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PERFORMANCE ENHANCEMENT OF ROUTING IN WIRELESS AD HOC NETWORKS USING HYBRID SWARM INTELLIGENCE-BASED HYBRID OPTIMIZATION ALGORITHM IN NS-2

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Abstract

Routing in wireless ad hoc networks is challenging due to dynamic topology, interference, and limited node resources. Traditional single-metric routing schemes often suffer from high packet overhead, route instability, and poor performance under heavy load. This paper presents a Hybrid Swarm Intelligence-based Hybrid Optimization Routing (HSI-HOR) approach for wireless ad hoc networks. The proposed method uses a hybrid optimization algorithm combining features of swarm intelligence techniques using Optimization to select energy-efficient, low-delay, and reliable routes while minimizing routing control overhead. The algorithm is implemented in NS-2 by extending a reactive routing protocol and is evaluated under different node densities and traffic loads. Performance is compared with a baseline AODV-like protocol in terms of packet delivery ratio, average end-to-end delay, routing overhead, and energy consumption. Simulation results show that HSI-HOR improves packet delivery ratio and reduces routing overhead and delay, especially under medium and high loads, demonstrating its suitability for performance-critical wireless communication scenarios.

Keywords Wireless ad hoc networks; NS-2; routing performance; swarm intelligence; hybrid optimization; routing overhead; metaheuristic routing.

1. Introduction

Wireless ad hoc networks are collections of mobile or static wireless nodes that communicate without fixed infrastructure. Each node forwards packets on behalf of others, creating multi-hop communication paths. Such networks are widely used in emergency response, military operations, vehicular networks, community networks, and large-scale sensing environments.

Routing in these networks must deal with frequent changes in topology, limited battery power, fluctuating link quality, and interference. Traditional routing protocols such as AODV and DSR use shortest-path or hop-count-based decisions and simple control logic. Although they

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work reasonably well under light load, their performance often degrades in dense or highly loaded networks. Problems include increased delay, packet drops due to congestion or link failures, and high routing overhead due to repeated route discoveries and error messages.

Swarm intelligence-based optimization techniques, inspired by the collective behavior of ants, birds, bees, or other natural systems, offer promising tools for routing decisions. They provide distributed, adaptive, and robust solutions. However, single swarm methods may still face limitations such as slow convergence or sensitivity to parameter settings.

This work proposes a Hybrid Swarm Intelligence-based Hybrid Optimization Routing (HSI-HOR) algorithm that combines features from two swarm-based optimization approaches (for example, ant colony concepts for path construction and particle-swarm-like refinement for route quality adjustment). The method is designed to:

Improve routing performance metrics such as packet delivery ratio and end-to-end delay.

Reduce routing overhead in terms of control packet exchanges.

Ensure more balanced energy consumption and increased route stability.

The algorithm is implemented in NS-2 and evaluated through simulation. The proposed protocol is compared with a baseline AODV-like routing scheme under different network sizes and traffic conditions.

The main contributions of this research are to be followed

- A hybrid swarm intelligence routing model integrating global path exploration and local refinement.
- A hybrid optimization scheme that combines route quality evaluation with overhead minimization.
- An NS-2 based performance study of routing metrics and overhead using realistic ad hoc scenarios.

2. Related Work

Routing in ad hoc networks has been approached through classical protocols as well as bio-inspired techniques.

Classical protocols like AODV, DSR, and OLSR use hop count, periodic hello messages, and reactive or proactive strategies. While these protocols are standardized and widely used, they do not exploit advanced optimization for route selection, and they often treat all links and nodes in a relatively simple way.

Swarm intelligence methods, such as ant colony and particle swarm, have been applied to routing to improve path selection. Ant Colony-based routing uses artificial pheromone trails and probabilistic forwarding to discover and maintain good paths. Particle Swarm-based methods treat routes as solutions in a search space and move them towards better-performing neighbors. These methods offer adaptiveness and can handle dynamic environments.

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Hybrid approaches combine two or more metaheuristics to exploit their strengths and reduce weaknesses. For example, ant colony can be used for global exploration, while another method refines the best routes locally. Several studies have shown that hybrid metaheuristic routing strategies can outperform single-method approaches in terms of convergence speed and solution quality.

However, some existing works focus mainly on theoretical optimization performance and do not fully evaluate protocol-level metrics such as routing overhead, control packet volume, and energy consumption in network simulators like NS-2. The present work addresses this by integrating a hybrid swarm intelligence approach into a full routing protocol implementation and evaluating detailed performance metrics, including overhead, using NS-2.

3. System Model

3.1 Network Model

The network considered is a wireless multi-hop ad hoc network with the following characteristics:

- Nodes are randomly deployed in a two-dimensional area.
- Each node has a limited transmission range and uses an IEEE 802.11-based MAC.
- All nodes can act as routers and forward packets for others.
- Nodes have finite energy supplied by batteries.
- The wireless channel is shared and subject to interference and contention.
- Node mobility can be static or low-speed random movement. For simplicity, in the initial evaluation, nodes are assumed static during each simulation run.

3.2 Traffic Model

- Traffic is generated by multiple constant bit rate (CBR) flows over UDP:
- A set of sources and destinations is selected randomly.
- Each source sends packets at a fixed rate to its destination.
- Three traffic load levels are considered:
- Low: fewer flows and lower send rate,
- Medium: moderate number of flows and rate,
- High: larger number of flows and higher rate.
- This model allows observation of how the routing protocol behaves under light and heavy traffic.

3.3 Energy Model

The NS-2 energy model is used:

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- All nodes start with the same initial energy.
- Energy is consumed when transmitting, receiving, or listening to the channel.
- Remaining energy is tracked throughout the simulation.
- The hybrid swarm algorithm uses the energy information to prefer healthier nodes and avoid nodes near depletion.

4. Hybrid Swarm Intelligence-Based Hybrid Optimization Routing (HSI-HOR)

4.1 Conceptual Overview

- The HSI-HOR algorithm aims to combine:
- Global path exploration – discovering multiple potential routes between a source and destination, inspired by ant colony behaviour, and
- Local route quality refinement – adjusting and improving route decisions using swarm-like optimization based on quality metrics and overhead observations.
- The protocol works within a reactive routing framework but augments route discovery and maintenance with swarm-based learning and adaptation.

4.2 Key Metrics for Optimization

HSI-HOR evaluates routes using several routing-related metrics:

- Packet delivery success on links
- Links that have a higher success rate in forwarding packets are preferred.
- Queue and congestion level
- Nodes with lower queue occupancy are preferred to reduce delay and buffer drops.
- Route length
- Shorter routes are generally preferred if they do not suffer from poor quality or congestion.
- Energy status
- Nodes with higher remaining energy are to saved to avoid overloading weak nodes.
- Control overhead impact
- The algorithm observes how often route discoveries and control messages are triggered and attempts to adjust route selections to reduce these events.
- Instead of using explicit mathematical formulas, these metrics are combined conceptually into a route quality score inside the routing agent implementation. The score is used to rank candidate routes.

4.3 Hybrid Swarm Mechanism

The hybrid swarm intelligence mechanism operates in two phases:

4.3.1 Exploration Phase (Ant-like Behavior)

- During route discovery, multiple route request packets are propagated through the network with additional fields carrying path quality indicators.
- Each intermediate node updates these indicators based on its local view of link success, energy, and queue status.
- The destination receives several potential routes (like ant paths) and stores their observed quality scores.
- A set of promising routes is selected instead of a single path. A primary route and backup routes are identified.

4.3.2 Refinement Phase (Swarm-like Optimization)

Over time, as data flows through the chosen routes, performance feedback is collected, such as observed delay, success or failure count, and overhead incurred.

The routing agent treats current routes as particles or solutions. Routes that show better performance get higher preference, while poorly performing routes are gradually discarded.

The decision to switch from one route to another is influenced by both instantaneous observations and accumulated history, similar to how swarm solutions are attracted to better neighbors.

Importantly, this refinement process is implemented as simple rules within the NS-2 routing agent, such as:

Increase preference for routes that maintain high delivery and low delay over a period.

Decrease preference for routes that trigger repeated route error messages or require frequent rediscovery.

Promote backup routes when primary routes show signs of degradation.

4.4 Routing Procedure

The routing procedure with HSI-HOR can be summarized as:

4.4.1 Route Discovery

When a source has data to send and no valid route, it broadcasts a route request. Intermediate nodes forward this request while updating path quality indicators. Multiple candidate routes arrive at the destination.

4.4.2 Route Selection

The destination compares candidate routes based on combined quality indicators and overhead contribution.

A primary route and a small set of backup routes are chosen and communicated back via route reply messages.

4.4.3 Data Forwarding and Learning

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Data packets flow along the primary route. Nodes along the route collect statistics such as success rate, queue delay, and occurrence of control messages related to that path.

These statistics are periodically shared locally to update the route preference.

4.4.4 Route Maintenance and Adaptation

When link failures occur, backup routes are activated if available, avoiding the need for immediate new discovery. If backup routes are also degraded, new route discovery is triggered.

The algorithm gradually shifts preference to routes that offer better trade-offs between delivery performance and overhead.

By reusing information gained during previous discoveries and forwarding periods, HSI-HOR aims to reduce the frequency of route discoveries and route errors, which directly lowers routing overhead.

5. NS-2 Simulation Setup

5.1 Simulation Environment

The simulations are conducted in NS-2 with the following setup:

- Simulation area: 1000 m × 1000 m
- Number of nodes: 50, 75, 100
- Simulation duration: 900 seconds
- Channel: wireless channel
- Propagation: two-ray ground model
- MAC: IEEE 802.11
- Antenna: omni-directional
- Queue type: Drop Tail
- Maximum queue length: fixed value (e.g., 50 packets)
- Node transmission range: approximately 250 meters
- Initial energy per node: 100 Joules
- Traffic: CBR over UDP
- Packet size: 512 bytes

Traffic loads:

- Low load: 10 CBR flows with low rate
- Medium load: 20 CBR flows with moderate rate
- High load: 30 CBR flows with higher rate
- Protocols compared:

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- Baseline: AODV-like routing (standard hop-count-based behaviour).
- Proposed: HSI-HOR (Hybrid Swarm Intelligence-based Hybrid Optimization Routing).

5.2 OTcl Integration (High-Level)

- The custom HSI-HOR agent is set as the ad hoc routing protocol in node-config.
- Nodes are created and positioned randomly.
- CBR agents and UDP agents are attached to the nodes to generate traffic.
- Tracing is enabled to record all events in a trace file.
- After simulation, AWK or Python scripts are used to parse trace files and calculate metrics.

5.3 Performance Metrics

The following metrics are used to evaluate performance:

- Packet Delivery Ratio (PDR)
- Average End-to-End Delay
- Routing Overhead (control packets per delivered data packet)
- Average Energy Consumption per Delivered Packet
- The values shown in the next section are example values that follow expected trends. You must replace them with your actual simulation results.

6. Results and Discussion

6.1 Packet Delivery Ratio

Table 1. Packet Delivery Ratio (%) for Baseline and HSI-HOR

Nodes	Load	Baseline PDR (%)	HSI-HOR PDR (%)
50	Low	94.5	96.1
50	Medium	86.2	92.4
50	High	77.0	87.8
75	Low	92.0	95.0
75	Medium	82.3	90.8
75	High	72.5	85.9
100	Low	90.1	93.9
100	Medium	79.4	89.6
100	High	69.0	83.7

The Hybrid Swarm Intelligence approach achieves higher packet delivery ratios across all scenarios. The improvement becomes more significant as traffic load and node density

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increase. The hybrid optimization algorithm tends to select routes that are more stable and less congested, and the availability of backup routes reduces packet loss during link failures.

6.2 Average End-to-End Delay

Table 2. Average End-to-End Delay (milliseconds)

Nodes	Load	Baseline Delay (ms)	HSI-HOR Delay (ms)
50	Low	44.3	46.0
50	Medium	75.6	68.5
50	High	118.9	99.2
75	Low	48.7	50.2
75	Medium	88.5	79.1
75	High	136.3	115.4
100	Low	52.0	53.7
100	Medium	97.2	85.6
100	High	154.6	128.3

Under low load, the proposed algorithm introduces only a slight increase in delay or remains similar to baseline due to additional route evaluation logic. Under medium and high loads, HSI-HOR significantly reduces delay. This is because the hybrid optimization algorithm avoids highly congested routes and reduces the number of route breaks and retransmissions.

6.3 Routing Overhead

Table 3. Routing Overhead (control packets per delivered data packet)

Nodes	Load	Baseline Overhead	HSI-HOR Overhead
50	Low	0.20	0.22
50	Medium	0.35	0.28
50	High	0.51	0.38
75	Low	0.22	0.24
75	Medium	0.40	0.32
75	High	0.56	0.41
100	Low	0.25	0.26
100	Medium	0.46	0.34
100	High	0.60	0.44

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At low load, HSI-HOR produces a small increase in overhead compared to baseline, due to additional information handling in route discovery and learning. However, under medium and high loads, HSI-HOR produces less overhead per delivered data packet. The reduction is due to fewer route discoveries, fewer route error broadcasts, and better use of backup routes. This directly fulfils the objective of minimizing packet overhead using hybrid swarm-based optimization.

6.4 Energy Consumption

Table 4. Average Energy Consumption per Delivered Packet (Joules)

Nodes	Load	Baseline Energy (J)	HSI-HOR Energy (J)
50	Low	0.015	0.016
50	Medium	0.023	0.020
50	High	0.033	0.028
75	Low	0.017	0.018
75	Medium	0.026	0.023
75	High	0.037	0.030
100	Low	0.019	0.020
100	Medium	0.029	0.025
100	High	0.040	0.032

Energy consumption differences are small at low traffic levels. Under medium and high loads, the hybrid swarm intelligence approach yields lower energy consumption per successfully delivered packet. Better routing decisions reduce wasteful retransmissions and repeated route discoveries, and the energy-aware preference in the swarm algorithm helps to distribute load, avoiding early exhaustion of particular nodes.

6.5 Overall Performance

The NS-2-based evaluation of HSI-HOR routing shows:

- Improved packet delivery ratio compared to baseline, especially in dense and high-load scenarios.
- Reduced end-to-end delay when the network is under stress.
- Noticeable reduction in routing overhead per delivered packet at medium and high loads.
- More efficient use of energy per delivered packet in heavily loaded networks.
- These improvements demonstrate that hybrid swarm intelligence and hybrid optimization can effectively enhance routing performance while controlling packet overhead.

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7.Conclusion

This paper has presented a Hybrid Swarm Intelligence-based Hybrid Optimization Routing algorithm (HSI-HOR) for wireless ad hoc networks and evaluated its performance using NS-2 simulations. The proposed approach combines exploration and refinement phases inspired by swarm intelligence to select and maintain efficient routes. It optimizes route quality based on link performance, congestion, energy status, and overhead observations.

Simulation results confirm that HSI-HOR improves packet delivery ratio, reduces average end-to-end delay, and significantly decreases routing overhead per delivered packet compared to a baseline AODV-like protocol. The advantages become more evident as node density and network load increase.

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