



Bio-Inspired AODV-ACO Routing Protocol for Optimal Routing in VANETs Networks

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ABSTRACT

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Vehicular ad hoc networks (VANETs) are specialized mobile networks conceived to simplify and facilitate communication between vehicles, as well as between vehicles and road infrastructure. These networks are a crucial element of Intelligent Transport Systems (ITS), enabling the application of a wide range of technologies, such as traffic management, accident prevention and road safety. To ensure efficient and reliable communication in these dynamic environments, where vehicles are moving fast and frequently changing position, a large variety of routing protocols have been proposed. In this work, the algorithm of ant colonies is applied to the Ad hoc On Demand Distance Vector (AODV) protocol to optimize the quality of service (QoS) in the VANET network, this proposed AODV-ACO consider three essential metrics for calculating the pheromone value such as received signal strength (RSS), available bandwidth and total latency to detect the optimal route. The simulation results show that the new proposed system (AODV-ACO) is more efficient than the original AODV routing algorithm in terms of delay, packet delivery rate and normalized routing load (NRL). With a 67.37 % reduction in NRL and 16.91 % decrease in end-to-end delay. These results highlight the protocol's ability to deliver more stable, efficient, and scalable communication in urban VANET environments.

1. INTRODUCTION

The active sector of vehicular ad hoc networks (VANETs) continues to captivate researchers, with significant efforts dedicated to addressing their inherent challenges related to security, mobility, routing, data delivery, and more [1, 2]. The primary purpose of these networks is to enable the exchange of information between vehicles, facilitating a range of applications related to safety, comfort, and entertainment. The architecture of VANETs is based on vehicles equipped with on-board units (OBUs), which play a crucial role in facilitating exchanges not only between the vehicles themselves, but also with fixed units (RSUs) installed along the road infrastructure thus creating a dynamic and versatile communication network at the service of intelligent mobility [3]. This type of network supports three main communication modes: vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and hybrid communication between vehicles (HVC) [4, 5].

Routing is a critical component in VANET research, as it underpins the functionality of VANET applications and enables their communication services. This process involves determining the best paths between the sender and receiver within the VANET node network [6].

However, the rapid mobility of vehicles combined with

frequent variations in network topology present significant challenges. This mobility can quickly render established routes obsolete, resulting in delayed data transfer, increased packet loss, and decreased routing performance. The dynamic nature of VANETs has motivated researchers to design reliable and adaptive routing protocols capable of discovering and maintaining efficient, durable routes, ensuring high-quality routing performance [6].

The primary objective of our contribution is to facilitate efficient communications by developing a stable, reactive, and delay-tolerant routing protocol that can effectively adapt to frequent topology changes while ensuring reliable data transfer in dynamic network environments.

In this contribution, we present an improved routing technique that synergistically fuses the AODV routing protocol with the principles of Ant Colony Optimization (ACO) algorithms. Our approach constructs optimal routes by calculating the pheromone value of the ACO using three key metrics: received signal strength (RSS), bandwidth and latency. By optimizing these critical factors, our methodology aims to improve the overall quality of service (QoS) in VANETs.

Our technique aims to leverage the strengths of each to improve the robustness, efficiency and responsiveness of routing in complex and dynamic network environments, such

as VANETs networks.

The principal innovation in our proposed AODV-ACO protocol, when compared with the existing hybrid AODV-ACO methodologies, lies in its pragmatic and holistic fitness function. In this study, three directly measurable and highly relevant QoS metrics –RSS, available bandwidth (BW), and latency (L) – are deliberately selected as the basic elements for pheromone calculation. This focus on real-time link quality and network capacity, as opposed to metrics such as residual energy (which is less critical in vehicle-powered nodes) or exclusive security features, is specifically designed to enhance route stability and efficiency in the highly dynamic and demanding context of urban VANETs.

The paper is organized as follows: Section 2 briefly outlines the AODV routing protocol and the ACO algorithm developed for VANET environments in Section 3. Section 4 present a detailed literature review and Section 5 offers a comprehensive explanation of the proposed AODV-ACO method, detailing its design and operational principles. The results and discussion of our method's performance are presented in Section 6. We conclude our paper and present some perspectives in Section 7.

2. AODV ROUTING PROTOCOL

AODV is a reactive routing protocol designed for ad-hoc networks wherein routes are created only when demanded. It utilizes three types of control messages to establish and maintain routes: route request (RREQ), route reply (RREP), and route error (RERR) [7].

In this type of protocol, when a network node needs to transmit data to a destination, it starts by checking its routing table for a fresh path. If a valid route exists, the node uses it to forward the packets [8]. Otherwise, the node initiates a route discovery process by broadcasting a RREQ message. Intermediary nodes receiving this request either respond with a RREP if they are the destination or have a current route to it, or they forward the RREQ. If so, they unicast a RREP message back to the source node, establishing a route [9]. Once it receives the RREP, the source takes the newly found path to exchange data packets with the receiver node. This on-demand approach allows AODV to create routes only when needed, reducing the overhead of maintaining unused routes in dynamic ad-hoc networks [5]. Figure 1 illustrates this process.

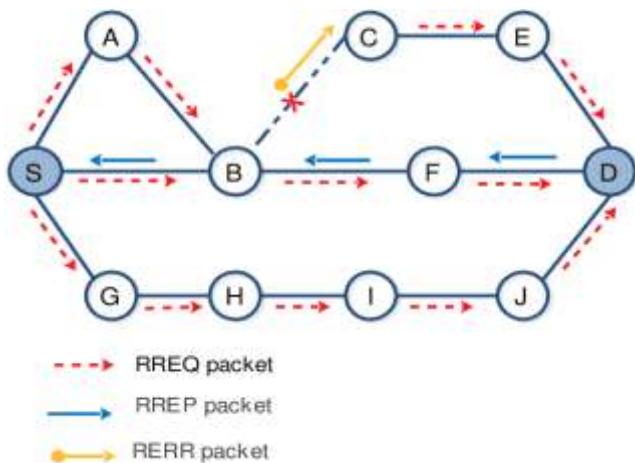


Figure 1. AODV routing protocol

3. ACO

In 1992, the ACO algorithm was developed by Marc Dorigo et al. This optimization method represents a swarm intelligence algorithm inspired by the foraging behavior of ants [10]. The original idea behind ACO is based on how ants explore their surroundings randomly in search of food sources. Ants secrete a certain amount of a chemical substance, known as a pheromone, which acts as a trail marker for subsequent ants [11].

Initially ants explore randomly, depositing pheromone trails. When an ant finds food, it leaves a pheromone trail on its return path [12]. Other ants are attracted to these trails, reinforcing paths with higher pheromone concentrations.

Shorter paths are favored as they accumulate more pheromone due to more frequent traversals. Longer, less-used paths experience pheromone evaporation [6].

This bio-inspired technique (ACO) has been applied to solve various network problems in vehicular ad-hoc networks (VANETs), such as routing, Internet access, and security. The deployment of ACO for VANET routing is inspired by similarities between network communication patterns and those observed in nature in certain species [13]. The foraging behavior of ants, where optimal paths are established through pheromone trails, resembles the process of routing data packets in the dynamic VANET environment, making ACO a suitable approach [6]. This process is shown in Figure 2.

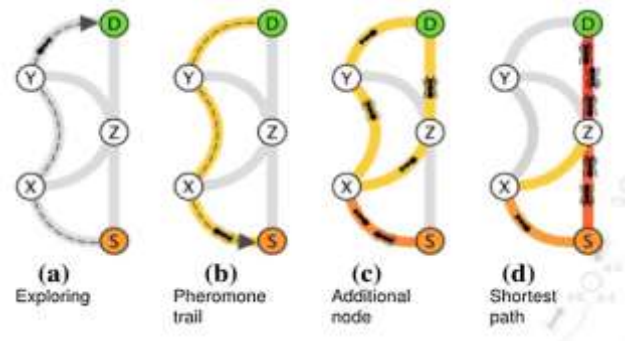


Figure 2. The procedure of ACO

4. RELATED WORK

In this section, a comprehensive review of the literature on ad hoc networks using the AODV protocol with the ACO optimization method is presented, along with the pros and cons.

A new route selection mechanism that combines the AODV reactive routing protocol and the ACO algorithm to optimize QoS in mobile ad-hoc networks (MANETs) was proposed in the study [14]. Inspired by ant colonies, it selects the optimal data delivery route based on the path's pheromone value, calculated using factors like end-to-end reliability, congestion, hop count, and nodes' residual energy. This mechanism aims to identify the most efficient and reliable routes. However, residual energy is an outdated metric in VANETs, where vehicles typically have continuous power supply. Moreover, their protocol does not consider essential metrics such as RSS or end-to-end latency, making it poorly suited to the highly dynamic topology and rapid mobility of VANET environments.

ACO based on a Modified AODV (MAODV) protocol for

secure data transmission in MANETs have been studied by Anantapur et al. [15]. MAODV utilizes ACO and considers four fitness functions: residual energy, distance, trust and node degree to detect optimal paths while mitigating blackhole attacks. While the integration of trust metrics enhances security, the approach primarily targets security at the expense of QoS. Additionally, the use of trust indicators and node degree significantly increases computational complexity, which is not ideal for embedded VANET systems requiring lightweight protocols.

Sindhvani et al. [16] proposed a novel approach that integrates the AODV routing protocol with the ACO technique for efficient data transmission in MANETs. In this research, a multicast-based path establishment strategy is introduced from source to destination, aiming to reduce congestion and optimize bandwidth utilization to improve the performance. However, this multicast-based strategy can lead to excessive routing overhead in high-density VANET environments, and the criteria used (e.g., hop count) remain conventional without considering radio link quality or physical-layer dynamics.

A new hybrid approach that modifies the AODV routing protocol by combining clustering K-Means methods with ACO to discover optimal routes in (MANETs) was presented in study [17]. The integration of these two techniques aims to leverage their respective strengths, enabling efficient route discovery while mitigating common MANET challenges like network dynamics, resource constraints, and security threats.

Their approach's incorporation of K-Means clustering may increase computational complexity and processing time, which may be impractical for real-time embedded VANET units like OBUs.

Nemade and Pujeri [18] proposed a novel Emergency Data Transmission using ACO (EDTA) protocol. EDTA enables ambulances to utilize any available route, prioritizing minimal communication overhead, reduced delays, and maximized throughput for prompter patient care. It introduces an ACO fitness function focusing on current vehicle speed and data/network congestion levels to optimize emergency data transmission in vehicular networks. This approach is limited to emergency situations, however, and does not apply to other VANET services such as safety alerts or infotainment. In addition, important parameters such as signal strength and bandwidth are not taken into account in the decision-making process, which can limit the stability and efficiency of selected routes.

Simaremare et al. [19] enhanced the performance of their suggested secure protocol using an ant algorithm. Ant agents deposit positive pheromone on trusted nodes, enabling path selection based on pheromone values. In their approach they evaluate and compare the protocol's performance, with and without the ant algorithm, under DoS/DDoS attacks. The integration of the ant algorithm aims to enhance security and reliability by prioritizing trusted routes. It focuses exclusively on trust without considering QoS improvements.

Table 1. Summary of related work

Reference	Protocol/Approach	Key Metrics	Strengths	Critical Limitations	Target Network	Strength of Our AODV-ACO Approach
Sarkar et al. [14]	Enhanced-ant-AODV	End-to-end reliability, Congestion, Hop count, Residual Energy	Considers multiple QoS factors.	-Uses residual energy, irrelevant for VANETs; does not consider RSS or latency.	MANET	-Integrates RSS, bandwidth, and latency, which are suitable for dynamic VANET environments.
Anantapur et al. [15]	MAODV (ACO-based)	Residual Energy, Distance, Trust, Node Degree	Enhances security against blackhole attacks.	-Focuses on security; adds complexity via trust and node degree unsuitable for embedded systems.	MANET	-Lightweight protocol optimized for QoS, suitable for real-time VANET deployment.
Sindhvani et al. [16]	AODV with ACO	Hop count (Multicast)	Reduces congestion via multicast.	-Multicast routing causes control overhead in dense networks; lacks link quality metrics.	MANET/VANET	-Unicast routing with link quality consideration for better reliability in urban VANETs.
Pamungkas et al. [17]	ANT-AODV with K-Means	Clustering with ACO	Efficient route discovery.	-High processing complexity due to K-Means clustering; not practical for OBUs.	MANET	-Avoids clustering to remain simple and real-time, suitable for embedded environments.
Nemade et al. [18]	EDTA	Vehicle Speed, Congestion	Optimized for emergency data.	-Limited to emergency scenarios; ignores signal strength and bandwidth.	VANET	-Generic solution supporting multiple VANET services with robust QoS.
Simaremare et al. [19]	Trust AODV with ACO	Trust (Pheromone)	Enhances security under attacks.	-Focuses only on trust; does not consider QoS metrics like delay or PDR.	MANET	-QoS-oriented protocol using physical-layer metrics with potential for future security integration.
Lee et al. [20]	MJTAR (ACO-based)	Real-time Traffic at Junctions	Traffic-aware junction selection.	-MJTAR Employs traffic-aware ACO selection of junctions; does not use AODV, nor link-quality metrics; targets junction-based routing rather than full end-to-end QoS optimization.	VANET	-Our protocol combines AODV + ACO with RSS, bandwidth, and latency metrics for link-level QoS routing, well-suited to dynamic urban VANET environments.

Lee et al. [20] proposed an intelligent routing protocol based on the ACO algorithm, titled Multiple-Junction-Based Traffic-Aware Routing (MJTAR), specifically designed for urban vehicular networks. Their approach dynamically

selects road junctions based on real-time traffic conditions, aiming to reduce congestion and improve routing efficiency. While MJTAR offers localized traffic-aware optimization, it presents notable limitations. The protocol does not rely on

AODV and does not incorporate critical link-quality metrics such as RSS, available bandwidth, or end-to-end latency, which are essential in highly dynamic VANET environments. Moreover, by focusing exclusively on junction-level decision-making, the approach overlooks full end-to-end route optimization. In contrast, our AODV-ACO approach combines the reactive nature of AODV with the adaptability of ACO, integrating physical-layer metrics directly into the pheromone computation. This enables a more robust and QoS-oriented routing solution, suitable for a wide range of VANET applications. The summary of related work is shown in Table 1.

5. PROPOSED METHOD

This section introduces our proposed AODV-ACO scheme, explaining its operating principles and design. As opposed to existing measures, the new proposed system takes into account the three most important factors for optimal route selection. AODV-ACO creates the best route from source to destination by considering the connection's RSS, latency, and available bandwidth.

Each node determines its pheromone count value using three metrics, as shown in Eq. (1) below. This value is then stored in the node's routing table as well as in the control packets RREQ and RREP. These packets carry the pheromone count information during the route discovery and establishment process.

5.1 Calculation of pheromone_val

When selecting the next hop to transmit a route request to the destination, choosing the geographically nearest node is not necessarily the best choice. This could be due to factors like insufficient bandwidth, high latency, or weak RSS at that neighboring node, which can impair reliable and efficient data transmission.

The routing system employs a pheromone value metric to judiciously select the next hop node. This pheromone value is calculated using a fitness function, which represents an optimization technique that is an integral part of many optimization algorithms and can be calculated as follows Eq. (1).

$$Phv = w_1 \times L + w_2 \times BW + w_3 \times RSS \tag{1}$$

where, L is a latency ,BW is the available bandwidth of the links, RSS represents the RSS at node j from node i, and the w_1 , w_2 , & w_3 are weight factors intended to determine the relative importance of each metric in the route selection process. In this initial study, based on the critical need for stable connections in VANETs, we assign a higher weight to RSS to prioritize link reliability. The weights are empirically set as where $w_3 = 0.4$, $w_2 = w_1 = 0.3$.

A comprehensive sensitivity analysis or dynamic weight adaptation strategy to optimize these parameters for different scenarios is a valuable direction for future research.

5.1.1 RSS

The RSS associated with each wireless link plays a crucial role in determining the reliability and stability of that link. Strong RSS indicates a robust connection, while weak signal strength can potentially lead to link breaks during data

transmission.

5.1.2 Latency

Corresponds to the time needed for a data packet to traverse the path between its source and destination over a network. This value is calculated using the following formula:

$$Latency = PerHopTime(rt) + (CURRENT_{Time} - rq \rightarrow rq_{timestamp}) \tag{2}$$

where, the $PerHopTime(rt)$ represents the average processing time per node and the term $(CURRENT_{Time} - rq \rightarrow rq_{timestamp})$ represents the elapsed time since the routing request rq was initiated.

5.1.3 Bandwidth

Available bandwidth evaluates the capacity of a network connection, whether wired or wireless, to transmit data in a given time interval. The formula used to calculate bandwidth is:

$$BW = 8 \times Packet \frac{end_{time} - start_{time}}{1000} \tag{3}$$

5.2 Modified AODV routing using ACO

The proposed routing scheme introduces five new fields into the routing table: RSSM, BW, L, Pheromone_val and the evaporation value. In addition to modifying the routing table, this algorithm also incorporates the Pheromone_val value as a new field in both the route request and route reply control packets. By including the Pheromone_val value in these packets, as shown in Figure 3 and Figure 4, the algorithm facilitates the dissemination and exchange of pheromone-related information during the route discovery and route establishment processes. The RSSM field stores the metric value of the RSS obtained from the subsequent station. The BW field records the value of the node's available bandwidth metric. The L field holds the latency metric value. The Pheromone_val field stores the total value of pheromones accumulated for the path between the source node and the current node, and the New_Ph field represents the new pheromone value after evaporation. All the new fields added to the routing table are illustrated in Figure 5, while the other fields conform to the standard implementation of the AODV protocol. This process involves four main steps:

Src_ad d	Src_s equen ceno	Request _id	Dest_ add	Dest_se quencen o	Hop_ Co unt	Pheromon e_val
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Figure 3. Modified RREQ format

Src_add	Dest_ad d	Dest_sequen ceno	Lifetime	HopCo unt	Phero mone_ val
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Figure 4. Modified RREP format

Dest_ad d	Seq uenc e_N o	H op Co un t	Nex t_H op	RSS	Ba nd wid th	Latenc y	Phero mone_ val	Ne w_ Ph
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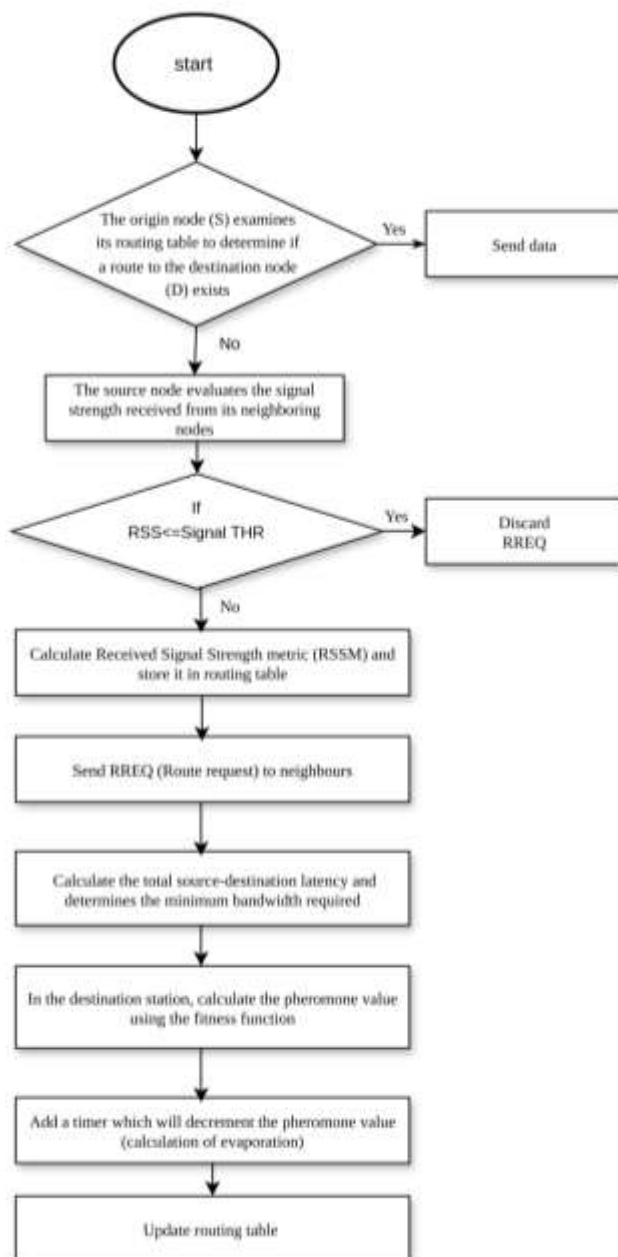
Figure 5. Modified routing table structure

Step 1: When a source node needs to transmit data to a destination station, it first consults its routing table to check whether a viable route to the destination already exists. If no route is detected, the source node starts a route discovery process by broadcasting a (RREQ) packet to all its neighboring nodes.

During this route discovery process, the source node

evaluates the signal strength received from its neighboring nodes. The RSS value is used to perform the first step in the neighbor node selection process. If the RSS is less than or equal to a predefined threshold (SIGNAL_THR), the source node discards packets with poor signals from those neighbors, the source node calculates the total source-destination latency and determines the minimum required bandwidth. Upon receiving a route request (RREQ), each neighbor checks if it's the destination. If not, it evaluates its bandwidth against the BANDWIDTH_THR threshold. The neighbor rejects the RREQ if its bandwidth is insufficient otherwise, it generates a routing table entry for the RREQ sender.

Discovery Mechanism



Packet forwarding mechanism

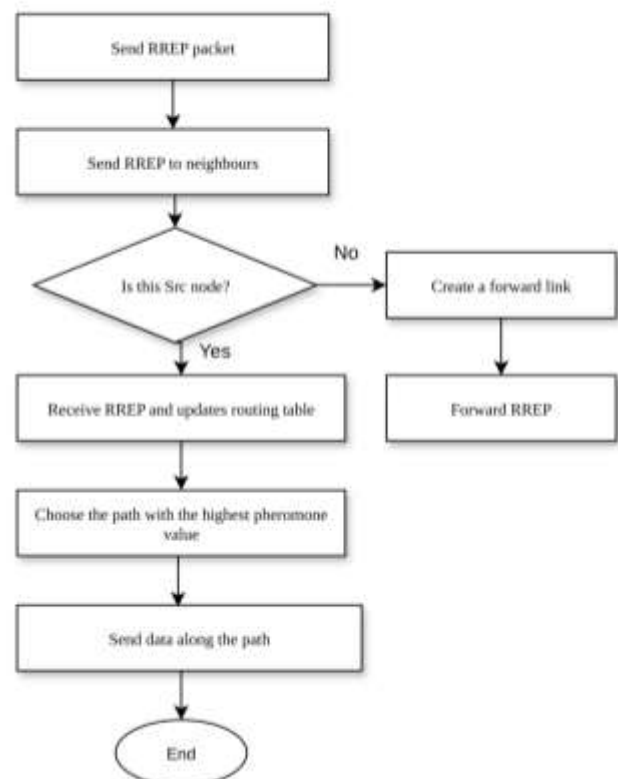


Figure 6. Flow chart of ACO-AODV

Step 2: As shown in flow chart (Figure 6) at the destination station, after evaluating the three parameters:

RSS, latency and bandwidth, the node uses a fitness function to compute the pheromone value based on these parameters. The calculated pheromone value is then added to the existing value in the Pheromone_val field of the received RREQ packet. This cumulative pheromone count is then recorded in two places: first, it is stored in the Pheromone_val field of the routing table entry corresponding to the RREQ sender node; second, it overwrites the Pheromone_val field of the RREQ packet itself. The updated RREQ, carrying the incremented pheromone count, is then forwarded to the next node.

Step 3: The pheromone value of the RREP message is refreshed using the highest pheromone value among the different RREQ messages received. Subsequently, the route with the highest pheromone value is the one that sends the RREP message.

When RREP successfully received and arrives at the destination, an entry is created in the routing table for the RREP sender, and the Pheromone_val field of this entry is updated. Then, the source station can transmit the packet to the destination.

Step 4: To take account of the natural evaporation of pheromones over time, a periodic evaporation mechanism is implemented. A timer is configured to be triggered regularly, thus gradually reducing the pheromone value associated with each routing table entry. The new pheromone value is calculated using this Eq. (4):

$$New_{Ph(u,j)} = (1 - q) \cdot ph(u,j), \text{ where } q \in (0,1) \quad (4)$$

The evaporation rate q is a crucial parameter that controls the balance between exploring new routes and exploiting known good ones. A higher value of q leads to faster forgetting of past routes. In our simulations, q was set to 0.1, and the evaporation timer was triggered every 5 seconds. This configuration allows recently used routes to remain attractive long enough to be beneficial while ensuring the routing table does not retain stale, obsolete paths.

This gradual reduction of pheromone levels ensures that the most recently utilized routes are favored, as their pheromone trails remain relatively strong. Conversely, older and less frequently traversed routes progressively become less attractive, as their pheromone trails gradually evaporate and diminish in potency, ultimately rendering them obsolete.

The flow chart of the new technique is shown in Figure 6. In terms of computational complexity, AODV-ACO introduces modest overhead. The primary additions are the calculations for RSS, bandwidth, latency, and the pheromone value for each RREQ, which are simple arithmetic operations ($O(1)$ per node). The periodic evaporation process is also light weight. This overhead is negligible compared to the significant reduction in the NRL achieved by selecting more stable routes, which reduces the frequency of costly route discovery processes. Therefore, AODV-ACO remains computationally feasible for real-time operation on VANET OBUs.

6. SIMULATION AND RESULTS

6.1 Simulation environment

In our approach, we simulated urban VANET scenarios from the downtown of Malaga, Spain [21, 22]. The NS-2 network simulator (version 2.35) was used for the various simulations, where the IEEE 802.11ext protocol was used for

the physical layer [23]. The wireless channel was modeled with a Nakagami radio propagation model. At the network layer, we used the AODV routing protocol. Finally, TCP was used for the transport layer. The simulated geographic area covered an area of $2 \text{ km} \times 1 \text{ km}$, with a number of vehicles varying from 10 to 45. Table 2 summarizes simulation parameters.

Table 2. Parameters used in simulation

Parameters	Value
Propagation Model	Nakagami ($m = 1.5$ for short distance, $m = 1.0$ for long distance)
PHY Layer	IEEE 802.11p
Routing Layer	AODV, AODV-ACO
Transport Layer	TCP
Area Size	$2000 \text{ m} \times 1000 \text{ m}$
Number of Vehicles	10, 15, 20, 30, 40, 45
Packet Size	512 bytes
Simulation Time	180 s
Mobility Model	Real-world trace (Malaga downtown scenario [21, 22])
Vehicle Speed Range	0 - 50 km/h (urban speed limits)
Transmission Range	250 m

6.2 Performance metrics

6.2.1 Packet delivery ratio

Packet delivery ratio measures the number of data packets that reach the destination compared to the number of packets originally sent by the source. More specifically, it's the ratio of packets received by the destination node to those emitted by the sending node station [24, 25]. This PDR is calculated by Eq. (5).

$$PDR = \frac{\sum_{i=0}^n \text{Packet received}}{\sum_{i=0}^n \text{Packet sent}} \times 100\% \quad (5)$$

6.2.2 Delay(D)

This measurement represents the average time taken for a data packet to travel from the transmitting vehicle to the receiving vehicle [25, 26]. This average is expressed in Eq. (6).

$$Delay = \frac{1}{n} \left(\sum_{i=0}^n \text{Packets received time}(n) - \text{Packets sent time}(n) \right) \quad (6)$$

6.2.3 NRL

The NRL index is obtained by dividing the total number of control packets sent by each node by the number of data packets received at the destinations [27]. The NRL is given by Eq. (7).

$$NRL = \frac{\sum_{i=0}^n \text{Routing control packets transmitted}}{\sum_{i=0}^n \text{Data packets received}} \quad (7)$$

6.3 Results and discussion

This section compares the performance of the new proposed AODV-ACO protocol with that of the existing AODV protocol. Three criteria are evaluated: packet delivery rate, transmission delay and routing overhead. Results are shown as the mean values over 5 simulation runs with

different random seeds.

Table 3. Performance analysis of PDR

Number of Vehicle	AODV-ACO	AODV Original
10	98.4774%	98.1249%
15	98.6164%	97.1268%
20	99.2129%	96.7861%
30	99.0059%	95.3866%
40	97.9627%	95.8655%
45	98.3849%	97.7397%



Figure 7. Packet delivery ratio

Figure 7 and Table 3 show the evolution of PDR for the two protocols, AODV-ACO and original AODV, depending on number of vehicles, the results show a better PDR of our AODV-ACO approach compared to the original protocol.

To achieve a high packet delivery ratio, packet losses during transmission must be minimized, mainly caused by route breakages. In vehicular ad-hoc networks (VANETs), route breakages during transmission pose a significant challenge to maintaining efficient communication. When a route fails, packets in transit are temporarily stored in the queues of intermediate nodes while the network attempts to establish an alternative path. However, since node queues have limited capacity, if a new path is not established quickly, queues fill up, and packets are dropped. This leads to additional losses and degrades the routing protocol's performance.

The proposed routing approach improves VANET network performance by integrating signal quality and bandwidth into its fitness function. This strategy prioritizes paths with robust links and sufficient capacity, effectively excluding connections between vehicles with low signal strength from the routing process. By favoring high-quality links and taking bandwidth capacities into account, the algorithm significantly reduces the probability of packet loss due to link instability or insufficient capacity. This refined selection method results in more reliable data transmission paths, minimizing route breaks and reducing the need for frequent route re-establishment. As a result, fewer packets are dropped due to queue overflows or transmission failures, leading to a significant improvement in packet delivery rates.

Figure 8 and Table 4 illustrate the impact of increasing the number of vehicles on Delay for proposed protocol AODV-ACO and original AODV; we can see that the end-to-end delay of AODV-ACO is better than AODV original.

In AODV-ACO, the selection of routing paths is not based only on the number of hops. It takes into account various

other critical factors such as the available bandwidth, the RSS, and the total latency from the source to the destination. This multi-objective approach allows AODV-ACO to steer clear of links with weak signal strengths, which are susceptible to instability and congestion. By avoiding such low-quality links, the protocol minimizes the necessity for packet retransmissions and reduces waiting times caused by queuing delays. As a result, AODV-ACO can deliver improved overall network performance and achieve lower end-to-end delays.

Table 4. Performance analysis of delay

Number of Vehicle	AODV-ACO	AODV Original
10	42,3723 ms	42,2856 ms
15	66,3256 ms	79,0442 ms
20	55,028 ms	58,4357 ms
30	55,3364 ms	71,8555 ms
40	67,5022 ms	79,9025 ms
45	60,3731 ms	79,5869 ms

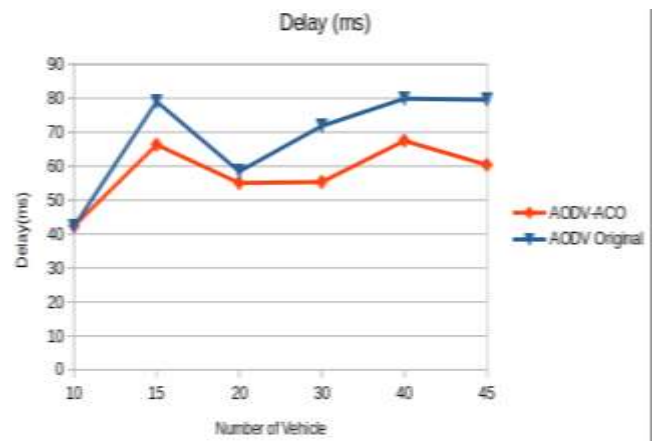


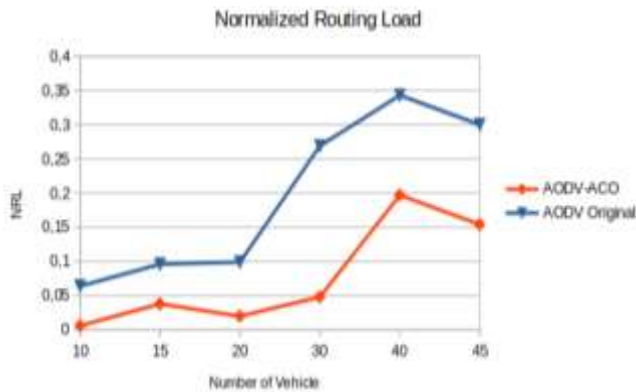
Figure 8. Delay (ms)

The cumulative effect of these improvements is better overall network performance. Specifically, the AODV-ACO protocol reduces end-to-end delays, as packets take more reliable and efficient paths through the network. This reduction in latency, combined with the protocol's ability to maintain stable routes, contributes to the improved QoS and robustness of the VANET communication system.

Figure 9 and Table 5 represent the NRL of AODV-ACO and AODV original. The graphical representation clearly demonstrates the reduced routing load associated with the AODV-ACO method when compared to the original AODV protocol. The latter suffers from elevated routing load levels due to the transmission of a significant volume of control packets during the process of routing path establishment. In contrast, the AODV-ACO method does not contribute to additional control packet transmissions, as the pheromone level is incorporated into the fitness function calculation. This pheromone-based approach not only mitigates the initial routing load but also facilitates continuous adaptation to the frequent topology changes in the network through periodic pheromone evaporation. This evaporation mechanism prevents excessive routing load accumulation while dynamically maintaining optimal paths. As a result, AODV-ACO efficiently minimizes the control routing load while seamlessly adapting to the dynamic characteristics of the urban environment.

Table 5. Performance analysis of NRL

Number of Vehicle	AODV-ACO	AODV Original
10	0.006	0.064
15	0.038	0.096
20	0.02	0.099
30	0.048	0.269
40	0.197	0.343
45	0.154	0.3

**Figure 9.** NRL

7. CONCLUSION

In this paper, a routing method based on the ACO technique named AODV-ACO has been proposed for VANET networks. The simulation results reveal that the performance of the proposed protocol increases when using the ACO technique in terms of packet delivery rate, delay and NRL.

The incorporation of ACO into AODV exploits the concept of pheromones to guide route selection towards optimal routes in terms of bandwidth, latency and signal strength. In addition, an evaporation mechanism is applied to the pheromone value to gradually decrease it over time, thus avoiding premature convergence towards sub-optimal solutions. By reinforcing the paths that meet these link quality criteria, AODV-ACO adaptively converges on a set of reliable, low-latency and uncongested paths, thereby improving key network performance.

Future research directions are threefold. First, we plan to apply and evaluate AODV-ACO in highway environments to assess its performance under high-speed mobility conditions. Second, we will conduct an in-depth parameter sensitivity analysis, particularly on the pheromone weights (w_1 , w_2 and w_3) and evaporation rate (q), to establish optimal configurations. Finally, we intend to enhance the protocol's robustness by integrating a trust model to identify and mitigate the impact of malicious nodes, thereby improving security without compromising QoS.

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