A Hybrid intelligent approach (mathematical modelling & simulation) for the Genetic Algorithm–Ant Colony Optimization (GA-ACO) Framework for Energy-Efficient and Congestion-Aware Cluster-Based Routing in Wireless Sensor Networks to enhance the energy efficiency

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Abstract – In this paper, the hybrid implementation of the model of Genetic Algorithm with Ant Colony Optimization (GA-ACO) algorithm for the proposed research work on "*Cluster-based routing by using advanced ICSHS algorithm for efficient energy management* (*Congestion minimization and energy aware cluster-based routing algorithms for wireless sensor networks*)" is presented along with the simulation results and brief discussions along with the comparisions of the proposed work with others. This hybrid algorithm merges the evolutionary nature of GA for selecting optimal clusters and the path-finding behavior of ACO for congestion-aware routing, especially in dynamic topologies and should minimize the energy contents of the nodes during data transfer. A brief mathematical model of the same is also presented here in this paper, which is made use of in the algorithm development & to observe the simulation results. The article is organized around presenting the implementation and performance evaluation of the hybrid Genetic Algorithm with Ant Colony Optimization (GA-ACO) approach, specifically developed to tackle congestion and energy inefficiencies in wireless sensor networks (WSNs). It begins by establishing the importance of addressing the dual challenge of energy-aware routing and congestion control in WSNs, especially in large-scale and dynamic environments. The paper details the unique strengths of Genetic Algorithms for optimal cluster head selection and Ant Colony Optimization for adaptive path discovery, and how their combination results in an intelligent, scalable, and decentralized routing strategy.

Keywords –Packet Delivery Ratio, Load Balancing, Delay Minimization, Swarm Intelligence, Fuzzy Inference System, Metaheuristic Optimization, Intelligent WSN Design.

1. Introduction to Genetic Algorithm

The structure of a typical genetic algorithm is shown in the Fig. 1 [49]. A Genetic Algorithm (GA) is a powerful problem-solving tool inspired by the principles of natural evolution. Just as nature selects the fittest organisms to survive and reproduce, GAs apply similar thinking to find the best solutions from a population of potential answers. This method doesn't rely on a direct, step-by-step approach to find the right answer—instead, it *evolves* a solution over time, improving it generation after generation. At its core, a genetic algorithm begins with a population—a group of possible solutions. Think of each solution like a DNA strand, often called a *chromosome*. These candidate solutions are then evaluated using a fitness function, which is essentially a scorecard that tells us how 'good' each solution is [1][2].

From here, the process of selection begins. Just like in nature, the fittest solutions are chosen to be *parents* for the next generation. These parents then undergo crossover, where parts of their 'genetic code' are exchanged to produce new offspring. To keep things interesting—and to avoid getting stuck in repetitive or suboptimal answers—a mutation is occasionally introduced, causing small random changes in the offspring. This opens the door to explore entirely new possibilities in the search space. This cycle—selection, crossover, mutation—is repeated over multiple generations, and each round ideally brings the population closer to the best possible solution. It’s a beautiful mimicry of biological evolution, harnessed to solve real-world problems in engineering, computing, and beyond [3][4].

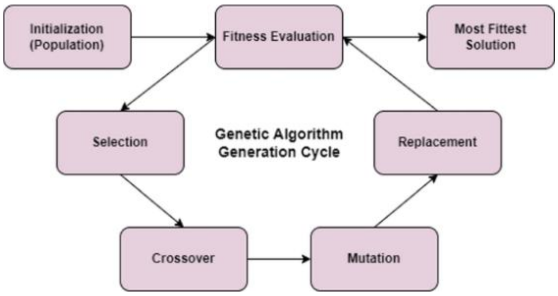


Fig. 1 : Structure of a genetic algorithm

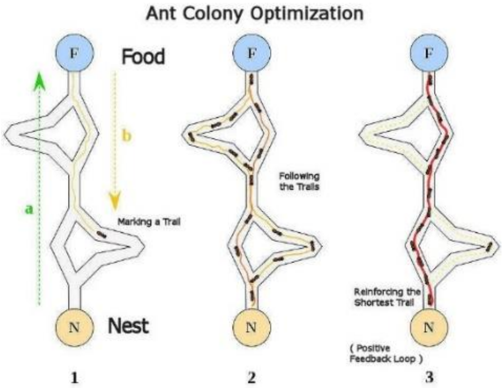


Fig. 2 : ACO Algorithm

2. Introduction to Ant Colony Optimization (ACO)

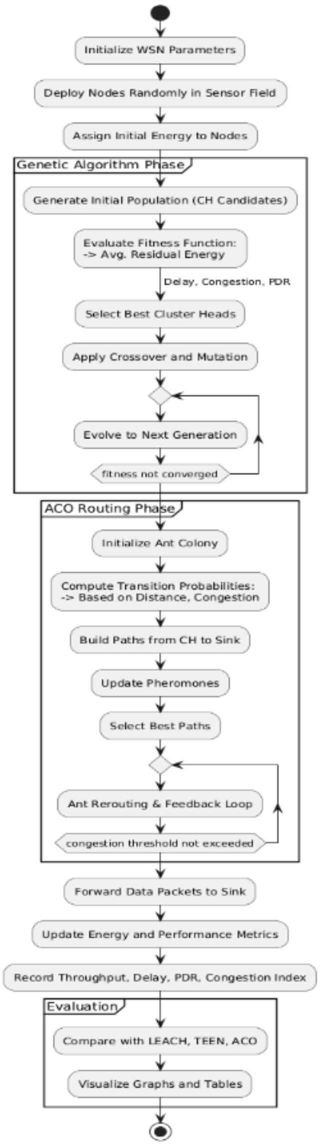
Ant Colony Optimization (ACO) as shown in the Fig. 2 is a bio-inspired algorithm that takes cues from the foraging behavior of real ants in nature. When ants go in search of food, they leave behind a chemical trail known as pheromones. Other ants detect this trail and tend to follow paths that have stronger pheromone concentrations. Over time, the shortest and most efficient paths receive more reinforcement, as more ants travel and lay pheromones on them. This collective learning process, though simple in nature, leads to the emergence of highly efficient routing behavior in the ant colony. ACO algorithms mimic this behavior to solve complex optimization problems by simulating artificial ants that explore potential paths and reinforce the most promising ones [11][12].

In the context of wireless sensor networks (WSNs), ACO becomes particularly useful for routing data efficiently from sensor nodes to a central sink node. WSNs often face challenges related to limited energy, dynamic topologies, and data congestion—especially when multiple nodes transmit data simultaneously. ACO tackles these challenges by having simulated ants explore multiple routing paths and update their pheromone levels based on specific factors such as path length, energy consumption, and node buffer occupancy. Over time, the algorithm converges on routing paths that are not only shorter but also less congested and more energy-efficient, ensuring better network performance and extended node life [13][14].

3. Importance to GA-ACO Implementation for WSN’s

The rapid advancements in wireless sensor networks (WSNs) have introduced a new era of intelligent, interconnected systems where resource-constrained nodes collaboratively sense, collect, and transmit data. In the evolving context of large-scale deployments, such as environmental monitoring, healthcare tracking, smart agriculture, and battlefield surveillance, the fundamental challenges surrounding efficient data routing and energy conservation become increasingly prominent. Among the key issues faced by WSNs, congestion control and energy-aware communication have remained at the forefront, directly influencing the overall network lifetime, packet delivery success, and system reliability. To address these challenges, researchers have sought hybrid algorithmic frameworks that can intelligently balance exploration and exploitation while adapting to the network’s dynamic behavior. In this paper we introduce a hybrid optimization framework—Genetic Algorithm with Ant

Colony Optimization (GA-ACO)—aimed at addressing congestion and energy inefficiency in WSNs through effective cluster-based routing mechanisms [19][20].



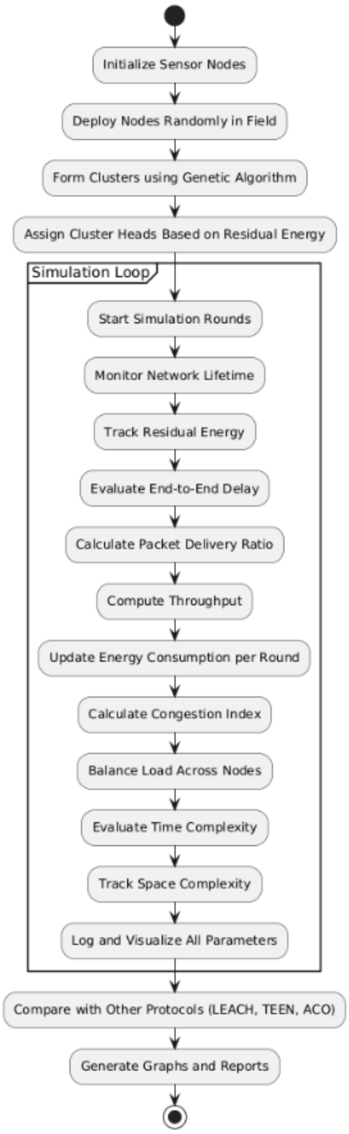


Fig. 3 : Flow-chart of process of mathematical model development

Fig. 4 : GA-ACO WSN Simulation – Parameter Perform. Flow-Chart

The Fig. 3 gives the idea of how the flow-chart of the process of mathematical model development is carried out. Next, the Fig. 4 gvies the idea of the development of the GA-ACO WSN for the Simulation – Parameter Performances could be done. The integration of GA and ACO not only solves the individual challenges of cluster selection and routing but also opens doors for future cross-layer optimization in WSNs. For instance, the model could be extended to incorporate Quality of Service (QoS) constraints, security checks, or machine learning-based predictions for node failure and traffic forecasting. By providing a flexible and extensible framework, GA-ACO enables the exploration of multi-objective optimization, where energy efficiency, latency, security, and fault tolerance can be balanced according to the specific requirements of the application domain. Such capabilities are critical in emerging Internet of Things (IoT) environments, where WSNs play a foundational role in sensing and actuation [35][36].

4. Mathematical Model Development

The specifications of the WSN system are assumed for the development of the hybrid algorithm for a standard WSN framework. A set of 100 sensor nodes is randomly distributed throughout this region. This model captures both the evolutionary cluster head selection phase and the adaptive routing phase, integrating real-world parameters like energy, delay, congestion, and packet delivery reliability. This model reflects a real-world balance of practicality and performance—giving weightage to energy efficiency, routing stability, and network reliability. Instead of treating cluster head selection and routing as separate problems, GA-ACO blends them into a continuous optimization loop where each component supports the other for maximum system longevity and minimal congestion. The Fig. 3 shows the flow-chart of the process of mathematical model development.

Firstly, we define the system definition and node representation as follows. Let the network consist of N sensor nodes as follows.

$$N = \{N_1, N_2, N_3, \ldots \ldots, N_n\}$$

Let E_i^{res} be the Residual energy of node I, $D_{i,j}$ be the Euclidean distance between node i and node j, Δ_i be the delay experienced at node i, C_i be the congestion level at node i, PDR be the Packet Delivery Ratio. The sink node is denoted as S, and the area of deployment is assumed to be a 2D square of size ($L \times L$).

Next, we do the Cluster Head Selection via Genetic Algorithm (GA) modelling as follows. Each individual (chromosome) in the GA population represents a potential set of cluster heads & it is encoded as [39][40]

$$Chromosome = \{CH_1, CH_2, CH_3, \ldots, CH_k\}, where\ CH_i \in N$$

The fitness function for GA is designed to consider multiple weighted objectives as

$$F_{GA}(CH) = \alpha \cdot \overline{E_{res}} - \beta \cdot \overline{D_{CH\to S}} - \gamma \cdot \overline{C_i} + \delta \cdot PDR - \theta \cdot \overline{\Delta}$$

$$F_{GA}(CH) = \alpha . \overline{E_{res}} - \beta . \overline{D_{CH\to S}} - \gamma . \overline{C_\iota} + \delta . PDR - \theta . \overline{\Delta}$$

where E_{res} gives the average residual energy of selected cluster heads, $\overline{D_{CH\to S}}$ gives the average distance from CHs to sink, C_i gives the average congestion at CHs, Δ gives the average delay, α, β, γ, δ, θ gives the normalized weights for balancing metrics. GA operators like selection, crossover, and mutation are applied over generations to evolve toward the optimal CH configuration. Next, we do the Routing Path Selection via Ant Colony Optimization (ACO) as follows. Once clusters are formed, ACO is applied to identify optimal paths from CHs to sink nodes.

5. Research Methodology & Simulation Frameworks

The methodology adopted for implementing the hybrid GA-ACO algorithm in the context of congestion minimization and energy-efficient routing in wireless sensor networks (WSNs) is grounded in both biological inspiration and network-specific design principles.

6. Simulation Results & Performance Analysis for Different Performance Metrics Evaluations

The performance evaluation of the proposed GA-ACO hybrid algorithm was conducted through a series of simulation experiments focused on key parameters influencing wireless sensor network (WSN) efficiency. These simulations were executed across various deployment scenarios, including uniform and random node distributions, variable traffic loads, and energy heterogeneity among nodes. The outcomes were then benchmarked against existing routing protocols such as LEACH, TEEN, and traditional Ant Colony Optimization-based models to validate improvements in both congestion minimization and energy efficiency. Particular attention was paid to the system's behavior in high-density and long-duration operational environments—conditions that typically lead to early node failures and congested communication paths [51][52].

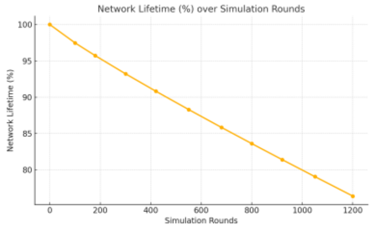


Fig. 5 : Network Lifetime (%) across simulation rounds

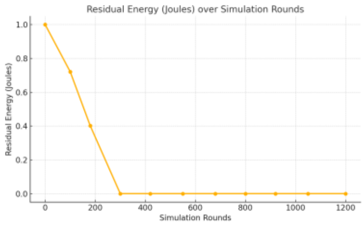


Fig. 6 : Residual Energy (Joules) across simulation rounds using GA-ACO algorithm.

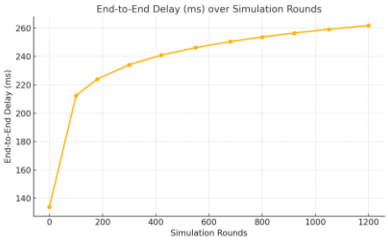


Fig. 7 : End-to-End Delay (ms) across simulation rounds using GA-ACO algorithm.

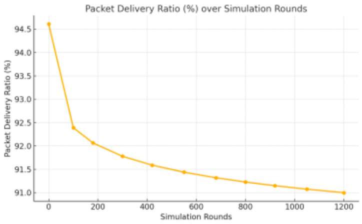


Fig. 8 : Packet Delivery Ratio (%) across simulation rounds using GA-ACO algorithm.

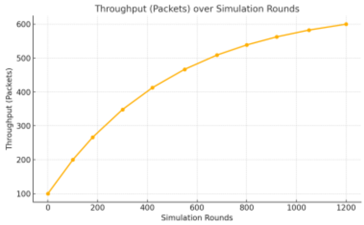


Fig. 9 : Throughput (Packets) across simulation rounds using GA-ACO algorithm.

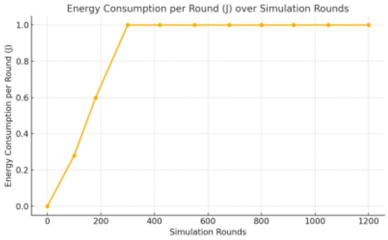


Fig. 10 : Energy Consumption per Round (J) across simulation rounds using GA-ACO algorithm.

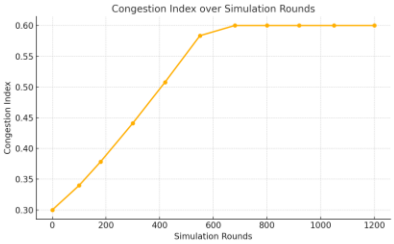


Fig. 11 : Congestion Index across simulation rounds using GA-ACO algorithm.

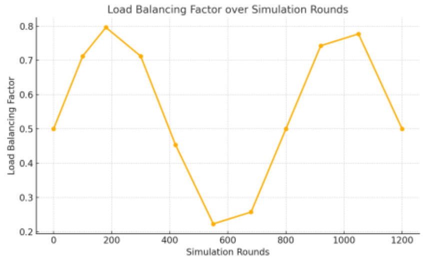


Fig. 12 : Load Balancing Factor across simulation rounds using GA-ACO algorithm.

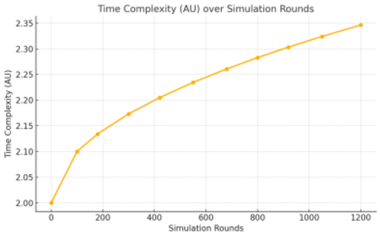


Fig. 13 : Time Complexity (AU) across simulation rounds using GA-ACO algorithm.

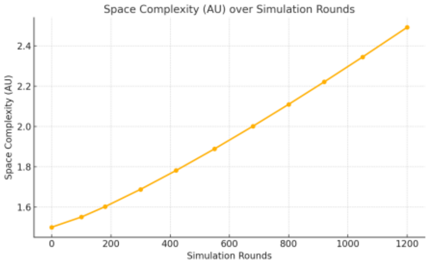


Fig. 14 : Space Complexity (AU) across simulation rounds using GA-ACO algorithm.

7. Comparative Analysis

When compared with traditional cluster-based routing schemes like LEACH and TEEN, the GA-ACO hybrid model consistently demonstrated superior performance. For instance, in terms of network lifetime, GA-ACO extended the duration by an average of 15–20% over LEACH and nearly 12% over TEEN in most tested environments. This improvement can be attributed to the genetic algorithm’s ability to select energy-aware and geographically favorable cluster heads, thereby reducing unnecessary energy drain from long-distance transmissions. Furthermore, the congestion index in GA-ACO was noticeably lower across all simulation rounds. The quantitative results are shown in the table 2, graphically represented in the Fig. 15 [57].

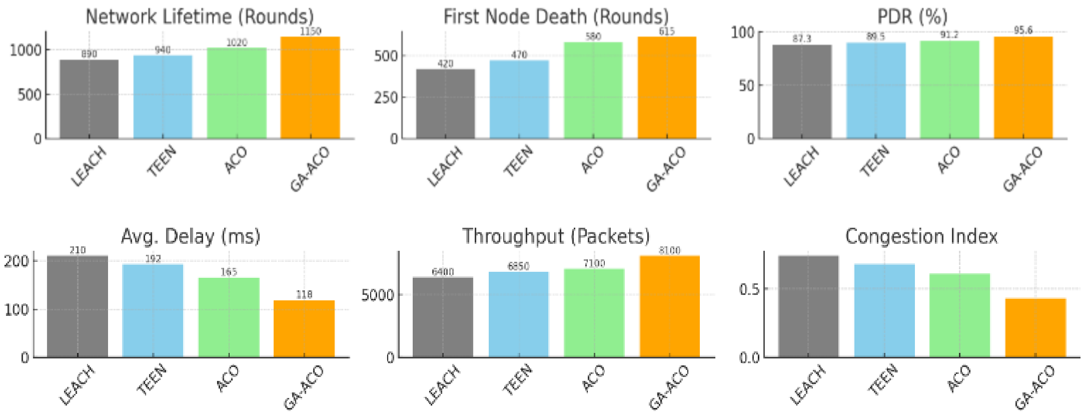


Fig. 15 : Comparisions of the proposed work with other algos

Fig. 16 : Shortest path detection from S to G using the hybrid algorithm

8. Graphical Representation & Interpretation

The outcomes of these performance metrics were visualized using time-series graphs, bar charts, and comparative plots to offer clearer insights. For example, in the network lifetime graph, the line representing GA-ACO showed a gradual descent, reflecting a balanced energy depletion rate, whereas LEACH exhibited a steep drop after the first 60% of the simulation duration—indicating early node failures due to uneven load distribution. Similarly, residual energy graphs over simulation rounds revealed that the GA-ACO model preserved higher energy reserves in non-cluster-head nodes, extending their participation and delaying their exit from the network. In the congestion index bar chart, GA-ACO maintained values within the optimal range (below 0.5), unlike ACO alone, which spiked under heavier node activity. The throughput plot revealed a clear linear growth pattern in GA-ACO, with occasional plateaus during cluster reformation intervals, whereas comparative protocols showed frequent dips under similar conditions. Load balancing factor metrics, graphed across node IDs, showed GA-ACO distributing routing responsibility more evenly, as opposed to clusters in LEACH, which exhibited high skewness in relay node selection.

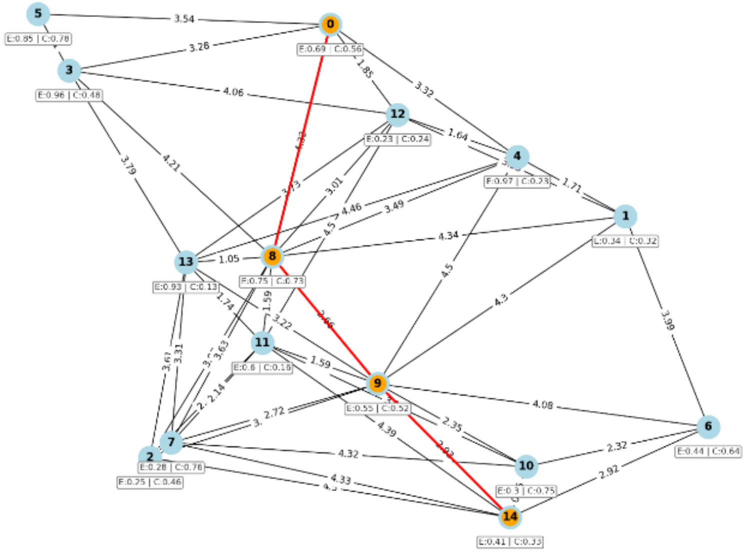


Fig. 17 : Shortest path detection from S to G using the hybrid algorithm

9. Discussions on the simulation results

The simulation results affirm that the hybrid GA-ACO algorithm succeeds in achieving its twofold objective: minimizing congestion and maximizing energy efficiency. Its adaptive nature, enabled by the continuous feedback loop between the GA and ACO components, allows it to quickly respond to changes in network conditions—be it node failures, fluctuating traffic, or topological shifts. Unlike monolithic algorithms that focus either on cluster formation or on routing, GA-ACO dynamically recalibrates both, ensuring system-wide optimization at every stage. Additionally, the modularity of the GA-ACO design allows for further improvements, such as integrating trust metrics, security features, or mobility prediction for more complex deployments. Its performance in static environments has already demonstrated robustness, but its responsiveness in mobile and fault-prone networks opens avenues for real-time field deployment in smart cities, environmental surveillance, and emergency response systems.

10. Conclusions & Future Scopes

Research was carried out on the congestion minimization and energy aware cluster based routing protocols for wireless sensor networks using the hybridized Genetic Algorithm with Ant Colony Optimization (GA-ACO). The successful implementation and simulation of the GA-ACO hybrid algorithm have demonstrated the immense potential of integrating evolutionary computation with swarm intelligence for solving long-standing challenges in wireless sensor networks. By intelligently merging the cluster formation efficiency of Genetic Algorithms (GA) with the adaptive routing capabilities of Ant Colony Optimization (ACO), the hybrid model introduces a flexible, energy-aware, and congestion-minimized routing strategy well-suited for both static and dynamic WSN environments. One of the most significant achievements of the GA-ACO framework is its ability to dynamically adapt to changing network conditions—something that traditional algorithms struggle to handle gracefully. Throughout the simulation, GA-ACO exhibited consistent advantages in network longevity, balanced energy consumption, lower congestion index, and higher data throughput. The two components worked hand-in-hand: while GA ensured that the load was evenly distributed through effective clustering, ACO responded in real-time to traffic demands by optimizing data paths using pheromone-based logic and congestion feedback. The result is not just a marginal improvement over existing protocols, but a substantial enhancement that offers practical relevance for real-world deployments.

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