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Optimized Energy-Efficient Routing for IEEE 802.11-Based Vehicular Ad-Hoc Networks: A BEE-AD-HOC Approach

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ABSTRACT

Vehicular Ad-Hoc Networks (VANETs) are a special type of Mobile Ad-Hoc Networks (MANETs), and they're becoming increasingly important for building smart transportation systems, improving road safety, and enabling real-time communication between vehicles. Despite their potential, VANETs face some tough challenges—mainly due to how often vehicles move, how frequently connections drop, and how fast the network's structure changes. These issues make it hard to maintain stable and efficient communication. Traditional routing protocols often struggle in these conditions. They usually don't handle energy use well or keep routes stable over time. To address this, our research introduces a new energy-efficient routing protocol called BEE-AD-HOC. Inspired by the way bees work together to find the best paths, this protocol is designed specifically for VANETs that use the IEEE 802.11 standard. BEE-AD-HOC aims to find routes that save energy while also minimizing data loss, delay, and extra communication overhead—even when vehicle movement is fast and unpredictable. The protocol considers several key factors when choosing a route, such as how much energy each node has left, how long it takes to send data, and how stable the connection is. Through simulations, we found that BEE-AD-HOC performs much better than existing routing protocols like AODV and DSR. It uses less energy, delivers more data successfully, and handles heavy, fast-changing traffic more efficiently. Thanks to its ability to adapt and stay reliable in real-world conditions, BEE-AD-HOC shows great promise for improving communication in modern vehicle networks.

1. Introduction

Vehicular Ad-Hoc Networks (VANETs), a branch of Mobile Ad-Hoc Networks (MANETs), enable communication between vehicles (V2V) and between vehicles and infrastructure (V2I) [1]. These networks work without a central control system, which makes routing especially challenging—particularly in fast-changing environments where network connections often shift and some nodes, like mobile roadside units or electric vehicles, have limited energy. Common routing protocols like AODV and DSR provide basic solutions, but they often waste energy because they need to constantly rediscover routes and resend data. Some newer protocols that focus on location or energy efficiency do better in certain cases, but they tend to fall short when vehicles are moving quickly or the network is changing rapidly [6]. This highlights the need for a smarter, energy-efficient routing strategy that's designed specifically for VANETs using the IEEE 802.11 standard.

2. Methodology

Proposed Algorithm: BEE-AD-HOC (Bio-inspired Energy-Efficient Ad-Hoc Routing Protocol)

It is specifically designed for **IEEE 802.11-based Vehicular Ad-Hoc Networks (VANETs)** and draws inspiration from **honeybee foraging behavior** to optimize routing decisions in a dynamic and energy-conscious manner and particularly how they locate, assess, and communicate optimal food sources. This biologically inspired behavior is adapted to the routing mechanism in VANETs to optimize energy usage, minimize delay, and enhance overall network performance.

Key Components of the Algorithm

1. **Scout Phase (Route Discovery):**

   Vehicles initially act as **scout bees**, broadcasting route request (RREQ) packets to discover potential paths to the destination. Each RREQ carries a fitness value calculated using a composite metric that includes:

- **Residual energy** of the transmitting node
- **Signal strength** of the link
- **Hop count**
- **Link stability** (based on relative vehicle speed and direction)

The fitness function F for a route is defined as:

$$F = w_1 \cdot E_r + w_2 \cdot S_s - w_3 \cdot H_c + w_4 \cdot L_s$$

Where:

E_r: Residual energy

S_s: Signal strength

H_c: Hop count

L_s: Link stability

w_i: Weights assigned to each parameter, based on network context

Only the most optimal RREQs (highest fitness) are forwarded, mimicking bees selecting promising paths.

2. **Onlooker Phase (Route Selection):** Once possible routes are identified, vehicles act like onlooker bees, choosing the best path based on an overall fitness score. Just like bees use a waggle dance to communicate the best food sources, the network nodes share route information to agree on the most energy-efficient and reliable option. Routes that have worked well in the past and use less energy are given priority.
3. **Forager Phase (Route Maintenance):** While data is being transmitted, vehicles take on the role of forager bees, constantly checking how well the chosen route is performing. If a connection fails or a node's energy drops too low, the system quickly switches to a backup route that was already

assessed but not yet used. This switch is guided by a pheromone-inspired scoring system, helping avoid delays from re-discovering new routes and keeping communication flowing smoothly [2], [3].

4. **Route Reinforcement (Learning Behavior)**: Routes that consistently deliver good performance are given higher priority for future use, while those that don't perform well are slowly phased out. This adaptive approach mirrors how bee colonies learn over time, helping the system continually improve its routing efficiency.

Simulation Setup

Parameter	**Value**
Simulator	NS-2.35
Area Size	1000 × 1000 meters
Number of Nodes	50, 100, 150
Mobility Model	Random Waypoint
MAC Protocol	IEEE 802.11p
Transmission Range	250 meters
Packet Size	512 bytes
Routing Protocols	AODV, DSR, BEE-AD-HOC
Simulation Time	200 seconds
Traffic Type	CBR (Constant Bit Rate)

Performance Metrics:

1. **Energy Consumption (Joules)** – Measures total energy used by all nodes during communication.
2. **Packet Delivery Ratio (PDR)** – Ratio of successfully delivered packets to those sent.
3. **End-to-End Delay (ms) –** Average delay experienced from source to destination.

Scenario Setup

Three mobility scenarios were tested:

1. **Low Density**: 50 vehicles, sparse network
2. **Medium Density**: 100 vehicles, urban congestion
3. **High Density**: 150 vehicles, dense traffic

Each scenario evaluates how BEE-AD-HOC handles dynamic topology, varying energy levels, and routing complexity under real-time constraints.

3. Literature Review

Perkins et al. – Ad hoc On-Demand Distance Vector (AODV) Routing

Perkins et al. developed the AODV routing protocol, which is still widely used in VANETs because it reacts to changes on demand and doesn't require much initial setup [1]. However, in fast-changing environments, AODV often triggers frequent route discoveries and generates a lot of control messages, which leads to high energy consumption. These drawbacks highlight the need for a more flexible and energy-efficient routing solution—likes BEE-AD-HOC. **Johnson et al. – Dynamic Source Routing (DSR)** Johnson et al. introduced the DSR protocol, which relies on source routing to manage end-to-end paths in ad hoc networks [2]. While DSR works well in smaller or less dynamic networks, it struggles to keep up in VANETs because of the constant movement of vehicles and the overhead of maintaining long route information. These challenges highlight the benefits of more decentralized, nature-inspired approaches—like the one used in BEE-AD-HOC. **Zaidi et al. – Energy-Aware VANET Routing Protocols Survey** Zaidi et al. carried out an in-depth review of energy-aware routing protocols in VANETs, highlighting key factors that affect energy efficiency—like node density, vehicle movement, and power limitations [3]. Their study underscores the need for adaptive, energy-focused designs, which supports BEE-AD-HOC's emphasis on using residual energy and link stability as key routing criteria. **Khan et al. – Ant Colony Optimization for VANET Routing** Khan et al. proposed a bio-inspired routing protocol based on Ant Colony Optimization (ACO), which uses virtual pheromone trails to discover and maintain efficient routes in VANETs [4]. While ACO has shown promise, it can be computationally heavy and slow to adapt—especially in high-speed scenarios. BEE-AD-HOC builds on this concept by applying bee colony behavior instead, offering quicker, and more efficient route adjustments with less processing overhead. **Senouci and Pujolle – Energy Efficient Routing in Ad Hoc Networks** Senouci and Pujolle introduced one of the early models for energy-efficient routing in wireless ad hoc networks, focusing on reducing control packet transmissions and optimizing power usage [5]. While their work wasn't specifically designed for VANETs, it helped establish the importance of including energy considerations in routing algorithms. BEE-AD-HOC builds on this foundation by adding dynamic energy-awareness to both route discovery and maintenance. For this related work many prominent researchers have done the work as- Bhawaria & Rathore (26), Bhawaria & Rathore (27), Bhawaria & Rathore (28), Rathore et al. (29), Bhawaria et al. (30), Bhawaria et al. (31), Mathur and Bhawaria (32), Meedal et al. (33).

4. Related work

Many routing protocols have been developed for Vehicular Ad-Hoc Networks (VANETs) to tackle challenges like high mobility, energy efficiency, and maintaining stable routes. Traditional reactive protocols such as AODV (Ad hoc On-Demand Distance Vector) and DSR (Dynamic Source Routing) are popular because they establish routes only when needed and have low setup costs. However, in rapidly changing network conditions, these protocols tend to generate a large number of control messages [2], which leads to higher energy use and increased packet loss.

To address these problems, researchers have turned to energy-aware and bio-inspired routing methods. For instance, EAODV enhances the original AODV by incorporating energy-related metrics to extend network lifetime—but it still struggles to adapt effectively in high-speed traffic scenarios. Other approaches, like Ant Colony Optimization (ACO) and Bee Colony Optimization (BCO), mimic natural behaviors such as pheromone signaling and group decision-making to manage routing. While these methods can improve route discovery and maintenance, they often come with high computational demands and require careful tuning, making them less practical for fast-moving vehicular networks.

BEE-AD-HOC offers a different solution. Inspired by how honeybees search for food, it uses a lightweight, adaptive approach to routing. It selects paths based on factors like remaining energy and signal strength, helping to keep energy usage low while ensuring quick communication and high packet delivery rates. Unlike more static systems, BEE-AD-HOC continuously learns from the network, reinforcing the best-performing routes and dropping the weaker ones. This leads to smarter resource use and more reliable communication in dynamic vehicular environments.

Simulation Results and Output

To evaluate the performance of BEE-AD-HOC, simulations were conducted using the NS-2 simulator across different node densities. The proposed protocol was compared with AODV and DSR using key performance indicators:

1. Energy Consumption (Joules)
2. Packet Delivery Ratio (PDR %)
3. End-to-End Delay (Milliseconds)

Simulation Results Table

Protocol	Energy Consumption (J)	Packet Delivery Ratio (%)	End-to-End Delay (ms)
AODV	320	82	150
DSR	290	85	140
BEE-AD-HOC	**210**	**91**	**105**

Key Observations:

1. **Energy Efficiency:** BEE-AD-HOC consumes ~34% less energy than AODV and ~28% less than DSR, thanks to its adaptive routing and reduced control overhead.
2. **Packet Delivery Ratio:** The protocol improves delivery success, achieving 91% PDR, compared to 82% and 85% for AODV and DSR, respectively.

3. **End-to-End Delay:** BEE-AD-HOC maintains lower average latency (105 ms), enhancing real-time communication performance.

These results confirm that BEE-AD-HOC offers a significant improvement in energy-aware routing efficiency for IEEE 802.11-based VANETs, especially under dynamic and high-mobility conditions.

Limitation of Study

This study introduces a new, energy-efficient routing protocol for VANETs, it does come with a few limitations. To start with, the BEE-AD-HOC algorithm was only tested in simulation using the NS-2 tool, which doesn't fully capture the real-world complexities of vehicular networks. The simulation used a Random Waypoint mobility model, which doesn't realistically reflect how vehicles move in structured urban traffic environments.

Another limitation is that the research focuses solely on VANETs using the IEEE 802.11 standard, which may not translate well to newer technologies like 5G or hybrid communication systems. Also, the study doesn't explore security concerns, such as how the protocol handles routing attacks or malicious behavior by nodes. While the algorithm is designed to adapt to changing network conditions, it doesn't use machine learning or predictive models—tools that could help improve real-time decisions in future versions. These limitations point to potential areas for future improvement and the need for testing in real-world scenarios.

5. Conclusion and Future Scope

Conclusion

This research introduces BEE-AD-HOC, a new bio-inspired routing algorithm designed to improve energy efficiency in IEEE 802.11-based Vehicular Ad-Hoc Networks (VANETs). Inspired by how honeybees search for food, the protocol uses a decentralized and flexible approach to routing. It can quickly adapt to changes in the network, which is essential in environments where vehicles move quickly and connections change often. BEE-AD-HOC chooses the best communication paths by considering several factors—like remaining battery power (residual energy), signal strength, number of hops, and how stable a connection is. These are combined into a single "fitness score" that helps the system find and maintain the most efficient routes with minimal extra traffic. Simulation results show that BEE-AD-HOC performs much better than traditional protocols like AODV and DSR. It uses less energy, delivers more data successfully, and reduces delays. These benefits make it a strong choice for real-time and safety-critical vehicle communication, where both speed and reliability matter most.

Future work

While the BEE-AD-HOC protocol demonstrates promising results in terms of energy efficiency and routing performance in VANETs, there remain several unexplored areas that present opportunities for future research:

1. **Integration with Heterogeneous Communication Standards (e.g., 5G, DSRC, and C-V2X):** This study is confined to IEEE 802.11-based VANETs. As real-world vehicular environments

increasingly incorporate heterogeneous communication technologies like 5G NR-V2X, Dedicated Short Range Communications (DSRC), and Cellular-V2X (C-V2X), future work could focus on adapting BEE-AD-HOC for interoperability across multiple standards to ensure broader applicability.

2. **Energy Harvesting in Vehicular Networks:** The current algorithm optimizes existing battery power usage, but it does not consider energy harvesting capabilities (e.g., solar-powered sensors or regenerative braking). Integrating such mechanisms can lead to a self-sustaining VANET model, further improving the longevity and sustainability of nodes.

3. **Dynamic Load Balancing Across Routes:** The current routing strategy prioritizes optimal paths but may unintentionally overload specific routes. Future enhancements could include traffic-aware or load-balancing extensions, distributing data flows across multiple viable paths to prevent bottlenecks and enhance network longevity.
4. **Predictive Routing Using AI/ML:** Incorporating machine learning models to predict vehicle movements, traffic density, or link stability can improve the adaptability of the routing protocol under real-time urban traffic conditions. This can be particularly useful for anticipating link breakages before they occur, thus reducing delay and packet loss.
5. **QoS-Aware Routing for Multimedia Applications:** As in-vehicle infotainment and V2X applications grow, VANETs will need to support Quality of Service (QoS) constraints such as bandwidth, jitter, and latency. Future versions of BEE-AD-HOC could integrate QoS-aware routing metrics to support multimedia data and safety-critical messages simultaneously.
6. **Mobility Model Realism and Geographic Constraints:** The current simulation uses the Random Waypoint model, which lacks realism in terms of road structures and driver behavior. Future research should utilize realistic mobility traces or models like SUMO (Simulation of Urban Mobility), considering factors like traffic lights, road curvature, and urban congestion.

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