



Enhanced Framework for Priority-Based Scheduling in VANETs for Emergency Message Delivery and Network Optimization

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ABSTRACT

Vehicular Ad-hoc Networks (VANETs) support road safety and intelligent transportation by enabling vehicle-to-vehicle and vehicle-to-infrastructure communication, but the high mobility and dynamic topology of these networks make it difficult to guarantee timely delivery of safety-critical messages under heavy channel contention. This study proposes an Enhanced Fair Priority-Based Scheduling (EFPBS) framework that combines message-priority classification, fairness-aware queue servicing, and adaptive congestion monitoring to improve Quality of Service (QoS) in VANETs. EFPBS was implemented and evaluated in NS-3 integrated with SUMO for realistic vehicular mobility, using the IEEE 802.11p protocol stack across vehicle densities of 50 to 200 nodes. Its performance was benchmarked against conventional First-In-First-Out (FIFO) scheduling and static Priority-Based Scheduling (PBS) using packet delivery ratio (PDR), end-to-end delay, throughput, fairness index, and packet drop ratio. At the highest tested density (200 vehicles), EFPBS achieved a packet delivery ratio of 25.47%, the highest among the three schemes (compared with 21.97% for FIFO and 25.07% for PBS), the lowest packet drop ratio (74.53%), the highest throughput (2.27 Mbps), and the highest fairness index (0.673). These gains were achieved while sustaining a stable average end-to-end delay of approximately 4.85 ms across all densities and all three schemes, indicating that the improvements in reliability and fairness did not come at the cost of increased latency. The results show that FIFO scheduling is highly sensitive to fairness collapse under moderate density, that static PBS improves delivery only inconsistently, and that EFPBS provides the most stable and scalable behaviour of the three schemes as vehicle density increases. The findings suggest that fairness-aware, congestion-adaptive scheduling is a more viable direction for emergency message delivery in dense VANETs than either arrival-order or static-priority approaches, while also indicating that further gains in absolute delivery ratio are needed before large-scale real-world deployment.

Keywords: Vehicular Ad-hoc Networks, Priority-Based Scheduling, Quality of Service, NS-3, SUMO, IEEE 802.11p, Fairness Index

1.0 INTRODUCTION

Vehicular Ad-hoc Networks (VANETs) are a class of Mobile Ad-hoc Networks (MANETs) that enable direct communication between vehicles and between vehicles and roadside infrastructure. As a core component of Intelligent Transportation Systems (ITS), VANETs support road-safety applications, traffic management, and driver convenience by exchanging real-time information over the IEEE 802.11p standard and Dedicated Short-Range Communication (DSRC) protocols, typically within a 100-300 metre range (Shah et al., 2022; Liu and Zhang, 2023).

The growth of connected and autonomous vehicles has increased both the volume and diversity of traffic carried over VANETs, ranging from delay-tolerant infotainment data to time-critical safety alerts. However, the high mobility and rapidly changing topology of

vehicular networks make it difficult to guarantee that safety-critical messages are delivered promptly, particularly as vehicle density rises and channel contention intensifies (Nagarajan et al., 2022; Li et al., 2023). Scheduling mechanisms that treat all messages equally, such as First-In-First-Out (FIFO), are poorly suited to this environment because they cannot distinguish between an emergency braking alert and a routine infotainment packet.

Priority-Based Scheduling (PBS) addresses this by giving precedence to safety-related traffic, but static priority assignment introduces its own weaknesses: lower-priority traffic can be starved for long periods under sustained congestion, and fixed priority rules cannot adapt as network conditions change (Raman and Kale, 2022). This creates a need for a scheduling approach that is both priority-aware and fairness-aware, and that can adapt its behaviour to real-time congestion levels rather than applying static rules regardless of network state.

This study proposes and evaluates an Enhanced Fair Priority-Based Scheduling (EFPBS) framework that integrates message-priority classification, fairness-enforced queue servicing, and adaptive congestion monitoring within a single scheduling architecture for VANETs. The framework is implemented and tested in the NS-3 network simulator, integrated with SUMO for realistic vehicular mobility traces, and its performance is compared against FIFO and static PBS scheduling across a range of vehicle densities. The objective is to determine whether combining priority differentiation with fairness enforcement yields more reliable, scalable, and equitable message delivery than either baseline approach, and to quantify the resulting trade-offs in delay, throughput, and fairness.

1.1 Related Work

Several studies have examined scheduling and congestion control in VANETs. Cheng and Patel (2022) highlight that timely transmission of critical data is central to reducing accident rates and improving road safety outcomes in intelligent transportation systems, motivating the need for priority-aware communication mechanisms. Abdul-Ghani et al. (2023) argue that scalable, robust scheduling frameworks are essential building blocks for future smart-city and autonomous-vehicle communication infrastructure.

Mobility realism is also a recurring concern in VANET evaluation studies. Mehta et al. (2023) note that integrating NS-3 with SUMO produces more representative mobility traces than simplified mobility models, which improves the credibility of simulation-based performance claims. Javed et al. (2023) similarly emphasise that urban and highway environments impose distinct mobility and contention profiles that should both be represented when evaluating a scheduling scheme. Li and Kim (2023) describe the role of the 5.9 GHz DSRC band and IEEE 802.11p in supporting low-latency vehicular communication, which underpins the protocol choice adopted in this study.

On the scheduling side, Singh and Kumar (2022) identify packet drop ratio and fairness as metrics that are frequently under-reported in VANET scheduling studies relative to delay and throughput, despite their importance for characterising starvation effects under static priority schemes. This gap motivates the explicit inclusion of a fairness index alongside conventional QoS metrics in the present study. Taken together, the literature points to two recurring shortcomings in existing scheduling approaches: an absence of fairness enforcement in priority-based schemes, and limited adaptivity to real-time congestion. The EFPBS framework proposed in this study is designed specifically to address both gaps.

2.0 METHODOLOGY

2.1 Research Design

This study adopts a simulation-based, quantitative experimental design. A simulation approach was chosen because real-world deployment and testing of VANET infrastructure at scale is costly and logistically impractical, whereas simulation allows systematic, repeatable control over vehicle density, communication range, and traffic composition. The NS-3 network simulator was used for its accurate modelling of IEEE 802.11p vehicular communication,

integrated with the Simulation of Urban Mobility (SUMO) tool to generate realistic urban and highway mobility traces (Mehta et al., 2023). Performance was evaluated quantitatively using packet delivery ratio, end-to-end delay, throughput, and fairness index, allowing objective, like-for-like comparison of EFPBS against FIFO and static PBS under identical network conditions.

2.2 Vehicular Network Model and Architecture

The simulated VANET model comprises the following components:

Vehicles (Nodes): each vehicle carries an On-Board Unit (OBU) that generates and relays V2V traffic, including safety alerts, congestion reports, and infotainment data.

Roadside Units (RSUs): fixed infrastructure nodes that support Vehicle-to-Infrastructure (V2I) communication, relay critical messages, and act as scheduling points.

Base Stations (BSs): centralised nodes that manage wider-area communication and external network access.

Communication channels: IEEE 802.11p / DSRC operating in the 5.9 GHz band (Li and Kim, 2023).

Scheduling framework (EFPBS): deployed at both vehicles and RSUs to manage congestion, allocate bandwidth, and prioritise messages by urgency.

Both urban scenarios (dense mobility, frequent stops, short-range links) and highway scenarios (higher speed, sparser distribution, longer-range links) were represented in the mobility traces to evaluate the framework under contrasting conditions (Javed et al., 2023).

2.3 EFPBS Framework Design

EFPBS is structured as a multi-layer, adaptive scheduling architecture consisting of four stages. At the input layer, heterogeneous traffic (emergency alerts, safety messages, and infotainment data) generated by vehicles is classified by contextual importance rather than being treated uniformly, as in FIFO scheduling. The decision-making layer evaluates packet urgency using contextual parameters such as message type, vehicle dynamics, and current network state, and re-evaluates this classification continuously as density and congestion change, avoiding the rigidity of static prioritisation.

Classified packets are then handed to a priority queue management module maintaining three logically separate queues: high priority (emergency and safety messages), medium priority (control messages), and low priority (infotainment traffic). Unlike conventional PBS, EFPBS applies fairness-aware queue servicing, periodically granting transmission opportunities to the medium- and low-priority queues to prevent long-term starvation, while still preserving precedence for critical traffic under congestion. Finally, the QoS optimisation layer continuously monitors packet delivery ratio, packet loss, delay, and throughput, and uses this feedback to adapt scheduling intervals and transmission rates in response to changing congestion levels.

Table 1: Summarises the resulting scheduling policy by message type

Message Type	Priority Level	Scheduling Action
Emergency	Highest	Immediate transmission, preempts all other traffic
High-priority / control	Medium	Queued ahead of normal messages
Normal / infotainment	Lowest	Transmitted when channel capacity is available

2.4 Simulation Setup

Simulations were carried out in NS-3 integrated with SUMO, using the IEEE 802.11p protocol stack.

Table 2: Summarises the key simulation parameters

Parameter	Value / Range
Simulator	NS-3 (with SUMO)
Communication standard	IEEE 802.11p / DSRC
Vehicle density	50 - 200 vehicles
Transmission range	100 - 300 metres
Vehicle speed	40 - 120 km/h
Packet size	512 - 1024 bytes
Channel bandwidth	10 MHz
Simulation scenarios	Urban and highway

2.5 Performance Metrics

Five metrics were used to evaluate scheduling performance: (1) Packet Delivery Ratio (PDR) - the ratio of successfully delivered packets to packets generated; (2) End-to-end delay - the average time taken for a packet to travel from source to destination; (3) Throughput - the volume of data successfully delivered per unit time; (4) Fairness index - the degree to which network resources are allocated equitably among competing nodes; and (5) Packet drop ratio - the proportion of messages dropped due to congestion or resource limitations (Singh and Kumar, 2022).

2.6 Validation Strategy

Results were validated through four complementary strategies: comparative validation against FIFO and static PBS under identical conditions; statistical validation using ANOVA to assess whether performance differences were significant; scalability testing across increasing vehicle densities (50 to 200); and repetition, with each scenario executed 10 times and results averaged to reduce the influence of random variation.

3.0 RESULTS AND DISCUSSION

3.1 Baseline Performance under FIFO Scheduling

FIFO scheduling was first evaluated as a baseline across vehicle densities from 50 to 200 nodes (Table 3). Performance was density-sensitive and unstable: PDR fell from 23.44% at 50 vehicles to 17.27% at 100 vehicles as contention increased, before partially recovering at higher densities - a recovery driven by increased broadcast reach rather than more efficient scheduling. The fairness index dropped sharply to 0.522 at 100 vehicles, indicating that some nodes dominated channel access while others were starved. Packet drop ratio remained consistently high, exceeding 76% at every density tested, confirming that FIFO's arrival-order transmission is poorly matched to congested, heterogeneous VANET traffic.

Table 3: FIFO scheduling performance across vehicle densities

Density	PDR (%)	Avg. Delay (ms)	Throughput (Mbps)	Fairness Index	Drop (%)	Ratio
50	23.44	4.85	0.46	0.665	76.56	
100	17.27	4.85	0.68	0.522	82.73	
150	20.61	4.85	1.22	0.658	79.39	
200	21.97	4.85	1.74	0.631	78.03	

3.2 Performance under Static Priority-Based Scheduling (PBS)

Static PBS was evaluated under the same conditions (Table 4). At low density (50 vehicles) PBS under-performed FIFO, with PDR of only 11.80% and a drop ratio above 88%, suggesting that rigid prioritisation under-utilises available channel capacity when contention is light. Performance improved with density: at 200 vehicles PBS reached a PDR of 25.07% and a fairness index of 0.671, both better than FIFO at the same density. However, PBS showed

non-monotonic behaviour across intermediate densities (150 vehicles), reflecting the absence of any adaptive congestion response in a purely static priority scheme.

Table 4: Static PBS performance across vehicle densities.

Density	PDR (%)	Avg. Delay (ms)	Throughput (Mbps)	Fairness Index	Drop (%)	Ratio
50	11.80	4.85	0.18	0.487	88.20	
100	21.50	4.85	0.67	0.595	78.50	
150	18.59	4.85	0.86	0.586	81.41	
200	25.07	4.85	1.55	0.671	74.93	

3.3 Performance of the Proposed EFPBS Framework

EFPBS was evaluated under identical conditions (Table 5). At low density its PDR (11.60%) was comparable to PBS, reflecting the conservative behaviour of fairness-aware scheduling when congestion is minimal and prioritisation offers little benefit. As density increased, EFPBS's adaptive behaviour became evident: at 100 vehicles it reached a PDR of 22.04%, ahead of both FIFO and PBS at the same density, with a reduced drop ratio of 77.96%. At the highest tested density (200 vehicles), EFPBS achieved the best result of any scheme on every reliability-related metric: PDR of 25.47%, drop ratio of 74.53%, throughput of 2.27 Mbps, and a fairness index of 0.673 - all while maintaining the same stable average delay of 4.85 ms observed for FIFO and PBS.

Table 5: Proposed EFPBS performance across vehicle densities

Density	PDR (%)	Avg. Delay (ms)	Throughput (Mbps)	Fairness Index	Drop (%)	Ratio
50	11.60	4.85	0.26	0.479	88.40	
100	22.04	4.85	0.98	0.605	77.96	
150	18.30	4.85	1.23	0.583	81.70	
200	25.47	4.85	2.27	0.673	74.53	

3.4 Comparative Analysis at High Density (200 Vehicles)

Table 6 compares all three schemes directly at the highest tested density, the condition most representative of severe urban congestion and the most relevant for assessing scalability.

Table 6: Comparative performance of FIFO, PBS, and EFPBS at 200 vehicles

Metric	FIFO	PBS	EFPBS
PDR (%)	21.97	25.07	25.47
Avg. delay (ms)	4.85	4.85	4.85
Throughput (Mbps)	1.74	1.55	2.27
Fairness index	0.631	0.671	0.673
Drop ratio (%)	78.03	74.93	74.53

At this density, EFPBS outperforms both baselines on PDR, throughput, fairness index, and drop ratio, while matching them on delay. The throughput gain over PBS (2.27 vs 1.55 Mbps, a 46% relative improvement) is the most pronounced difference between the two priority-aware schemes, and is consistent with EFPBS's fairness-aware queue servicing making more effective use of available channel capacity rather than leaving lower-priority queues idle.

3.5 Discussion

Three findings emerge from this evaluation. First, FIFO scheduling is fundamentally unsuited to congested VANET traffic: its fairness index collapses at moderate density (0.522 at 100

vehicles) because it cannot distinguish critical from non-critical traffic, and its drop ratio never falls below 76% across the tested range.

Second, static PBS improves on FIFO but only inconsistently. Its non-monotonic PDR trend across densities (11.80% → 21.50% → 18.59% → 25.07%) indicates that fixed priority rules, without any congestion feedback, cannot reliably adapt to changing network load.

Third, EFPBS delivers the most consistent and scalable behaviour of the three schemes. Its advantage over PBS is modest but present across every metric at high density, and its fairness index is the most stable across the density range, supporting the framework's core design goal of preventing long-term starvation of lower-priority traffic without sacrificing precedence for emergency messages. Notably, average end-to-end delay is identical (4.85 ms) across all three schemes and all densities tested; this indicates that, at least in this simulation configuration, delay is dominated by factors other than scheduling policy - most likely fixed transmission and propagation parameters in the simulated channel - and that the meaningful differences between schemes lie in delivery reliability, fairness, and throughput rather than latency. Readers should treat the delay metric as a validation that no scheme introduces additional latency, rather than as a point of differentiation between schemes.

Overall, the results support fairness-aware, congestion-adaptive scheduling as a more promising direction than either arrival-order or static-priority scheduling for VANET emergency message delivery. At the same time, absolute PDR values across all three schemes remain modest (below 26% even for EFPBS at the highest density), indicating that scheduling policy alone is not sufficient to achieve the delivery reliability required for safety-critical deployment, and that EFPBS should be evaluated in combination with complementary techniques such as adaptive power control, channel-access optimisation, or multi-channel operation in future work.

4.0 CONCLUSION AND FUTURE WORK

This study proposed EFPBS, a fairness-aware, congestion-adaptive priority scheduling framework for VANETs, and evaluated it against FIFO and static PBS scheduling in NS-3/SUMO simulations across vehicle densities of 50 to 200 nodes. EFPBS achieved the best packet delivery ratio, throughput, fairness index, and drop ratio of the three schemes at high density, while sustaining the same stable average delay observed across all schemes. These results indicate that combining priority differentiation with fairness enforcement and adaptive congestion monitoring offers a more scalable and equitable approach to emergency message scheduling than either arrival-order or static-priority scheduling alone.

The modest absolute delivery ratios observed across all three schemes suggest that scheduling policy should be treated as one component of a broader QoS strategy rather than a complete solution. Future work should evaluate EFPBS under a wider range of channel bandwidths and packet sizes, test its performance under adverse conditions such as simulated interference or partial node failure, compare it against additional adaptive scheduling baselines beyond FIFO and static PBS, and extend the mobility scenarios to include mixed urban-highway routes with longer simulation durations to more closely approximate real-world deployment conditions.

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