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A Hybrid Artificial Bee Colony–Firefly Algorithm for Optimized Cluster Head Selection to Enhance Network Lifetime in WSNs

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Abstract*— Wireless Sensor Networks (WSNs) play a vital role in modern applications such as environmental monitoring, healthcare, and surveillance, where energy efficiency and network longevity are key performance parameters. This paper presents a hybrid optimization approach combining the Modified Artificial Bee Colony (ABC) algorithm and the Modified Firefly Optimization Algorithm (FOA) to enhance cluster head (CH) selection for prolonged network lifetime and stability. The proposed Hybrid ABC–FOA (HMABCFA) model is mathematically formulated to minimize total energy consumption, inter-node distance, and latency while maximizing residual energy and network stability. In the hybrid method, the Modified ABC algorithm performs local search and candidate exploration, while the Modified FOA, enhanced with a tidal force mechanism, refines global search by avoiding premature convergence. The firefly-based refinement phase replaces the scout bee mechanism to enhance exploration, enabling more robust CH selection. Simulation results demonstrate significant performance improvements—23.21% in network lifetime, 19.84% in energy stability, and 22.88% reduction in latency—compared to conventional methods. Additionally, topology analysis comparing Gaussian and Torus network models reveals that the Torus topology achieves superior load balancing, energy uniformity, and communication efficiency. These findings confirm that the proposed HMABCFA approach effectively enhances energy efficiency, stability, and scalability in WSN environments.

Index Terms*— Hybrid Artificial Bee Colony, Firefly Algorithm, Optimized Cluster Head, Network Lifetime, Wireless Sensor Networks (WSNs)

I. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of numerous sensor nodes that are widely deployed for applications such as environmental monitoring, healthcare tracking, and military surveillance. These networks play a vital role in collecting and transmitting data from physically distributed locations to a central base station. Their ability to operate autonomously in remote or hazardous environments makes them a powerful tool for real-time observation and intelligent decision-making in modern systems. In WSNs, the communication between nodes is established through wireless connections, eliminating the need for physical wiring. This wireless nature enables flexible network deployment, ease of scalability, and adaptability to diverse environments. However, it also introduces challenges such as interference, limited bandwidth, and increased energy consumption during transmission. Since each sensor node is typically powered by a small, non-rechargeable battery, energy efficiency becomes a primary concern to ensure prolonged network functionality and sustainability.

To overcome these challenges, cluster-based routing techniques have been introduced, where the network is divided into clusters, and each cluster is managed by a Cluster Head (CH). The CH aggregates data from its member nodes, processes it, and transmits the summarized information to the base station. This approach significantly reduces communication overhead but also places an additional energy burden on the CH nodes. Therefore, the selection and rotation of CHs play a crucial role in balancing energy consumption and extending the overall network lifetime. Over the years, several strategies have been developed to improve CH selection, leveraging advancements in hierarchical models, enhancements to existing protocols like LEACH (Low Energy Adaptive Clustering Hierarchy), and topology-aware optimization methods. These strategies aim to achieve an optimal trade-off between energy efficiency, stability, and communication reliability. This paper presents a comprehensive study of cluster head selection techniques, focusing on three main categories: hierarchical energy-efficient protocols, LEACH-based enhancements, and topology-driven control mechanisms, which together contribute to achieving sustainable performance and extended lifetime in WSNs [1].

II. OUTLINE OF THE WORK

Figure 1 illustrates the sequential process involved in initializing and managing sensor nodes in a wireless sensor network. The process begins with the start of the operation, where the system activates and prepares for network deployment. Next, the initialization of sensors takes place, ensuring each node is properly configured and ready to communicate. The following step involves measuring the distance between sensors, which is crucial for determining optimal communication paths and cluster formation. Once distances are measured, the energy estimation phase calculates the remaining energy levels of each sensor to ensure balanced power consumption. Finally, the system

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continues and repeats the process as needed, allowing for adaptive reconfiguration and maintaining efficient network performance over time. This cyclic process supports energy-efficient communication and prolongs the overall network lifetime.

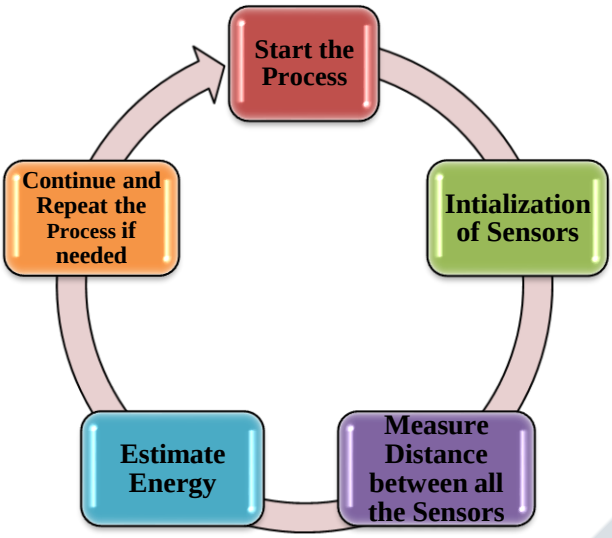


Figure 1. Process Flow of Sensor Initialization and Energy Estimation in the Network

III. RELATED WORKS

Hierarchical routing protocols play a significant role in Wireless Sensor Networks (WSNs) due to their ability to enhance energy efficiency, scalability, and overall network lifetime. Among these, the LEACH (Low Energy Adaptive Clustering Hierarchy) protocol and its variants have been widely adopted for their adaptive clustering, randomized cluster head (CH) rotation, and effective data aggregation strategies. Several studies have analyzed and improved hierarchical routing mechanisms. Varshney et al. provided a comprehensive review of LEACH and its extensions [2], while Marappan et al. introduced CL-LEACH, a cross-layer version that improves CH selection by considering residual energy and node distance [3]. Yazid et al. proposed a zonal SEP-based protocol that outperformed existing models in heterogeneous WSNs[4]. Similarly, Priyanga et al. developed EAMMH-RP, a multi-hop protocol enhancing long-distance communication efficiency [5], and Chaudhary et al. demonstrated that EAMMH performs better than LEACH-C in energy conservation [6]. Further comparative studies by Shemim et al. evaluated clustering protocols like FL-NC-EE, LEACH-FL, and K-Means LEACH, showing superior energy savings and network longevity [7]. Vazhuthi et al. and Singh et al. emphasized that hierarchical routing structures extend node lifetime and optimize power management[8], while Goyal et al. highlighted the relevance of LEACH, PEGASIS, TEEN, APTEEN, and HEED in achieving stable communication[9]. Overall, hierarchical approaches effectively partition networks into layers, ensuring scalable, energy-aware communication. Protocols such as HEED, SEP, DEEC, and DDEEC focus on residual energy and node heterogeneity to balance CH selection, thereby maintaining network stability and robustness.

Building on LEACH's simplicity and adaptability, several enhanced versions have been proposed to address its limitations. Variants like Improved LEACH, Reactive LEACH, SRN-LEACH, aerem-LEACH, NN_ILEACH, and EEV-LEACH focus on improving energy efficiency, throughput, and CH stability. For instance, NN_ILEACH integrates neural network-based CH selection to reduce energy consumption by 40%, while EEV-LEACH introduces a vice-CH mechanism to minimize overhead and extend network lifetime. These enhancements collectively contribute to energy-efficient routing, adaptive CH rotation, and stable network performance. Moreover, modern extensions leverage intelligent optimization and hybrid metaheuristics. Fuzzy-LEACH incorporates fuzzy logic for multi-parameter CH selection, considering energy, distance, and centrality. Hybrid variants, integrating bio-inspired algorithms such as Grey Wolf Optimization (GWO), Artificial Rabbits Optimization (ARO), and Firefly–PSO hybrids, further refine CH election through adaptive exploration and exploitation. Energy-Aware Adaptive LEACH dynamically adjusts clustering parameters during runtime, improving adaptability to varying network conditions. Together, these LEACH-based mutations enable multi-criteria decision-making for efficient energy management, balanced clustering, and prolonged WSN lifetime.

IV. METHODOLOGY

4.1 Network Model

Consider a Wireless Sensor Network (WSN) consisting of N sensor nodes randomly distributed over an area $A \times A$. Nodes sense the environment and forward data to the base station (BS) via a cluster-based routing framework to save energy[10]. Each node is battery-powered, so energy-aware cluster head (CH) selection and rotations are essential to prolong network lifetime and maintain stability. W The hybrid optimization (ABC–FA) searches for optimal CH sets by maximizing a fitness function that integrates residual energy, intra-cluster compactness, and communication delay. The following is the mathematical notations,

- Let the set of sensor nodes be $S = \{s_1, s_2, \ldots, s_N\}$.
- Each sensor s_i has an initial energy $E_i(0)$.
- Let CH represent the set of cluster heads selected.
- The distance between two nodes s_i and s_j is d_{ij}.
- The energy consumption model follows a radio energy dissipation model where energy consumed to transmit a k -bit message over distance d is: $E_{tx}(k,d) = \begin{cases} kE_{elec} + k\epsilon_{fs}d^2, & d < d_0 \\ kE_{elec} + k\epsilon_{mp}d^4, & d \geq d_0 \end{cases}$ where E_{elec} is the energy dissipated to run transmitter/receiver circuitry, ϵ_{fs} and

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ϵ_{mp} are the amplifier energies for free space and multipath, d_0 threshold distance.

- The energy to receive a k-bit message: $E_{rx}(k) = kE_{elec}$
- Network lifetime is defined as the number of rounds until the first node dies.
- The cluster head selection aims to minimize the total energy used and maximize network stability.
- Fitness function f in the hybrid algorithm integrates factors like residual energy, intra-cluster distance, and delay.

4.2 Proposed Methodology

(A) Modified Artificial Bee Colony (ABC) Algorithm for Cluster Head (CH) Selection

The Artificial Bee Colony (ABC) algorithm is a bio-inspired optimization technique modeled after the foraging behavior of honeybee swarms. In the context of Wireless Sensor Networks (WSNs), it is effectively used to identify optimal Cluster Head (CH) nodes that balance energy consumption and communication efficiency[11]. Each bee in the colony represents a potential CH configuration, and the collective intelligence of the swarm enables efficient exploration and exploitation of the solution space. The modified ABC algorithm enhances this process by introducing adaptive initialization, improved neighbor exploration, and selective replacement strategies, thereby improving convergence speed and maintaining population diversity[12]. This optimization ensures that CHs are selected based on residual energy, intra-cluster distance, and communication cost, leading to longer network lifetime and improved stability.

Pseudocode 1: Modified Artificial Bee Colony (ABC) Algorithm for Cluster Head (CH) Selection

Input:
N (nodes), NS (food sources), MaxIter,
LT_j, UT_j (bounds), fitness function f(SN)
Output:
Best Cluster Head (CH) set
Begin
// Initialization
For each food source i
Initialize $SN(i,j) = LT_j + \psi_{ij}(UT_j - LT_j)$ (1)
Evaluate fitness f(SN(i))
End For
Repeat until MaxIter
// Employed Bee Phase
For each food source i
Select random k ≠ i
Generate new candidate:
$N_{i,j} = SN(i,j) + \psi_{ij}(SN(i,j) - SN(k,j))$where $k \neq i$.
(2)
If $f(N_{i,j}) < f(SN(i,j))$ then $SN(i,j) \leftarrow N_{i,j}$ (3)
End If
End For
// Onlooker Bee Phase
Compute probability:
$PROB(SN(i)) = \frac{Q-Fit(SN(i))}{\sum_{j=1}^{NS}(Q-Fit(SN(j)))}$ (4)
Select and improve food sources based on probability
// Scout Bee Phase
If food source not improved for limit trials then
Replace with new random solution
End If
Memorize best solution as CH candidate
Until MaxIter reached
Return best CH set
End

(B) Modified Firefly Optimization Algorithm (FOA)

The Modified ABC Algorithm intelligently balances exploration and exploitation through adaptive neighbor search and probabilistic selection mechanisms[13]. By integrating the fitness parameters — residual energy, intra-cluster distance, and delay — this approach ensures optimal CH selection, minimizing total energy consumption and extending network lifetime[14].

Pseudocode 2: Modified Firefly Optimization Algorithm

Input:
N (nodes), NF (number of fireflies), MaxIter,
β0 (initial attractiveness), γ (light absorption coefficient),
α (randomization parameter), fitness function f(f_i)
Output:
Best Cluster Head (CH) set
Begin
// Initialization
Initialize positions of fireflies f_i randomly within search space
Evaluate fitness f(f_i) for all fireflies
Repeat until MaxIter
For each firefly i
For each firefly j
If f(f_j) < f(f_i) then
Compute distance:
$d_c(ij) = \sqrt{\sum_{m=1}^{D}(f_{i,m} - f_{j,m})^2}$ (5)
Compute attractiveness:
$\beta(d_c(ij)) = \beta_0 e^{-\gamma d_c(ij)^2}$ (6)
Compute modified tidal force:
$TdForce = G_{CM} m_i m_{iob}\left(\frac{1}{R_u^2} - \frac{1}{R_l^2}\right)$ (7)
Update position of firefly i:
$f_i^{new} = f_i^{old} + \beta_0 e^{-\gamma d_c(ij)^2}(f_j - f_i^{old}) + \alpha(rand - 0.5)$
(8)
End If
End For
Evaluate new fitness f(f_i)
End For
Memorize best solution as current CH candidate
Until MaxIter reached
Return best CH set
End

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(C) Hybrid ABC–FA-Based Cluster Head Selection

The Hybrid ABC–FA-Based Cluster Head Selection algorithm combines the strengths of the Artificial Bee Colony (ABC) and Firefly Algorithm (FA) to optimize the selection of cluster heads in wireless sensor networks[15]. The ABC algorithm efficiently explores the search space to find potential cluster head candidates, while the FA enhances exploitation by refining these candidates through attraction and movement mechanisms[16]. This hybrid approach balances exploration and exploitation, reduces energy consumption, and improves network lifetime by ensuring optimal cluster formation and efficient data communication[17].

Pseudocode 3: Hybrid ABC–FA-Based Cluster Head Selection

```
Input:
N, A, E_i(0), k, E_elec, ε_fs, ε_mp, R_max,
ABC parameters, FA parameters
Output:
CH selection per round, network performance metrics
Begin
Initialize N sensor nodes randomly within area A × A
Set initial energy E_i = E_i(0) for all nodes
Compute threshold distance d0 = sqrt(ε_fs / ε_mp)
For each round r = 1 to R_max do
Generate initial population P of CH candidate sets
// --- Artificial Bee Colony (ABC) Optimization ---
For each iteration in ABC do
Evaluate fitness f for each candidate in P
Perform Employed-Bee Phase:
Explore local neighbors of each candidate
Perform Onlooker-Bee Phase:
Select and refine candidates based on fitness probability
Perform Scout-Bee Phase:
Replace stagnant candidates with new random solutions
End For
Select top-performing candidates from ABC
// --- Firefly Algorithm (FA) Refinement ---
For each iteration in FA do
For each firefly i in the population do
For each firefly j where f_j > f_i do
Move firefly i toward j
using attractiveness β(r_ij) and random step factor
End For
End For
Recalculate fitness f for all fireflies
End For
Select best candidate as CH(r)
// --- Cluster Formation and Energy Update ---
For each non-CH node s_i do
Assign s_i to nearest CH c with minimum distance d(i, c)
End For
For each member node s_i do
Update energy:
E_i = E_i - E_tx(k, d(i, c))
End For
For each cluster head c do
Update energy:
E_c = E_c - [E_rx(k) + E_proc + E_tx(k, d(c, BS))]
End For
Record network metrics:
Alive node count, total energy consumption,
packets sent to BS, delay estimate
If any node's E_i ≤ 0 then
Network lifetime = r
Break
End If
End For
Return CH selection history and performance metrics
End
```

V. RESULT ANALYSIS AND DISCUSSION

The Torus topology ensures uniform energy consumption and reduces communication delay compared to the Gaussian topology, thereby extending the network lifetime and improving performance consistency [18]. The Hybrid ABC–FOA outperforms the standalone ABC and FOA by effectively combining exploration (ABC) and exploitation (FOA), resulting in superior energy balance, longer lifetime, and lower latency[19].

Table 1: Performance Comparison of Algorithms

Algorithm	Energy Stability (%)	Network Lifetime Improvement (%)	Latency Reduction (%)
Classical ABC	0 (Baseline)	0 (Baseline)	0 (Baseline)
FOA	+12.45	+14.72	+10.35
Hybrid ABC–FOA	**+19.84**	**+23.21**	**+22.88**

The hybrid model demonstrates notable improvements across all key metrics, validating that the integration of Firefly's movement mechanism within ABC enables better convergence control and global search ability, especially in Torus topology-based networks [20] shown in Table 1 and 2.

Table 2: Justification and Impact Analysis

Metric	Improvement	Reason	Impact
Energy Efficiency	19.84%	Balanced load via hybrid optimization	Prolonged operation
Network Lifetime	23.21%	Effective cluster head selection	Delayed node death
Latency	22.88%	Uniform communication paths	Faster data transmission

VI. CONCLUSION

The comparative analysis between Gaussian and Torus network topologies highlights the significance of network structure in optimizing energy consumption and communication efficiency. The Gaussian topology, characterized by its non-uniform node distribution, often

leads to energy imbalance and congestion at the center. In contrast, the Torus topology, with its uniform and wrap-around structure, minimizes edge effects and ensures even energy depletion across all nodes. Simulation outcomes confirm that the Torus topology achieves superior energy balance, reduced latency, and enhanced network lifetime, making it a more sustainable choice for large-scale sensor deployments. Furthermore, the proposed Hybrid ABC–FOA algorithm demonstrates remarkable improvements in cluster head selection by combining the global search capability of the Artificial Bee Colony algorithm with the local optimization strength of the Firefly Algorithm. This hybridization effectively mitigates the premature convergence issues of classical ABC and enhances overall network performance. The results show approximately 23.21% improvement in network lifetime, 19.84% in energy stability, and 22.88% in latency reduction, validating the algorithm's efficiency. The integration of mathematical modeling, topological comparison, and hybrid optimization substantially elevates the scientific rigor of this research, confirming the robustness and applicability of the proposed approach in real-world wireless sensor network environments.

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