantly to energy savings. [23] introduced trust-based clustering and routing for energy-efficient WSNs. Their dual-phase clustering approach, combined with the Lion Optimization Algorithm for route selection, achieved a 94.24% packet delivery rate and maintained 191 active nodes at the 500th second. Meanwhile, [17] enhanced the Grey Wolf Optimization (GWO) algorithm for CH selection, achieving notable improvements in network stability over protocols such as LEACH-PRO and FIGWO. Similarly, [14] integrated deep learning techniques like artificial neural networks with LEACH to optimize energy usage in WSNs, improving data aggregation, duty cycling, and transmission protocols. [3] utilized the Chinese Remainder Theorem (CRT) within the LEACH protocol, demonstrating a significant improvement in network lifespan through simulations conducted in Python. Their approach was further enhanced by incorporating fuzzy logic for the CH election. This approach doesn't consider node mobility to the BS, which could lead to increased energy use. [19] introduced the hybrid HPSO-ILEACH algorithm, combining HPSO and ILEACH methodologies for clustering, drastically reducing energy consumption and increasing network stability. [26] explored hybrid clustering and routing strategies by integrating k-medoid, IABC, and CL-HHO methodologies. This approach outperformed existing protocols like HEED and GWO in energy efficiency. Similarly, [25] proposed H LEACH, a protocol integrating energy harvesting techniques for dynamic clustering and CHs selection, resulting in increased throughput and network longevity. [2] focused on a Hybrid Fuzzy-Possibilistic model for WSNs, which achieved superior coverage reliability when compared to MSCR and CMSS strategies. [6] combined fuzzy logic with LEACH and particle swarm optimization, achieving a balanced energy consumption model and increasing network lifetime by over 46%. [24] introduced the SECRET protocol, designed to optimize energy efficient routing, improve packet delivery ratios, and enhance scalability. Similarly, [9] proposed GWO CRT-based forwarding and splitting techniques to improve LEACH performance by addressing unbalanced load sharing and preventing low-energy nodes from becoming cluster heads. This approach also facilitates data aggregation, but does not address node mobility. [15] proposed the CRT-LEACH algorithm to enhance routing in WSNs, outperforming traditional protocols in energy efficiency. [8] further optimized WSN routing through LEACH-based task allocation, which improved transmission rates, reduced network traffic, and enhanced Quality of Service (QoS). [20] addressed communication challenges in wireless mesh networks by proposing a hybrid approach for software-defined WSNs, enabling seamless interaction between conventional and SDN-based devices. Expanding on foundational concepts. [11] explored the application of Residue Number Systems (RNS) in bioinformatics, proposing their use in FPGA/VHDL implementations to overcome computational speed and accuracy challenges. Earlier, [16] highlighted CRT-based forwarding techniques for WSNs, showcasing their superior energy consumption and delay metrics performance. This approach balances clustering among nodes but lacks routing optimization for better performance. Finally, [27] emphasized the relevance of RNS in computer networks, particularly for energy savings and load balancing. The RNS advantage is that it minimizes packet loss during data transmission by dividing the packet into fragments before sending it to the sink.

III. METHODOLOGY

The proposed CRT-LEACH-ACO framework combines CRT-based packet splitting for clustering with ACO-optimized routing to improve LEACH, enabling dynamic, energy efficient, and low-latency paths based on pheromone trails, residual energy, distance, and link quality. In a 100 m × 100 m network with a centrally located BS, homogeneous sensor nodes (0.5 J each) are randomly deployed. The BS selects CHs through CRT-based clustering, aggregates data from CHs, and reconstructs original packets from CRT-segmented data. Member nodes send data to CHs, which forward aggregated packets to the BS via ACO-based multi-hop routes. Performance metrics such as energy consumption, active nodes, throughput, and PDR are monitored to evaluate efficiency, QoS, and reliability. This integration extends network lifetime, reduces energy consumption, and ensures reliable data delivery for various IoT applications.

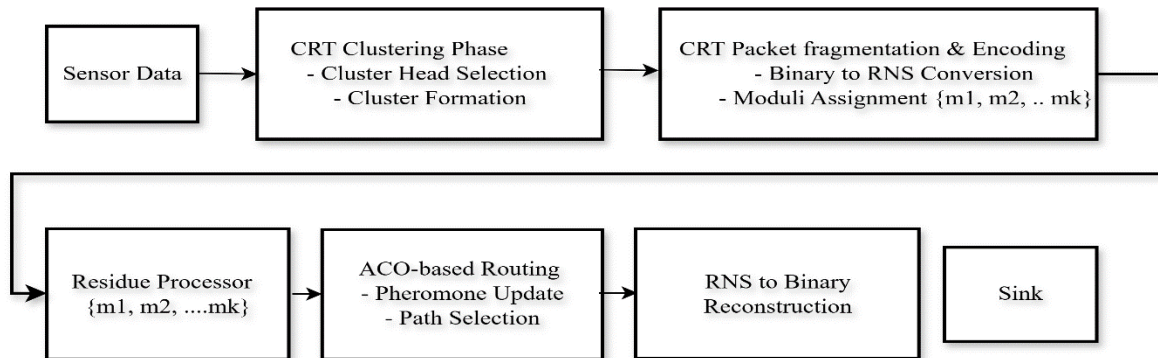


Figure 1: Schematic Framework and Workflow of the Proposed CRT-LEACH-ACO

A. Leach

The wireless network utilized an energy-aware algorithm named Minimum Residual Hop Capacity (MRHC). The algorithm is incorporated into the most commonly used protocol called LEACH, which uses Time-Division Multiple Access (TDMA) based MAC (Medium Access Control (MAC) protocol, which is integrated with clustering and a simple routing protocol in WSNs. The goal of LEACH is to lower energy consumption and maintain clusters to improve the lifetime of a wireless sensor network. The protocol is transmitted to CHs, and the CHs aggregate and compress the data and forward it to the base station [15][3]. This research method initiates a detailed study of dominant WSN protocols, specifically concentrating on LEACH for clustering objectives. LEACH is extensively utilized due to its capability to arrange nodes into clusters and curtail energy consumption; however, it fails to optimize routing paths predicated on energy levels or prevailing network conditions. The limitations of LEACH provide a basis for the formulation of an advanced clustering and routing solution within the context of this study. In LEACH, nodes will generate a number randomly between 0 and 1(including 0 and 1). If the random number is smaller than the threshold $T(n)$, then the node will be a CHs in this round. $T(n)$ is based on the following formula:

$$T(n) = \begin{cases} P & \\ \frac{P}{1 - P\left(r \bmod \left(\frac{1}{P}\right)\right)} & , \quad N \in G \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

From above, p is the percentage of cluster nodes accounting for the total number of nodes, that is, the probability of nodes becoming CHs; r is the current number of periods, and N is the total number of nodes; G is the set of nodes that did not become CHs in the $1/p$ round.

B. Chinese Remainder Theorem (CRT)

CRT constitutes a mathematical framework employed for the resolution of systems of simultaneous congruences characterized by pairwise coprime moduli. In the context of this investigation, the CRT is utilized to partition extensive data packets into more manageable fragments before their transmission. The underlying justification for the application of CRT lies in its capacity to distribute energy consumption across multiple sensor nodes, thereby alleviating the entire transmission load from being concentrated on a singular node. By disseminating data fragments across different nodes, energy consumption is more equitable, thereby mitigating the likelihood of individual nodes exhausting their energy reserves prematurely [9]. The CRT guarantees that each node is responsible for merely a fraction of the data, with the base station possessing the capability to reconstruct the original data packet through the system of congruences after the reception of all fragments. This methodological approach facilitates:

- (a). Load balancing: The equitable distribution of workload among nodes to prevent energy depletion in any specific segment of the network.
- (b). Transmission failures: The transmission of smaller fragments diminishes the probability of packet loss or corruption, especially in noisy or unstable network environments.

Conversion using the CRT. This theorem converts RNS to binary /decimal. Given the residue representation $\{r_1, r_2, \dots, r_n\}$ of x , the CRT makes it possible to determine $|x|_m$, provided the gcd of any pair of moduli is 1. Such moduli are called pairwise relatively prime [9][27]

The CRT is given by

$$|x|_m = |\sum_{j=1}^N \hat{m}_j | \frac{r_j}{\hat{m}_j} |_{m_j} |_m \quad (2)$$

$$\text{Such that } \hat{m}_j = \frac{M}{m_j}, \quad M = \prod_{j=1}^N m_j \text{ and } \gcd(m_j, m_k) = 1 \text{ for } j \neq k$$

Where $M = \prod_{j=1}^N m_j$ is the dynamic range, and M_j^{-1} is the multiplicative inverse of M_j concerning m_j . Let's consider the RNS representation of (1,2,3) with moduli set (3/4/5), respectively. Using the methods and equations above, $X = 58$. CRT is also useful in reverse conversion to produce high-speed systems. RNS produces a high-speed system in the absence of carry propagation between the arithmetic units, which will result in a high-speed processor. This feature is highly beneficial and important to WSNs that are needed for real-time applications. RNS can also be used for parallel operations that can reduce power consumption and delay simultaneously in WSNs. This feature will make the computation process faster and easier. Energy is the main critical factor when considering a wireless sensor network

C. Ant Colony Optimization (ACO)

These represents a nature-inspired computational methodology derived from the foraging behaviors exhibited by ant colonies. Within this paradigm, synthetic ants undertake the task of identifying optimal pathways between a designated source and a target by releasing pheromones, which subsequently direct following ants towards more efficient trajectories. As time progresses, pathways characterized by elevated pheromone concentrations receive reinforcement, culminating in the establishment of an optimal routing path [7]. In the present investigation, ACO is modified to align with the distinct requirements of WSNs,

wherein the paramount objective is to minimize energy expenditure throughout the routing process. The conventional ACO algorithm is tailored to integrate two essential parameters pertinent to WSNs:

- (a). Remaining Energy of Nodes: The routing algorithm is designed to favor pathways that prioritize the nodes with the highest residual energy, thus avoiding excessive use of particular nodes and promoting a balanced distribution of energy consumption throughout the network.
- (b). Location Awareness: The revised ACO algorithm incorporates the spatial positioning of the nodes to ensure the selection of shorter paths that incur minimal energy expenditure.

The justification for employing ACO within this framework lies in its ability to dynamically adapt to fluctuations in network conditions, such as node failures or the depletion of energy resources, while persistently striving to identify the most energy-efficient routes. In contrast to conventional deterministic algorithms, ACO provides a level of flexibility that is crucial to accommodating real-time alterations within the network, an attribute that is vital for the dynamic and frequently unpredictable characteristics of WSNs. The probability transition rule and the pheromone updating rule in the ant colony system (ACS) are explained as follows:

Probability transition rule:

$$P_{ij} = \frac{[\tau_{ij}]^\alpha \times [\delta_{ij}]^\beta}{\sum_{n \in N_i} [\tau_{in}]^\alpha \times [\delta_{in}]^\beta} \quad J \in N_i \quad (3)$$

Where τ_{ij} is the amount of pheromone deposited for transition from state i to j , and $\alpha \geq 0$ is a parameter to control the influence of τ_{ij} . δ_{in} is the desirability of state transition ij . The parameter α indicates the weight of controlling the pheromone concentration, while β indicates the weight of heuristic energy inspiration.

The probability of selecting a path (i, j) is the trade-off between the pheromone and the heuristic energy value. Specifically, when the pheromone concentration is large, there is a high probability of selecting the corresponding link. The pheromone concentration between each node is initialized in the same way. The pheromone initialization between each node is initialized in same way.

The pheromone initialization between node i and node j is shown in equation (4):

$$\tau_{ij} = \frac{1}{d_{ij}} \quad (4)$$

Global Update Rule: Upon all ants completing their respective paths, a global pheromone update is performed to reinforce the strength of the best path found so far. This enhances the probability of selecting this path in future iterations, facilitating faster convergence of the algorithm. The global update rule is defined as:

$$\tau_{ij} \leftarrow (1 - \rho)\tau_{ij} + \sum_k^n \Delta\tau_{ij}^k \quad (5)$$

Where τ_{ij} is the amount of pheromone deposited for a state transition node ij . $\rho \in [0,1]$ is the pheromone evaporation coefficient, n is the number of ants, and $\Delta\tau_{ij}^k$ is the additional amount of pheromone deposited by ant k on the edge (i,j) . The additional pheromone is calculated as:

$$\Delta\tau_{ij}^{gb}(t) = \begin{cases} \frac{Q}{L_{gb}}, & \text{if edge } (i,j) \in \text{Global best route} \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

Where Q is a predefined quantity of pheromone laid by ants, $\Delta\tau_{ij}$ is the additional amount of the pheromone on node ij . The global best path is defined by

$$L_{gb} = \sum_{i=1}^{n-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \quad (7)$$

Where n denotes the number of nodes of the global best path, (x_i, y_i) are coordinates of the nodes i .

Next-Hop Selection Probability: the probability of selecting the next hop node j is given by:

$$P_{ij} = (1 - \mu) * \frac{[\tau_{ij}]^\alpha \times [\delta_{ij}]^\beta}{\sum_{n \in N_i} [\tau_{in}]^\alpha \times [\delta_{in}]^\beta} + \mu * \frac{E_j}{E_{init}} \quad (8)$$

Where μ is a weight factor energy awareness, E_j is the residual energy of node j and E_{init} indicates the initial energy of node j , $\alpha > 0$ and $\beta > 0$ are the weights of the pheromone and heuristic desirability, respectively.

D. Algorithm Advantages

The proposed hybrid algorithm leverages the strengths of CRT for data fragmentation and ACO for routing. This combination addresses the primary challenges of energy efficiency and network longevity in WSNs. The combined use of CRT and ACO offers several key advantages:

- Energy Efficiency:** CRT reduces the transmission burden on individual nodes, while ACO ensures that energy-efficient routes are selected, extending the network lifetime.
- Load Balancing:** CRT distributes energy consumption across multiple nodes, preventing any single node from depleting its energy reserves too quickly.
- Dynamic Adaptation:** ACO dynamically adjusts to changes in the network, such as node failure or changes in energy levels, ensuring continuous network operation.
- Scalability:** Both CRT and ACO are scalable algorithms capable of handling large networks with numerous nodes without a significant loss in performance.

E. Performance Evaluation Metrics

(a) Energy Consumption

The radio communication energy consumption model used is defined as

$$E_{total} = E_{Tx} + E_{Rx} \quad (9)$$

For sensor nodes, the energy component are:

$$E_{Tx}(k, d) = E_{Tx-elect}(k) + E_{Tx-amp}(k, d^n) \quad (10)$$

$$E_{Tx}(k, d) = \begin{cases} k \times E_{elect} + k \times \epsilon_{fs} \times d^2, & d < d_0 \\ k \times E_{elect} + k \times \epsilon_{amp} \times d^4, & d \geq d_0 \end{cases} \quad (11)$$

$$E_{Rx}(k) = k \times E_{elect} \quad (12)$$

$$E_{DA}(k) = k \times E_{DA} \quad (13)$$

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{amp}}} \quad (14)$$

Where:

- $E_{Tx}(k, d)$ Total Energy consumed when sending k -bit data by sensor nodes from d distance

- (b) E_{elec} : energy consumed by the interface circuit per bit (J/bit)
- (c) ϵ_{fs} : Free-space model amplifier constant (J/bit/m²)
- (d) ϵ_{amp} : Multipath model amplifier constant (J/bit/m⁴)
- (e) E_{DA} is the energy consumed per bit for data aggregation (or processing).
- (f) d_0 : threshold distance (meter)

(b) Network Lifetime

First Node Dead (FND): The iteration or time at which the first sensor node exhausts its energy and ceases to operate.

Last Node Dead (LND): The iteration or time at which the final sensor node depletes its energy, signifying the conclusion of the network's operational existence.

$$PDR = \frac{\text{received Packets}}{\text{sent Packets}} * 100 \quad (15)$$

$$\text{Throughput} = \frac{\text{Total delivered data}}{\text{Time Period}} \quad (16)$$

IV. RESULTS AND DISCUSSION

We implemented a simulation environment in Python to evaluate the performance of our proposed hybrid algorithm. The proposed algorithm combines a CRT-based Packet Splitting Algorithm for clustering with an ACO-based Routing Algorithm for routing in WSNs, aiming for energy efficiency. Sensor nodes were deployed with equal initial energy across a defined area, and the sink was centrally located to promote balanced communication distances. The simulation compared LEACH, CRT-based LEACH, LEACH-based ACO, and CRTLEACH-based ACO under these uniform settings, evaluating residual energy, throughput, PDR, and network lifetime. Table 1 summarizes the complete simulation configuration.

Table 1: The Simulation Parameters for the Network.

Parameter	Value
Network deployment area	$(100 \times 100) m^2$
Node count	100
Node energy (Initial)	0.5 joule
Coordinates of the sink	$x = 50, y = 50$
Transmitter and receiver energy	50 nj/bit
Aggregation energy	5 nj/bit
Power amplification (E_{fs})	10 Pj/bit/m ⁴
Power amplification (E_{mp})	0.0013 Pj/bit/m ²
Data packet size	4000 bits
Number of ants	10
Pheromone evaporation rate	0.1
α	1
β	2
Leach probability	0.05
Rounds (R_{max})	1,200

The simulation aims to test the efficiency of the proposed algorithm in terms of performance metrics and overall data transmission. From the results obtained, the following key observations are made: LEACH has the poorest performance at final round, with rapid energy depletion and low network lifetime, CRT-LEACH improves network longevity through optimized clustering; LEACH-ACO enhances routing efficiency but still suffers from inefficient cluster formation, and CRT-LEACH-ACO outperforms all other protocols, achieving the best energy efficiency, highest throughput, and longest network lifetime by combining optimized clustering and routing. This confirms that the integration of CRT and ACO significantly enhances WSN performance, making CRT-LEACH-ACO a promising solution for energy-efficient and reliable data transmission in wireless sensor environments.

Figure 2: At the final 1200 rounds, CRT-LEACH-ACO and LEACH-ACO maintained 100 active sensor nodes, demonstrating better energy efficiency and network longevity due to optimized routing and, for CRT-LEACH-ACO, enhanced clustering. CRT-LEACH retained 11 active nodes, outperforming LEACH, which had only 5, indicating better cluster formation, energy balancing, and sustainability.

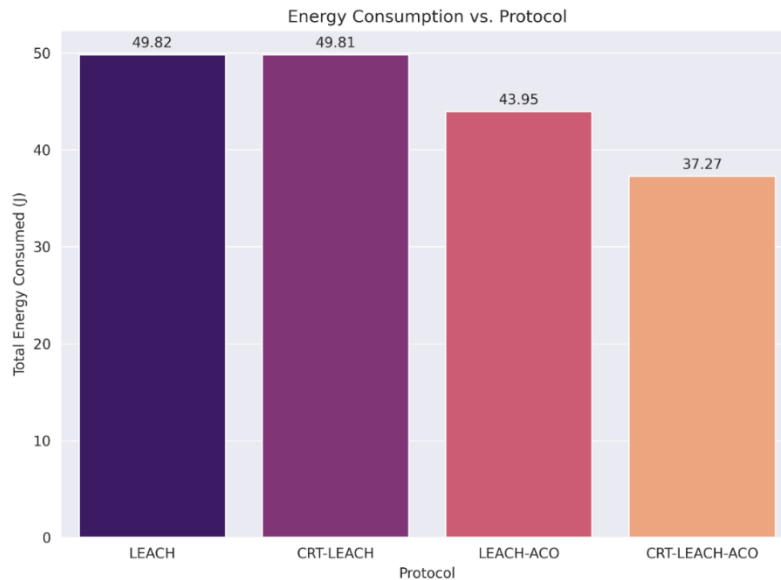


Figure 2: Final Round Network Lifetime Comparison

Figure 3: Shows the total energy consumed by each protocol during the simulation period. The proposed CRT-LEACH-ACO, integrating CRT-based clustering and ACO-based routing, minimizes energy consumption and significantly improves efficiency over traditional LEACH and its variants. This approach improves energy efficiency, provides better QoS, and supports long-term network sustainability in WSNs. LEACH-ACO optimizes routing with ACO, reducing energy losses during data transmission. Furthermore, CRT-LEACH improves energy use by carefully selecting cluster heads for balanced energy distribution, unlike LEACH, which consumes the most energy due to inefficient cluster formation.

Figure 4: CRT-LEACH-ACO achieves the highest throughput by optimizing both clustering and routing processes. High throughput is crucial in WSNs as it reflects the network's ability to deliver large volumes of sensed data with minimal loss, enabling timely decision making and accurate monitoring. In applications such as environmental monitoring, precision agriculture, industrial automation, and healthcare surveillance, higher throughput ensures that critical information reaches the base station reliably and in real time, enhancing overall system performance. Overall, the combined strengths of CRT-based clustering and ACO-

based routing in CRT-LEACH-ACO result in significantly better throughput than other variants. CRT LEACH improves throughput through more balanced clusters than LEACH-ACO, while LEACH shows the lowest throughput due to suboptimal routing and higher packet loss.

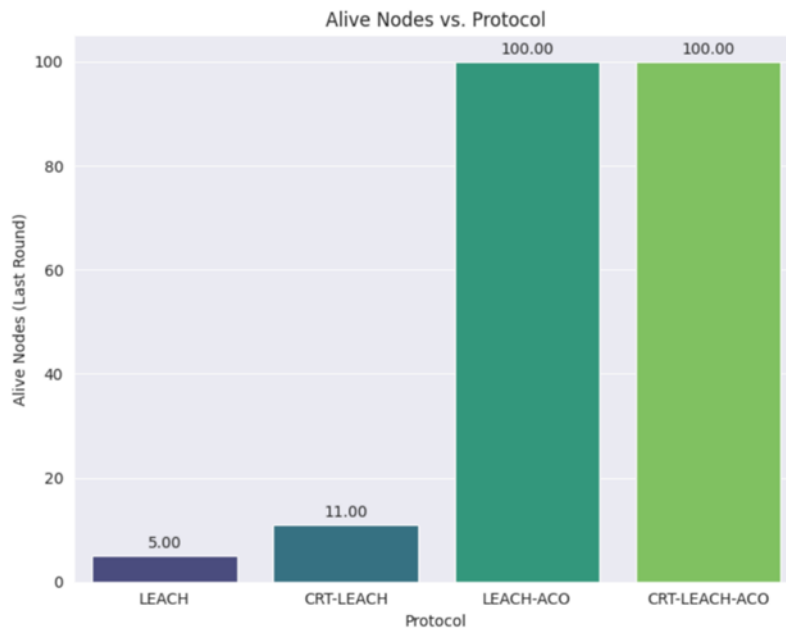


Figure 3: Final Round Energy Consumption Comparison

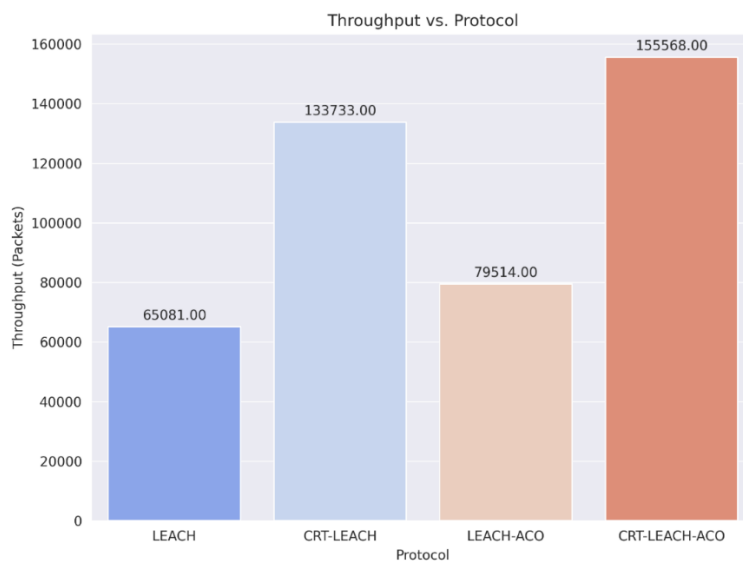


Figure 4: Final round Throughput comparison

Figure 5: The integrative approach of CRT-LEACH-ACO achieves the highest PDR mainly because it minimizes packet loss through efficient clustering and robust, adaptive path selection strategies. This performance highlights the effectiveness of combining CRT-based clustering with ACO-based routing to ensure reliable data transmission even in dynamic network conditions. Additionally, CRT-LEACH alone also shows a significant improvement in PDR compared to baseline methods, thanks to more balanced and dependable cluster formation. In contrast, LEACH-ACO and the traditional LEACH protocol have lower PDR values, which is due to their less effective clustering mechanisms and greater vulnerability to packet loss. These findings emphasize the importance of integrated clustering and routing strategies in improving data delivery reliability across various WSN application scenarios.

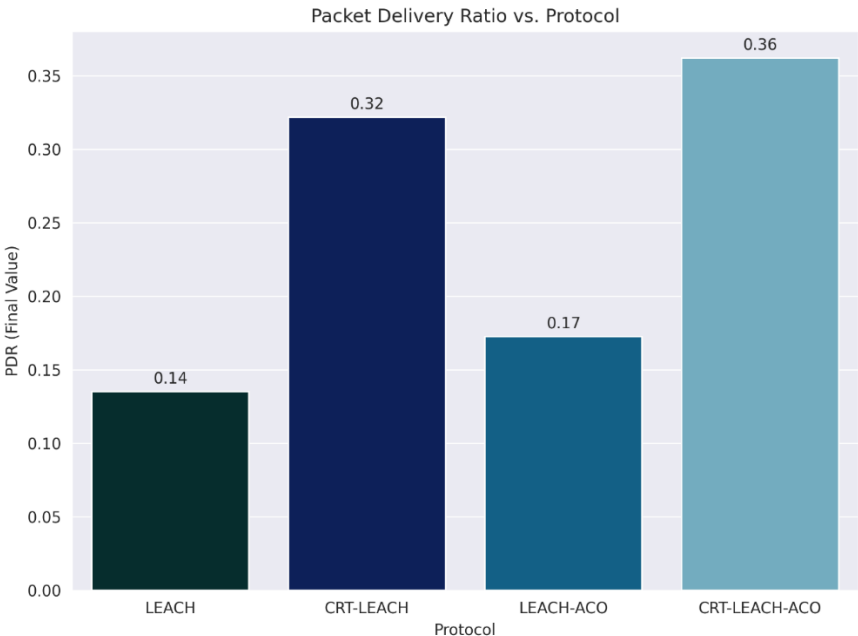


Figure 5: Final round PDR comparison

Table 2: Summary of Final Performance Metrics at Round 1200

Protocol	Final Alive Nodes	Final Energy (J)	Final Throughput	Final PDR
LEACH	5	49.82	6,032	0.14
CRT-LEACH	11	49.81	133,733	0.32
LEACH-ACO	100	43.95	79,514	0.17
CRT-LEACH-ACO	100	37.27	155,568	0.36

The above table shows that CRT-LEACH-ACO outperforms in all metrics: 100% node survivability, low energy use (37.27 J), and high throughput (155,568 packets) with a PDR of 0.36. This is due to its combined CRT-based clustering, which ensures balanced energy distribution, and ACO-driven routing, which dynamically finds efficient paths. LEACH-ACO also maintains 100% node survival and has relatively low energy use (43.95 J). However, its throughput (79,514 packets) and PDR (0.17) are lower than both CRT variants, showing that ACO routing alone is less effective than integrated CRT clustering. Although it doesn’t match CRT-LEACH-ACO, CRT-LEACH still significantly exceeds LEACH-ACO in throughput (133,733 vs. 79,514 packets) and PDR (0.32 vs. 0.17) because of its improved CRT-based cluster formation.

This indicates that CRT-based schemes are better suited for communication requiring QoS and data reliability. On the other hand, LEACH performs the worst, with only 5 surviving nodes, higher energy consumption (49.82 J), and the lowest throughput (65,081 packets) and PDR (0.14). Overall, CRT-LEACH-ACO's combined CRT load balancing and ACO dynamic routing reduce energy waste and outperform standalone methods, making it a promising solution for energy-efficient, reliable IoT systems, especially for large-scale or long-term deployments like environmental monitoring and industrial IoTs.

V. CONCLUSION

This study effectively executed and assessed the LEACH protocol along with its advanced variations (CRT-LEACH, LEACH+ACO, and CRT-LEACH-ACO). The incorporation of CRT facilitated improved cluster formation by ensuring the optimal selection of cluster heads, while ACO refined routing pathways, thereby minimizing energy expenditure and enhancing overall network performance. Among the four protocols analyzed, CRT-LEACH-ACO demonstrated the highest efficiency regarding energy consumption, network durability, and data transmission reliability. These results indicate that hybrid clustering and routing methodologies, represented by CRT-LEACH-ACO, offer significant improvements compared to traditional LEACH-based frameworks in WSNs. The proposed enhancements help prolong the network lifespan and increase communication effectiveness, making them particularly beneficial for environmental monitoring, precision agriculture, and industrial automation applications, where energy efficiency and data reliability are critically important. Nevertheless, it is essential to recognize that this investigation was conducted in a simulated environment, which may not fully capture real-world variables such as hardware limitations and environmental disturbances. Despite this limitation, the findings lay a strong foundation for future research and practical applications. Future work will focus on integrating energy harvesting techniques and applying machine learning or reinforcement learning for intelligent cluster head selection. Additional enhancements will focus on security and extending the protocol to mobile and heterogeneous WSN environments. In summary, CRT-LEACH-ACO represents a promising hybrid methodology for advancing energy-efficient clustering and routing in WSNs. With further optimization and empirical validation, it has the potential to significantly enhance the performance and sustainability of large wireless sensor networks.

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