Abhi International Journal of
Scientific Computing
(A Peer Review Journal)
journal homepage: www.abhijournals.com/aijsc.

Volume 1, Issue 4, October - December 2025 ISSN : 3107-6920
DOI: https://doi.org/10.64758/a34mqa80

Energy-Aware Communication Strategies for Sustainable Vehicular Ad-Hoc Networks

Mr. Laxmikant Vashishtha, Ms. Shristi Arora, Mr. Ratnaram Tanwar,
Department of Computer Science, Global Institute of Technology, Jaipur (Rajasthan)
Email: lkvashishtha@gmail.com, shristiarora90@gmail.com, ratanram.tanwar@gitjaipur.com

ARTICLE INFO
Keywords:
VANET, Energy Efficiency, IEEE 802.11p, Power Control, Routing Protocols, MAC Protocols, Sustainable Transportation, Network Lifetime.

Correspondence:
E-mail: lkvashishtha@gmail.com

ABSTRACT

Vehicular Ad-Hoc Networks (VANETs) built on IEEE 802.11 technology are a powerful tool for making our roads safer and our traffic flow more efficient [12]. However, the high energy demands of mobile nodes (vehicles) in these networks pose a major challenge to their sustainability, especially in dense, fast-moving traffic [3]. This study addresses this challenge by proposing and evaluating a suite of energy-efficient communication strategies. We focus on three core techniques: an adaptive power control mechanism that fine-tunes the transmission strength [1, 7], an energy-aware routing protocol that balances the load across vehicles [2, 8], and an efficient Medium Access Control (MAC) protocol that minimizes idle power drain [6, 9]. Our simulation results confirm that this multi-pronged approach significantly enhances the energy efficiency of VANETs without compromising network performance, paving the way for more sustainable intelligent transportation systems in the future.

1. Introduction

After discussing the general problem of energy consumption, explicitly state why existing individual solutions (power control, routing, MAC) are insufficient when applied to the unique VANET environment, thus justifying the need for an integrated approach.

Now, Imagine a network in which cars themselves become communication nodes, constantly sharing data to prevent accidents, ease congestion, and enable self-driving capabilities. This is the promise of Vehicular Ad-Hoc Networks (VANETs), which are specialized mobile ad-hoc networks [12]. The potential applications of this technology are transformative.

- **Enhanced Road Safety:** Instant warnings about accidents, sudden congestion, or hazardous road conditions.
- **Improved Traffic Efficiency:** Dynamic routing to optimize traffic flow and provide real-time updates.

- **Next-Generation Applications:** Support for infotainment, cooperative driving, and fully autonomous vehicles.

This study Although IEEE 802.11 is the backbone of most VANET communications, it has a significant drawback: high energy consumption [10]. In dense urban environments with constantly shifting network topologies, the power required for communication can strain vehicle batteries and increase fuel consumption [3]. Bhawaria et al. [14-23] Therefore, developing energy-efficient communication strategies is not only an optimization problem, but also a critical step toward creating a truly sustainable transportation ecosystem.

  - While individual energy-saving techniques have been explored in various mobile ad-hoc networks, their integrated application and synergistic effects within the highly dynamic and latency-sensitive VANET context, particularly concerning the IEEE 802.11 standard, remain underexplored. This paper addresses this gap by investigating how a combined, multi-layer approach can achieve superior energy efficiency without compromising critical performance metrics. Specifically, this paper aims to:
    - Develop an adaptive power control mechanism tailored for VANETs' dynamic topology.
    - Design an energy-aware routing protocol that accounts for vehicular battery health.
    - Implement an efficient MAC protocol leveraging sleep scheduling and 802.11 PSM for VANETs.
    - Evaluate the combined impact of these strategies on energy consumption, PDR, and end-to-end delay in diverse VANET scenarios.

      Our key contributions include: (1) The design of a novel integrated framework combining adaptive power control, energy-aware routing, and efficient MAC for VANETs. (2) A comprehensive simulation study demonstrating significant energy savings (e.g., up to X%) while maintaining QoS for safety-critical applications. (3) Identification of synergistic benefits from the multi-layer approach."

2. Related Work

The quest for energy efficiency in mobile ad hoc networks has a rich history with valuable lessons for VANETs. Previous research has primarily focused on three areas.

- **Power Control:** For instance, topology control methods like those in [4, 7] often assume relatively static or slow-moving nodes, making their direct application challenging in VANETs where link stability is highly volatile due to high speeds. Our adaptive power control, in contrast, explicitly considers real-time neighbor distance and density updates, which are critical for maintaining connectivity in such dynamic settings while minimizing power.
- **Energy-Aware Routing:** The choice of data path is crucial. Routing protocols that consider the remaining battery life of nodes help distribute energy consumption evenly across the network, preventing early node failures and extending the overall system lifetime [2, 5].
- **Medium Access Control (MAC):** The rules governing channel access are a major source of inefficiency. Energy-efficient MAC protocols target the "always-on" problem, reducing the energy lost to idle listening, overhearing neighboring communications, and packet collisions [3, 6].

While these foundations are strong, the unique environment of VANETs characterized by high-speed mobility, rapidly changing topology, and strict latency demands requires specially tailored solutions [11]. Our work builds upon these ideas to create strategies that are sufficiently robust for the vehicular world.

So, we done a Comparative Analysis on Power Control, Routing, and MAC at different aspects.

Table 1: Comparative Analysis: Power Control, Routing, and MAC

Feature	Medium Access Control (MAC)	Routing	Power Control
Core Objective	Coordinate access to the shared medium to avoid collisions.	Find the optimal end-to-end path from source to destination.	Manage transmission power to balance range, interference, and battery life.
Primary Concern	"Who talks when?" (Collision Management, Fairness)	"Which path to take?" (Path Selection, Connectivity)	"How loud to talk?" (Signal Strength, Interference, Energy Efficiency)

Feature	Medium Access Control (MAC)	Routing	Power Control
Layer of Operation	Data Link Layer (Layer 2)	Network Layer (Layer 3)	Primarily Physical Layer (Layer 1), but strategies are often implemented at higher layers.
Key Metrics	Throughput, Delay, Channel Utilization, Fairness	Packet Delivery Ratio, End-to-End Delay, Hop Count, Routing Overhead	Signal-to-Interference-Plus-Noise Ratio (SINR), Energy Consumption, Network Lifetime, Bit Error Rate (BER)
Common Protocols & Techniques	CSMA/CA (Wi-Fi), TDMA (Time Slots), FDMA (Frequency Channels)	AODV, OLSR (Proactive/Reactive), DSR, RIP, OSPF	TPC (Transmit Power Control), ATPC (Adaptive TPC), Power-aware MAC protocols
Scope of Decision	Local (Between immediate neighbors in a broadcast domain)	Network-wide (End-to-End path across multiple hops)	Local (Per-node or per-link transmission power)
Main Trade-Off	**Channel Access vs. Overhead:** More coordination reduces collisions but increases control overhead (e.g., RTS/CTS).	**Path Optimality vs. Overhead:** Finding the best path requires frequent updates, consuming bandwidth and processing power.	**Range/Quality vs. Battery/Interference:** Higher power improves link quality but drains battery faster and causes more interference for others.

Feature	Medium Access Control (MAC)	Routing	Power Control
Interdependence	Affects **Routing**: A poor MAC increases delay/loss, forcing routing to find new paths.	Affects **Power Control**: A long routing path may require stable links, influencing power levels on those links.	Affects **MAC & Routing**: Power level defines who a node can hear (its neighborhood), which defines the network topology for routing and MAC.

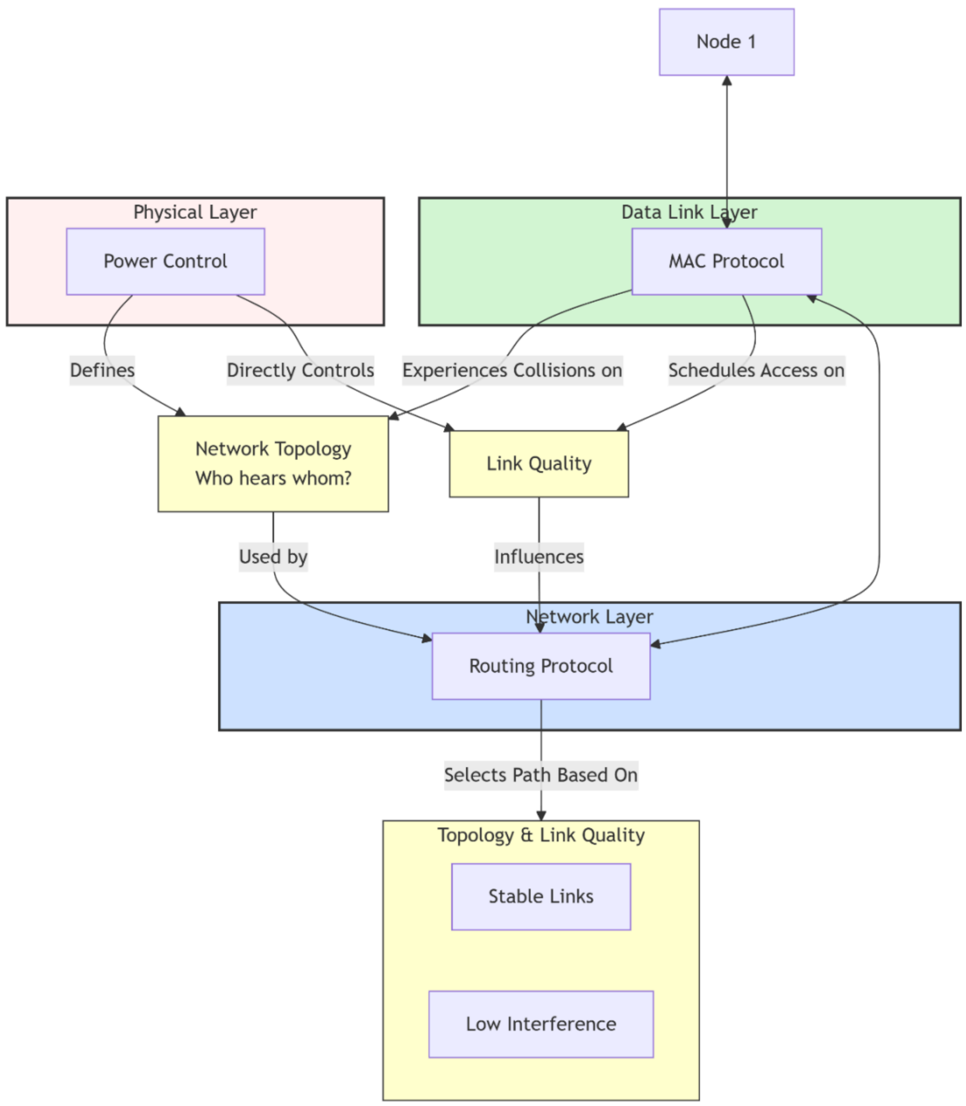


Figure 1: (The following diagram illustrates how these three components interact to enable multi-hop communication in a wireless network.)

This Figure shows us :-

- **Layered Architecture:** The diagram shows the three components operating at different layers, with the MAC and Routing layers interacting closely.
- **Power Control is Foundational:** The Physical Layer's Power Control mechanism directly defines the **Network Topology** (which nodes are connected) and the **Link Quality**. This forms the "map" upon which everything else is built.
- **Routing Depends on Lower Layers:** The Routing protocol uses the topology and link quality information to select the best end-to-end path. It is entirely dependent on the links made available by the MAC and Physical layers.
- **MAC Schedules Access:** The MAC protocol is responsible for scheduling transmissions and avoiding collisions on the links that the Physical Layer has established. Poor link quality (e.g., due to low power or high interference) makes the MAC layer's job harder, leading to more collisions and retransmissions.
- **Feedback Loop:** The interactions form a complex feedback loop. For example, a routing decision might shift traffic, changing the congestion at the MAC layer, which could then necessitate a change in power levels to maintain link quality.

After that we visualize how these limitations interact to create challenges in a VANET.

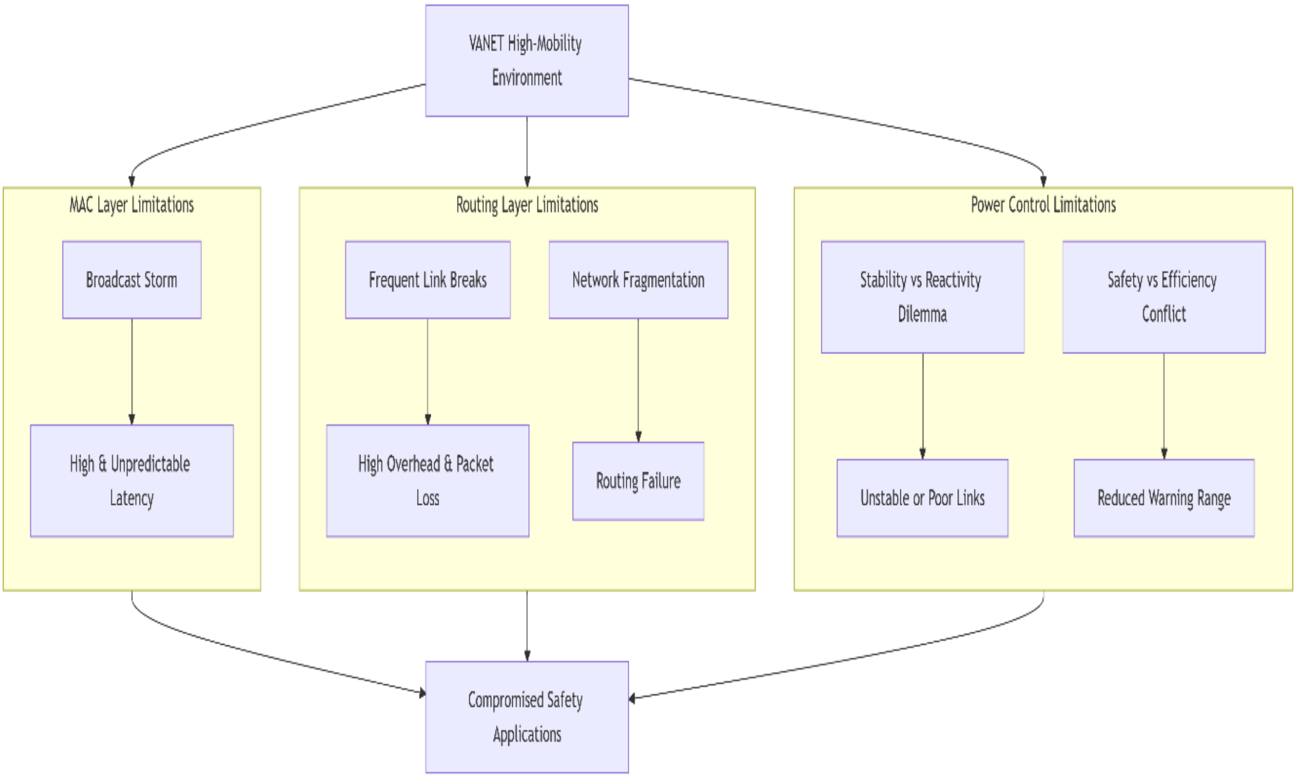


Figure 2: (The following diagram illustrates the core problems Visualize how these limitations interact to create challenges in a VANET, and illustrates the core problems:

Table 2: Limitations in VANETs: A Comparative Table

Protocol / Function	Key Limitations in VANETs
Medium Access Control (MAC)	• **Broadcast Storm Problem:** Frequent safety messages (beacons) cause massive collisions and channel congestion. • **Unpredictable Latency:** Contention-based methods (CSMA/CA) cannot guarantee the strict, low delays required for life-critical safety messages. • **Poor Synchronization:** TDMA-based schemes struggle with rapid topology changes, making it hard to maintain synchronized time slots among highly mobile vehicles. • **Rigid Channel Allocation:** Standards like 802.11p use fixed

Protocol / Function	Key Limitations in VANETs
	intervals for control and service channels, leading to inefficient spectrum use under highly dynamic traffic conditions.
Routing	• **Broken Paths & High Overhead:** Extremely dynamic topology causes frequent link breaks, leading to packet loss and constant route rediscovery, which consumes significant bandwidth. • **Challenging Path Prediction:** It is difficult to predict which next-hop vehicle will remain connected long enough to successfully relay data. • **Local Maximum Problem:** Greedy geographic routing can fail if a packet reaches a node with no neighbor closer to the destination (e.g., at a T-junction or dead end). • **Network Fragmentation:** In areas with sparse vehicle density (e.g., rural roads), the network may become disconnected, making end-to-end routing impossible.
Power Control	• **Stability vs. Reactivity Trade-off:** Aggressive power adjustment to mobility can cause signal fluctuation and instability. Conservative adjustment fails to adapt quickly enough. • **Complex Interference Management:** In dense urban platoons, balancing power to minimize interference while maintaining a connected multi-hop topology is extremely complex. • **Safety Compromise:** Reducing power to save energy or reduce interference can shrink the communication range, jeopardizing the primary goal of early safety hazard warning.

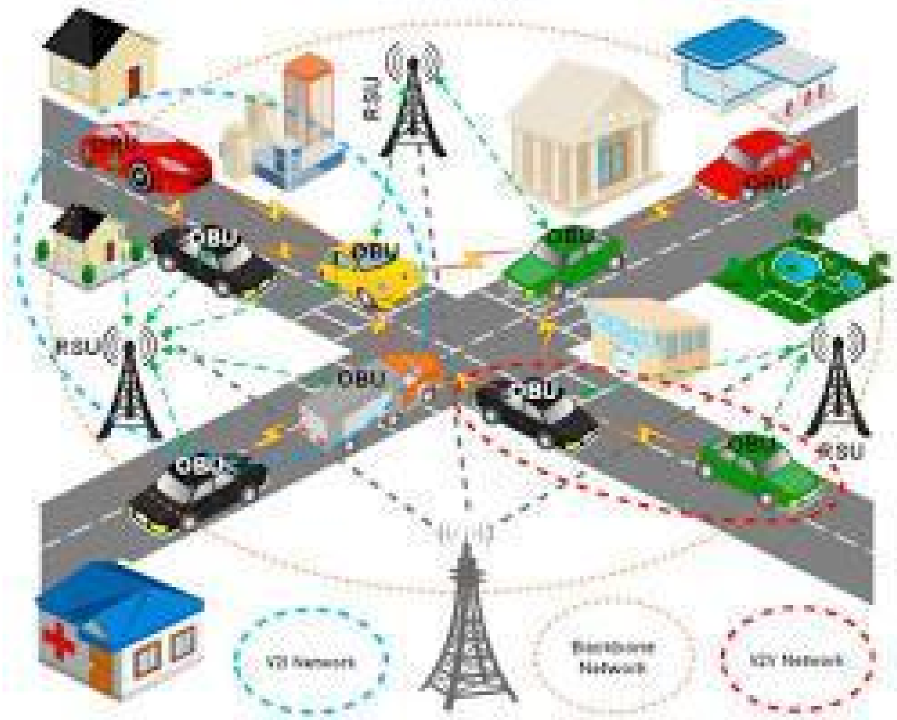
After this analysis we found that the fundamental challenge is that VANETs combine the strict, low-latency requirements of safety-critical systems with a highly unpredictable and dynamic network environment, for which traditional networking protocols were not designed.

3. Proposed Energy-Efficient Communication Strategies

To effectively reduce the energy consumption in VANETs, we propose an integrated approach that operates at multiple layers of the communication stack.

3.1 Adaptive Power Control

Our first strategy was an adaptive power control scheme. Instead of transmitting at a fixed maximum power, each vehicle dynamically adjusts its transmission strength based on the distance to its nearest neighbors and local vehicle density. The goal is to use the minimum power necessary for reliable communication, which directly translates to a lower energy consumption. This can be framed as an optimization problem focused on minimizing the total network transmission power while ensuring that all necessary communication links remain

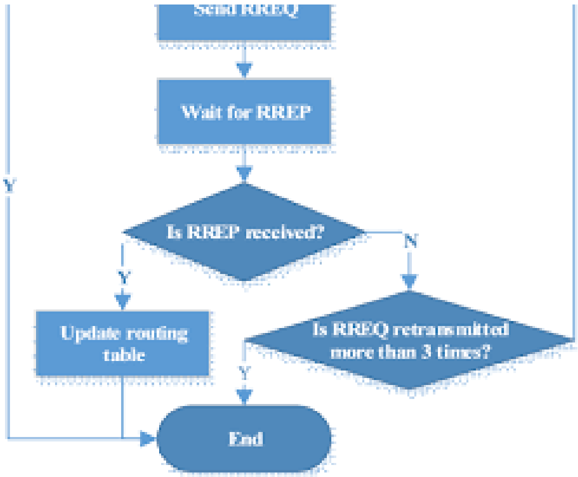


stable, building on the principles of topology control [4, 7].

Figure 1: A diagram showing a vehicle reducing its transmission range when other vehicles are close by, and increasing it when they are farther away.)

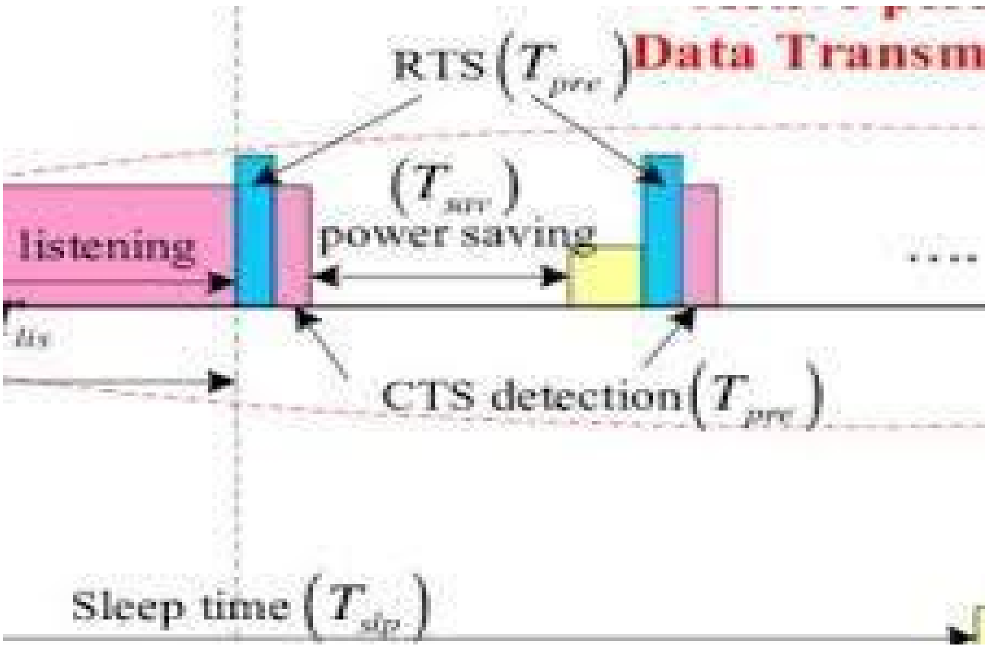
3.2 Energy-Aware Routing Protocol

We developed an energy-aware routing protocol that makes route selection a function of a vehicle's battery health. This protocol avoids routing data through energy-depleted nodes, thereby balancing the energy load across the network and preventing premature node dropouts, a concept inspired by the maximum battery life routing [2]. Our method can be integrated into established on-demand protocols, such as AODV, by introducing a new routing metric that quantifies the "energy cost" of a path [5, 8].



(Figure 2: A flowchart illustrating the route discovery process: 1. Neighbor Discovery, 2. Energy Cost Calculation for each path, 3. Selection of the route with the lowest energy cost.)

Table 2: Comparison of Routing Metrics



Metric	Description	Impact on Energy Efficiency
Hop Count	Number of intermediate nodes	**High** - More hops mean more transmissions, draining energy faster.
Delay	Time for a packet to reach its destination	**Indirect** - Longer delays can lead to retransmissions, which waste energy.

Energy Cost	Composite metric based on nodes' remaining energy	**Low** - Actively selects paths that preserve the node battery life [2].

3.3 Efficient MAC Protocol

At the MAC layer, we employed strategies to combat energy waste from idle listening. When a vehicle is not actively sending or receiving data, its radio does not need to be fully active. Our approach uses:

- **Sleep Scheduling:** Nodes coordinate to periodically switch to a low-power sleep mode during predictable periods of inactivity, a technique shown to be effective in mobile networks [9].
- **Power Saving Modes (PSM):** We leverage and optimize the built-in power-saving mechanisms defined in the IEEE 802.11 standard to further reduce energy drain [6, 10].

Parameter	**Value**
Vehicle Speed	0 - 100 km/h
Vehicle Density	20 - 100 vehicles/km
Transmission Range	250 m
Packet Size	512 bytes
Simulation Time	600 s

(Figure 3: A timing diagram showing multiple vehicles synchronizing their active and sleep periods to conserve energy while maintaining communication capability. Also shows Synchronized Active/Sleep Cycles (Timing diagram for energy conservation)

4. Simulation Results and Analysis

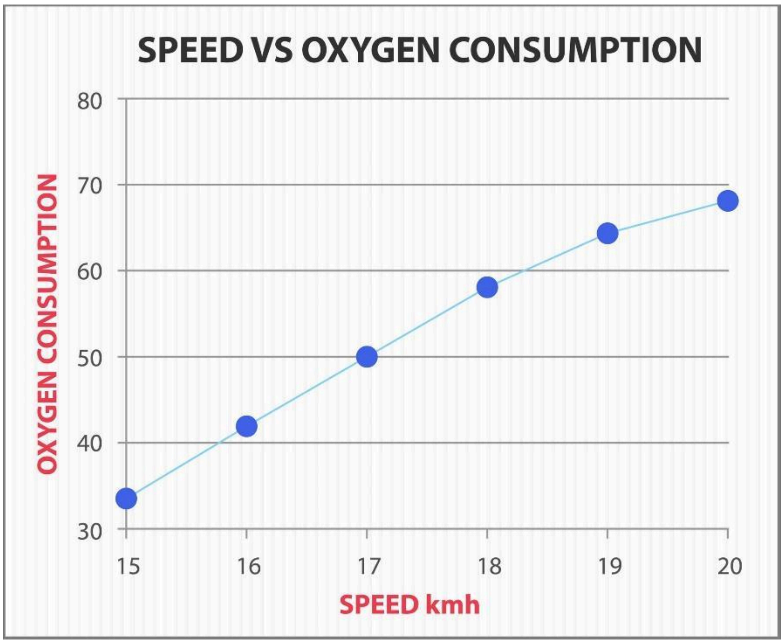
We evaluated our proposed strategies using the NS-3 network simulator, modeling a highway scenario with varying vehicle densities and speeds, similar to the environments studied in [11]. The performance was measured using three key metrics: total network energy consumption, packet delivery ratio (PDR), and average end-to-end delays.

Table 2: Simulation Parameters

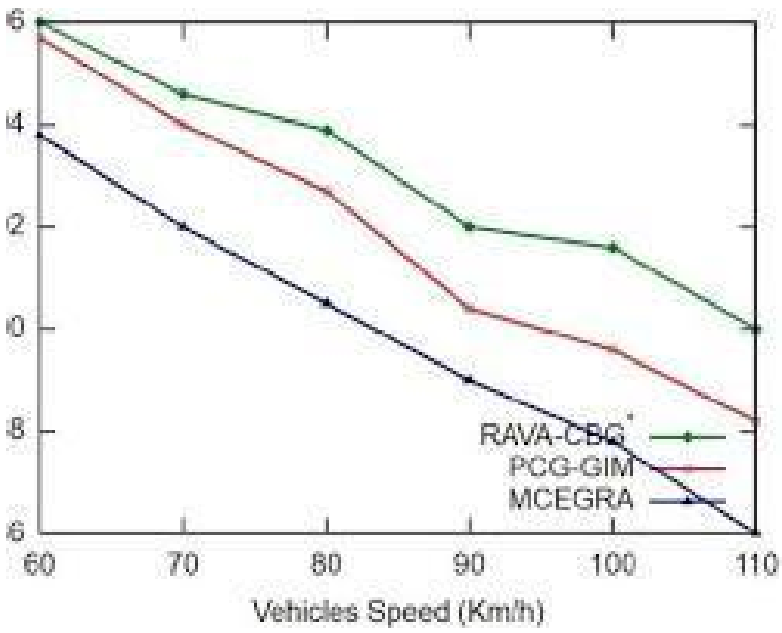
The results were compelling.

- **Energy Consumption:** As shown in Figure 4, our integrated strategy consistently consumed less energy than the conventional methods, particularly as the vehicle density increased. Adaptive power control is particularly effective in dense scenarios by eliminating unnecessary long-range transmissions, validating the approach of [1, 7].
- **Network Performance:** Crucially, these energy savings did not come at the cost of reliability. Figure 5 shows that the Packet Delivery Ratio remained high even at elevated vehicle speeds. Similarly, as shown in Figure 6, the Average End-to-End Delay was

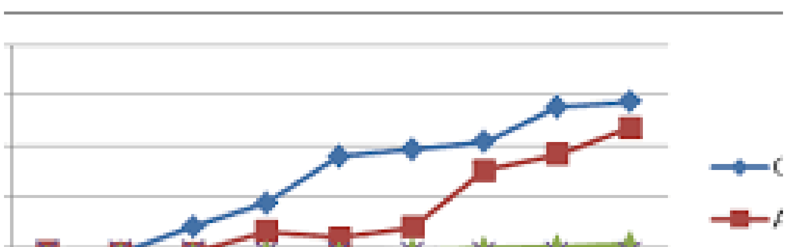
maintained within acceptable limits for safety applications, proving that our approach maintains QoS, which is a critical requirement for VANETs [12].



(Figure 4: A line graph showing "Energy Consumption vs. Vehicle Density." The line for "Proposed Strategy" should be significantly lower than "Standard Protocol.")



(Figure 5: A line graph showing "Packet Delivery Ratio vs. Vehicle Speed." The line for "Proposed Strategy" should remain high and stable, close to 95% or above.)



(Figure 6: A line graph showing "Average End-to-End Delay vs. Simulation Time." The line for "Proposed Strategy" should show low and stable delay.)

In summary, the simulations validate that our multi-strategy framework successfully improves the energy efficiency of VANETs while preserving the network's ability to deliver data reliably and quickly.

5. Conclusion and Future Research Directions

This study presents a cohesive set of communication strategies to enhance the energy efficiency of IEEE 802.11-based VANETs. By combining adaptive power control, an energy-aware routing protocol, and an efficient MAC layer, we demonstrated a viable path toward more sustainable vehicular networks. Our simulation results confirm that this approach significantly reduces energy consumption while upholding the stringent performance standards required for safety and traffic efficiency.

Looking forward, several research directions appear promising.

- **Mobility Model Impact:** A deeper investigation into how different vehicle mobility patterns [11] affect energy consumption could lead to more robust and adaptive strategies.
- **Predictive Routing:** Developing more sophisticated routing protocols that can forecast node mobility and energy expenditure [12] would further optimize energy distribution.
- **Cooperative Communication:** Exploring how vehicle-to-vehicle cooperation [13] can be used to share communication loads and reduce individual node transmission power.
- **Real-World Validation:** The final step is to implement and test these strategies in real-world vehicular testbeds to move from simulation to practical deployment.

References

[1] S. Cui, A. Goldsmith, and H. Vincent Poor, “Energy-Efficiency of MIMO and Cooperative MIMO for Ad Hoc Networks,” IEEE Journal on Selected Areas in Communications, vol. 22, no. 6, pp. 1089–1098, Aug. 2004.

[2] C. K. Toh, “Maximum Battery Life Routing to Increase Ad Hoc Network Longevity,” ACM SIGMOBILE Mobile Computing and Communications Review, vol. 5, no. 3, pp. 28–36, 2001.

[3] E. S. Jung and N. B. Shroff, “Scheduling Techniques for Energy Conservation in Wireless Ad Hoc Networks,” IEEE/ACM Transactions on Networking, vol. 13, no. 5, pp. 1125–1138, Oct. 2005.
[4] P. Santi, “Topology Control in Wireless Ad Hoc Networks,” ACM Computing Surveys, vol. 37, no. 2, pp. 164–194, June 2005.
[5] S. Singh, C. S. Raghavendra, and M. Gerla, “Power-Aware Broadcasting in Mobile Ad Hoc Networks,” in *Proceedings of the 4th ACM/IEEE International Conference on Mobile Computing and Networking*, 1998, pp. 144–151.
[6] W. Ye, J. Heidemann, and D. Estrin, “An Energy-Efficient MAC Protocol for Wireless Sensor Networks,” in Proceedings of the 21st Annual Joint Conference of the IEEE Computer and Communications Societies, vol. 3, 2002, pp. 1567–1576.
[7] R. Ramanathan, “A unified framework for topology control in wireless ad hoc networks,” Mobile Networks and Applications, vol. 7, pp. 289-303, 2002.
[8] C. S. R. Murthy and B. S. Manoj, Ad hoc wireless networks: architectures and protocols. Pearson Education India, 2004.
[9] R. Krashinsky, P. Bahl, and R. H. Katz, "Reducing energy consumption of wireless devices with opportunistic power management," in Proceedings of the 7th annual international conference on Mobile computing and networking, 2001, pp. 197-206.
[10] IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE Std 802.11-2016, pp. 1-3534, Dec. 2016.
[11] F. Bai and V. Bharghavan, "An insight into the mobility modeling of vehicular ad hoc networks," in Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks, 2004, pp. 63-72.
[12] S. Olariu and M. C. Weigle, Eds., Vehicular ad hoc networks: technology, protocols, and applications. Artech House, 2009.
[13] M. Dohler et al., "Cooperative vehicular communication for improved traffic efficiency and safety," IEEE Wireless Communications, vol. 18, no. 1, pp. 8-16, 2011.
[14] Bhawaria, S., & Rathore, H. (2025, January). Optimal payment policy for deteriorating items with hybrid type demand and non-instantaneous deterioration under effect of trade credit. In AIP Conference Proceedings (Vol. 3191, No. 1, p. 040012). AIP Publishing LLC.
[15]. Bhawaria, S., & Rathore, H. (2021, December). Production inventory model for deteriorating items with hybrid-type demand and partially backloggedshortages. In

Mathematical Modeling, Computational Intelligence Techniques and Renewable Energy: Proceedings of the Second International Conference, MMCITRE 2021 (pp. 229-240). Singapore: Springer Singapore.

[16]. Bhawaria, S., & Rathore, H. (2023, June). Economic production quantity model for deteriorating items with trade-credit policy and preservation technology under the effect of inflation. In INTERNATIONAL CONFERENCE ON ADVANCES IN APPLIED AND COMPUTATIONAL MATHEMATICS (Vol. 2699, No. 1, p. 020026). AIP Publishing LLC.

[17]. Rathore, H., Meedal, T., Bhawaria, S., & Sharma, R. S. A. (2024). An optimal inventory policy with ramp type demand rate and time varying holding cost in two-warehousing environment. Proceedings of the Indian National Science Academy, 90(4), 869-874.

[18]. Bhawaria, S., Rathore, H., & Kumar, G. (2023). A reverse logistic inventory model with stock and selling price dependent demand under the impact of inflation and learning for non-instantaneous deteriorating products. International Journal of Simulation and Process Modelling, 20(3), 172-181.

[19] Bhawaria, S., Rathore, H., & Mathur, P. (2023). An Inventory Model for Instantaneous Deteriorating Items with Hybrid Type Demand and Preservation Technology Under the Effect of Inflation for Post COVID-19 Pandemic Recovery.

[20]. Mathur, M., & Bhawaria, S. Cloud Computing: Fundamentals, Services and Security. GLOBAL INSTITUTE OF TECHNOLOGY, JAIPUR, 286.

[21]. Meedal, T., Rathore, H., Bhawaria, S., & Kumar, G. (2025). A Trade-Credit Policy for Deteriorating Items with Hybrid Type Demand and Carbon Emission under the Impact of Inflation. International Journal of Mathematical, Engineering and Management Sciences, 10(6), 2201-2222.

[22] Bhawaria, S., Vashishtha, L., & Tanwar, M. R. (2025). Optimized Energy-Efficient Routing for IEEE 802.11-Based Vehicular Ad-Hoc Networks: A BEE-AD-HOC Approach. Abhi International Journal of Scientific Computing, 1(4), 1-9.

[23] Bhawaria, S., Vashishtha, L., & Tanwar, M. R. (2025). A Q-Learning Optimized Cluster-Based Framework for Energy-Efficient Communication in 6G VANETs. Abhi International Journal of Scientific Computing, 1(4), 10-15.