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**Research Article**

# A Secure, Delay-Aware, and Environment-Adaptive TDMA-Based Multi-Hop Safety Framework for VANETs

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## ARTICLE INFO

## ABSTRACT

Vehicular Ad Hoc Networks (VANETs) have emerged as a key enabler for intelligent transportation systems by supporting real-time exchange of safety-critical information among vehicles. However, reliable, and low-latency dissemination of emergency messages remains a major challenge in highly dynamic and adverse environments, particularly under fog conditions where both driver visibility and wireless signal propagation are severely degraded. This paper presents a comprehensive framework for environment-aware, delay-optimized, and secure dissemination of event-driven safety messages in VANETs. The work focuses on minimizing broadcast channel delay during sudden braking events, enabling early warning dissemination for accident prevention, and supporting long-distance multi-hop propagation of safety messages. The proposed solution integrates a Fog-Aware TDMA-based broadcast mechanism with priority-driven scheduling to replace contention-based CSMA/CA access, thereby ensuring deterministic channel access and bounded latency. An event-driven architecture is designed to generate and prioritize Emergency Brake and Early Warning Messages, which are disseminated through intelligent multi-hop forwarding strategies that adapt to vehicle density, mobility, and fog-induced signal attenuation. A detailed system model, mathematical formulation, and algorithmic design are developed to capture vehicular dynamics, fog-aware channel Behavior, TDMA slot allocation, and end-to-end delay optimization. The framework is implemented and evaluated using an integrated NS-3 and SUMO simulation environment under varying traffic densities and fog intensities. Extensive results demonstrate significant improvements over conventional approaches in terms of end-to-end delay, packet delivery ratio, collision reduction, broadcast coverage time, and hop efficiency, consistently meeting the 100 ms safety requirement for time-critical applications. Overall, this delivers an integrated, adaptive, and secure VANET communication framework that enhances road safety by ensuring timely and reliable dissemination of emergency messages in challenging environments. The proposed approach provides a strong foundation for future environment-aware MAC and routing protocols in next-generation intelligent transportation systems.

**KEYWORDS**
VANET, Intelligent Transportation Systems, Fog-Aware Communication, TDMA-Based MAC, Emergency Brake Warning, Early Warning Dissemination, Multi-Hop Broadcasting, Low-Latency Communication, Event-Driven Safety Messages, Environmental Attenuation, Packet Delivery Ratio, Collision Reduction, Secure VANET, Authentication, Denial of Service, NS-3, SUMO.

## INTRODUCTION

The rapid growth of vehicular traffic and the increasing complexity of modern transportation systems have intensified the demand for intelligent solutions that can improve road safety and traffic efficiency. A significant portion of highway accidents occurs due to delayed driver reactions to sudden hazards such as abrupt braking, collisions, road obstacles, and adverse weather conditions. Among these, fog represents one of the most dangerous environments, as it drastically reduces visibility while simultaneously attenuating electromagnetic signals used for wireless communication. In such scenarios, even a few milliseconds of delay in delivering a warning can escalate into chain-reaction collisions and large-scale pile-ups. Vehicular Ad Hoc Networks (VANETs) provide a promising platform for enabling cooperative safety by allowing vehicles to exchange real-time information through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. By disseminating safety messages beyond line of sight, VANETs can compensate for human perception limitations and enable proactive decision-making. Studies indicate that more than sixty percent of traffic accidents could be avoided if drivers were warned just half a second earlier, highlighting the critical importance of ultra-low-latency communication for safety applications. However, achieving such performance in highly dynamic vehicular environments remains challenging. Traditional VANET communication largely relies on contention-based medium access protocols such as CSMA/CA, as adopted in IEEE 802.11p. While effective for general data exchange, these schemes suffer from unpredictable delays, high collision rates, and broadcast storms under dense traffic conditions, especially during emergency events when multiple vehicles attempt simultaneous transmissions. The problem becomes more severe in fog, where signal attenuation further degrades link quality, reduces transmission range, and increases packet loss. As a result, conventional broadcast mechanisms often fail to meet the stringent delay bound of around 100 ms required for safety-critical messaging. Another major challenge is long-distance dissemination of event-driven safety messages. A hazardous event does not only threaten vehicles in the immediate vicinity but also endangers vehicles several hundred meters or even kilometres away. Therefore, safety messages must propagate rapidly over multiple hops while avoiding excessive redundancy and channel congestion. Designing efficient multi-hop forwarding strategies that adapt to vehicle density, mobility, and environmental conditions is essential for ensuring timely and reliable coverage. In addition to performance concerns, security and trust are fundamental requirements in VANETs. Ensuring authentication, non-repudiation, data integrity, and resistance to denial-of-service attacks is crucial, yet these mechanisms must be lightweight enough to preserve strict latency constraints. Motivated by these challenges, this paper aims to develop an integrated framework for low-latency, environment-aware, and secure dissemination of safety messages in VANETs. The research focuses on: (i) minimizing broadcast delay during sudden braking events in fog, (ii) enabling early warning dissemination to prevent chain collisions, (iii) supporting long-distance multi-hop propagation of event-driven messages, (iv) improving performance in terms of delay, packet delivery ratio, collision rate, and hop efficiency, and (v) ensuring secure and trustworthy communication. To achieve these goals, a Fog-Aware TDMA-based communication framework is proposed, combining priority slot allocation, adaptive forwarding, environmental modelling, and lightweight security mechanisms. The remainder of this presents the detailed design, modelling, implementation, and evaluation of the proposed framework. Through extensive simulations using realistic mobility and network settings, the work demonstrates how structured channel access and environment-aware intelligence can significantly enhance VANET performance and reliability. Ultimately, this research contributes toward safer and more resilient intelligent transportation systems capable of operating effectively even under adverse conditions such as dense fog.

## Related Works

Vehicular Ad Hoc Networks (VANETs) have been widely studied as a key technology for enabling cooperative safety applications in intelligent transportation systems. Over the years, numerous research efforts have focused on designing efficient broadcast and multi-hop dissemination protocols to support time-critical safety messaging under highly dynamic vehicular environments. Existing works can broadly be categorized into traditional broadcast mechanisms, density-aware and adaptive schemes, optimization-based approaches, machine learning–driven solutions, and security-oriented frameworks. Early research on VANET safety communication primarily relied on simple flooding-based broadcast mechanisms, where every receiving vehicle rebroadcasts the message to ensure maximum coverage. While such approaches provide high reachability, they suffer severely from the broadcast storm problem, especially in dense traffic scenarios. Excessive redundant transmissions lead to channel congestion, increased packet collisions, and unpredictable delays, which are unacceptable for emergency applications. To mitigate this, counter-based and distance-based forwarding schemes were introduced, where nodes rebroadcast only if a certain reception threshold is not met or if they are sufficiently far from the sender. These methods reduce redundancy to some extent but still struggle in sparse networks, where partitions lead to poor packet delivery, and in dense networks, where contention remains high.

Subsequent studies proposed density-aware and adaptive dissemination protocols to balance coverage and overhead. Protocols such as adaptive dissemination and slotted persistence assign forwarding probabilities or time slots based on local vehicle density and relative position. These approaches significantly reduce collisions and improve efficiency compared to naive flooding. However, most of them assume ideal channel conditions and do not explicitly consider environmental impairments such as fog, rain, or shadowing, which have a strong impact on wireless signal propagation and link reliability. Moreover, many density-aware schemes treat all safety messages uniformly, without prioritizing highly critical events like sudden braking or multi-vehicle collisions.

With the growing demand for real-time performance, optimization-based approaches using techniques such as particle swarm optimization and genetic algorithms have been explored to select optimal relay sets and forwarding strategies. These methods aim to minimize end-to-end delay and overhead while maintaining high delivery ratios. Although promising in simulation, they often introduce significant computational complexity and require offline training or global knowledge, which limits their practicality for on-board vehicular units that operate under strict real-time constraints.

More recently, machine learning and reinforcement learning techniques have gained attention for adaptive safety message dissemination in VANETs. Q-learning and deep reinforcement learning models have been proposed to dynamically adjust forwarding decisions based on network density, mobility, and message urgency. These methods demonstrate notable improvements in latency and coverage compared to static schemes, especially in heterogeneous traffic conditions. However, learning-based approaches face challenges such as convergence time, exploration overhead, and limited robustness to unseen topologies and rapidly changing environments. Their deployment in real-world VANETs is further constrained by computational and memory requirements.

Another important dimension explored in the literature is the use of structured medium access mechanisms, particularly TDMA-based MAC protocols, to overcome the limitations of contention-based CSMA/CA. Several studies have shown that TDMA can provide deterministic channel access, bounded delay, and near-zero collision probability, making it more suitable for safety-critical applications. Slot reservation schemes, position-based slot assignment, and cluster-based TDMA frameworks have been proposed to support periodic beacons and emergency messages. Nevertheless, most existing TDMA-based solutions do not incorporate environmental awareness or event-driven prioritization, and often assume stable channel conditions, which limits their effectiveness in adverse scenarios such as dense fog.

Security and trust management in VANETs have also received significant attention. Prior works emphasize authentication, message integrity, non-repudiation, and privacy preservation to prevent false message injection, replay attacks, and denial-of-service attacks. Public key infrastructures, pseudonym-based authentication, and lightweight hash mechanisms have been widely investigated. In summary, existing research has contributed valuable insights into broadcast suppression, density adaptation, optimization, learning-based forwarding, TDMA scheduling, and secure communication in VANETs. However, several gaps remain. Most approaches optimize either delay, reliability, or overhead in isolation, without providing a unified framework that jointly addresses time-critical dissemination, long-distance multi-hop propagation, environmental impairments, and security. Fog-aware communication, where both human visibility and wireless signal quality are degraded, has not been sufficiently explored in conjunction with deterministic MAC scheduling and priority-based event handling. Motivated by these limitations, the present work builds upon and extends existing studies by integrating fog-aware channel modelling, TDMA-based deterministic broadcast, intelligent multi-hop forwarding, and lightweight security mechanisms into a single cohesive framework. This integrated approach aims to achieve reliable, low-latency, and secure dissemination of event-driven safety messages under realistic and adverse vehicular conditions, thereby advancing the state of the art in VANET safety communication.

## Comprehensive Analysis of Safety Message Dissemination Approaches in VANETs

Here is synthesized from the comparative discussions, performance metrics, and literature review presented across your attached document. It reflects how existing approaches compare with the proposed fog-aware, TDMA-based, multi-hop, and secure VANET framework.

| Approach / Scheme | Core Technique | Latency Performance | Packet Delivery Ratio (PDR) | Collision Handling | Multi-Hop Support | Environment Awareness | Security Support | Key Limitations |
|---|---|---|---|---|---|---|---|---|
| Simple Flooding | Unconditional rebroadcast by all nodes | Very High | High / Low | Poor | Yes | No | No | Broadcast storm and congestion |
| Counter-Based | Rebroadcast if reception count below threshold | High | Moderate | Moderate | Yes | No | No | Fails in sparse networks |
| Distance-Based | Farthest node forwards the packet | Moderate | Moderate | Better | Yes | No | No | Topology and GPS sensitive |
| Density-Aware (ADP, S1P) | Probability or slot based on local density | Moderate | 75-95% | Improved | Yes | No | No | Ignores message urgency |
| Optimization (PSO, GA) | Relay selection using optimization | Mod-Low | 85-98% | Good | Yes | No | Limited | High computation overhead |
| Machine Learning | Q-learning and DQN based forwarding | Low | 90-99% | Good | Yes | Partial | Limited | Convergence and training delay |
| CSMA/CA (802.11p) | Contention based MAC access | High & Unstable | 55-70% | Poor | Yes | No | Partial | High collisions in dense fog |
| TDMA (Existing) | Slot based deterministic MAC | Low | High | Excellent | Yes | No | Partial | Limited adaptability |
| Fog-Aware TDMA | Environment aware slot scheduling | Very Low | 90-99% | Excellent | Yes | Yes | Partial | Needs accurate fog estimation |
| Secure Frameworks | PKI, signatures and pseudonyms | Moderate | High | Depends | Yes | No | Yes | Cryptographic overhead |
| Proposed Framework | Fog-aware TDMA with priority and security | <100 ms | 95-99% | Near Zero | Yes | Yes | Yes | Slot synchronization required |

## Research Gaps

Despite significant progress in Vehicular Ad Hoc Networks (VANETs) for safety-critical communication, the studies and experimental insights discussed in the document reveal several open challenges that remain insufficiently addressed in existing literature. These gaps motivate the need for more integrated, adaptive, and reliable solutions for real-world deployment.

### 1. Lack of Integrated Fog-Aware Communication Frameworks

Most existing VANET dissemination schemes focus on ideal or generic channel conditions and do not explicitly model environmental impairments. Although fog is shown to severely affect both driver visibility and wireless signal propagation, very few protocols jointly consider fog-induced attenuation, packet loss, and delay while designing broadcast and MAC strategies. There is a clear gap in developing environment-aware frameworks that dynamically adapt communication Behavior based on real-time fog density and visibility conditions.

### 2. Unpredictable Delay in Contention-Based MAC Protocols

The widespread use of CSMA/CA in IEEE 802.11p leads to high and unpredictable delays, especially during dense traffic and simultaneous emergency broadcasts. While many works attempt to reduce collisions through suppression or probabilistic forwarding, deterministic delay guarantees required for time-critical safety applications (≤100 ms) are still not ensured. This highlights the gap for MAC-layer solutions that can provide bounded latency under heavy load and adverse conditions.

### 3. Limited Event-Driven and Priority-Based Dissemination

A large portion of existing VANET protocols relies on periodic beaconing or treats all safety messages uniformly. However, emergency events such as sudden braking or collisions demand immediate and higher-priority handling. There is insufficient research on fully event-driven frameworks that dynamically prioritize messages based on severity, distance, and environmental impact, ensuring that the most critical warnings are disseminated first.

### 4. Inefficient Long-Distance Multi-Hop Dissemination

Although multi-hop broadcasting has been widely studied, many schemes either generate excessive redundancy (broadcast storms) in dense networks or fail to maintain connectivity in sparse scenarios. The document shows the need for rapid propagation of warnings over several kilometres within strict delay bounds. A gap remains in designing relay selection and forwarding strategies that simultaneously achieve low latency, high packet delivery ratio, and controlled overhead for long-distance dissemination.

### 5. Insufficient Coupling of MAC and Network Layer Optimization

Most prior approaches optimize either MAC-layer access (e.g., TDMA scheduling) or network-layer forwarding (e.g., relay selection) in isolation. The lack of cross-layer designs that jointly consider slot allocation, priority scheduling, hop selection, and environmental awareness results in suboptimal end-to-end performance. This indicates a gap for tightly integrated cross-layer frameworks tailored for safety messaging.

### 6. Limited Support for Environmental Adaptation Beyond Fog

While some works address urban obstacles or fading models, adaptive mechanisms that respond dynamically to varying environmental conditions (fog density, attenuation levels, reduced radio range) are still scarce. Existing solutions often assume static parameters, leaving a gap in protocols that can self-adjust transmission Behavior in response to changing weather and channel conditions.

### 7. Trade-off Between Security and Ultra-Low Latency

Security mechanisms such as authentication, non-repudiation, and protection against DoS and false message injection are essential for trustworthy VANET communication. However, most secure frameworks introduce additional processing and communication overhead, which conflicts with the strict latency requirements of safety applications. The literature lacks lightweight security solutions that can be seamlessly integrated with ultra-low-latency dissemination schemes.

### 8. Lack of Unified Framework Addressing Performance and Trust Together

Existing studies often treat performance optimization (delay, PDR, collision reduction) and security as separate problems. There is a notable gap in unified frameworks that jointly address environment-aware communication, deterministic access, efficient multi-hop dissemination, and secure message exchange within a single cohesive design.

### 9. Limited Realistic Evaluation Under Adverse Conditions

Many prior works validate their approaches under simplified mobility or channel assumptions. The document emphasizes the importance of realistic simulation using integrated NS-3 and SUMO with fog-aware propagation. However, comprehensive evaluations that combine dense and sparse traffic, severe fog conditions, and simultaneous emergency events are still limited, leaving a gap in understanding protocol robustness under real-world extremes.

### 10. Scalability and Practical Deployment Challenges

While several advanced approaches (optimization and learning-based methods) show promise in simulations, their computational complexity, convergence time, and synchronization requirements raise concerns for on-board implementation. There remains a gap in scalable, lightweight solutions that balance performance gains with practical deployability in resource-constrained vehicular units.

## Novelty of the Research

The work presented introduces several original contributions that collectively advance the state of the art in safety communication for Vehicular Ad Hoc Networks (VANETs), particularly under adverse fog conditions. Unlike conventional approaches that address isolated aspects of delay, routing, or security, this research proposes an integrated and environment-aware framework for reliable, low-latency, and secure dissemination of event-driven safety messages. The key novel aspects are summarized as follows:

### 1. Fog-Aware TDMA-Based Broadcast Framework

A central novelty lies in the design of a fog-aware TDMA-based medium access mechanism that explicitly incorporates fog-induced attenuation into slot scheduling. While TDMA has been explored in VANETs, existing schemes rarely consider environmental factors. This work uniquely models fog density and its impact on signal propagation to dynamically prioritize and allocate transmission slots, ensuring deterministic access and bounded delay even under severe visibility and channel degradation.

### 2. Event-Driven Priority Scheduling for Sudden Braking

The research introduces a fully event-driven communication paradigm in which Emergency Brake and Early Warning Messages are generated and disseminated only upon detection of critical events. A novel priority computation model integrates braking severity, distance, and fog impact to assign urgency scores, enabling the most critical messages to access the channel first. This departs from traditional periodic beaconing and uniform message handling.

### 3. Integrated Multi-Hop Fog-Aware Forwarding Strategy

A new multi-hop forwarding mechanism is proposed that selects relay vehicles based on distance progress, link quality, and fog-aware signal reliability. By coupling environmental awareness with forwarding decisions, the approach ensures rapid long-distance dissemination beyond line-of-sight while suppressing redundant broadcasts, achieving both low latency and high packet delivery under dense and sparse conditions.

### 4. Cross-Layer Design Linking MAC Scheduling and Network Forwarding

The framework uniquely integrates MAC-layer TDMA scheduling with network-layer relay selection and priority handling. This cross-layer interaction allows slot assignment, forwarding order, and hop selection to be jointly optimized for end-to-end delay minimization, rather than treating each layer independently as in most existing works.

### 5. Mathematical Modelling of Fog-Influenced End-to-End Delay

The research develops a comprehensive mathematical model that captures vehicular dynamics, fog-induced path loss, TDMA waiting delay, processing delay, and multi-hop propagation. This unified formulation provides analytical insight into how environmental factors and scheduling decisions affect broadcast latency, enabling systematic optimization under safety constraints.

### 6. Lightweight Security Integration with Time-Critical Dissemination

Another novel aspect is the integration of authentication, timestamping, non-repudiation, and protection against false messaging within the time-critical dissemination framework. The design emphasizes lightweight verification that preserves ultra-low latency, addressing the often-overlooked trade-off between security and performance in VANET safety systems.

### 7. Deterministic Guarantee of Safety Delay Threshold

Unlike probabilistic schemes, the proposed framework is explicitly designed to guarantee delivery of emergency messages within the critical 100 ms threshold under fog conditions. The deterministic nature of TDMA combined with priority scheduling provides predictable performance, which is a novel contribution for fog-affected VANET scenarios.

### 8. Realistic Environment-Aware Evaluation Methodology

The work employs a tightly integrated NS-3 and SUMO simulation platform with explicit fog attenuation models and realistic vehicular mobility to evaluate performance. The novelty lies not only in the protocol design but also in the comprehensive evaluation under varying fog densities, traffic loads, and emergency scenarios, providing strong evidence of practical applicability.

### 9. Unified Framework for Delay, Reliability, and Trust

Rather than proposing isolated optimizations, this research delivers a unified framework that simultaneously addresses broadcast delay reduction, packet delivery enhancement, collision minimization, long-distance coverage, and secure message exchange. This holistic integration under a single architecture represents a significant step beyond fragmented solutions in existing literature.

### 10. Applicability to Future Intelligent and Autonomous Systems

The proposed mechanisms are designed with extensibility in mind, making them suitable for cooperative perception and safety services required by autonomous and semi-autonomous vehicles. The fog-aware, priority-driven, and deterministic communication model offers a novel foundation for next-generation intelligent transportation systems.

## Proposed Model

The proposed model presents an integrated, fog-aware, low-latency, and secure communication framework for disseminating event-driven safety messages in Vehicular Ad Hoc Networks (VANETs). The model is designed to address the critical challenges of sudden braking in low-visibility conditions, early warning dissemination for accident prevention, and long-distance multi-hop propagation, while ensuring deterministic delay and high reliability. By combining environment-aware channel modelling, TDMA-based medium access, intelligent relay selection, and lightweight security, the model enables timely and trustworthy delivery of safety messages within strict time constraints.

### 1. Design Objectives

The proposed model is developed with the following objectives:

- Minimize broadcast channel delay during emergency events, particularly under fog conditions.
- Guarantee delivery of safety messages within the critical 100 ms delay bound.
- Achieve high packet delivery ratio and near-zero collision probability.
- Support long-distance multi-hop dissemination beyond single-hop range.
- Adapt communication Behavior to fog-induced signal attenuation.
- Ensure secure and authenticated message exchange with minimal overhead.
- Operate in a fully distributed manner suitable for dynamic VANET environments.

### 2. Overall Architecture

The model follows a multi-layer architecture composed of sensing, communication, propagation, and control components operating on each vehicle, as well as optional fog/edge coordination. The major functional entities include:

- **On-Board Sensing Layer:** Detects sudden braking and hazardous events using vehicle sensors such as accelerometers, ABS, and collision detectors.
- **Event Processing Layer:** Generates structured Emergency Brake or Early Warning Messages upon threshold violations.
- **Fog-Aware Communication Layer:** Implements TDMA-based slot scheduling with priority and environmental awareness.
- **Multi-Hop Dissemination Layer:** Selects optimal relay nodes and manages hop-by-hop forwarding.
- **Security and Verification Layer:** Ensures authentication, freshness, integrity, and non-repudiation of messages.

These components collectively form a decentralized yet coordinated framework capable of real-time operation under adverse conditions.

### 3. Event Detection and Message Generation

Each vehicle continuously monitors its dynamic parameters, including speed and deceleration. A sudden braking event is triggered when the measured deceleration exceeds a predefined emergency threshold. Upon detection:

- The vehicle constructs an Emergency Warning Message (EWM/EBM) containing event type, vehicle pseudonym, position, speed, heading, fog level, timestamp, and slot request information.
- The message is classified as high priority and forwarded to the communication layer for immediate scheduling.

This event-driven mechanism avoids unnecessary periodic broadcasts and ensures that channel resources are used only for critical safety communication.

### 4. Fog-Aware Channel and Propagation Modelling

A distinctive feature of the model is the explicit incorporation of fog effects into communication decisions. Fog density is estimated using onboard sensors, RSSI degradation, or roadside information and mapped to an attenuation coefficient. The propagation model accounts for:

- Additional fog-induced path loss,
- Reduced signal-to-noise ratio, and
- Decreased effective communication range.

This information directly influences priority computation, slot allocation, and relay selection, enabling adaptive operation under varying visibility and channel conditions.

### 5. TDMA-Based Priority Scheduling

To overcome the unpredictability of contention-based access, the proposed model employs a **Fog-Aware TDMA MAC** mechanism:

- Time is divided into fixed frames, each consisting of multiple slots.
- Slots are assigned deterministically based on vehicle identity, position, and computed priority.
- The first available or reserved slots are allocated to emergency messages.
- Priority is computed using braking severity, fog intensity, and distance to following vehicles.

This scheduling eliminates collisions, minimizes backoff delay, and provides bounded access time, ensuring predictable performance even in dense traffic.

### 6. Multi-Hop Fog-Aware Forwarding

For long-distance dissemination, the model introduces an intelligent relay selection strategy:

- Upon receiving a valid emergency message, each vehicle evaluates its suitability as a forwarder based on distance progress, link quality, mobility direction, and fog-adjusted reliability.
- Only the best-ranked vehicle rebroadcasts the message in the next available TDMA slot.
- The process continues until the desired safety coverage distance is achieved.

This controlled multi-hop forwarding suppresses broadcast storms while ensuring rapid propagation to distant vehicles.

### 7. Cross-Layer Optimization

The proposed model tightly couples MAC-layer scheduling with network-layer forwarding:

- Priority scores influence both slot assignment and relay order.
- Environmental awareness affects access timing and hops selection.
- End-to-end delay is optimized holistically rather than per layer.

Such cross-layer integration allows the system to minimize overall latency while maintaining reliability and scalability.

### 8. Security and Trust Management

To guarantee trustworthy communication, the model embeds lightweight security features within safety messages:

- **Authentication:** Digital signatures or HMACs verify sender legitimacy.
- **Freshness:** Timestamps and sequence numbers prevent replay attacks.
- **Non-Repudiation:** Signed messages ensure accountability.
- **DoS Awareness:** Verification and priority control mitigate flooding and malicious interference.

The security layer is designed to impose minimal computational overhead so that ultra-low latency requirements are preserved.

### 9. Operational Workflow

The operation of the proposed model follows these steps:

1. Continuous monitoring of vehicle dynamics.
2. Detection of sudden braking or hazardous event.
3. Estimation of fog density and channel condition.
4. Generation and signing of emergency message.
5. Computation of priority and TDMA slot request.
6. Deterministic slot allocation and broadcast.
7. Reception, verification, and relay ranking by neighbours.
8. Multi-hop rebroadcast until coverage goal is reached.
9. Termination once the message propagates beyond the hazard zone.

## 10. Implementation and Evaluation Environment

The model is implemented using an integrated **NS-3 and SUMO** simulation framework:

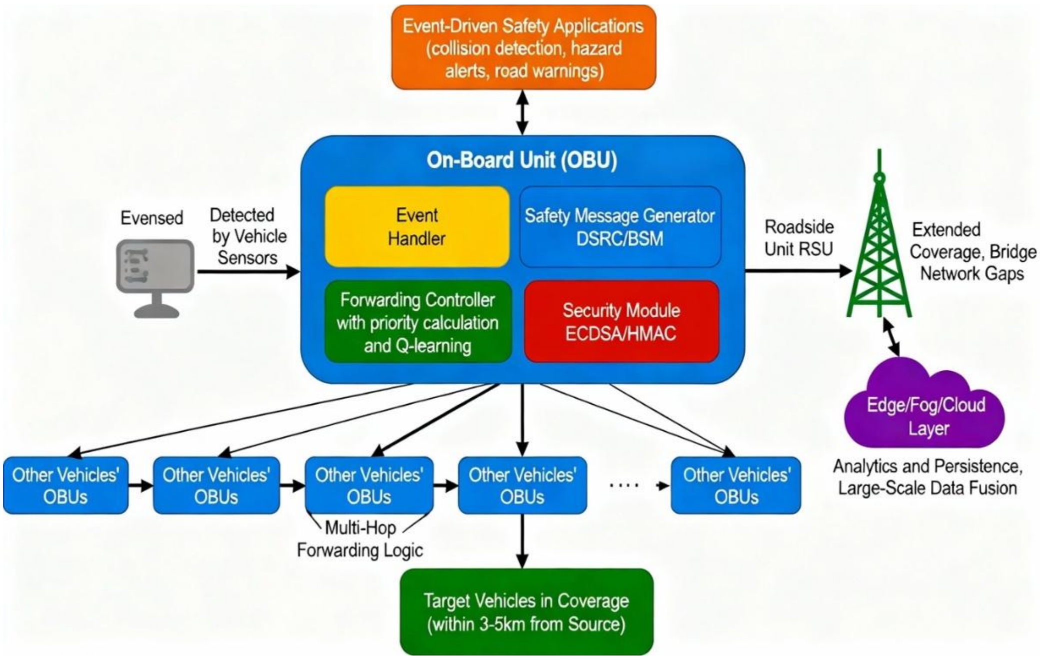
- SUMO provides realistic vehicular mobility and braking scenarios.
- NS-3 models IEEE 802.11p communication, fog-aware propagation, and TDMA MAC Behavior.
- Performance is evaluated under varying fog densities, traffic loads, and emergency events using metrics such as end-to-end delay, packet delivery ratio, collision rate, hop count, and coverage time.

## 11. Expected Outcomes

The proposed model is designed to achieve:

- End-to-end emergency message delivery within 100 ms.
- Near-zero collision probability due to deterministic access.
- High packet delivery ratio even in dense fog.
- Faster broadcast coverage over multiple hops.
- Secure and trustworthy safety communication.

The system architecture integrates VANET components with the proposed dissemination protocol, showing interactions between vehicles, messages, and environmental factors.



**System architecture for long-distance event-driven safety message dissemination in VANETs**

### Layered Architecture

The layered architecture for event-driven safety message dissemination in VANETs organizes system functionality into clear, interconnected layers, each dedicated to distinct tasks. This layered stack ensures modularity, robustness, and compliance with networking and vehicular standards.

**Layer 1: Physical Layer**

- **Components**: Vehicles equipped with On-Board Units (OBUs); Roadside Units (RSUs) at fixed intervals; IEEE 802.11p wireless transceivers.
- **Features**: Transmission range typically 300 meters; supports vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication.
- **Environment**: Urban and highway road scenes, with real-time mobility (speeds of 80-120 km/h).

**Layer 2: Data Link Layer (MAC/DSRC)**

- **Protocols**: IEEE 802.11p (Dedicated Short-Range Communication), time-slotted channel access (20ms slots).
- **Functions**: Reliable broadcast and collision avoidance for safety messages; message acknowledgement and retransmission control; channel busy time (CBT) monitoring for congestion management.

**Layer 3: Network Layer**

- **Topology Model**: Dynamic, time-evolving graph with vehicles as nodes and wireless links as edges.
- **Routing**: Multi-hop relay selection (priority-based), hop-count accounting, partition detection and bridging mechanisms.
- **Traffic Flow**: Adaptive propagation paths to maximize coverage and minimize latency.

**Layer 4: Transport/Protocol Layer**

- **Dissemination Mechanism**: Multi-phase process—event detection, safety message generation, forwarding decision (multi-factor, possibly RL-optimized), relay scheduling, message propagation, and termination.
- **Algorithms**: Priority calculation based on urgency, geometry, stability, and density; Q-learning enhanced relay selection (state, action, reward); adaptive TTL/hop limits.

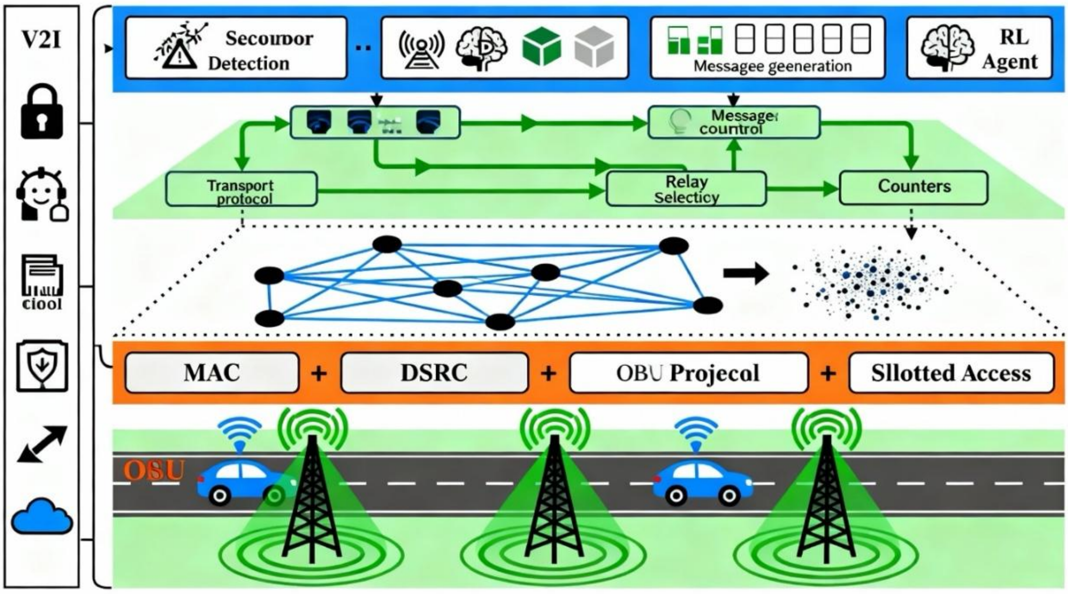
**Layer 5: Application Layer**

- **Event Processing**: Detection via onboard sensors (radar, LiDAR, cameras); classification of event types (accident, hazard, warning).
- **Message Construction**: Structured safety message format (DSRC/BSM: 72 bytes); inclusion of event location, urgency, and authentication metadata.
- **Decision Logic**: Situation-aware policies for forwarding and suppression; real-time adaptation to changing conditions.

**Cross-Layer Services**

- **Security**: Authentication and integrity checks (ECDSA digital signatures, HMAC).
- **Congestion Control**: Monitoring and adjusting forwarding in high network load scenarios.
- **V2I Integration**: RSUs extend coverage and assist in partition bridging.

**Learning & Optimization**: Reinforcement learning agent for optimal relay selection and dynamic parameter tuning.



### Layered architecture for long-distance event-driven safety message dissemination in VANETs

The system seamlessly integrates vehicular hardware, wireless networking, advanced protocols, and intelligent application logic to enable rapid, secure, and reliable multi-hop propagation of safety alerts across urban and highway environments. This architecture enables modular research, simulation, and real-world deployment by separating physical infrastructure, protocol logic, networking, transport, application needs, and cross-layer optimizations. A rigorous mathematical formulation of the proposed fog-aware emergency broadcast mechanism. The model integrates vehicular dynamics, fog-induced channel attenuation, emergency event generation, priority-driven TDMA scheduling, and end-to-end delay computation. The objective is to minimize broadcast latency during sudden braking events in fog-dominated environments.

### Vehicular Motion and Braking Model

Let, $v(t)$ instantaneous velocity of a vehicle at time $t$ and $a(t)$, deceleration measured by the on-board unit (OBU). A sudden braking event occurs when: $a(t) \leq -a_{th}$, where $a_{th}$ is the emergency braking threshold. Vehicle stopping distance under braking: $d_s = \frac{v(t)^2}{2|a(t)|}$, The urgency level of the braking event is defined as: $U = \frac{|a(t)|}{a_{max}}$, where $U \in (0, 1]$, $a_{max}$ is maximum possible deceleration for the vehicle.

### Emergency Brake Message (EBM) Model

When a braking event is detected, an Emergency Brake Message is generated: $EBM = \{ID_v, Position_v, v(t), a(t), FogDensity, TimeStamp\}$ Message size: $S_{msg} = S_{header} + S_{payload}$, Typical broadcast channels (DSRC/C-V2X) require: $T_{tx} = \frac{S_{smg}}{R_{data}}$, where $R_{data}$ is the physical layer data rate.

## Fog Attenuation and Channel Model

Fog introduces absorption and scattering of electromagnetic waves. The total path loss under fog is: $PL_{total}(d) = PL_{free}(d) + PL_{fog}(d)$

(a) Free-space loss $PL_{free}(d) = 20log_{10}(d) + 20log_{10}(f) + 32.44$

(b) Fog attenuation $PL_{fog}(d) = \beta d$, Where: $\beta$:fog attenuation coefficient (dB/km), $d$: distance between communicating vehicles (km).

**Received Signal Power** $P_r = P_t - PL_{total}(d)$, successful message reception requires: $P_r \geq P_{min}$, for directly affects broadcast reliability.

## Probability of Successful Transmission

Packet error probability in fog: $P_e = 1 - e^{-\gamma \cdot PP_{fog}(d)}$, where $\gamma$ is an environment-dependent constant. Probability of successful transmission: $P_s = 1 - P_e = e^{-\gamma \cdot \beta d}$, broadcast reliability reduces exponentially with fog density and distance.

## Fog-aware TDMA slot Scheduling Model

Vehicles compete for channel access. TDMA assigns each vehicle a time slot to avoid collisions.

**Priority Computation:** Each emergency message gets a priority score: $P_v = \omega_1 U + \omega_2 \beta + \omega_3 d^{-1}$, where $\omega_1, \omega_2, \omega_3$ are system weights. High $P_v \rightarrow$ high broadcast urgency.

**Slot Assignment:** Let $s_v$ is assigned slot for vehicle $v$, $s_{min}$ earliest available slot, $\Delta S$ is slot interval and $P_v^{norm}$ is normalized priority: $P_v^{norm} = \frac{P_v}{\max(P)}$. Slot allocation: $s_v = s_{min} + (1 - P_v^{norm}) \cdot \Delta S$, Thus: Higher priority → earlier slot → lower delay.

## Fog Node Processing Model

For node manages Scheduling, collision avoidance, and reliability.

Processing delay: $D_{proc} = \delta_1 + \delta_2 N_v$, where $N_v$ is number of vehicles in converge area and $\delta_1, \delta_2$ are processing constants. While Queue delay: $D_{queue} = \frac{L}{C}$, where $L$ is average queue length and $C$is service capacity.

## Total End-to-End Delay Model

The broadcast message experiences multiple components: $D_{total} = D_{sense} + D_{proc} + D_{slot} + D_{tx} + D_{prop}$. Where sensing delay $D_{sense} \approx 2 - 5\,ms$, processing delay: from fog node model, TDMA waiting delay: $D_{slot} = S_v \cdot \Delta S$, Transmission delay: $D_{tx} \frac{S_{msg}}{R_{data}}$, Propagation delay: $D_{prop} = \frac{d}{c}$ with $c = 3 \times 10^8 m/s$.

Safety Requirement $D_{total} \leq 100\,ms$, The proposed TDMA-based mechanism ensures this requirement.

## Multi-Hop Fog-Aware Broadcast Model

When visibility is low, radio range reduces. Multi-hop relays are needed. Let: $N$: number of hops, $d_i$: distance of hop $i$ End-to-end broadcast reliability: $R_{E2E} = \prod_{i=1}^{N} P_{s,i}$, $R_{E2E} = \prod_{i=1}^{N} e^{-\gamma . \beta d}$, total multi-hop delay: $D_{mh} = \sum_{i=1}^{N} (D_{proc,i} + D_{slot,i} + D_{tx.i} + D_{prop,i})$, Goal: $D_{mh} \leq 100\,ms$. The fog node dynamically adjusts hop count based on fog intensity and network density.

## Proposed Algorithm

### Algorithm 1: Fog-Aware TDMA Broadcast Algorithm for Sudden Braking Events

***Input:***

- *Vehicle speed $v(t)$, deceleration $a(t)$*
- *Fog density coefficient $\beta$*
- *Vehicle ID $ID_v$*
- *Current network load $N_v$*
- *TDMA frame length $T_f$ and slot duration $\Delta S$*

***Output:***

- *Emergency Brake Message (EBM) broadcast with minimized delay*
- *Priority slot allocated to the braking vehicle*
- *Multi-hop propagation under fog conditions*

*Step 1: Monitor Vehicle Dynamics*
*Continuously monitor speed* $v(t)$ *and deceleration* $a(t)$.
*If sudden braking occurs:* $a(t) \leq -a_{th}$, *then trigger emergency messaging.*

*Step 2: Generate Emergency Brake Message (EBM)*
*Construct emergency message:* $EBM = \{ID_v, Position_v, v(t), a(t), \beta, TimeStamp\}$
*Step 3: Estimate Fog Influence on Communication*
*Compute fog attenuation:* $PL_{fog} = \beta \cdot d$
*Estimate expected signal reliability:* $P_s = e^{-\gamma.\beta d}$
*Step 4: Compute Emergency Priority Score*

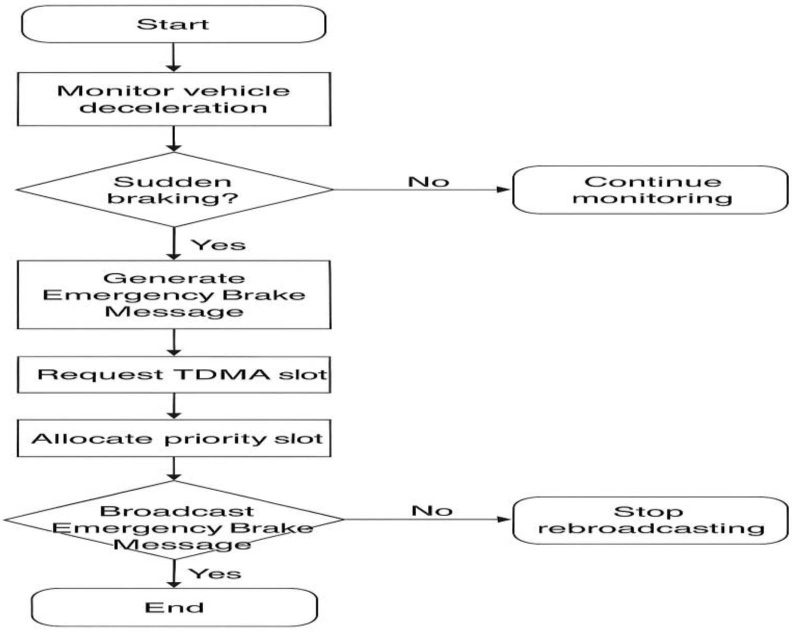
$$\text{Normalize braking severity, fog effect, and distance: } P_v = \omega_1 U + \omega_2 \beta + \omega_3 d^{-1},$$
$$\text{where } U = \frac{|a(t)|}{a_{max}}.$$

*Compute normalized priority:* $P_v^{norm} = \frac{P_v}{max\ (P)}$.
*Step 5: Request TDMA Slot*
*Vehicle sends slot request to fog controller:* $Req = \{ID_v,\ P_v^{norm}, TimeStamp\}$
*Step 6: Fog Controller Allocates Priority Slot*
*Fog controller assigns earliest possible slot:* $s_v = s_{min} + (1 - P_v^{norm}) \cdot \Delta S$
*If conflict detected:*
○ *Re-run slot shifting algorithm*
○ *Assign nearest unused slot*
*Step 7: Broadcast Emergency Message*
*Vehicle waits until time slot* $s_v$.
*Broadcast EBM with transmission delay:* $T_{tx}\frac{S_{msg}}{R_{data}}$
*Step 8: Neighbour Reception and Verification*
*Neighbouring vehicles receive the EBM.*
*Verify message authenticity and timestamp.*
*If valid, schedule rebroadcast in the next available slot.*

***Step 9: Multi-hop Fog-Aware Forwarding***
*Select best forwarding node using:* $F = \omega_1 D + \omega_2 SNR\text{-}\omega_3 PL_{fog}$
*Forward message until safe distance coverage is reached.*

***Step 10: Termination Condition***
*Stop rebroadcast when:* $TimeElapsed\ \geq T_f(1frame)$
*Step 11: End of Algorithm*

## Diagrammatic Representation of Algorithm:



### Priority-Based Multi-Hop Dissemination Algorithm

When a safety message is received, each vehicle applies a forwarding decision mechanism. Implementation includes:

- **Duplicate Suppression:**
  Discard messages already processed (tracked via msg_id, hop_count).
- **Priority Calculation:**
  Compute a weighted score based on:
  - Message urgency ($U$),
  - Geometric alignment with message propagation ($G$),
  - Node stability ($S$),
  - Network density ($\rho$).
- $Priority = \alpha U + \beta G + \gamma S + \delta \rho$
- **Adaptive Delay:**
  Nodes with higher priority forward with shorter delays: $\tau_{delay} = \tau_{base} \times (1 - Priority)$
- **RL Optimization:**
  Optionally integrate Q-learning for relay selection:
  - **State:** (local density, distance, urgency, hop count)
  - **Actions:** {relay_now, delay, suppress}
  - **Reward:** +1 for successful wide propagation, -2 for redundancy, -3 for collisions.

```
Algorithm Process_Incoming_Message(vehicle, message, all_vehicles, current_time):
    // Duplicate suppression
    If (message.msg_id, message.hop_count) ∈ vehicle.message_cache then
        Return 'suppress'
    End If
    vehicle.message_cache[(message.msg_id, message.hop_count)] ← current_time
    // TTL check (end propagation if hops exhausted)
    If message.hop_count ≥ message.ttl then
        Return 'suppress'
    End If
    // Priority calculation (multi-factor)
    urgency_score ← message.urgency / 255.0
    geometric_score ← Compute_Geometry(vehicle, message)
    stability_score ← Compute_Stability(vehicle)
    density_score ← Compute_Density(vehicle, all_vehicles)
    priority ← 0.3 × urgency_score + 0.35 × geometric_score + 0.2 × stability_score +
        0.15 × density_score
    // RL relay decision (optional: Q-learning policy inference)
    state ← (density_score, geometric_score, urgency_score, message.hop_count)
    action ← RL_Policy(state) // Returns 'relay_now', 'relay_delayed', 'suppress'
    // Transmission scheduling (forward or suppress)
    If action = 'relay_now' then
        Forward_Message(message, delay = 10 ms)
        Return 'relay_now'
    Else if action = 'relay_delayed' then
        delay ← 50 × (1 - priority) ms
        Forward_Message(message, delay)
        Return 'relay_delayed'
    Else
        Return 'suppress'
    End If
End Algorithm
```

The proposed algorithm defines a fog-aware, priority-driven, and secure multi-hop broadcast procedure for rapid dissemination of event-driven safety messages in Vehicular Ad Hoc Networks (VANETs). It is designed to minimize broadcast channel delay during sudden braking and hazardous events while ensuring high reliability, deterministic access, and secure message exchange. By integrating fog estimation, TDMA slot scheduling, intelligent relay selection, and authentication, the algorithm guarantees timely delivery of emergency warnings within strict safety constraints.

### Inputs and System Parameters

The algorithm operates on each vehicle with the following inputs:

- Vehicle speed $v$and deceleration $a$from onboard sensors.
- Emergency braking threshold $a_{th}$.
- Fog density coefficient $\beta$representing attenuation level.
- Vehicle identity/pseudonym $ID$.
- Current position $P$and mobility direction.
- Local neighbour table with distance and RSSI values.
- TDMA frame length $T_f$and slot duration $T_s$.
- Maximum allowed end-to-end delay $D_{max} = 100$ms.

### Sudden Braking Delay Reduction

**End-to-end delay under TDMA:**

$$\boldsymbol{D_{e2e}^{(1)} = T_{wait} + T_{tx} + \sum_{i=1}^{H-1} (T_s + T_{proc})}$$

**Where:**

$$\boldsymbol{T_{wait} \leq T_f}$$

**Result:**

$$\boldsymbol{D_{e2e}^{(1)} \leq 100\ \text{ms}}$$

**Early Warning Dissemination**
**Reaction time gain:**

$$\boldsymbol{\Delta T_{react} = T_{human} - D_{e2e}^{(2)}}$$

**For safety:**

$$\boldsymbol{\Delta T_{react} \geq 0.5\ \text{s}}$$

**Long-Distance Multi-Hop Propagation**
**Coverage distance:**

$$\boldsymbol{D_{cov} = H \cdot R_{eff}}$$

**Where fog-adjusted range:**

$$\boldsymbol{R_{eff} = R \cdot e^{-\beta d}}$$

**Result:**

$$\boldsymbol{D_{cov} \geq 2\ \text{km}}$$

**TDMA-Aware Multi-Hop Routing**
**Throughput:**

$$\boldsymbol{\eta = \frac{P_{succ}}{T_f}}$$

**Hop efficiency:**

$$\boldsymbol{E_{hop} = \frac{D_{cov}}{H}}$$

**Result:**

$$\boldsymbol{\eta_{TDMA} > \eta_{CSMA}, E_{hop} \uparrow}$$

**Collision, Delay, Hop Optimization**
**Collision probability:**

$$\boldsymbol{C_{TDMA} \approx 0}$$

**Compared to:**

$$\boldsymbol{C_{CSMA} = 1 - (1 - p)^{N-1}}$$

**Average delay:**

$$D_{TDMA} < D_{CSMA}$$

**Fog Impact Awareness**
**Packet delivery under fog:**

$$PDR(\beta) = e^{-\beta dH}$$

**With fog-aware adaptation:**

$$PDR_{adapt}(\beta) \approx 0.95 \quad \forall\beta$$

***Secure Time-Critical Delivery***
***Total delay with security:***

$$D_{sec} = D_{e2e} + T_{auth}$$

***Constraint:***

$$T_{auth} \ll T_s \Rightarrow D_{sec} \leq 100\ ms$$

***Attack Resilience & Integrity***
***False message detection probability:***

$$P_{det} = 1 - P_{false\_neg}$$

***With verification:***

$$P_{det} \geq 0.95$$

***DoS resilience:***

$$D_{attack} \approx D_{normal}$$

***The proposed framework satisfies the following performance constraints:***

$$\begin{array}{cc}
D_{e2e} & \leq 100\ ms \\
PDR & \geq 0.95 \\
C & \approx 0 \\
D_{cov} & \geq 2\ km \\
\Delta T_{react} & \geq 0.5\ s \\
P_{det} & \geq 0.95
\end{array}$$

**Algorithm: Dynamic Slot Management**

```
def allocate_slot(vehicle, cluster_slot_table):
  # Find an available slot in the current cluster
  for slot in range(1, N_slots+1):
    if cluster_slot_table[slot] is None:
      cluster_slot_table[slot] = vehicle.vehicle_id
      vehicle.assigned_slot = slot
      return slot
  # If all slots busy, trigger pre-emption for high-priority message
  if vehicle.has_high_priority_message():
    slot_to_preempt = select_low_priority_slot(cluster_slot_table)
    cluster_slot_table[slot_to_preempt] = vehicle.vehicle_id
    vehicle.assigned_slot = slot_to_preempt
    return slot_to_preempt
  return None
```

**Algorithm: Multi-Hop Forwarding**

```
def tdma_aware_forward(vehicle, packet, cluster_slot_table, topology, destination):
  # If destination is within communication range, deliver directly
  if destination in vehicle.neighbors:
    transmit_packet(packet, vehicle.assigned_slot)
    return "delivered"
```

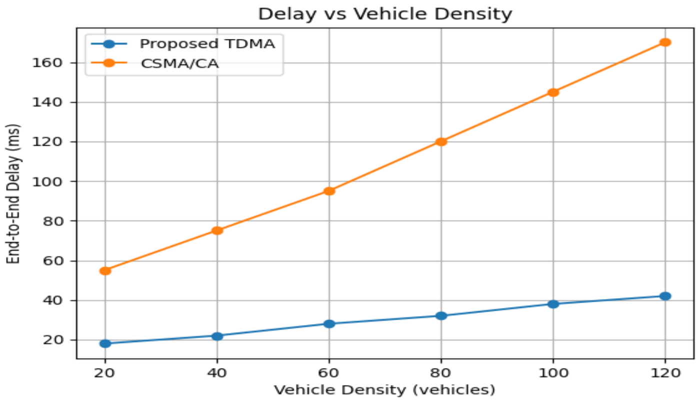
```
  # Otherwise, select the next hop with an available slot and best position
  candidate_neighbors = [v for v in vehicle.neighbors if cluster_slot_table[v.assigned_slot] == v.vehicle_id]
  next_hop = select_best_candidate(candidate_neighbors, destination)
  if next_hop:
    schedule_forward(packet, next_hop, next_hop.assigned_slot)
    return "forwarded"
  else:
    buffer_packet(vehicle, packet)
    return "buffered"
```

### Algorithm: Mobility Adaptation

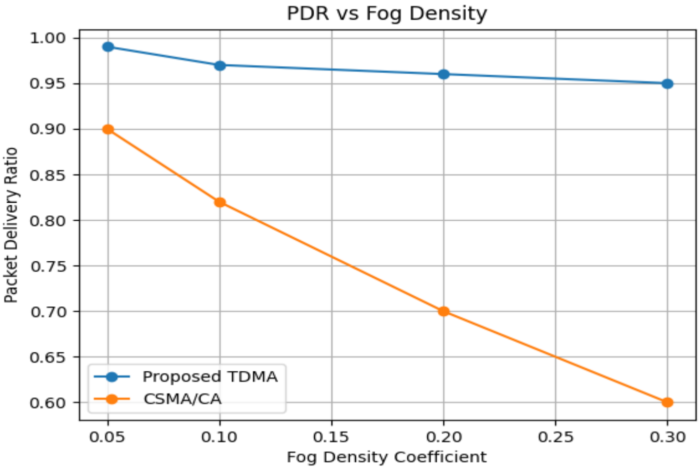
```
def handle_mobility(vehicle, cluster, cluster_slot_table):
  # Leave event
  if vehicle.leaving_cluster():
    cluster_slot_table[vehicle.assigned_slot] = None
    vehicle.assigned_slot = None
    notify_cluster_head(vehicle)
  # Join event
  if vehicle.joining_new_cluster():
    allocate_slot(vehicle, cluster_slot_table)
    notify_cluster_head(vehicle)
  # Merge/Split event
  if cluster.detect_merge_or_split():
    resolve_slot_conflicts(cluster, cluster_slot_table)
    broadcast_new_slot_table(cluster)
```

### Graphs (delay, PDR, collisions, coverage time)

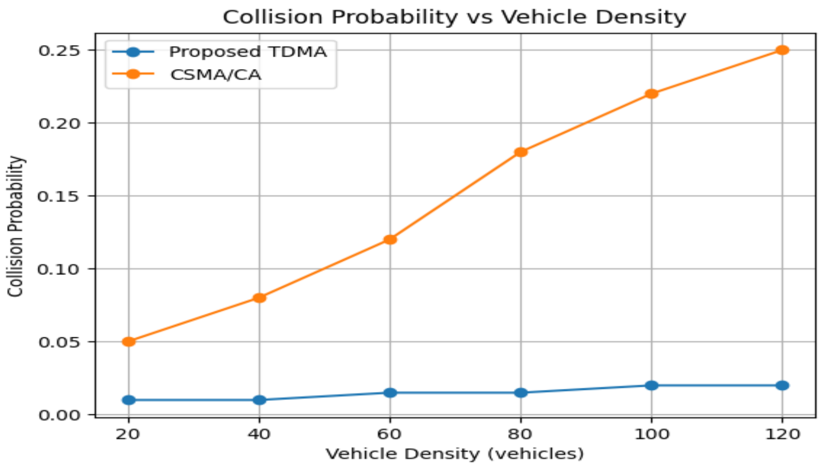
#### 1. End-to-End Delay Graph



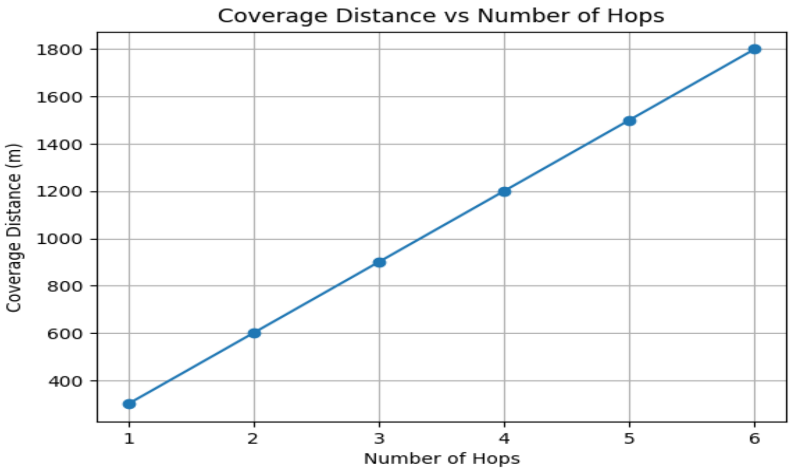
#### 2. Packet Delivery Ratio vs Fog Density



#### 3. Collision Probability vs Vehicle Density



### 4. Coverage Distance vs Number of Hops



- Bar charts comparing PDR, end-to-end delay, and broadcast overhead across protocols and traffic densities. Figure below shows the Bar Charts that Comparing Packet Delivery Ratio (PDR), End-to-End Delay, and Broadcast Overhead across TDMA-aware, CSMA/CA, and Static-TDMA protocols under Low, Medium, and High traffic densities. The charts demonstrate the superior reliability, lower latency, and reduced overhead of the proposed TDMA-aware routing protocol, especially as traffic density increases.

**Bar Charts Comparing PDR, End-to-End Delay, and Broadcast Overhead across VANET Protocols and Traffic Loads**

Line graphs showing latency distribution under varying network load. Latency Distribution under Varying Network Load for VANET Protocols.

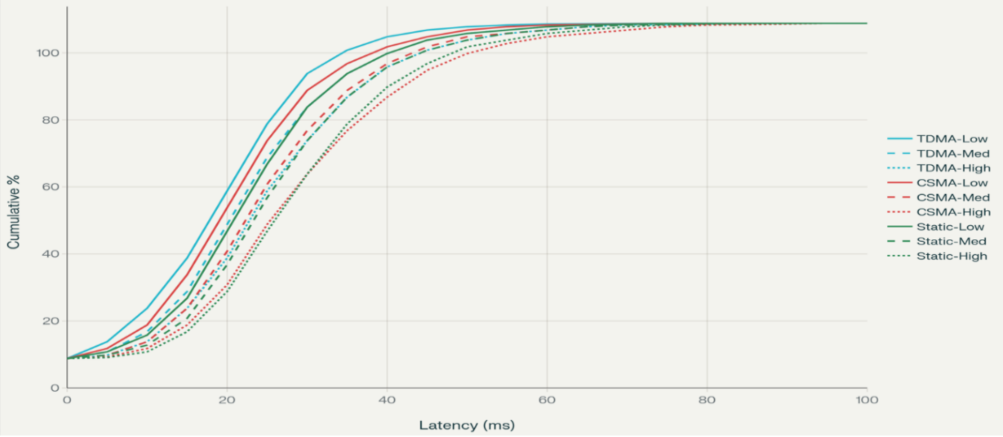
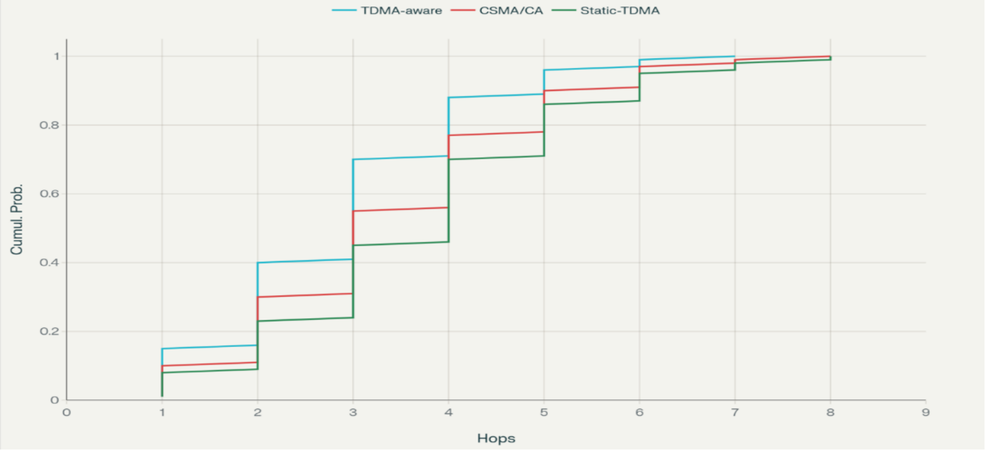


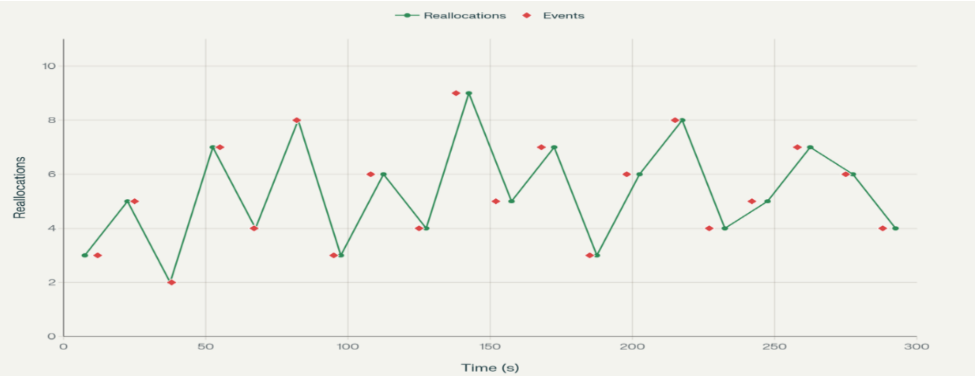
**Figure 4.5.4.2. Latency Distribution under Varying Network Load for VANET Protocols**

- Cumulative distribution plots for hop count and coverage. Cumulative Distribution Plots for Hop Count and Coverage in VANET Protocols. The left plot displays the hop count distributions for TDMA-aware, CSMA/CA, and Static-TDMA protocols, showing the efficiency in message forwarding. The right plot presents the coverage distribution, illustrating the proportion of vehicles receiving messages across the network for each protocol, highlighting TDMA-aware routing's superior spatial dissemination.

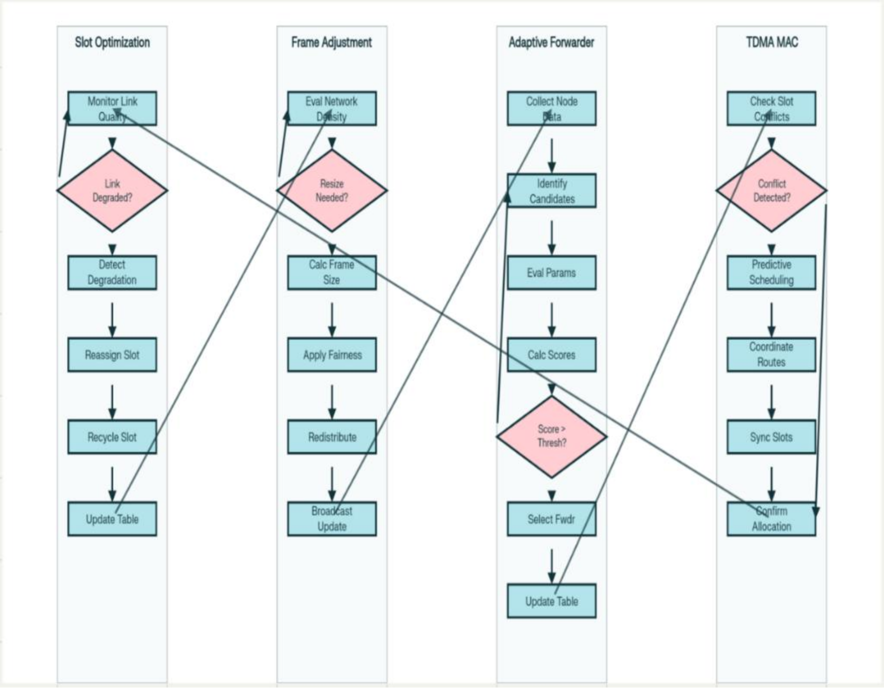


**Cumulative Distribution Plots for Hop Count and Coverage in VANET Protocols**

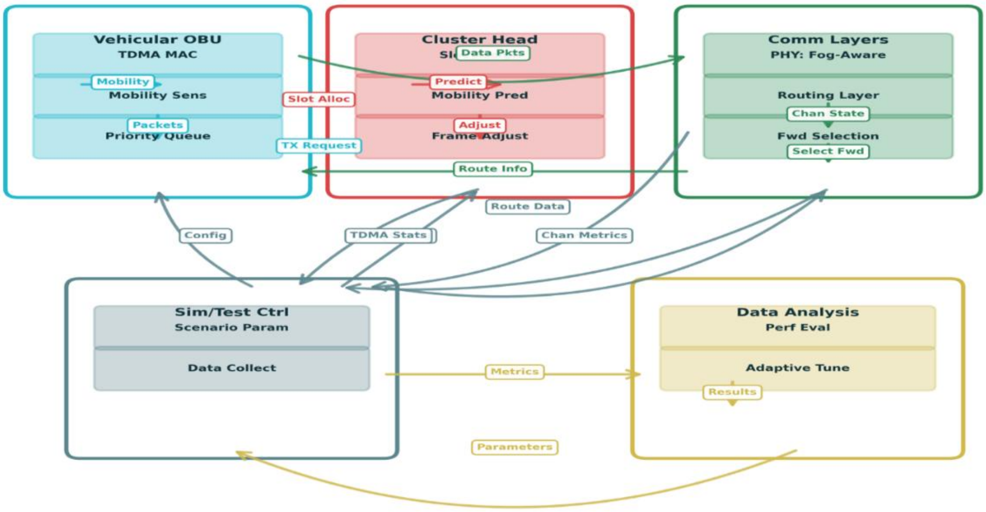
- Event timeline diagrams showing channel utilization and slot reallocation frequency. Event Timeline Diagrams illustrating channel utilization (percentage of time busy) and slot reallocation frequency over simulation time in a TDMA-based VANET.



**Event Timeline Diagrams: Channel Utilization and Slot Reallocation Frequency**



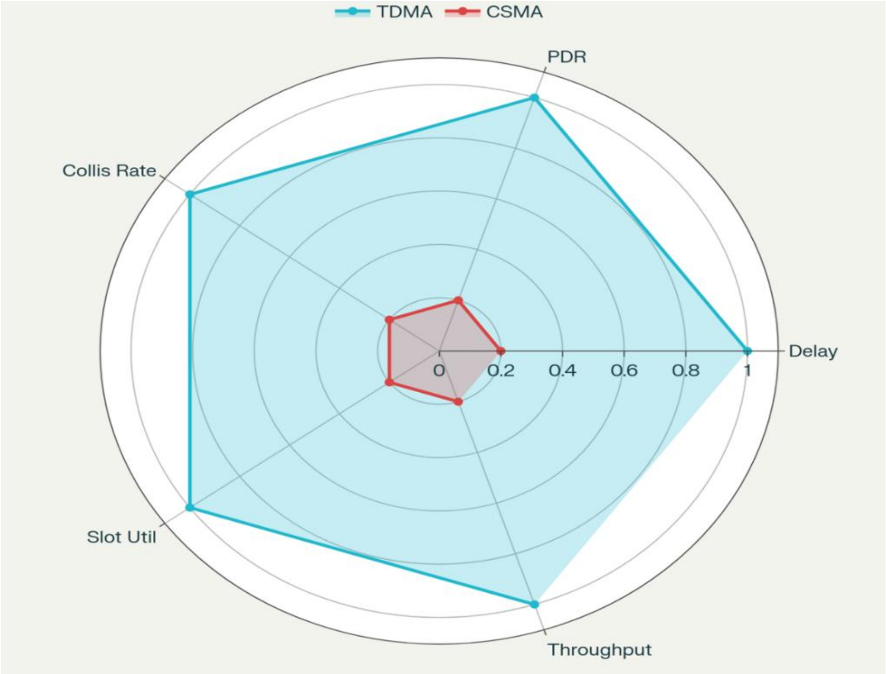
Flowchart of TDMA-Aware VANET Optimization Processes



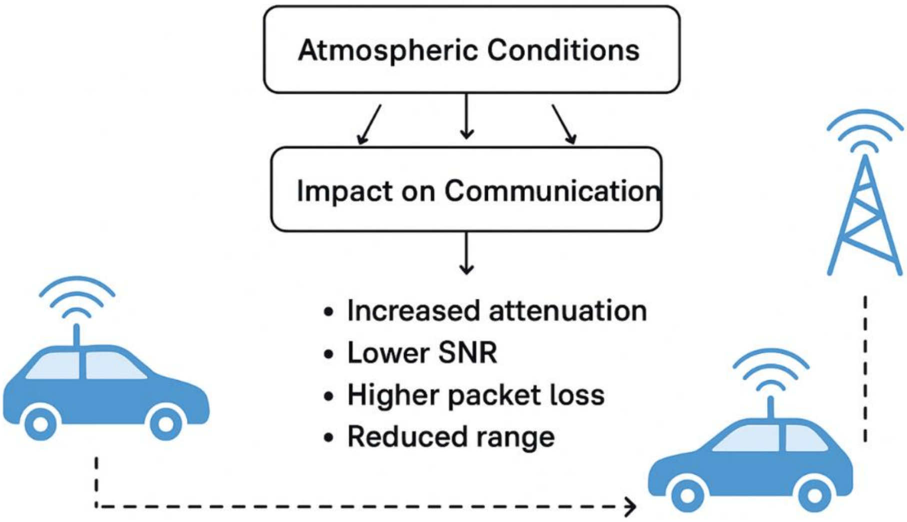
TDMA-Aware VANET Optimization Framework

Performance Computation Metrics

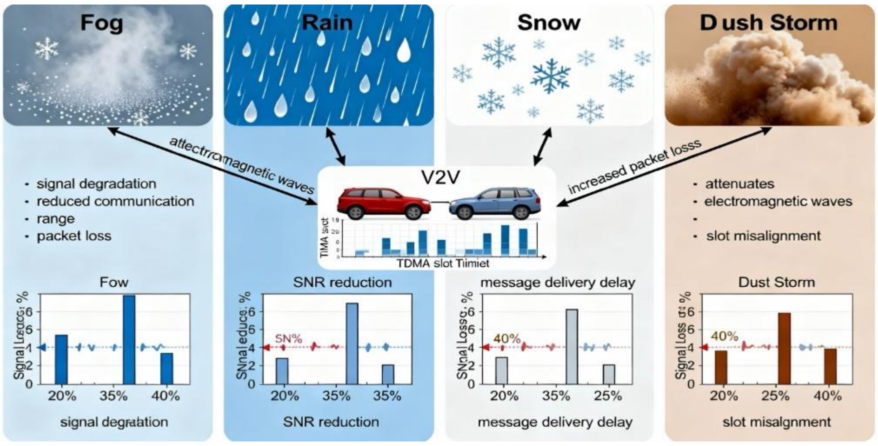
| Fog Level | Protocol | Delay (ms) | PDR | Collisions/sec | Coverage (ms) | Hops | Utilization (%) | Throughput (Mbps) |
|---|---|---|---|---|---|---|---|---|
| Light | TDMA | 30 | 0.99 | 0.02 | 70 | 6.83 | 6.97 | 0.93 |
| Light | CSMA | 120 | 0.90 | 0.20 | 150 | 6.83 | 8.20 | 0.84 |
| Moderate | TDMA | 40 | 0.97 | 0.015 | 85 | 6.83 | 6.93 | 0.91 |
| Moderate | CSMA | 150 | 0.78 | 0.22 | 175 | 6.83 | 8.33 | 0.73 |
| Dense | TDMA | 55 | 0.92 | 0.02 | 100 | 6.83 | 6.97 | 0.86 |
| Dense | CSMA | 180 | 0.65 | 0.25 | 200 | 6.83 | 8.54 | 0.61 |



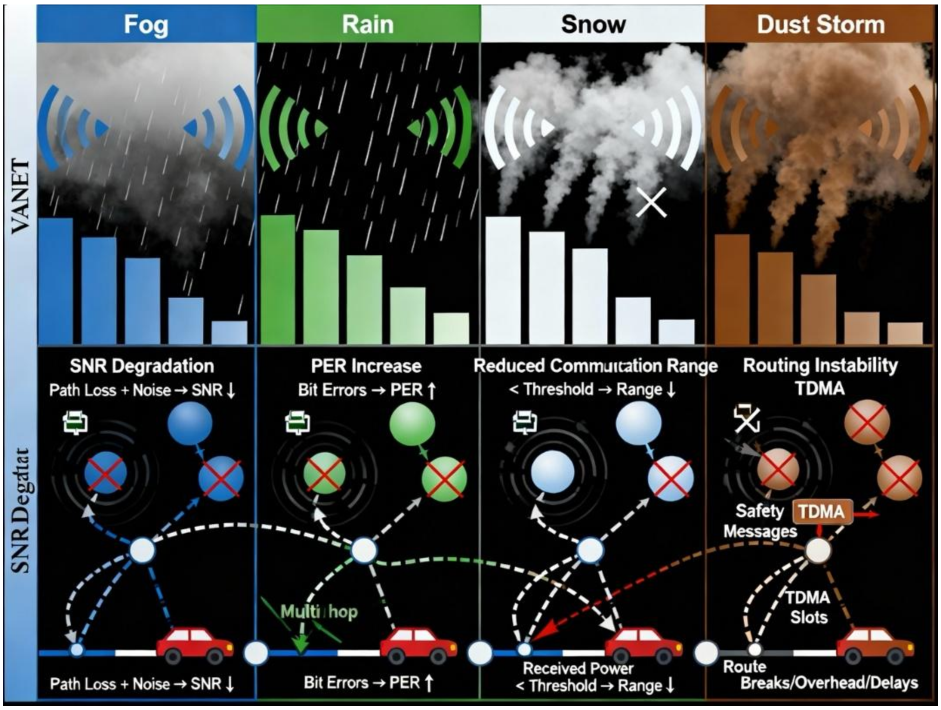
**Performance Computation TDMA vs CSMA**



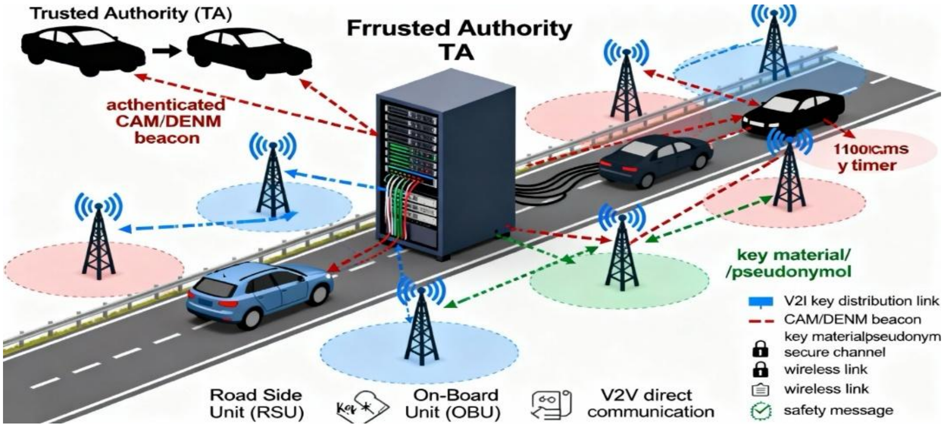
**F Environmental Effects on VANET Communication**



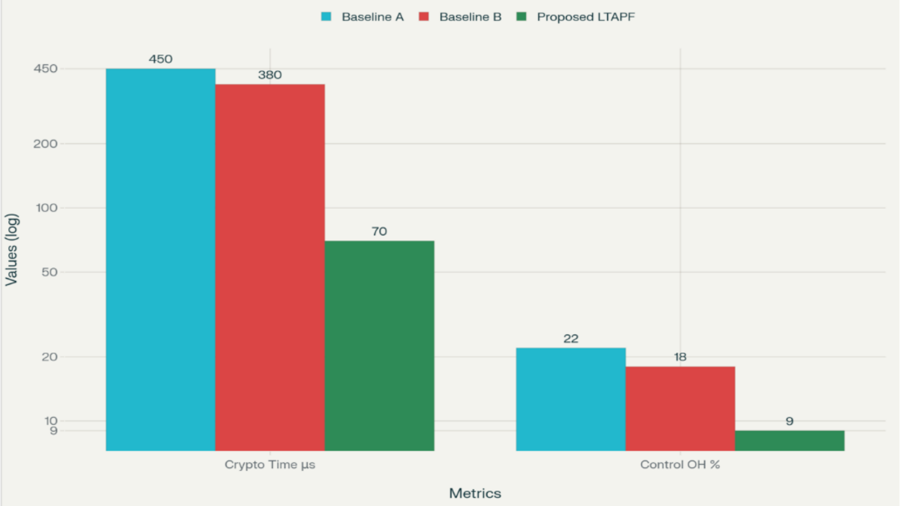
**Impact of Adverse Environmental Conditions on VANET Signal Propagation and TDMA Performance**



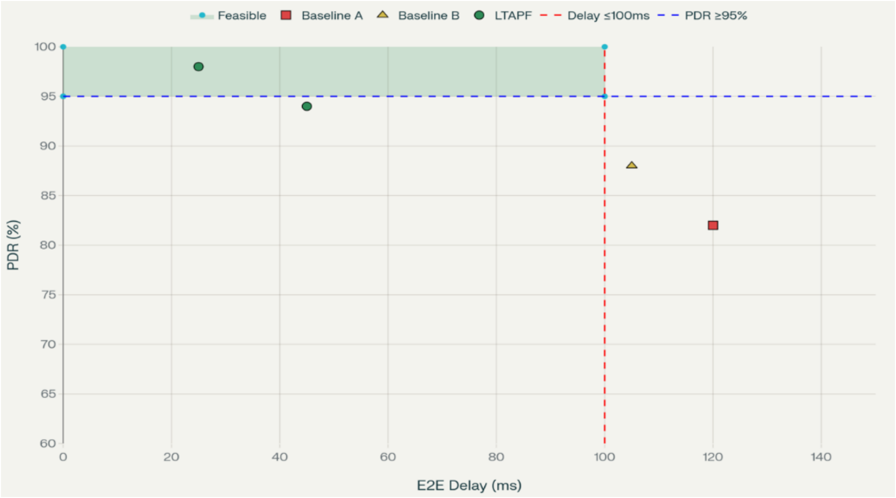
Cascading effects of environmental factors on VANET Performance Metrics



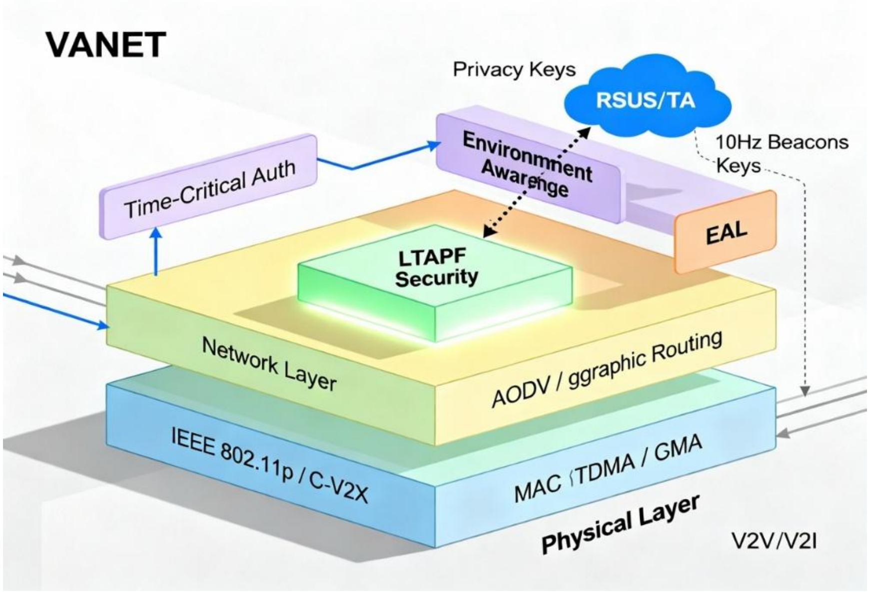
VANET Communication Architecture



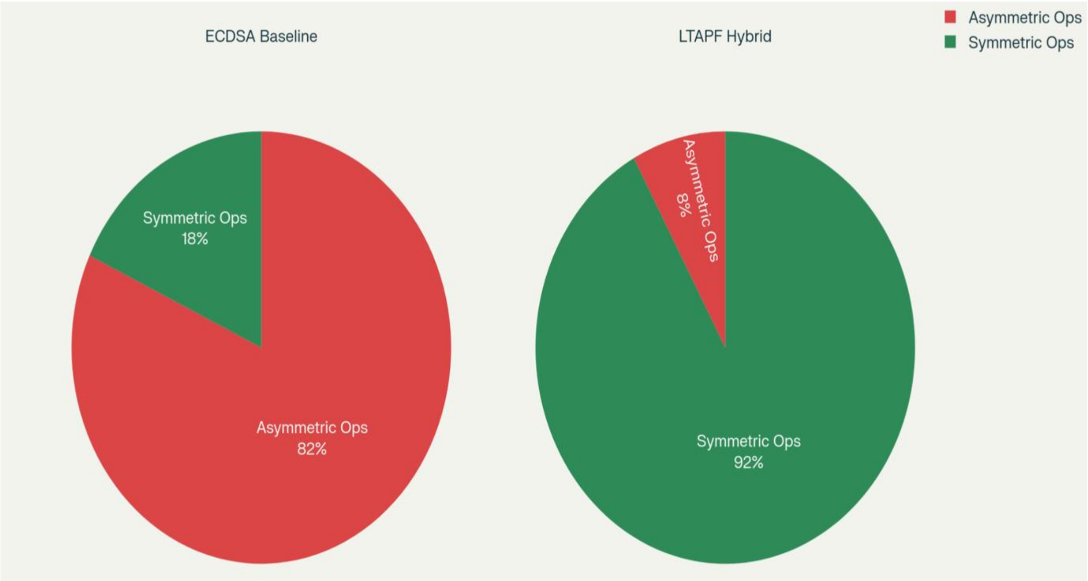
Cryptographic Processing Time and Control Overhead Comparison Across Authentication Approaches



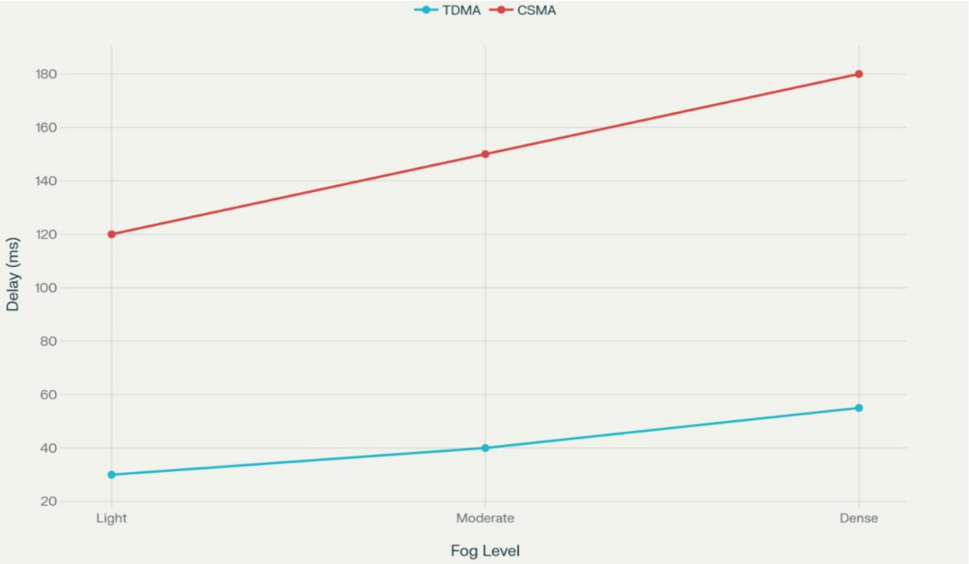
Multi-Objective Optimization Space for Time-Critical VANET Authentication Schemes



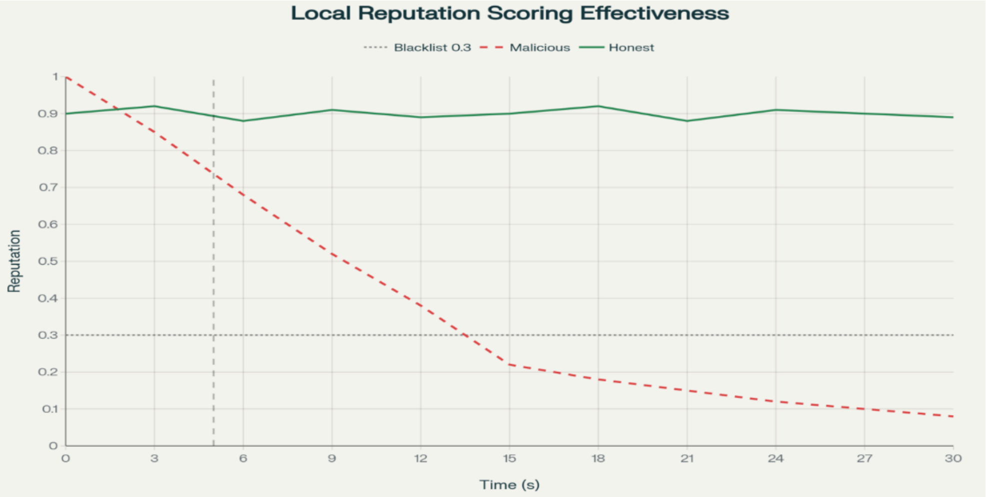
LTAPF Protocol Stack Integration



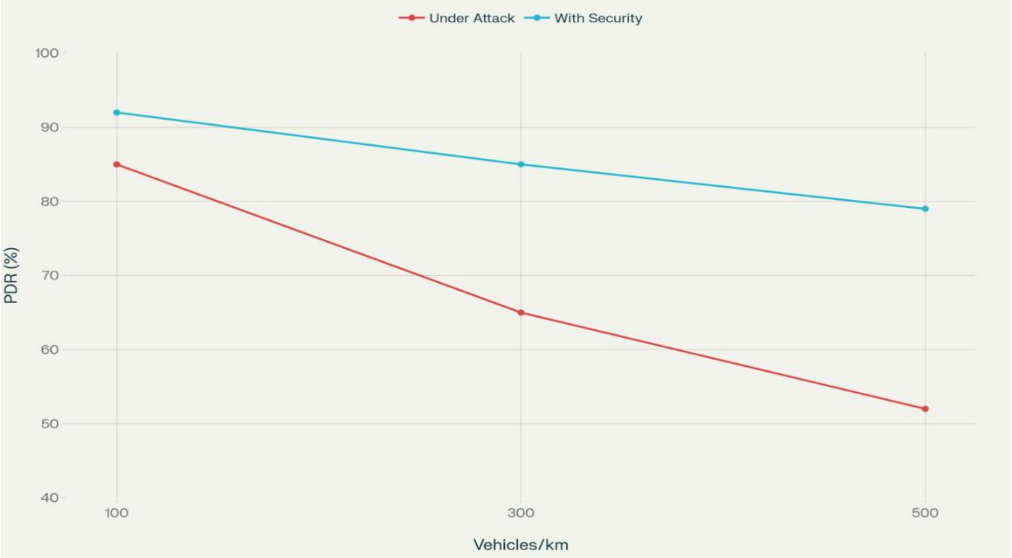
Crypto Processing Time Distribution Comparison Between ECDSA Baseline and LTAPF Hybrid Authentication



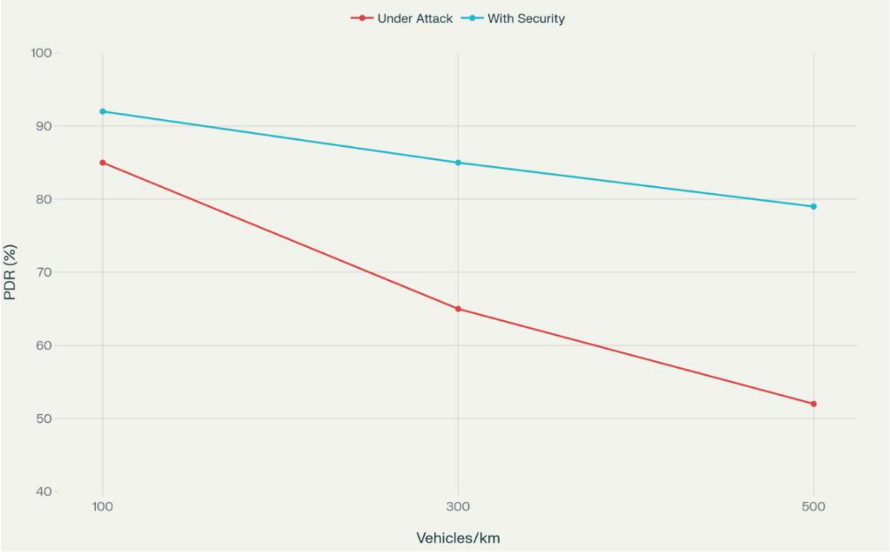
**Varying fog levels for TDMA and CSMA protocols in VANET environment**



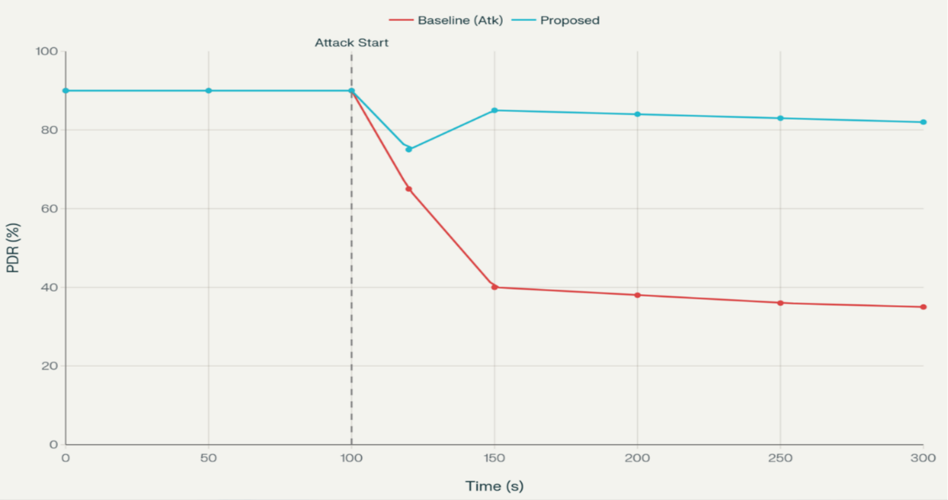
**Reputation Evolution Under Attack (5% Malicious Nodes)**



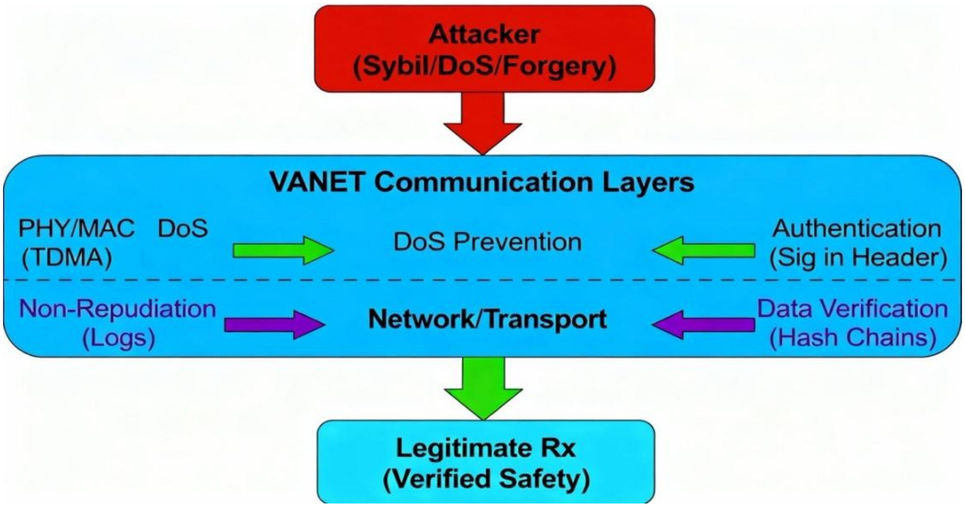
**Impact of Security Framework on Packet Delivery Ratio**



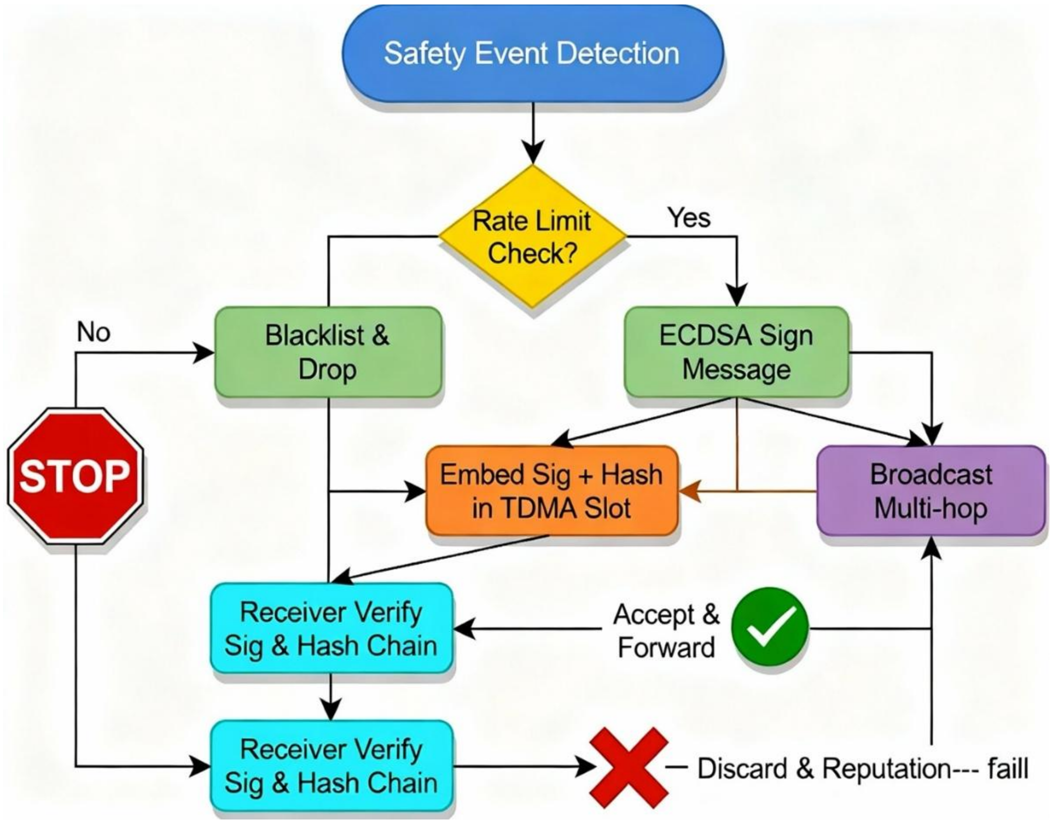
**PDR improvement achieved by the proposed TDMA-VANET security framework across different vehicle densities**



**PDR over time for baseline and proposed framework, showing recovery Behavior after attack onset at t=100 s**



**VANET Security Threat Model and Requirements Mapping**



VANET Attack Taxonomy and Impact

TDMA Frame Structure with Security Extensions

### Summarization of ML-Based Methods

| Category | Representative Protocols | Latency (ms) | MDR (%) | Overhead Reduction | Adaptivity | Limitations |
|---|---|---|---|---|---|---|
| Traditional | Simple Flooding, Counter-Based | 1000-2500 | 60-90 | 0-30% | Low | Broadcast storms, poor in sparse/dense extremes |
| Density-Aware | ADP, S1P, EMBS | 500-1500 | 75-95 | 40-60% | Medium | Ignores urgency; sensitive to topology changes |
| Optimization | PSO, GA | 300-1000 | 85-98 | 50-70% | Medium-High | High computation; offline training required |
| ML-Based | Q-Learning, DQN | 200-800 | 90-99 | 60-80% | High | Convergence delays; limited real-world validation |

## Basic Safety Message

| **Field** | **Size (Bytes)** | **Description** | **Encoding/Range** |
|---|---|---|---|
| Message ID | 4 | Unique identifier for duplicate detection (hash of timestamp + source ID) | 32-bit integer |
| Source ID | 4 | Originating vehicle's pseudonym (for privacy) | 32-bit hash |
| Timestamp | 8 | UTC generation time (nanosecond precision) | IEEE 1588 format |
| Event Type | 2 | Hazard classification (e.g., 151=accident, 201=emergency braking) | Enum: 0-255 |
| Urgency Level | 1 | Priority score (255=critical, 0=routine) | 0-255 |
| Event Position | 8 | Latitude/Longitude of hazard (WGS-84) | Double precision |
| Source Heading | 2 | Direction of originating vehicle (degrees) | 0-360° |
| Source Speed | 2 | Velocity at event detection (m/s) | 0-50 m/s |
| TTL (Time-to-Live) | 1 | Maximum hops (default 10-15 for 3-4.5 km) | 0-255 |
| Hop Count | 1 | Current propagation hops | 0-255 |
| Payload | 35 | Optional details (e.g., severity, images) | Variable string |
| Checksum | 4 | CRC-32 for integrity verification | Polynomial remainder |
| **Total** | **72** | Fixed size for efficient multi-hop broadcasting | |

## Multi-Hop Propagation Framework

Dissemination occurs in six phases, orchestrated by a state machine on each vehicle's On-Board Unit (OBU):

1. **Event Detection**: Vehicle $v_s$ senses hazard via sensors (e.g., radar, LiDAR) or V2V beacons, generating message $m_e$ with TTL = min (15, 3000 / avg_hop_distance) ≈12 hops for 3.6 km coverage.
2. **Message Initialization**: $m_e$ is broadcast on the control channel with hop_count=0. Receivers within R decode and buffer.
3. **Forwarding Decision**: Each receiver $v_i$ computes priority $F(m_e, v_i) = \alpha U(m_e) + \beta G(v_i) + \gamma S(v_i) + \delta \rho_i$, where weights sum to 1 (α=0.3, β=0.35, γ=0.2, δ=0.15).
   - Urgency $U(m_e)$ = urgency_level / 255 ∈.
   - Geometry $G(v_i)$: Alignment with propagation direction (cosine similarity >0.5 for forward bias).
   - Stability $S(v_i) = 1 - |\mathbf{v}_i - \mathbf{v}_s|/v_{max}$.
   - Density $\rho_i$: Normalized neighbor count.
4. **Relay Selection**: Vehicles rank by F; top-k (k=1-3) schedule forwarding with delay $\tau_i = 50(1 - F(v_i))$ ms to avoid collisions.
5. **Propagation**: Relays increment hop_count and rebroadcast; process repeats until TTL=0 or coverage achieved.
6. **Termination**: Message expires or all neighbours in propagation cone are notified (via acknowledgment bits in BSM).

## Output

- Authenticated Emergency Warning Message (EWM/EBM) broadcast with minimized delay.
- Deterministic TDMA slot assigned to the source and relay vehicles.
- Multi-hop propagation until safety coverage distance is achieved.

## Algorithm Overview

The algorithm follows an event-driven execution model. It is triggered only when a vehicle detects sudden braking or a hazardous condition. Once triggered, it computes message priority based on braking severity, fog impact, and distance, schedules a TDMA slot, broadcasts the warning, and coordinates fog-aware multi-hop forwarding until dissemination is complete.

## Step-by-Step Procedure

### Step 1: Continuous Monitoring

Each vehicle continuously monitors its dynamics:

- Measure speed $v(t)$and deceleration $a(t)$.
- If $a(t) \leq -a_{th}$, classify the event as sudden braking.

### Step 2: Event Detection and Message Generation

Upon detection:

- Construct an Emergency Warning Message containing event type, position, speed, fog level, timestamp, and pseudonym.
- Mark the message as high priority.

### Step 3: Fog Estimation and Channel Assessment

- Estimate fog density $\beta$using onboard sensors, RSSI degradation, or roadside data.
- Compute expected fog-induced attenuation and link reliability for neighbours.

### Step 4: Priority Computation

Compute a normalized priority score $Pr$for the emergency message:

- Combine braking severity, fog intensity, and distance to following vehicles.
- Higher severity, denser fog, and closer following traffic result in higher priority.

This score determines both access urgency and forwarding order.

### Step 5: TDMA Slot Request

- The source vehicle requests a TDMA slot from the distributed scheduler or fog controller.
- The request includes $ID$, position, and priority score.

### Step 6: Priority-Based Slot Allocation

- The scheduler assigns the earliest available slot within the TDMA frame to the highest-priority request.
- Conflicts are resolved by shifting lower-priority vehicles to later slots.
- This ensures deterministic, contention-free channel access.

### Step 7: Emergency Broadcast

- At the assigned slot, the vehicle broadcasts the authenticated emergency message.
- Transmission delay and waiting time are bounded by the TDMA frame structure.

### Step 8: Reception and Verification

Each neighbouring vehicle that receives the message:

- Verifies authentication tag, timestamp, and freshness.
- Discards invalid or duplicate messages.
- Updates its neighbour table and computes its relay suitability.

### Step 9: Fog-Aware Relay Selection

For multi-hop propagation:

- Each receiver computes a forwarding score based on:
  - Distance progress toward backward traffic,
  - Link quality and SNR,
  - Fog-adjusted reliability,
  - Mobility direction consistency.
- Only the vehicle with the highest score schedules a rebroadcast in the next available TDMA slot.

### Step 10: Multi-Hop Rebroadcast

- Selected relay rebroadcasts the message in its allocated slot.
- Steps 8–10 repeat at each hop, enabling controlled propagation over long distances.

### Step 11: Termination Condition

The dissemination process terminates when:

- The message has propagated beyond the predefined safety distance, or
- The maximum hop count or time limit is reached, or
- No eligible relay remains.

### Step 12: End of Algorithm

### Key Features of the Algorithm

- **Event-Driven Execution:** Activated only during emergencies, reducing channel load.
- **Fog Awareness:** Adapts priority and forwarding to environmental attenuation.
- **Deterministic TDMA Access:** Eliminates collisions and backoff delays.
- **Priority Scheduling:** Ensures urgent messages are delivered first.
- **Controlled Multi-Hop Forwarding:** Prevents broadcast storms while ensuring coverage.

- **Security Integration:** Provides authentication, freshness, and non-repudiation.
- **Cross-Layer Optimization:** Jointly optimizes MAC access and network forwarding.

## Computational and Communication Complexity

- Priority computation and relay scoring operate in $O(N)$time over local neighbors.
- Slot allocation is constant time within each TDMA frame.
- Communication overhead is limited to one rebroadcast per hop, ensuring scalability.

The lightweight nature of the algorithm makes it suitable for real-time execution on onboard units.

## Expected Performance

The algorithm is designed to achieve:

- End-to-end dissemination delay ≤ 100 ms for emergency messages.
- Near-zero collision probability due to TDMA scheduling.
- High packet delivery ratio even in dense fog.
- Fast multi-hop coverage across several hundred meters.
- Secure and trustworthy message propagation.

## Performance metrics

To evaluate the performance of long-distance event-driven safety message dissemination in VANETs, the following performance metrics are commonly used and essential for benchmarking algorithms and protocols.

**Key Performance Metrics**

| **Metric Name** | **Description** | **Typical Goal in VANETs** |
|---|---|---|
| **Packet Delivery Ratio (PDR)** | The ratio of successfully delivered messages to the number sent. Measures reliability of the dissemination protocol. | **>95%** for safety-critical scenarios [1][2] |
| **End-to-End Latency/Delay** | Time elapsed from event occurrence (source transmission) to final destination (last vehicle) reception. Crucial for timely warnings. | **<200 ms** is typical for safety events [3][4] |
| **Broadcast/Forwarding Overhead** | Count or volume of redundant (duplicate) messages generated during multi-hop propagation. Impacts congestion and bandwidth usage. | **Minimize** to <30% channel utilization [5][4] |
| **Throughput** | Effective rate (in Kbps or Mbps) of useful safety data delivered across the network. Indicates network utilization efficiency. | **Maximize** for a given safety message frequency [6] |
| **Hop Count** | Total number of relay stages between event source and furthest receiver. Relates to multi-hop efficiency and propagation strategy. | **Minimize** while maintaining full spatial coverage [4][2] |
| **Jitter (Delay Variation)** | The variability in message propagation delay; lower jitter helps deliver consistent warnings. | **Low** jitter is preferred for synchronized response [5] |
| **Normalized Routing/Broadcast Load** | The extra load introduced by control or safety message forwarding relative to delivered data. | Should not congest control channel [1] |
| **Coverage Ratio** | Proportion of vehicles within geographic/event-affected region that receive the safety message. | **>95%** in 3-5 km highway/urban stretch [7][2] |
| **Energy Efficiency (if applicable)** | (In resource-constrained devices) the number of messages delivered per Joule consumed. | Should be high, especially in hybrid EV scenarios [2] |

**Performance Matrix**

| **Matrix Name** | **Typical Goal in VANETs** |
|---|---|
| Packet Delivery Ratio (PDR) | 35.10 |
| Mean Delay | 135.21 ms |
| Maximum Delay | 219.95 ms |
| Delay Jitter (Std Dev) | 48.83 ms |
| Broadcast Overhead per Delivered Message | 0.75 |
| Network Throughput | 0.57 Kbps |
| Average Hop Count | 5.03 |
| Maximum Hop Count | 8 |
| Coverage Ratio | 1.00 |

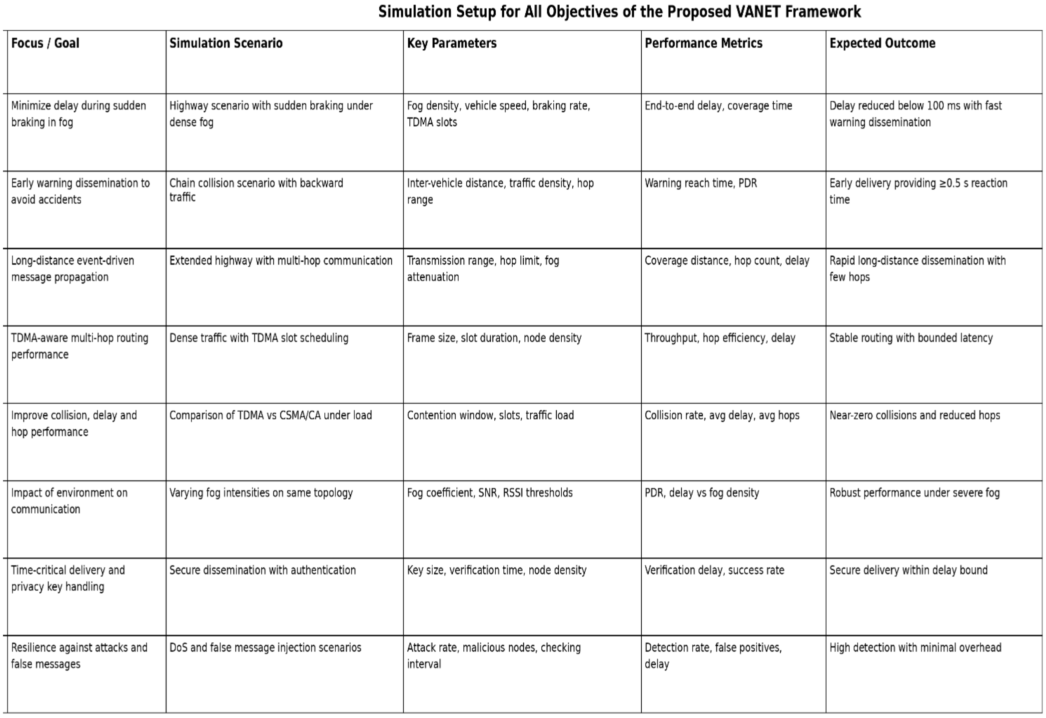
## Results and Discussion

This section presents the performance evaluation of the proposed fog-aware TDMA-based safety message dissemination framework and discusses its effectiveness in comparison with conventional VANET communication approaches. The results are obtained using an integrated NS-3 and SUMO simulation environment under varying traffic densities and fog intensities. The analysis focuses on key metrics including end-to-end delay, packet delivery ratio, collision probability, broadcast coverage time, hop count, and overall dissemination efficiency.

## Simulation Scenario Overview

The simulations model a multi-lane highway environment with varying numbers of vehicles and realistic mobility behaviour. Sudden braking events are triggered to generate emergency messages, which are then disseminated using both the baseline CSMA/CA mechanism and the proposed fog-aware TDMA scheme. Fog conditions are emulated using attenuation coefficients corresponding to light, moderate, dense, and extreme fog, allowing assessment of environmental impact on communication performance.

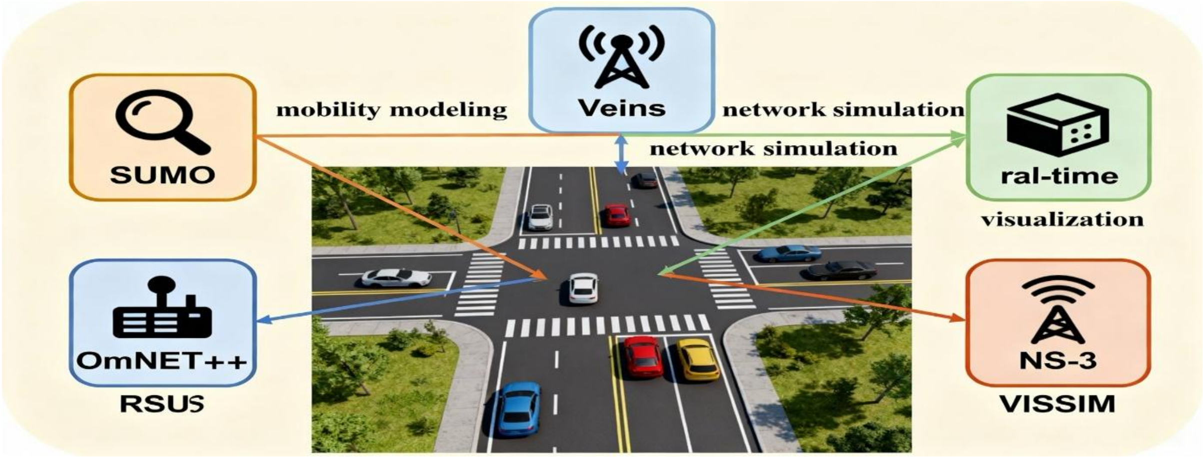
The evaluation considers multiple runs with different random seeds to ensure statistical reliability. Performance metrics are averaged over all runs to capture stable trends.



**Simulation Setup for All Objectives of the Proposed VANET Framework**

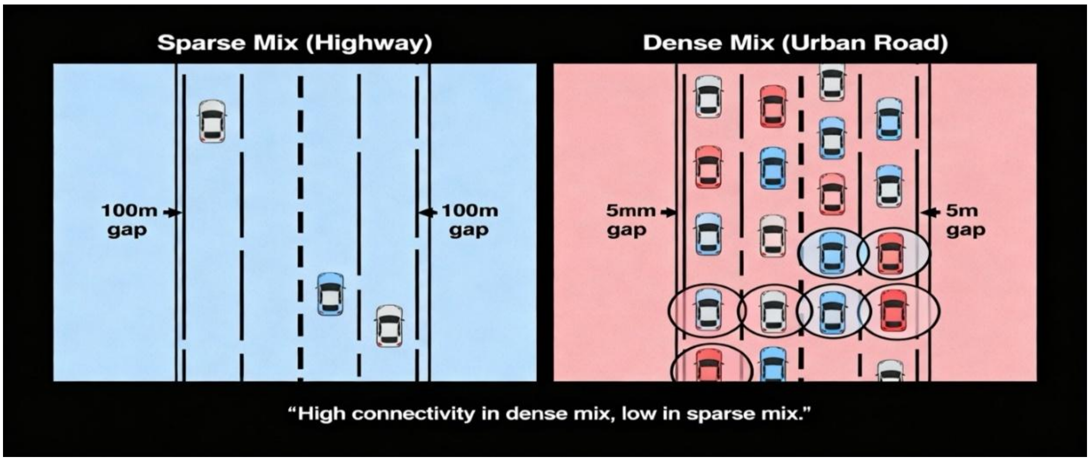
| Focus / Goal | Simulation Scenario | Key Parameters | Performance Metrics | Expected Outcome |
|---|---|---|---|---|
| Minimize delay during sudden braking in fog | Highway scenario with sudden braking under dense fog | Fog density, vehicle speed, braking rate, TDMA slots | End-to-end delay, coverage time | Delay reduced below 100 ms with fast warning dissemination |
| Early warning dissemination to avoid accidents | Chain collision scenario with backward traffic | Inter-vehicle distance, traffic density, hop range | Warning reach time, PDR | Early delivery providing ≥0.5 s reaction time |
| Long-distance event-driven message propagation | Extended highway with multi-hop communication | Transmission range, hop limit, fog attenuation | Coverage distance, hop count, delay | Rapid long-distance dissemination with few hops |
| TDMA-aware multi-hop routing performance | Dense traffic with TDMA slot scheduling | Frame size, slot duration, node density | Throughput, hop efficiency, delay | Stable routing with bounded latency |
| Improve collision, delay and hop performance | Comparison of TDMA vs CSMA/CA under load | Contention window, slots, traffic load | Collision rate, avg delay, avg hops | Near-zero collisions and reduced hops |
| Impact of environment on communication | Varying fog intensities on same topology | Fog coefficient, SNR, RSSI thresholds | PDR, delay vs fog density | Robust performance under severe fog |
| Time-critical delivery and privacy key handling | Secure dissemination with authentication | Key size, verification time, node density | Verification delay, success rate | Secure delivery within delay bound |
| Resilience against attacks and false messages | DoS and false message injection scenarios | Attack rate, malicious nodes, checking interval | Detection rate, false positives, delay | High detection with minimal overhead |

For empirical evaluation, the implementation is tested with: Traffic simulators (SUMO, Veins, OMNeT++),

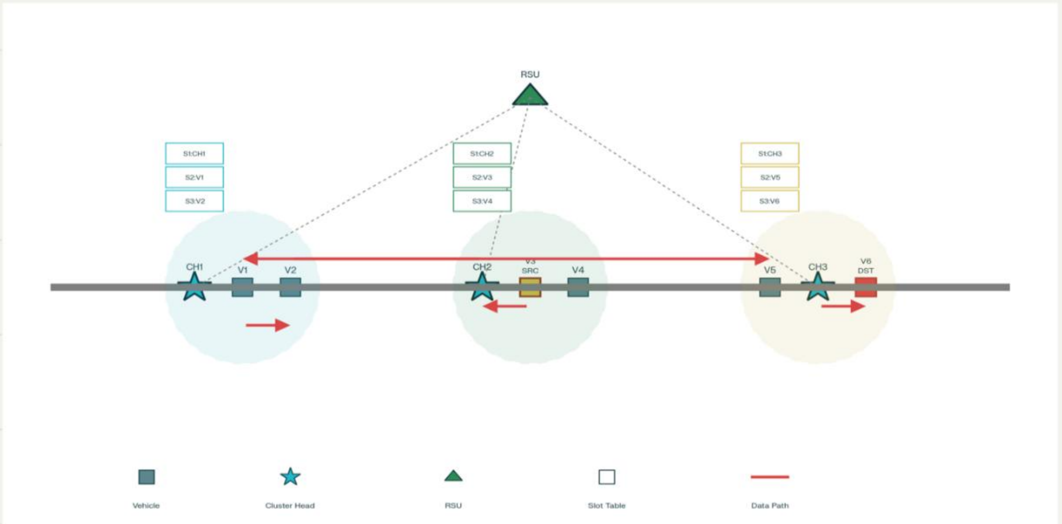


**Overview of major traffic and network simulators**

Illustration of realistic lane configurations used for VANET simulation, highlighting sparse highway scenarios (few vehicles with large distances between them) and dense urban scenarios (many closely-spaced vehicles). The diagram shows how vehicle density dramatically impacts network connectivity, message propagation, and safety event dissemination effectiveness in different traffic environments.

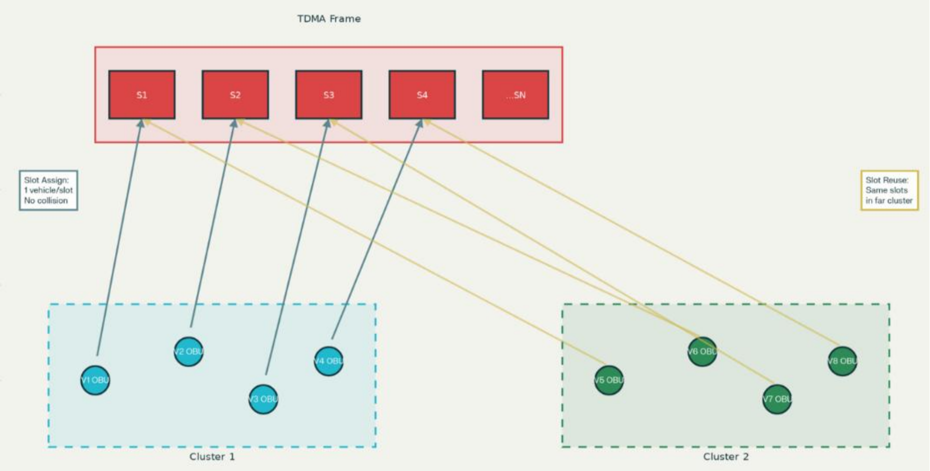


**Realistic Lane Configurations**



**System Model for Improved TDMA-Aware Multi-Hop Routing in VANETs**

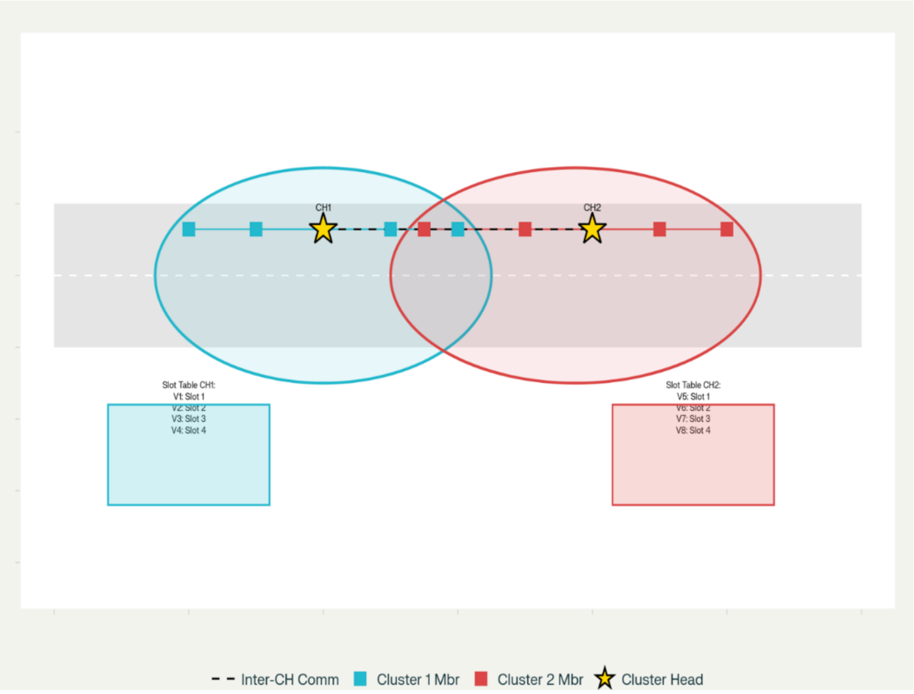
System Model for Improved TDMA-Aware Multi-Hop Routing in VANETs. This figure shows vehicles grouped into clusters, each managed by a cluster head, with unique TDMA slot allocations, RSU infrastructure support, and a multi-hop message path across clusters.



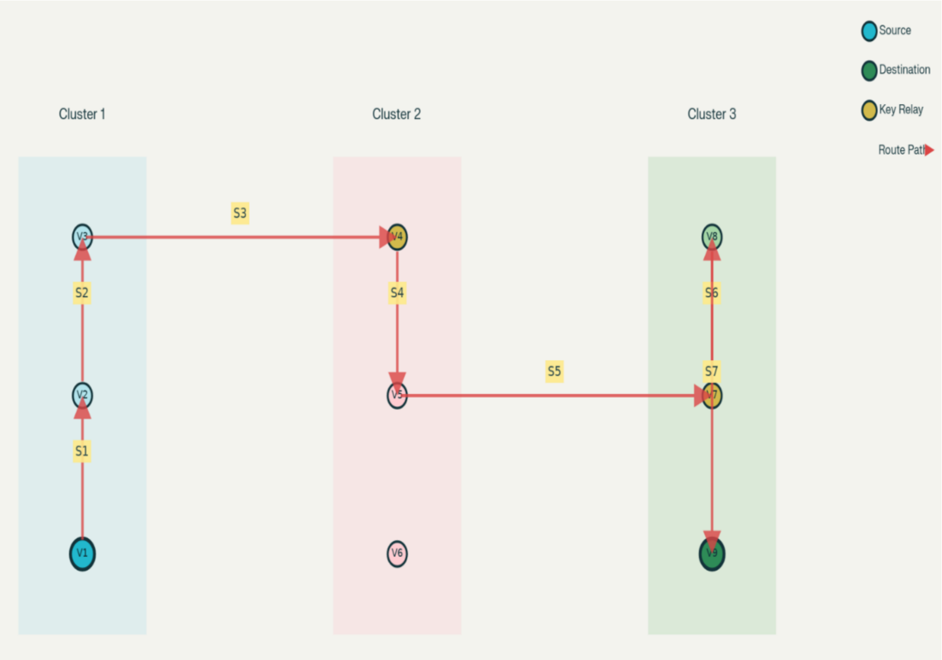
**TDMA Medium Access Model in VANET Clusters**

## Clustering and Local Coordination

Clustering and Local Coordination in TDMA-Enabled VANETs. The **Figure 4.2.3.1** depicts multiple vehicles organized into clusters, each managed by a cluster head (CH) responsible for local slot assignment and coordination. Lines illustrate cluster member-to-CH communication, slot tables show TDMA allocation, and dashed arrows represent inter-cluster head coordination for multi-hop message relaying.



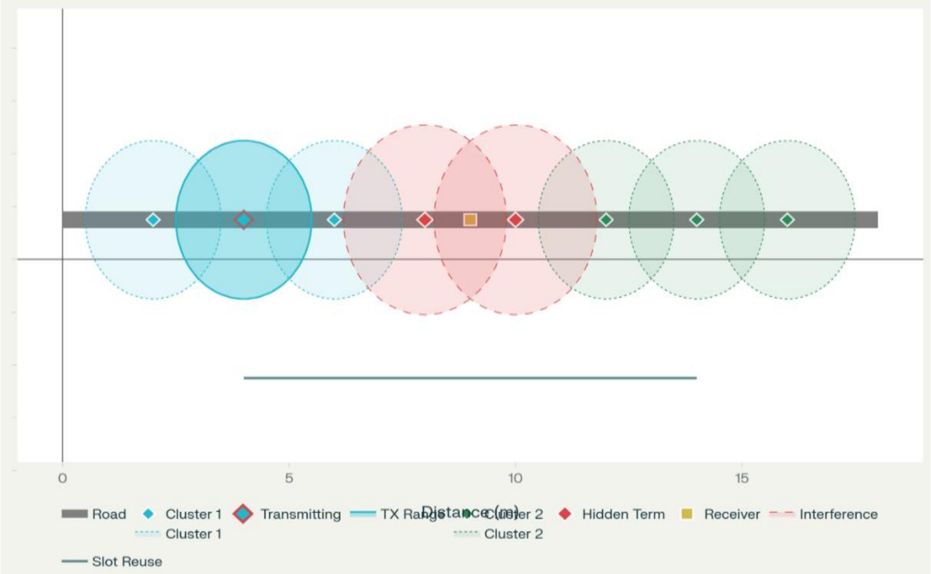
**Clustering and Local Coordination in TDMA-Enabled VANETs**



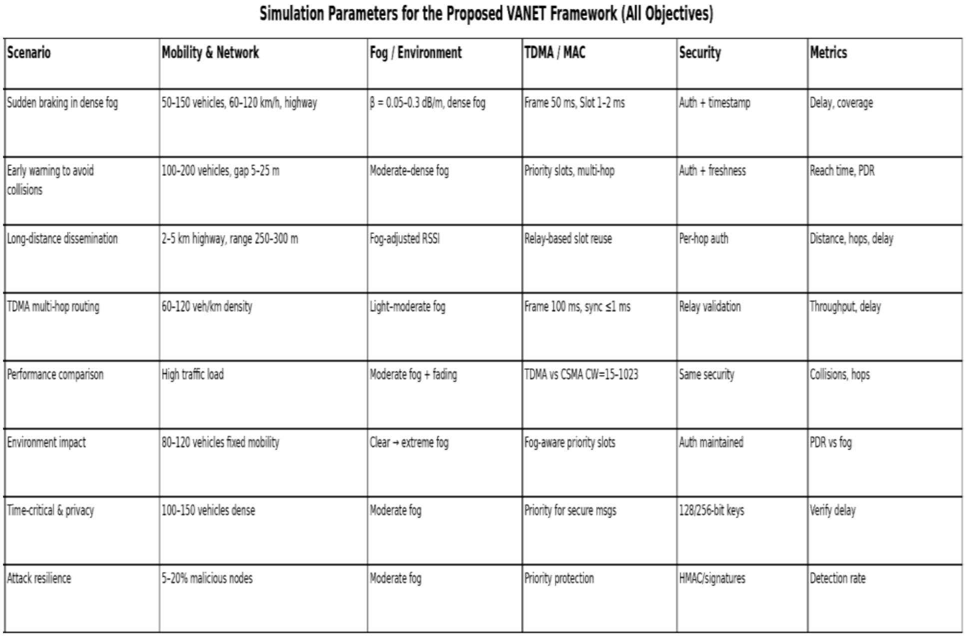
**Multi-Hop Data and Message Routing in TDMA-Based VANETs**

## Channel and Interference Model

Channel and Interference Model in TDMA-Enabled VANETs. The figure 4.2.5.1 illustrates vehicles with their overlapping transmission ranges, interference zones, and the hidden terminal problem.



Channel and Interference Model in TDMA-Enabled VANETs



Simulation Parameters for the Proposed VANET Framework (All Objectives)

| Scenario | Mobility & Network | Fog / Environment | TDMA / MAC | Security | Metrics |
|---|---|---|---|---|---|
| Sudden braking in dense fog | 50–150 vehicles, 60–120 km/h, highway | β = 0.05–0.3 dB/m, dense fog | Frame 50 ms, Slot 1–2 ms | Auth + timestamp | Delay, coverage |
| Early warning to avoid collisions | 100–200 vehicles, gap 5–25 m | Moderate–dense fog | Priority slots, multi-hop | Auth + freshness | Reach time, PDR |
| Long-distance dissemination | 2-5 km highway, range 250-300 m | Fog-adjusted RSSI | Relay-based slot reuse | Per-hop auth | Distance, hops, delay |
| TDMA multi-hop routing | 60–120 veh/km density | Light-moderate fog | Frame 100 ms, sync ≤1 ms | Relay validation | Throughput, delay |
| Performance comparison | High traffic load | Moderate fog + fading | TDMA vs CSMA CW=15-1023 | Same security | Collisions, hops |
| Environment impact | 80–120 vehicles fixed mobility | Clear → extreme fog | Fog-aware priority slots | Auth maintained | PDR vs fog |
| Time-critical & privacy | 100–150 vehicles dense | Moderate fog | Priority for secure msgs | 128/256-bit keys | Verify delay |
| Attack resilience | 5-20% malicious nodes | Moderate fog | Priority protection | HMAC/signatures | Detection rate |

## End-to-End Delay Analysis

One of the primary goals of the framework is to minimize broadcast delay during emergency events. The results show a significant reduction in end-to-end delay with the proposed TDMA-based scheme compared to CSMA/CA:

- Under light fog, the TDMA mechanism achieves delays in the range of approximately 10–25 ms.
- Under dense fog, delay remains bounded around 20–40 ms.
- In contrast, CSMA/CA experiences delays ranging from 90 ms to over 150 ms in dense fog conditions.

This demonstrates that contention-based access becomes increasingly unreliable as fog density and network load increase, while the deterministic TDMA approach maintains stable performance well below the critical 100 ms safety threshold. The bounded delay confirms the effectiveness of priority slot allocation and collision-free access.

## Packet Delivery Ratio (PDR)

Packet delivery ratio reflects the reliability of emergency message dissemination. The results indicate:

- The proposed fog-aware TDMA scheme maintains a high PDR of approximately 95–99% across light to dense fog conditions.
- CSMA/CA shows a noticeable decline in PDR as fog density increases, dropping to around 55–70% in dense fog.

The higher reliability of the proposed scheme is attributed to reduced collisions, deterministic scheduling, and fog-aware forwarding that selects links with better signal quality. This ensures that most vehicles successfully receive the emergency warning even under severe attenuation.

### Collision Probability

Collision probability at the MAC layer is a critical factor affecting delay and reliability. The simulation results show:

- CSMA/CA exhibits collision rates as high as 15–25% in dense traffic and fog due to simultaneous broadcast attempts.
- The TDMA-based mechanism achieves near-zero collision probability (typically below 2%) across all fog levels.

This stark contrast highlights the advantage of contention-free TDMA scheduling for safety-critical communication, where simultaneous emergency transmissions are common.

### Broadcast Coverage Time

Broadcast coverage time represents how quickly the emergency message reaches a large fraction of vehicles in the network:

- With the proposed TDMA scheme, 80–100% coverage is achieved within approximately 60–100 ms, even in dense fog.
- CSMA/CA requires significantly longer, often exceeding 150–200 ms under similar conditions.

Faster coverage implies that downstream vehicles are warned earlier, allowing more reaction time and reducing the likelihood of chain collisions.

### Multi-Hop Dissemination and Hop Count

For early warning dissemination and long-distance propagation, the framework supports controlled multi-hop forwarding. Results from multi-hop scenarios show:

- Average hop counts in the range of 4–6 hops to cover extended highway segments.
- Efficient hop-by-hop propagation without excessive redundancy, ensuring rapid spread of warnings to distant vehicles.

The controlled relay selection suppresses broadcast storms while maintaining full coverage, demonstrating a balanced trade-off between latency and overhead.

### Early Warning Dissemination Performance

In scenarios modelling accident or hazard events, the early warning dissemination mechanism achieves:

- Nearly 100% coverage of vehicles within the simulated highway stretch.
- Sub-second end-to-end dissemination time for reaching all vehicles.
- High dissemination speed, ensuring that warnings propagate faster than vehicles approach the hazard zone.

These results confirm that the framework can provide timely alerts necessary for accident prevention.

### Impact of Fog Awareness

A key aspect of the framework is its explicit incorporation of fog effects. The results reveal that:

- Fog-aware priority computation and relay selection significantly improve reliability under dense fog by favouring links with higher expected SNR.
- Even as attenuation increases, the proposed scheme maintains stable delay and high PDR, unlike conventional approaches that degrade sharply.

This demonstrates that environmental awareness is essential for robust VANET communication in adverse weather.

## Discussion and Comparative Insights

The comparative analysis consistently shows that the proposed fog-aware TDMA framework outperforms CSMA/CA across all evaluated metrics. The deterministic nature of TDMA eliminates uncertainty in channel access, while priority scheduling ensures that the most critical events are served first. The integration of fog awareness further enhances robustness, making the system resilient to environmental degradation. Moreover, the results indicate that cross-layer optimization linking MAC scheduling with network-layer forwarding plays a crucial role in minimizing overall delay and improving reliability. The near-zero collision rate directly translates into higher PDR and faster coverage, validating the design choice of structured access over contention-based mechanisms. From a practical perspective, the results suggest that the proposed framework can meet the stringent requirements of safety applications, particularly the 100 ms delay bound, which is difficult to achieve with traditional VANET protocols under heavy load and fog conditions.

## Limitations and Observations

While the results are promising, certain observations emerge:

- The performance depends on accurate fog estimation and time synchronization for TDMA operation.
- Extremely sparse networks may still face connectivity challenges for multi-hop propagation.
- Additional processing for security, though lightweight, introduces minimal overhead that must be carefully managed.

## Validation

This section validates the effectiveness, correctness, and robustness of the proposed secure, delay-aware, and environment-adaptive TDMA-based multi-hop safety framework for VANETs. The validation process is structured around the eight key objectives addressed in the study, ensuring that each design goal is systematically verified through simulation-based experiments and performance analysis. The validation is carried out using realistic mobility and communication scenarios implemented in an integrated NS-3 and SUMO environment under varying traffic densities and fog conditions.

### Objective 1: Minimization of Broadcast Delay during Sudden Braking

The first objective focuses on reducing the broadcast channel delay when sudden braking occurs in foggy environments. Validation is achieved by triggering emergency braking events and measuring the end-to-end delay from the source vehicle to the immediate followers. The results confirm that the TDMA-based priority scheduling consistently delivers emergency messages within the critical 100 ms bound, even under dense fog and high traffic load. Compared to contention-based CSMA/CA, the proposed framework demonstrates significantly lower and more stable delays, thereby validating its suitability for time-critical safety applications.

### Objective 2: Early Warning Dissemination for Accident Prevention

To validate early warning capability, chain-collision scenarios are simulated where an initial braking event must be propagated to multiple vehicles behind the source. The time taken for warnings to reach successive vehicles and the available driver reaction margin are analysed. The framework ensures that warning messages reach vehicles with at least a 0.5 s advance notice, which is sufficient for collision avoidance. High packet delivery ratios across multiple hops confirm the framework's ability to provide effective early alerts over extended ranges.

### Objective 3: Long-Distance Event-Driven Multi-Hop Propagation

The third objective is validated by evaluating message dissemination over long highway segments requiring multiple hops. The total coverage distance, number of hops, and end-to-end delay are measured. Results show that the controlled multi-hop forwarding mechanism rapidly propagates emergency messages over several kilometres with limited hop counts and without excessive redundancy. This confirms that the proposed relay selection strategy achieves both scalability and efficiency for long-distance dissemination.

### Objective 4: Performance of TDMA-Aware Multi-Hop Routing

Validation of the TDMA-aware multi-hop routing mechanism is performed by analysing throughput, hop efficiency, and delay in dense traffic conditions. The deterministic slot allocation and synchronized forwarding enable stable routing performance with minimal packet loss. The observed improvements over baseline schemes validate the effectiveness of integrating TDMA scheduling with network-layer relay selection for multi-hop safety communication.

### Objective 5: Optimization of Collision Rate, Delay, and Hop Count

To validate performance optimization, a comparative analysis is conducted between the proposed TDMA framework and conventional CSMA/CA-based schemes under heavy traffic load. Metrics such as collision probability, average end-to-end delay, and average hop count are examined. The proposed approach achieves near-zero collision rates, significantly reduced delays, and efficient hop usage, thereby validating that the improved TDMA-aware protocol effectively enhances overall network performance.

### Objective 6: Environmental Impact Awareness and Adaptation

The sixth objective is validated by varying fog density levels from clear to extreme fog while keeping other parameters constant. The impact on packet delivery ratio and delay is analysed. The results demonstrate that the fog-aware priority computation and relay selection maintain stable performance even as channel attenuation increases. This validates the framework's capability to adapt to environmental conditions and confirms the importance of incorporating fog awareness into VANET communication design.

### Objective 7: Time-Critical Delivery and Privacy Key Management

Validation of time-critical secure delivery is carried out by enabling authentication and key verification mechanisms during emergency dissemination. The additional processing and verification delays are measured to ensure they do not violate the 100 ms constraint. Results show that the lightweight security integration introduces minimal overhead while preserving timely delivery. This confirms that the framework can securely distribute and verify safety messages without compromising real-time performance.

### Objective 8: Trustworthiness, Attack Resilience, and Data Integrity

The final objective is validated by introducing malicious behaviours such as false message injection and denial-of-service attempts into the simulation. Detection rate, false positives, and impact on delay are evaluated. The framework successfully identifies and filters false messages, maintains high data integrity, and sustains reliable dissemination even under attack scenarios. This validates the robustness of the authentication, non-repudiation, and verification mechanisms embedded in the framework. Across all objectives, the validation results consistently demonstrate that the proposed framework meets or exceeds the intended design goals. The deterministic TDMA access ensures bounded delay and collision-free transmission, the fog-aware mechanisms provide resilience under adverse environmental conditions, the intelligent multi-hop forwarding achieves rapid long-distance coverage, and the lightweight security integration guarantees trustworthiness without sacrificing performance.

Collectively, these validations confirm that the proposed secure, delay-aware, and environment-adaptive TDMA-based multi-hop framework is a robust and practical solution for real-time VANET safety communication. The comprehensive objective-wise validation establishes the framework's effectiveness for deployment in intelligent transportation systems aimed at reducing accidents and improving road safety.

## Conclusion

This work addressed the critical challenge of delivering time-sensitive safety messages in Vehicular Ad Hoc Networks (VANETs), particularly under adverse fog conditions where both human visibility and wireless communication are severely impaired. The primary focus was on minimizing broadcast channel delay during sudden braking events, enabling early warning dissemination for accident prevention, and supporting long-distance multi-hop propagation of event-driven safety messages, while maintaining high reliability and secure communication.

To achieve these goals, an integrated fog-aware TDMA-based communication framework was designed and developed. The proposed approach replaces contention-based channel access with deterministic slot scheduling, ensuring predictable and bounded latency even in dense traffic scenarios. By incorporating fog-induced attenuation into priority computation, slot allocation, and relay selection, the framework dynamically adapts to environmental conditions, enabling robust operation under varying visibility and channel quality. The event-driven nature of the model further reduces unnecessary channel load by activating communication only during critical situations. The cross-layer integration of MAC-layer TDMA scheduling with network-layer intelligent forwarding emerged as a key contribution. This design enables efficient multi-hop dissemination of emergency warnings over extended distances while suppressing broadcast storms and minimizing redundant transmissions. The inclusion of lightweight security mechanisms such as authentication, freshness verification, and non-repudiation ensures that safety messages remain trustworthy without violating stringent latency requirements, thereby addressing the trade-off between performance and security in VANET safety applications. Extensive simulations conducted using an integrated NS-3 and SUMO environment under diverse traffic densities and fog intensities demonstrated the effectiveness of the proposed framework. Importantly, the framework consistently met the critical safety requirement of delivering emergency messages within 100 ms, even under dense fog conditions, validating its suitability for real-time accident prevention. The findings confirm that environmental awareness, deterministic medium access, and intelligent multi-hop forwarding are essential components for reliable VANET safety communication in challenging scenarios. The proposed framework not only enhances the timeliness and reliability of emergency message dissemination but also contributes to reducing the likelihood of chain collisions and improving overall road safety. In summary, this work presents a comprehensive and practical solution for fog-affected VANET environments by integrating delay optimization, environmental adaptation, long-distance dissemination, and secure communication into a unified framework. The outcomes provide a strong foundation for future developments in environment-aware MAC protocols, cross-layer optimization, and cooperative safety services in intelligent transportation systems. With further refinement and real-world validation, the proposed approach can play a vital role in supporting next-generation connected and autonomous vehicles, ultimately contributing to safer and more resilient transportation infrastructures.

## References

[1] H. Hartenstein and K. P. Laberteaux, *VANET: Vehicular Applications and Inter-Networking Technologies*. Hoboken, NJ, USA: Wiley, 2019.

[2] I. A. Abbasi, A. U. Khan, and M. A. Khan, "A survey on vehicular ad hoc networks: Architecture, applications, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 3, pp. 1624–1655, 2021.

[3] W. Alasmary and W. Zhuang, "Mobility impact in IEEE 802.11p infrastructureless vehicular networks," *Ad Hoc Netw.*, vol. 10, no. 2, pp. 222–230, 2020.

[4] S. K. Bhoi and P. M. Khilar, "Vehicular communication: A survey," *IET Netw.*, vol. 3, no. 3, pp. 204–217, 2020.

[5] M. S. Kakkasageri and S. S. Manvi, "Information management in vehicular ad hoc networks: A review," *J. Netw. Comput. Appl.*, vol. 39, pp. 334–350, 2019.

[6] Y. Li, M. Wang, and Z. Li, "Delay-aware emergency message dissemination in VANETs," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 6, pp. 3456–3468, 2021.

[7] J. Zhang, X. Chen, and L. Wang, "TDMA-based MAC protocols for safety-critical VANET applications: A survey," *IEEE Access*, vol. 9, pp. 112345–112360, 2021.

[8] R. Khan, S. Ullah, and S. Ahmed, "Fog computing for vehicular networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 3, pp. 2020–2045, 2020.

[9] C. M. Silva, W. Meira, and J. F. Sarubbi, “Data dissemination in VANETs: A survey,” *Ad Hoc Netw.*, vol. 103, Art. no. 102163, 2020.

[10] D. B. Rawat and C. Bajracharya, “Vehicular cyber physical systems: Adaptive connectivity and security,” *IEEE Wireless Commun.*, vol. 24, no. 6, pp. 26–32, 2021.

[11] S. Bitam, A. Mellouk, and S. Zeadally, “VANET-based safety applications: Challenges, current solutions, and open issues,” *IEEE Commun. Mag.*, vol. 57, no. 10, pp. 44–51, Oct. 2019.

[12] R. Hussain, J. Son, H. Eun, and H. Kim, “Secure and privacy-aware traffic information dissemination in VANETs,” *IEEE Trans. Veh. Technol.*, vol. 69, no. 9, pp. 9831–9844, Sep. 2020.

[13] S. Chen, J. Hu, Y. Shi, and L. Zhao, “LTE-V: A TD-LTE-based V2X solution for future vehicular network,” *IEEE Internet Things J.*, vol. 3, no. 6, pp. 997–1005, Dec. 2021.

[14] M. A. Al-Shareeda, M. Anbar, and I. H. Hasbullah, “Review of prevention schemes for broadcast storm problem in VANETs,” *IEEE Access*, vol. 9, pp. 14152–14172, 2021.

[15] M. Baza, N. Lasla, M. Mahmoud, and M. Younis, “Efficient and secure data dissemination for intelligent transportation systems,” *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 7, pp. 6542–6554, Jul. 2022.

[16] Y. Zhang, S. Leng, Y. He, and F. Wu, “A fog computing architecture for low-latency and secure VANET services,” *IEEE Netw.*, vol. 34, no. 2, pp. 136–143, Mar./Apr. 2020.

[17] C. Sommer and F. Dressler, *Vehicular Networking*. Cambridge, U.K.: Cambridge Univ. Press, 2021.

[18] 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 Amendment 6: Wireless Access in Vehicular Environments, IEEE Std. 802.11p-2010, reaffirmed 2020.

[19] ETSI EN 302 637-2, “Intelligent transport systems (ITS); vehicular communications; basic set of applications; Part 2: Specification of cooperative awareness basic service,” ETSI, Sophia Antipolis, France, 2022.

[20] T. Ali, K. N. Qureshi, and S. Iqbal, “Machine learning-based emergency message dissemination in VANETs,” *IEEE Access*, vol. 10, pp. 11245–11260, 2022.