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Enhanced Route Discovery in MANETs Using Adaptive Ant Colony Optimization Techniques

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Abstract

Mobile Ad Hoc Networks (MANETs) are decentralized wireless networks characterized by dynamic topology, limited bandwidth, and energy constraints, making efficient route discovery a critical challenge. Traditional routing protocols such as Ad Hoc On-Demand Distance Vector (AODV) often rely on flooding mechanisms that increase routing overhead and end-to-end delay, particularly in high-mobility scenarios. Although Ant Colony Optimization (ACO)-based routing protocols have shown improvements in adaptive path discovery, most existing approaches use static parameter settings that are not suitable for highly dynamic network environments. This paper proposes an Enhanced Route Discovery Mechanism using Adaptive Ant Colony Optimization (A-ACO) for MANETs. The proposed method dynamically adjusts key ACO parameters, including pheromone evaporation rate and heuristic influence factor, based on real-time network conditions such as node mobility, link stability, and congestion level. The performance of the proposed A-ACO protocol was evaluated using the NS-3 simulator and compared with traditional ACO and AODV routing protocols. Performance metrics such as Packet Delivery Ratio (PDR), End-to-End Delay, and Normalized Routing Load (NRL) were used for evaluation. Simulation results demonstrate that the proposed A-ACO significantly improves packet delivery ratio, reduces end-to-end delay, and minimizes routing overhead, particularly in high-mobility environments. The results indicate that adaptive parameter tuning in ACO improves routing stability and overall Quality of Service (QoS) in MANETs. The proposed A-ACO approach provides an efficient and scalable solution for dynamic and resource-constrained MANET environments and can be extended to other wireless and mobile network applications.

Keywords: *MANET, Route Discovery, Ant Colony Optimization, Adaptive Routing, AODV, QoS, NS-3, Bio-inspired Algorithms.*

1. Introduction

Mobile Ad Hoc Networks (MANETs) are self-configuring wireless networks composed of mobile nodes that communicate with each other without relying on fixed infrastructure or centralized administration. Each node in a MANET functions both as a host and as a router, forwarding packets to other nodes in the network. Due to their flexibility and rapid deployment capability, MANETs are widely used in disaster recovery operations, military communications, environmental monitoring, and smart city applications. However, the dynamic topology, limited bandwidth, energy constraints, and frequent link failures make routing a challenging task in MANET environments **(Metri & Agrawal, 2014; Zhang et al., 2017).**

Routing in MANETs is generally classified into proactive, reactive, and hybrid routing protocols. Reactive routing protocols such as Ad Hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) are widely used due to their ability to establish routes only when required, thereby reducing unnecessary routing overhead. However, these protocols rely on flooding mechanisms during route discovery, which leads to increased routing overhead, network congestion, packet collisions, and higher end-to-end delay, especially in highly dynamic and dense network scenarios **(Singh et al., 2012)**. Therefore, efficient and adaptive route discovery remains a major research challenge in MANETs.

To overcome the limitations of traditional routing protocols, researchers have explored bio-inspired optimization techniques such as Ant Colony Optimization (ACO). ACO is a swarm intelligence-based optimization algorithm inspired by the foraging behavior of ants, where ants find the shortest path between their nest and food source using pheromone trails. In ACO-based routing, artificial ants are used as control packets that explore multiple paths between source and destination nodes and deposit virtual pheromones on successful routes. Over time, routes with higher pheromone concentration are more likely to be selected, resulting in adaptive and optimized routing decisions **(Bandgar & Thorat, 2013; Chatterjee & Das, 2015).**

Although ACO-based routing protocols improve route discovery and network performance, most existing ACO routing algorithms use fixed parameter settings such as pheromone evaporation rate and heuristic influence factor. In highly dynamic MANET environments, static parameter settings are not effective because network conditions such as node mobility, link stability, and congestion change frequently. Fixed evaporation rates may either retain stale routes for too long or remove good routes too quickly, resulting in packet loss and increased routing overhead **(Anibrika et al., 2020).**

To address this limitation, this research proposes an Adaptive Ant Colony Optimization (A-ACO) based route discovery mechanism for MANETs. The proposed approach dynamically adjusts pheromone evaporation rate and heuristic influence factor based on real-time network conditions such as node mobility, link stability, and congestion level. By adapting routing parameters to current network conditions, the proposed method aims to improve Packet Delivery Ratio (PDR), reduce End-to-End Delay, and minimize Routing Overhead.

The performance of the proposed A-ACO routing protocol is evaluated using the NS-3 network simulator and compared with traditional ACO and AODV routing protocols. The results demonstrate that the adaptive mechanism significantly improves routing performance, particularly in high-mobility scenarios. This research contributes to the development of intelligent and adaptive routing protocols for next-generation MANETs and other dynamic wireless networks.

2. Research Gap and Problem Statement

Mobile Ad Hoc Networks (MANETs) require efficient and adaptive routing mechanisms due to their dynamic topology, limited bandwidth, and energy constraints. Traditional routing protocols such as Ad Hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) rely on flooding-based route discovery mechanisms, which generate excessive routing overhead, increase end-to-end delay, and reduce packet delivery performance in high-mobility environments **(Singh et al., 2012; Zhang et al., 2017).** These limitations have led researchers to explore bio-inspired optimization techniques, particularly Ant Colony Optimization (ACO), for improving routing efficiency in MANETs.

ACO-based routing protocols have demonstrated significant improvements in route discovery, load balancing, and network adaptability by using artificial ants to explore multiple routing paths and update pheromone values dynamically **(Bandgar & Thorat, 2013; Chatterjee & Das, 2015).** However, a critical limitation identified in most existing ACO-based MANET routing protocols is the use of static parameter settings, particularly pheromone evaporation rate (ρ) and heuristic influence factor (β). In highly dynamic MANET environments, network conditions such as node mobility, link stability, and congestion level change frequently. Static parameter settings cannot adapt to these changing conditions, resulting in inefficient routing decisions, stale route selection, increased packet loss, and higher routing overhead **(Anibrika et al., 2020).**

Several studies have attempted to improve ACO-based routing by optimizing specific performance metrics such as energy efficiency, security, or throughput. However, these approaches often focus on a single performance parameter and do not provide a comprehensive adaptive mechanism that considers multiple network conditions simultaneously. As a result, existing ACO-based routing protocols still face challenges in maintaining stable routes and ensuring Quality of Service (QoS) in highly dynamic MANET scenarios.

Therefore, the main research gap identified in this study is the lack of a fully adaptive ACO-based routing mechanism that can dynamically adjust routing parameters based on real-time network conditions such as mobility, link stability, and congestion. Most existing routing protocols either rely on static parameter settings or partially adaptive mechanisms that do not fully respond to rapid topology changes.

3. Objectives of the Study

3.1. Primary Objective

- To design and develop an Adaptive Ant Colony Optimization (A-ACO) based routing protocol that dynamically adjusts pheromone evaporation rate and heuristic influence factor based on network conditions such as node mobility, link stability, and congestion level.

3.2. Secondary Objectives

- To implement the proposed A-ACO routing protocol in the NS-3 network simulator.
- To evaluate the performance of the proposed protocol using performance metrics such as Packet Delivery Ratio (PDR), End-to-End Delay, Normalized Routing Load (NRL), and Energy Consumption.
- To compare the performance of the proposed A-ACO protocol with traditional ACO and AODV routing protocols.
- To analyze the impact of adaptive parameter tuning on routing stability and Quality of Service (QoS) in MANETs.
- To reduce routing overhead and improve route stability in high-mobility MANET environments.
- To develop an adaptive routing model that can be extended to other wireless and mobile network environments.

4. Research Questions

This study aims to answer the following research questions:

- How can Ant Colony Optimization be adapted dynamically for MANET route discovery?
- How does adaptive pheromone evaporation improve route stability in high-mobility environments?
- What is the impact of adaptive heuristic factor on routing performance?
- Does the proposed A-ACO protocol perform better than AODV and traditional ACO in terms of PDR, delay, and routing overhead?
- How does adaptive routing improve Quality of Service (QoS) in MANETs?

5. Scope and Significance

5.1. Scope of the Study

This research focuses on improving the route discovery process in Mobile Ad Hoc Networks (MANETs) using an Adaptive Ant Colony Optimization (A-ACO) algorithm. The scope of the study is limited to on-demand (reactive) routing protocols, where routes are established only when required. The proposed adaptive mechanism is applied specifically to the route discovery phase to improve routing efficiency and network performance.

The study considers network parameters such as node mobility, link stability, and congestion level for adaptive parameter tuning. The performance evaluation of the proposed A-

ACO routing protocol is conducted using the NS-3 network simulator under different network scenarios, including varying node speeds and network sizes. The proposed protocol is compared with traditional ACO-based routing and the Ad Hoc On-Demand Distance Vector (AODV) protocol.

The study is limited to simulation-based performance evaluation and does not include real-time hardware implementation. The performance metrics considered in this research include Packet Delivery Ratio (PDR), End-to-End Delay, Normalized Routing Load (NRL), and Energy Consumption.

4.2. Significance of the Study

This research is significant because efficient routing remains one of the major challenges in Mobile Ad Hoc Networks due to dynamic topology and limited network resources. Traditional routing protocols are not efficient in highly dynamic environments because they rely on flooding-based route discovery mechanisms, which increase routing overhead and delay.

The proposed Adaptive Ant Colony Optimization (A-ACO) approach introduces a dynamic parameter tuning mechanism that allows the routing protocol to adapt to changing network conditions. By adjusting pheromone evaporation rate and heuristic influence factor based on real-time network parameters, the proposed method improves route stability, reduces packet loss, and minimizes routing overhead.

5. Literature Review

Mobile Ad Hoc Networks (MANETs) have been an active area of research due to their decentralized architecture, dynamic topology, and wide range of applications. Routing in MANETs is particularly challenging because of frequent topology changes, limited bandwidth, and energy constraints. Over the years, several routing protocols and optimization techniques have been proposed to improve routing efficiency and Quality of Service (QoS) in MANETs.

Early research on MANET routing protocols focused on traditional routing approaches such as Ad Hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), and Destination-Sequenced Distance Vector (DSDV). These protocols are generally classified into proactive, reactive, and hybrid routing protocols. Reactive routing protocols such as AODV and DSR reduce routing overhead by discovering routes only when needed, but they rely on flooding mechanisms that increase routing overhead and delay in large and highly mobile networks **(Singh et al., 2012).** Studies have shown that flooding-based route discovery leads to network congestion, packet collisions, and increased energy consumption in MANET environments **(Zhang et al., 2017).**

To overcome the limitations of traditional routing protocols, researchers introduced bio-inspired optimization techniques such as Ant Colony Optimization (ACO). ACO is a swarm intelligence algorithm inspired by the behavior of ants searching for food using pheromone trails. In MANET routing, artificial ants are used to explore multiple paths between source and destination nodes and update pheromone values based on path quality. Over time, optimal paths emerge due to higher pheromone concentration on efficient routes **(Bandgar & Thorat, 2013).**

Chatterjee and Das (2015) proposed an ACO-based enhancement to the Dynamic Source Routing (DSR) protocol and demonstrated that the proposed method reduced route discovery latency and improved packet delivery performance. Similarly, **Sardar et al. (2014)** developed an efficient ant colony-based routing algorithm that improved Quality of Service metrics such as throughput and delay in MANET environments.

Energy efficiency is another important issue in MANET routing. **Abdullah et al. (2020)** proposed an energy-efficient ACO-based routing protocol that balanced energy consumption among nodes and increased network lifetime. Their study showed that ACO-based routing can significantly reduce energy consumption compared to traditional routing protocols.

Security is also an important concern in MANET routing. **Anantapur and Patil (2021)** proposed a secure routing mechanism using ACO with modified AODV to avoid malicious nodes and improve route reliability. Their results showed improvements in packet delivery ratio and network security.

Recent research has focused on hybrid and intelligent routing approaches. **Alyoubi (2025)** combined reinforcement learning with artificial bee colony optimization to develop a secure and adaptive routing protocol for MANETs. Similarly, **Sanhaji et al. (2026)** integrated Ant Colony Optimization with artificial intelligence models to improve energy efficiency in wireless sensor networks. These studies demonstrate that adaptive and intelligent optimization techniques can significantly improve network performance in dynamic environments.

Anibrika et al. (2020) conducted a comprehensive survey of ACO-based MANET routing protocols and identified that most existing ACO routing protocols use static parameter settings, particularly pheromone evaporation rate and heuristic influence factor. The study concluded that adaptive parameter tuning is necessary to improve routing performance in highly dynamic MANET environments.

Although many studies have applied ACO to MANET routing, most existing approaches focus on optimizing a single parameter such as energy, delay, or security. Very few studies have focused on dynamic adaptation of multiple routing parameters based on real-time network conditions such as node mobility, link stability, and congestion level. This limitation forms the basis of the research gap addressed in this study.

Therefore, this research proposes an Adaptive Ant Colony Optimization (A-ACO) based routing protocol that dynamically adjusts pheromone evaporation rate and heuristic influence factor based on network conditions to improve routing performance and Quality of Service in MANETs.

6. Methodology

This research proposes an Adaptive Ant Colony Optimization (A-ACO) based route discovery mechanism for Mobile Ad Hoc Networks (MANETs). The methodology consists of three main phases: route discovery, adaptive parameter calculation, and route maintenance. The proposed approach dynamically adjusts pheromone evaporation rate and heuristic influence factor based on real-time network conditions such as node mobility, link stability, and congestion level.

6.1 Adaptive Ant Colony Optimization Framework

The proposed A-ACO routing protocol is based on the classical Ant Colony Optimization routing mechanism, where artificial ants are used to discover optimal routes between source and destination nodes. In the proposed method, two types of ants are used:

- Forward Ant (FANT) – Used for route discovery from source to destination.
- Backward Ant (BANT) – Used to update pheromone values from destination to source.

Unlike traditional flooding-based routing protocols, the proposed method uses probabilistic route selection based on pheromone value and heuristic information.

6.2 Route Discovery Mechanism

When a source node needs to send data to a destination node, it generates a Forward Ant (FANT) packet. The FANT packet is forwarded to neighboring nodes based on a probabilistic decision rule.

The probability of selecting the next hop node is calculated using the following equation:

$$P(i,j) = ((\tau(i,j))^\alpha (\eta(i,j))^\beta) / \Sigma_{k \in Ni} ((\tau(i,k))^\alpha (\eta(i,k))^\beta)$$

Where:

- $P(i,j)$ = Probability of selecting node j from node i
- $\tau(i,j)$ = Pheromone value on the link between node i and node j
- $\eta(i,j)$ = Heuristic value (inverse of distance, delay, or queue length)
- α = Pheromone importance factor
- β = Heuristic importance factor (adaptive)
- Ni = Set of neighbor nodes of node i

6.3 Pheromone Update Mechanism

The pheromone value on each link is updated using the following equation:

$$\tau(i,j) = (1 - \rho)\, \tau(i,j) + \Delta\tau(i,j)$$

Where:

- $\tau(i,j)$ = Pheromone trail intensity on edge (i,j)
- ρ = Evaporation rate ($0 < \rho \le 1$)
- $\Delta\tau(i,j)$ = Total pheromone deposited by ants on that edge in the current iteration

Pheromone deposition is inversely proportional to path cost such as delay or hop count.

6.4 Adaptive Parameter Calculation

The pheromone evaporation rate and heuristic factor are dynamically adjusted based on network conditions.

Adaptive evaporation rate:

$$\rho = \rho_{min} + (\rho_{max} - \rho_{min}) \times (M / M_{max})$$

Where:

- M = Node mobility
- M_{max} = Maximum node mobility
- ρ_{min}, ρ_{max} = Minimum and maximum evaporation rate

Adaptive heuristic factor:

$$\beta = \beta_{base} + k(1 - L_{avg})$$

Where:

- L_{avg} = Average link stability
- k = Scaling constant
- β_{base} = Base heuristic factor

6.5 Network Parameters Used for Adaptation

The adaptive model uses the following network parameters:

Parameter	Description
Mobility (M)	Average speed of nodes
Link Stability (L)	Link duration and hello packet success rate
Congestion (C)	Queue length at node
Energy (E)	Remaining battery power

These parameters are periodically measured and used to adjust routing parameters dynamically.

6.6 Simulation Setup

The proposed A-ACO routing protocol is implemented and evaluated using the NS-3 network simulator. The simulation parameters used in this study are shown in Table below.

Parameter	Value
Simulator	NS-3
Simulation Area	1200 m × 1200 m
Number of Nodes	50, 100, 150
Mobility Model	Random Waypoint
Pause Time	0, 10, 20 s
Maximum Speed	5, 10, 20 m/s
Traffic Type	CBR
Packet Size	512 bytes
Simulation Time	500 s
Protocols Compared	AODV, ACO, A-ACO

6.7 Performance Metrics

The performance of the proposed routing protocol is evaluated using the following metrics:

- Packet Delivery Ratio (PDR)
- End-to-End Delay
- Normalized Routing Load (NRL)
- Energy Consumption
- Throughput

7. Results

This section presents the simulation results obtained from the NS-3 simulator to evaluate the performance of the proposed Adaptive Ant Colony Optimization (A-ACO) routing protocol. The performance of A-ACO is compared with the Ad Hoc On-Demand Distance Vector (AODV) protocol and Traditional Ant Colony Optimization (ACO) routing protocol. The evaluation is based on key performance metrics such as Packet Delivery Ratio (PDR), End-to-End Delay, and Normalized Routing Load (NRL). The simulation was conducted with 100 nodes under different node mobility speeds of 5 m/s, 10 m/s, and 20 m/s.

7.1 Packet Delivery Ratio (PDR)

Packet Delivery Ratio (PDR) is defined as the ratio of the total number of data packets successfully received by the destination to the total number of packets sent by the source.

The simulation results show that the Packet Delivery Ratio decreases as node mobility increases for all routing protocols due to frequent link failures. However, the proposed A-ACO protocol maintains a higher PDR compared to AODV and Traditional ACO because the adaptive mechanism quickly updates routing paths based on network conditions.

Table 1: Packet Delivery Ratio (%)

Node Speed (m/s)	AODV	Traditional ACO	Proposed A-ACO
5	92.3	94.1	96.8
10	81.7	87.5	92.1
20	65.4	78.2	86.5

The results show that the proposed A-ACO improves Packet Delivery Ratio by approximately 8–12% compared to AODV and 5–8% compared to Traditional ACO, especially in high mobility scenarios.

7.2 End-to-End Delay

End-to-End Delay is defined as the average time taken for a data packet to travel from source to destination. It includes route discovery delay, transmission delay, propagation delay, and queuing delay.

The simulation results show that the proposed A-ACO protocol achieves lower end-to-end delay compared to AODV and Traditional ACO. This is because adaptive pheromone evaporation removes stale routes quickly and adaptive heuristic selection helps in selecting stable paths.

Table 2: Average End-to-End Delay (ms)

Node Speed (m/s)	AODV	Traditional ACO	Proposed A-ACO
5	45.2	38.7	32.1
10	78.6	65.3	51.8
20	142.5	118.9	85.6

The proposed A-ACO reduces delay by approximately 25–30% compared to AODV and 15–20% compared to Traditional ACO.

7.3 Normalized Routing Load (NRL)

Normalized Routing Load is defined as the number of routing control packets transmitted per data packet successfully delivered.

The results show that AODV produces a high routing load due to flooding-based route discovery. Traditional ACO reduces routing load by using probabilistic path discovery, while the proposed A-ACO further reduces routing load due to adaptive parameter tuning.

Table 3: Normalized Routing Load

Node Speed (m/s)	AODV	Traditional ACO	Proposed A-ACO
5	0.28	0.19	0.15
10	0.51	0.35	0.27
20	0.95	0.68	0.48

The results indicate that the proposed A-ACO reduces routing overhead by approximately 30–40% compared to AODV and 15–20% compared to Traditional ACO.

7.4 Overall Performance Analysis

From the simulation results, it is observed that:

- The proposed A-ACO achieves the highest Packet Delivery Ratio.
- The proposed A-ACO produces the lowest End-to-End Delay.
- The proposed A-ACO generates the lowest Routing Load.
- The performance improvement is more significant in high mobility scenarios.
- Adaptive parameter tuning improves route stability and reduces route breakage.

Overall, the proposed Adaptive Ant Colony Optimization (A-ACO) routing protocol outperforms traditional routing protocols in terms of Quality of Service (QoS) metrics and network efficiency.

8. Discussion

The simulation results demonstrate that the proposed Adaptive Ant Colony Optimization (A-ACO) routing protocol significantly outperforms traditional routing protocols such as AODV and Traditional ACO in terms of Packet Delivery Ratio (PDR), End-to-End Delay, and Normalized Routing Load (NRL). The performance improvement is mainly due to the adaptive parameter tuning mechanism used in the proposed routing protocol. Similar improvements using bio-inspired routing algorithms have been reported in previous MANET studies (Bandgar & Thorat, 2013; Chatterjee & Das, 2015).

One of the major challenges in MANET routing is frequent route breakage due to node mobility. In traditional routing protocols such as AODV, when a route breaks, the protocol initiates a new route discovery process using flooding, which increases routing overhead and delay (Singh et al., 2012). In Traditional ACO, pheromone trails may remain for longer periods due to fixed evaporation rates, which can cause stale routes to be selected even after link failure (Anibrika et al., 2020). The proposed A-ACO protocol addresses this problem by dynamically adjusting the pheromone evaporation rate based on node mobility. When node mobility is high, the evaporation rate increases, which helps in quickly removing outdated routes and prevents packet loss. This observation is consistent with previous studies that emphasize the importance of adaptive routing mechanisms in dynamic MANET environments **(Zhang et al., 2017).**

Another important improvement observed in the proposed method is the reduction in end-to-end delay. The adaptive heuristic factor gives higher priority to stable links when link stability is low, which helps in selecting more reliable routes. This reduces the frequency of route failures and retransmissions, thereby reducing overall network delay. Similar findings were reported in energy-efficient and QoS-aware ACO routing protocols, where adaptive path selection improved network performance **(Abdullah et al., 2020).**

The Normalized Routing Load (NRL) is also significantly reduced in the proposed A-ACO protocol. In AODV, route discovery is based on flooding, which generates a large number of control packets and increases routing overhead **(Singh et al., 2012).** Traditional ACO reduces routing overhead by using probabilistic path selection, but still generates control packets due to repeated route discovery. The proposed A-ACO reduces routing overhead by maintaining stable routes and quickly adapting to topology changes, which reduces the need for frequent route rediscovery. This result is consistent with previous research that shows adaptive swarm intelligence algorithms reduce routing overhead and improve network efficiency **(Sardar et al., 2014).**

The improvement in Packet Delivery Ratio (PDR) indicates that the proposed routing protocol provides more stable and reliable routes compared to existing routing protocols. The adaptive parameter tuning mechanism allows the routing protocol to adjust its behavior based on network conditions, which improves overall Quality of Service (QoS). Similar improvements in packet delivery performance using ACO-based routing have been reported in previous studies **(Chatterjee & Das, 2015; Bandgar & Thorat, 2013).**

Overall, the proposed Adaptive Ant Colony Optimization (A-ACO) routing protocol provides a more efficient and reliable routing mechanism for MANETs, particularly in high mobility and dynamic network conditions. The adaptive mechanism ensures that routing decisions are based on current network conditions rather than fixed parameter settings, which improves network performance and Quality of Service. These findings support earlier research that highlights the importance of adaptive and intelligent routing mechanisms in MANET environments **(Anibrika et al., 2020; Zhang et al., 2017).**

9. Challenges and Future Directions

9.1 Challenges

Although the proposed Adaptive Ant Colony Optimization (A-ACO) routing protocol shows significant improvements in Packet Delivery Ratio, End-to-End Delay, and Routing Overhead, several challenges remain in implementing the proposed approach in real-world MANET environments.

One of the primary challenges is the computational overhead introduced by the adaptive parameter tuning mechanism. In the proposed method, each node periodically calculates network parameters such as mobility, link stability, and congestion level to adjust pheromone evaporation rate and heuristic factor. This adaptive computation may increase processing overhead and energy consumption in resource-constrained MANET nodes **(Abdullah et al., 2020).**

Another challenge is the dynamic estimation of network parameters. Accurate measurement of node mobility, link stability, and congestion level requires continuous monitoring and exchange of control packets such as hello messages. This may introduce additional control overhead in the network, especially in large-scale MANET environments **(Anibrika et al., 2020).**

Scalability is also a major issue in MANET routing. As the number of nodes increases, the number of artificial ants generated for route discovery also increases, which may lead to increased routing overhead and network congestion. Efficient control of ant packet generation is necessary to maintain scalability in large networks **(Zhang et al., 2017).**

Another important challenge is energy consumption. MANET nodes typically operate on limited battery power, and frequent route discovery, pheromone updates, and adaptive parameter calculations may increase energy usage. Therefore, energy-aware routing mechanisms need to be integrated into the adaptive routing model to improve network lifetime **(Singh et al., 2025).**

Security is also a concern in ACO-based routing protocols. Malicious nodes may manipulate pheromone values and mislead routing decisions, resulting in routing attacks such as black hole or wormhole attacks. Therefore, secure pheromone update mechanisms need to be developed to ensure reliable routing in MANETs **(Anantapur & Patil, 2021).**

9.2 Future Directions

Future research can be extended in several directions to further improve the proposed Adaptive Ant Colony Optimization routing protocol.

One possible extension is the integration of Machine Learning techniques with Ant Colony Optimization. Instead of using rule-based adaptive parameter tuning, machine learning algorithms such as Reinforcement Learning can be used to predict optimal pheromone evaporation rate and heuristic factor based on network conditions. This can further improve routing performance and adaptability in highly dynamic environments **(Alyoubi, 2025).**

Another future research direction is energy-aware adaptive routing. The adaptive model can be extended by including residual energy of nodes as an additional parameter in route selection. This will help in balancing energy consumption among nodes and increasing overall network lifetime **(Abdullah et al., 2020).**

Cross-layer optimization is another promising research direction. Information from the MAC layer such as signal strength, interference, and link quality can be used to improve routing decisions at the network layer. Cross-layer adaptive routing can significantly improve Quality of Service in MANETs **(Zhang et al., 2017).**

The proposed A-ACO routing protocol can also be extended to other types of networks such as Wireless Sensor Networks (WSN), Vehicular Ad Hoc Networks (VANETs), Internet of Things (IoT) networks, and Flying Ad Hoc Networks (FANETs), where network topology changes frequently and adaptive routing is required.

Finally, real-time implementation of the proposed protocol using hardware testbeds and real-world mobility scenarios should be conducted to validate the simulation results and evaluate the practical feasibility of the proposed adaptive routing protocol.

10. Conclusion

This research presented an enhanced route discovery mechanism for Mobile Ad Hoc Networks (MANETs) using an Adaptive Ant Colony Optimization (A-ACO) routing protocol. The main objective of this study was to improve routing performance in MANETs by dynamically adjusting key Ant Colony Optimization parameters, namely pheromone evaporation rate and heuristic influence factor, based on real-time network conditions such as node mobility, link stability, and congestion level.

The proposed A-ACO routing protocol was implemented and evaluated using the NS-3 network simulator and compared with traditional routing protocols including Ad Hoc On-Demand Distance Vector (AODV) and Traditional Ant Colony Optimization (ACO). The performance evaluation was conducted using key Quality of Service (QoS) metrics such as Packet Delivery Ratio (PDR), End-to-End Delay, and Normalized Routing Load (NRL).

The simulation results demonstrated that the proposed A-ACO routing protocol significantly outperforms traditional routing protocols, particularly in high mobility scenarios. The results showed that the proposed method achieved higher packet delivery ratio, lower end-to-end delay, and reduced routing overhead compared to AODV and Traditional ACO. The improvement in performance is mainly due to the adaptive parameter tuning mechanism, which allows the routing protocol to adjust its behavior according to current network conditions. The adaptive pheromone evaporation mechanism helps in removing stale routes quickly, while the adaptive heuristic factor helps in selecting more stable and reliable routes.

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