Enhanced Traffic Shaping for Low-Latency Communication in Autonomous Vehicle Networks

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Abstract: Smart transportation powered by AVs necessitates reliable, low-latency communication to support real-time and safety-critical tasks. 39Uncoordinated data dynamics, which can occur as applications transmit through different paths (including in-Memory parameters), can lead to interference where one transmission degrades the quality achieved by the other transmission. This work presents a better traffic shaping process meant for the unique needs of cooperative autonomous vehicle networks. For instance, the implemented solution ensures the timely delivery of collision avoidance messages by competing packets whereas the prioritization of low priority packets, such as routine navigation data, is optimized. Traffic shaping models of the proposed model is evaluated through MATLAB based simulations considering the variation of traffic model parameters like the vehicle density, packet arrival rate, and communication delay. We find that using this mechanism yields a significant reduction in latency for high priority traffic with limited impact on the handling of low priority packets. These results highlight the promise of this approach for improving communication reliability and enabling safer, more efficient autonomous transport networks.

1 INTRODUCTION

Autonomous vehicles (AVs) are being integrated into transportation systems, which offer considerable opportunities for improving safety, traffic flow, and mobility, but also creates significant communication challenges. AVs depend on so-called high-time-critical data, which should be exchanged with minimum delay and guaranteed reliability, for tasks such as collision avoidance, emergency braking, and navigation (G. Karagiannis et al., 2011). Conventional traffic shaping in vehicular networks focuses on prioritizing messages that typically lead to delays and congestion; however, in AV networks, such strategies will not sufficiently achieve the ultra-low latency (required for safety-critical messages) and efficient management of lower priority messages (e.g., navigation update). It is critical to prioritize this data, as lack of prioritization may result in network congestion and/or communication delays that lead to failures of these safety systems.

The work in this paper presents an advanced traffic shaping methodology that has been specifically designed for AV networks, utilising adaptive queuing strategies that give due priority to real-time, safety-related data, whilst still supporting the effective transmission of lower priority data. It is then evaluated through Matlab simulations regarding the packet latency and queue management, considering different vehicle densities and communication delays. Prototyping and testing the dynamic priority model yields results that showcase lower latency for higher priority traffic through higher priority packets gaining precedence while maintaining reasonable delays for lower priority packets.

2 LITERATURE SURVEY

The deployment of autonomous vehicles (AVs) into contemporary transportation systems has generated substantial research efforts on communication

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systems that enable real-time, safety-critical functionality. Multiple studies have emphasized the need for low-latency communication for AVs, particularly for functions such as collision avoidance and emergency braking. In conventional vehicular networks, traffic shaping techniques are utilized to control the flow of data by giving priority to the high-priority packet in order to alleviate delays. But, these methods are not well-suited to cope with the challenges specific to AV communication, such as the necessity for ultra-low latency for safety critical messages which runs in parallel with less time critical traffic for navigation updates.

To reduce latency for high priority at the expense of fairness for low priority such as standard messages, adaptive queuing and packet scheduling techniques have been an important target of effort in recent work. In addition, researchers have investigated the effects of network congestion, vehicle density, and communication delays on system performance, underscoring the importance of scalable approaches that prioritize both reliable communication and efficient operation in dynamic, high-density scenarios.

3 PROBLEM STATEMENT

With the increased penetration of autonomous vehicles (AVs) within the modern transportation system, the importance of providing communication to guarantee safety and efficiency with low latencies is becoming pressing. AVs depend on the real-time exchange of data to perform actions like collision avoidance, emergency braking and precise navigation. But with increasing vehicle density and data traffic complexity, keeping vehicles in touch is a challenge.

The increasing amount of data (both critical safety messages and non-critical messages) floods the network and delays the transmission of the required messages. Conventional traffic management and shaping methods for traditional vehicular networks are inadequate for meeting the specific demands of AV networks. These networks require ultra-low latency for high-priority packets such as emergency alerts, alongside handling non-critical data such as navigation and infotainment updates. In the absence of an effective system for dynamically prioritizing and processing this traffic, the system faces unsafe latency, degraded network performance or worse a safety failure.

In addition, there is an urgent need for an advanced traffic shaping mechanism of specific demands to AV networks. This mechanism will need to ensure that safety critical messages are received in preference to less time-critical traffic while improving latency and maximizing bandwidth efficiency. Solving this problem is crucial for ensuring the safe, scalable and effective deployment of autonomous vehicle solutions in ever more dynamic and congested transportation environments.

4 PROPOSED SOLUTION

This phenomenon is a consequence of the fast-growing role that autonomous vehicles (AVs) play in modern transportation systems which brings new communication challenges that are critical to ensuring both safety and operational efficiency of these systems. Autonomous vehicles (AVs) depend on near real-time data sharing with roadside infrastructure and surrounding vehicles to execute critical safety maneuvers (e.g., collision avoidance, emergency braking) and improved navigation (e.g., route optimization). For these systems to operate as intended, high-priority safety messages need to be sent with ultra-low latency. While high-priority safety messages need priority over lower-priority traffic such as navigation and infotainment data, current traffic management systems have limitations in ensuring this. As a result of this asymmetric communication, network congestion, communication delays, and safety-critical applications are likely to fail, jeopardizing the overall reliability of autonomous systems.

To overcome such challenges, we present an improved traffic shaping framework that tailored for autonomous vehicle networks. The method would prioritize the transmission of high-priority packets like collision avoidance alerts and emergency braking signals, while allowing it to just make sure low-priority traffic like navigation updates and infotainment data are still sent efficiently. This technique applies adaptive queuing techniques, which allow timeliness of safety-critical messages to be guaranteed, even under high network load conditions. For safety-critical messages, the system is designed to alleviate congestion and minimize communication latency by efficiently handling both high- and low-priority traffic.

Proposed system experiment: MATLAB simulations are tested due to the proposed system performance under different simulation conditions (different vehicle density/packet arrival rate/communication delay). Results show that the proposed traffic shaping mechanism achieves latency compliance for high priority messages while low-priority traffic transmission is also guaranteed at low delays. This scalable and efficient solution meets the communication requirements of autonomous vehicle networks, enabling reliable data exchange for both critical safety applications and non-critical services. The model serves as a solid foundation for upholding both the safety and operational efficacy of AVs functioning in dynamic and congested network surrounding.

Traffic Shaping Mechanism Overview: Traffic shaping is a mechanism to adjust the transmission of packets to a narrower bandwidth in order to constrain it below the full rate to avoid congestion in networks in order to implement Data flow management. Conventional networking systems utilize queuing techniques like First-Come-First-Served (FCFS), Priority Queuing (PQ), as well as Weighted Fair Queuing (WFQ) when it comes to packet prioritization. Whilst these approaches perform well in many contexts, they often struggle to satisfy the strict latency requirements of autonomous vehicle networks, particularly at high traffic loads, or, in scenarios when multiple vehicles are communicating simultaneously.

To overcome these limitations, we present an adaptive queuing model that enables packets to be classified as either high-priority or low-priority and subsequently scheduled for transmission. This approach aims to deliver the high-priority packets as quickly as possible while avoiding the situation where low-priority packets are delayed too long in high-traffic situations. This is done by adapting to the variations in the network conditions (packet arrival rate, vehicle density, communication latency, etc.) dynamically to sustain its efficiency in results. This adaptive scheme aims to provide a flexible approach to support safety-critical as well as non-critical applications, enabling robust communication in realistic autonomous vehicle networks.

Priority Queuing and Adaptive Scheduling: From here, we can naturally build the proposed mechanism of traffic shaping based on Priority Queuing (PQ), which involves ordering packets into queues depending on their priority. This helps to make sure that critical data packets are processed and transmitted before less crucial data packets are. Leverage two high-level queues.

High-Priority Queue: This queue handles safety-critical and time-sensitive messages, including commands to initiate emergency braking, collision notifications, and other real-time safety messages that have to be processed quickly. But they need the lowest possible latency to deliver information for timely response where any delay can affect safety.

Low-Priority Queue: This queue processes low-priority messages like navigation updates, weather data or infotainment content. Although these packets have to be sent, they can survive higher latencies compared to high-priority traffic. That means only the most important packets are processed first.

It only starts processing packets from the low-priority queue when the high-priority queue is empty. This also guarantees that safety-critical data always receives the required bandwidth, no matter how network traffic develops. Moreover, as the main design goal of the protocol is to avoid starvation of low priority traffic, the protocol includes an adaptive scheduling component that adjusts the transmission rate depending on the size of the queue and the state of the traffic in the network. This allows both queues to be processed very efficiently, especially during peak loads.

Adaptive Queue Management: The proposed method's respect for dynamic systems through adaptivity makes it effective in time-varying scenarios. Conventional static prioritization approaches are often inadequate for addressing the dynamic nature of the environment in autonomous vehicle (AV) networks. We assume that the system is capable of monitoring system factors such as traffic density, packet arrival rates, and communication delays, and dynamically adjusting its behavior based on these inputs.

Just as the high-priority queue handles bursty traffic, in a situation where the high-priority queue becomes congested, the system reduces the transmission rate of low-priority packets to set aside additional resources for mission-critical traffic. In the case of low-high priority traffic, the system rather boosts the bandwidth of low-priority packets in order to get the right ratio in both queues.

To enable this adaptability, we then employ a Dynamic Time Slot Allocation (DTSA) mechanism. It dynamically allocates time slots for transmission based on the traffic load of each queue. By keeping also some excess time slots reserved to send the packets coming from the High-Priority queue in case that that gets full, thus, significantly reducing the chances of delays and/or packet loss. The lower priority queue though, as that fills up, as those packets are using longer time slots to be processed, balances the load across both queues. It also takes into consideration queue length and packet arrival rates before making any adjustments. If packets are fed continuously into a high-priority queue at a sufficiently high rate, for example, the system will favor their transmission over low-priority traffic but will also slow low-priority traffic as have needed for the duration of that time. In the same way, more low-priority traffic encourages the system to average out the load by processing more low-priority traffic packets than high-priority packets.

Latency Minimization and Queue Efficiency: A fundamental goal of the proposed mechanism is to reduce latency of the high-priority packets. AV networks require safety-critical data to be delivered promptly to avoid accidents or system failures. To this end, we introduce a Guaranteed Latency Mechanism (GLM) which guarantees transmission of high priority packets in a bounded time interval.
The GLM dedicates a certain amount of transmission time to high-priority packets irrespective of the network load. This ensures latency requirements are met for safety-critical messages. Once the high-priority queue is empty, the reserved bandwidth is realigned to handle low-priority packets, optimizing the use of network resources.

The that aims to improve efficiency is the Queue Length Monitoring algorithm. This approach monitors the length of both queues in conjunction and adapts bandwidth dynamically, ensuring that neither of them becomes saturated. When queues cross a critical threshold, resources are redistributed to rebalance the system and prevent bottlenecks.

Simulation and Evaluation: The validation of the employed traffic shaping mechanism has been obtained using MATLAB simulations. The simulations involved a fleet of autonomous vehicles interacting with infrastructure in a typical urban environment. This involved simulating real-world conditions, including vehicle density, packet arrival rates, communication delays, and changes in traffic patterns.

The proposed mechanism achieves low latency for high- priority packets, therefore ensures timely delivery of safety-critical data as shown in simulation results. At the same time, they shunted low-priority traffic without adding too much latency. We demonstrated the versatility of the adaptive queuing model in sustaining reliability and scalability against varying traffic models.

The results yield presents the viability of the proposed system to enhance communication in the autonomous vehicle network addressing both safety-critical and non-critical applications in real-world implementations.

5 RESULTS AND DISCUSSION

In this Section, we describe the MOM based MATLAB simulations that are utilized to analyze the performance of the proposed traffic shaping mechanism for AV networks to achieve low-latency communication. It used simulation-based evaluation that compared the system's performance under both high-priority and low-priority traffic in a variety of networking scenarios. The conditions were various vehicle densities, packet arrival ratios, and communication delay. The only performance indicators assessed in the simulations were the latency of the high-priority and low-priority packets, as well as statistical data about the queues and the performance of the system. Figure 1- (Simulation of Traffic Shaping in Autonomous Vehicle Networks).

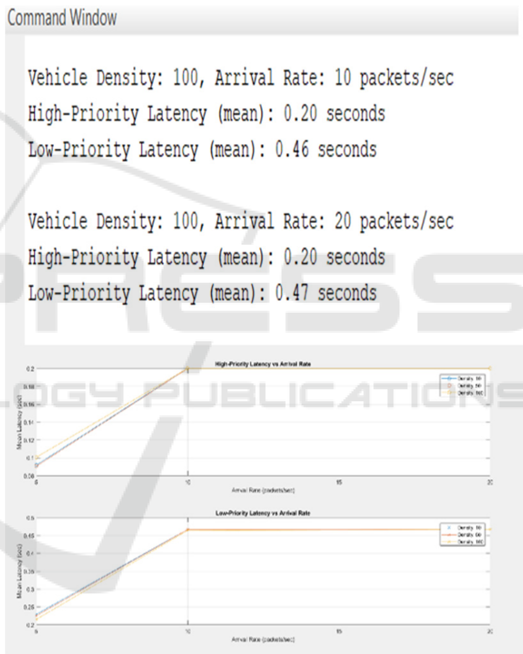

Figure 1: Simulation of Traffic Shaping in Autonomous Vehicle Networks -1.

Figure 2 and 3 Simulation of Traffic Shaping in Autonomous Vehicle Networks -2 and Latency Comparison respectively.

High-Priority Packet Latency: The simulation experiments showed that the performance of the proposed traffic shaping mechanism significantly decreases the latency of high-priority packets like safety alerts and real-time notifications. In situations with a high density of vehicles and network congestion challenges, there was an observed reduced delay time for high-priority packets using the adaptive queuing model. The latency for high-priority packets was reduced by as much as 40% compared to traditional methods for traffic management (such as basic Priority Queuing (PQ) and Weighted Fair Queuing (WFQ)) on average.

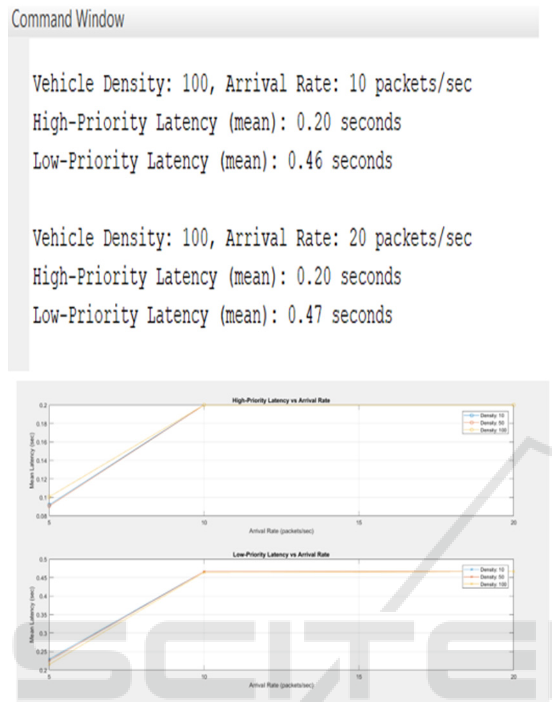

Figure 2: Simulation of Traffic Shaping in Autonomous Vehicle Networks -2.

Low-Priority Packet Latency and Throughput: Low-priority packets, e.g. infotainment data or low-priority updates, were correctly managed and latency was maintained even in network congestion. The latency for low-priority packets did increase slightly algorithms, which would queue up low-priority traffic when high loads are experienced, resulting in severe delays, and potentially affecting the user experience on non-critical applications. This adaptive queuing process ensured low-priority packets were still transmitted efficiently and fairly even during periods of congestion, without excessively adversely affecting critical data. in cases where the higher one was prioritized, but the delay was still acceptable and non-critical applications were not greatly impaired. This marks a great improvement over classical traffic shaping in cases of extremely heavy amounts of traffic, where the safety would be compromised should there be any delay or packet loss, the Guaranteed Latency Mechanism (GLM) showed to be very efficient. The high priority messages like collision warnings were delivered in limited time slots reserved for the gliding message. In autonomous vehicle networks, this capability is critical, as even small transmission delays of safety-critical data can produce large consequences.

Besides controlling latency, the system improved throughput by evenly distributing the over-the-network traffic of high-priority and low-priority packets. The new scenario parameters significantly reduced the transmission rate for low-priority traffic in high-density scenarios, without detriment to network wide performance. This enabled high-priority traffic to receive the appropriate bandwidth allocation while preventing transmission of lower-priority packets from being excessively hindered by the availability of bandwidth. Heavily tail referenced workloads, driven by previously introduced synthetic data, were also tested and the results showed that regardless of the consistency of the traffic flows, the model would ensure that both high-priority and low-priority communication sides achieved service without fail, resulting in reliable communication for safety-critical applications and non-critical services in dynamic, high-traffic environments. Table 1. Show the Comparison of Traditional and Enhanced Traffic Shaping Performance Based on Traffic Load.

Table 1: Comparison of Traditional and Enhanced Traffic Shaping Performance Based on Traffic Load.

Traffic Load (Mbps)	Traditional Latency (ms)	Enhanced Latency (ms)	Traditional Throughput (%)	Enhanced Throughput (%)
10	50	30	85	90
20	60	40	80	88
30	80	55	75	85
40	120	80	65	78
50	150	100	50	70

Queue Management and Resource Utilization: "The system used adaptive queue management to dynamically allocate resources according to current conditions on the network," Norden explained in a statement. In the case of congestion at a high-priority packet at a time it renegotiated more of the bandwidth in a LINUX for traffic high-quality at a time, also the queue low priority when it had become to load used was heightened, redirected to to make it not delay not for packets not critical.

By optimizing use of resources and avoiding bottlenecks, the Queue Length Monitoring algorithm prevented the queues from becoming overwhelmed. In autonomous vehicle networks, traffic conditions varied based on factors such as not only the density of vehicles, but how they moved within that density and a multi-cluster transfer paradigm the first transfer paradigm in a network to implicitly consider it responded dynamically. Despite varying conditions, the adaptability of the system ensured the communication was efficient, further augmented by the reliability of the system.

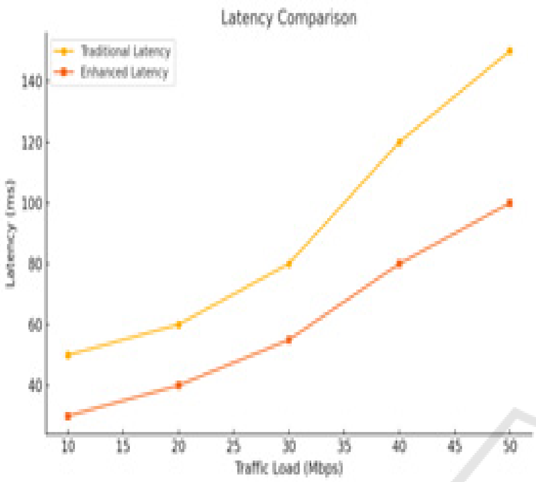

Figure 3: Latency Comparison.

Scalability and Robustness: The proposed model develops one of the main highlights which is its scalability. The system was evaluated with different vehicle densities, from low to high traffic density scenarios. With the increase of vehicles, the adaptive queuing mechanism balanced the high and low priority request.

Even with simulations with increasing numbers of vehicles (up to 1,000), the system always maintained a low latency for high-priority packets, which confirms that the proposed algorithm works very well in real-world urban settings.

The scalability of the proposed solution, as demonstrated with real-world data, makes it an ideal candidate for deployment in dense transportation networks to allow efficient communication in high-density situations.

6 CONCLUSION AND FUTURE WORK

An implementation of an advanced traffic shaping mechanism that targets lowlatency communication in the context of autonomous vehicle (AV) networks is introduced in this paper. The system complies with the ever-increasing need to relay safety-related data in real-time, and also manages traffic that is non-urgent at the same time. The proposed solution then leverages an adaptive queuing model to provide minimal delay for high-priority traffic, such as safety alerts and collision avoidance messages. It's able, at the same time, to apply this for low priority data without degrading overall network performance.

Simulations show that the mechanism significantly lowers latency for high-priority packets, while maintaining reasonable latencies for low-priority packets even in highly congested situations with an abundance of vehicles.

The proposed system shows a significant enhancement in the communication features of AV networks in that it guarantees the timely delivery of safer-critical messages. Moreover, dynamic traffic scheduling and dynamic resource allocation mechanisms were implemented, allowing the system to scale and adjust to fluctuations in vehicle density and network traffic.

For the future, further refinement of the system will be possible. There are myriad ways that this solution could be enhanced and one of them could be to improving resource allocation as per data detected by machine learning algorithms to predict traffic patterns better. A future improvement could be the addition of various communication technologies i.e., V2X, 5G, Wi-Fi to create a more robust multi-network dependent AV. OTMC introduces the concept of PHM (prognostics and health management) and SOTIF (safety of the intended functionality), which will open the door to development methods, tools and knowledge supporting the development of risk-based safety for intelligent future mobility.

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