**Proposed Work**

**Performance Evaluation of ACO and SA Against Alternative Optimization Techniques in VANETs**

Vehicular Ad Hoc Networks (VANETs) require robust message propagation mechanisms to ensure real-time communication, especially for critical applications such as emergency alerts and traffic management. Various optimization algorithms have been employed to enhance network performance, including node localization, routing efficiency, and data dissemination. Among these, Ant Colony Optimization (ACO) and Simulated Annealing (SA) have demonstrated superior performance compared to other metaheuristic techniques due to their adaptability and efficiency in dynamic environments. Particle Swarm Optimization (PSO) has been utilized in VANET routing because of its fast convergence rate and flexibility in handling dynamic network conditions. However, PSO is prone to premature convergence, which results in suboptimal routing paths in high-mobility VANET scenarios. In contrast, ACO’s pheromone-based learning mechanism dynamically adjusts to network topology changes, offering more reliable and stable routing. Genetic Algorithms (GA) have also been applied in VANET routing by leveraging evolutionary operations such as selection, crossover, and mutation to determine optimal paths. However, GA’s dependency on high computational resources and parameter tuning makes it less practical for real-time VANET operations. SA, on the other hand, provides an efficient search strategy by probabilistically accepting worse solutions, which prevents stagnation in local optima and enhances global search efficiency.

Grey Wolf Optimization (GWO) and Raccoon Optimization Algorithm (ROA) have been investigated for NLOS node localization in VANETs, offering improvements in positioning accuracy. However, their effectiveness diminishes in large-scale networks where message dissemination speed is crucial. ACO’s decentralized and adaptive nature ensures efficient and scalable message propagation, outperforming GWO and ROA in high-mobility environments. Other hybrid metaheuristic approaches, such as the Hybrid Invasive Weed Optimization and Squirrel Search Algorithm (HIWO-SSA) and Harris Hawk Optimization Algorithm (HHOA), have been explored for VANET optimization. Although these methods improve network performance, they often suffer from high computational complexity and require extensive fine-tuning. Additionally, techniques such as Hybrid Crow Search and Gray Wolf Optimization (CS-GWO) and the Improved Rank Criterion-Based NLOS Node Detection Mechanism have been studied for enhancing localization accuracy but lack real-time adaptability.

Recent advancements, including Received Signal Strength (RSS)-based localization, V2X Sidelink Localization, and 5G-based cooperative localization, have further improved VANET communication. However, these methods often require additional infrastructure, limiting their feasibility in fully decentralized environments. Other novel approaches, such as Weighted Inertia-Based Dynamic Virtual Bat Algorithm, Multi-Agent Deep Reinforcement Learning, and Improved Gaussian Process models, have been introduced to optimize message dissemination and decision-making processes. Additionally, ADMM over 5G-based VANETs and 5G Millimeter-Wave Systems have enhanced signal processing and localization accuracy but face challenges in seamless integration with existing vehicular networks. Given the limitations of these algorithms, ACO and SA stand out due to their ability to dynamically optimize routes, balance exploration and exploitation, and efficiently propagate messages in VANETs. This work proposes a hybrid ACO-SA approach, leveraging ACO’s pathfinding efficiency and SA’s ability to escape local optima, providing an ideal solution for VANET message dissemination. The following section presents the detailed workflow and expected improvements of the proposed hybrid model.

**Proposed Hybrid ACO-SA Approach for VANET Routing**

Vehicular Ad Hoc Networks (VANETs) require an efficient and adaptive routing mechanism to ensure seamless communication. The standalone application of Ant Colony Optimization (ACO) and Simulated Annealing (SA) algorithms provides distinct advantages but also exhibits limitations when employed separately. ACO is highly effective in discovering optimal paths based on pheromone trails; however, it tends to converge prematurely, leading to suboptimal solutions in highly dynamic environments. Additionally, ACO does not inherently prevent redundant node visits, which increases latency in VANET message propagation. Conversely, SA is proficient at escaping local optima through probabilistic swaps, yet it lacks an efficient path construction mechanism, making it insufficient for routing in VANETs when used alone. By integrating these two techniques, the hybrid ACO-SA approach overcomes individual weaknesses and enhances VANET message propagation.

ACO explores optimal paths based on distance and connectivity but does not inherently prevent redundant node visits, leading to unnecessary retransmissions and increased latency in VANET message propagation. SA optimizes paths by ensuring each node is visited exactly once, significantly reducing delays and improving network efficiency. In the proposed system, ACO determines the initial optimal path based on pheromone updates and heuristic values, while SA refines the route by eliminating redundant visits and optimizing path selection. This hybridization enhances the efficiency of VANET message propagation by combining ACO’s pathfinding capabilities with SA’s optimization strategy. By leveraging the strengths of both algorithms, the hybrid ACO-SA approach ensures reliable and adaptive routing in VANETs. ACO efficiently identifies optimal paths, while SA prevents unnecessary retransmissions, reducing latency and enhancing overall network performance. The ability to dynamically recalculate paths in response to network changes further improves adaptability and scalability. This hybrid strategy not only optimizes route selection but also enhances stability, making it a robust solution for real-time intelligent transportation systems.

**Workflow of the Hybrid ACO-SA Approach**

The process begins with the initialization of simulation parameters, including the network environment, ACO and SA settings, and the deployment of obstacles, moving vehicles, and key vehicles. The pheromone values in ACO are set using:

where is the initial pheromone level. Each vehicle is assigned movement, ensuring a dynamic and realistic VANET scenario. The distance between nodes is calculated using:

which helps in determining the optimal path for routing.

The initial path generation is conducted using ACO. Multiple ants construct paths based on heuristic values, computed as:

where represents the distance between nodes. The probability of an ant selecting a particular path is determined using:

where and control the influence of pheromone and heuristic values, respectively. After path selection, pheromone updates occur based on the rule:

where is the evaporation rate, is the pheromone deposit factor, and is the tour length of ant . If the path intersects obstacles or is suboptimal, the process is repeated until a feasible route is determined.

Once ACO generates an optimal path, SA is applied to refine the solution. SA works by adjusting the sequence of nodes to ensure that each node is visited exactly once, thereby reducing redundant transmissions. A probabilistic swap mechanism is employed using:

where represents the change in path cost and is the temperature parameter. The temperature is updated iteratively using:

where is the cooling rate. This mechanism prevents premature convergence and ensures that the final path is both optimal and efficient. The effectiveness of message propagation is further analyzed using:

which determines the delay associated with different node densities in VANETs.

After optimization, the final optimal path is selected, and vehicle positions are updated based on speed and direction. If the network conditions change dynamically, the algorithm re-evaluates the routing paths and identifies a new optimal solution. The hybrid ACO-SA approach continuously adapts to the network topology, ensuring low latency and high efficiency in VANET message propagation. The combination of ACO’s path exploration and SA’s refinement process significantly improves the reliability of VANET routing by dynamically adjusting to changing vehicular positions while minimizing computational complexity. Additionally, this approach effectively mitigates congestion by optimizing the selection of communication links, ensuring smoother data flow across the network. The integration of adaptive pheromone updates in ACO further enhances route stability, preventing frequent disruptions in transmission.

Initialize Simulation Parameters – Environment, Network, ACO and SA

Generate and deploy Obstacles, Moving Vehicles, Key Vehicles randomly and assign movement

Optimal path using Hybrid ACO - SA

Generate Initial Path using ACO

Initialize multiple ants

Compute heuristic values based on distance and connectivity

Compute Pheromone and update the trails

Path, not intersecting on obstacles and optimal?

No

Store the paths

Apply Simulated Annealing Optimization

Refine the path by adjusting node sequences

Reduce path cost using probabilistic swaps

Select the Final Optimal Path with lower path cost

Update the vehicle positions (if dynamic)?

Update the vehicle positions based on speed and direction

Ensure vehicles are still within communication range.

Yes

Yes

No

Re-run and Find a new optimal path.

Figure 1: Flowchart of Hybrid ACO-SA Approach