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Mass Platooning: Information Networking Structures for Long Platoons of Connected Vehicles

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ABSTRACT Investigating Vehicle-to-everything (V2X) communication, we dive into the concept of vehicle platoons, a key innovation in transport systems, introducing a new era of cooperative driving. This new approach is designed to enhance fuel efficiency and improve overall traffic flow. Crucially, the success of this system relies on keeping vehicles at closely monitored distances, particularly at high speeds, which depends on rapid and reliable data exchange among vehicles through a wireless communication channel that is intrinsically unstable. The possibility of improving platoon efficiency through wireless data exchange is clear, but addressing network issues such as data loss and delays is crucial. These problems can compromise platoon functionality and need careful handling for real-world applications. Present platooning models also struggle with forming 'long' platoons with multiple vehicles due to the limited range of Vehicle-to-Vehicle (V2V) communication. Quick and efficient traffic information sharing is crucial to ensure vehicles have adequate time to respond. Given the safety-critical nature of these communications, both reliability and ultra-low latency are essential, particularly in platooning contexts. To address these challenges, we suggest a distance-based, network-aware relaying policy specifically for long platoons of connected vehicles. The results of our simulations indicate that this relaying approach significantly decreases communication breakdowns and narrows the error gap between vehicles, all achieved with only a slight increase in computational demand.

INDEX TERMS Cooperative adaptive cruise control (CACC), information flow topology, long platoon, multi-agent systems (MASs), multi-hop broadcast, piggybacking.

I. INTRODUCTION

Annually, the United States witnesses over 30,000 fatalities due to highway accidents. On average, Americans lose 97 hours yearly to traffic jams, leading to an economic burden of approximately \$87 billion in 2018 alone, which translates to about \$1,348 per driver each year. From an environmental perspective, congestion led to the waste of 44.3 billion liters of fuel globally [1], [2], [3]. While road expansion offers a partial remedy, its feasibility is constrained by high costs and limited available land. An alternative solution lies in transitioning from individual driving to cooperative driving strategies [4], [5]. Specifically, the concept of platoon-based driving involves a convoy of vehicles sharing a common route, where each vehicle closely and consistently follows the preceding vehicles, thus forming a platoon, as depicted in Figure 1, represents a form of cooperative driving that can significantly mitigate these issues.

The conventional Cruise Control (CC) systems allow drivers to set a desired speed, which the vehicle then maintains automatically. Adaptive Cruise Control (ACC), leveraging local sensors like radar and LiDAR, dynamically adjusts the vehicle's acceleration to maintain a predetermined distance from the vehicle ahead. However, due to the limitations of these sensors, ACC cannot function at intervals less than one second, leading to challenges in maintaining consistent inter-vehicle distances, known as

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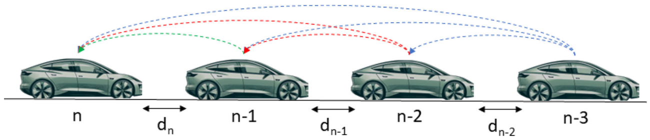


FIGURE 1. The diagram presents the communication framework among vehicles, where dashed lines represent the transmission of data between them. The notation d_n signifies the gap between the n^{th} vehicle and the one directly in front of it.

string stability issues [6]. To overcome these limitations, Cooperative Adaptive Cruise Control (CACC) technologies are being developed. CACC distinguishes itself by utilizing not just on-board sensor data but also incorporating kinematic data from other vehicles within the platoon, shared via Vehicle-to-Vehicle (V2V) communication, to enhance stability. Research outcomes suggested that the implementation of ACC might not substantially affect lane capacity. Conversely, CACC demonstrated a potential to substantially enhance lane capacity once its adoption reached moderate to high levels [7], [8]. The key to this improvement lies in the vehicles' ability to exchange information, enabling them to predict the movements of adjacent vehicles [9]. Consequently, a CACC-equipped vehicle can maintain a closer following distance to the vehicle ahead without compromising comfort or safety, thereby preserving the integrity of the platoon's string stability [10], [11].

The collective behavior of Connected and Automated Vehicles (CAVs) rely on each vehicle's mutual awareness of their surroundings. It is presumed that vehicles acquire accurate, real-time information about their surroundings through sensors, communications, and precise digital mapping [12], [13] A transitional period is anticipated where both cooperative and autonomous driving modes will share roadways. In this context, the role of driver behavior becomes pivotal for the development and functionality of connected vehicle technologies [14], [15]. Furthermore, it is essential to explore how the integration of these driving modes affects road safety, traffic efficiency, infrastructure capacity, and fuel consumption. Future advancements are expected to include vehicular networking strategies that incorporate social dynamics among vehicles [16], [17].

The cooperative management of the longitudinal motions in a group of CAVs can lead to several potential advantages for the transport system [18]:

- An increase in road capacity is achievable through minimizing the distances between vehicles [19].
- Reductions in energy usage and emissions of pollutants are possible by limiting unnecessary variations in speed and lowering the aerodynamic resistance encountered by following vehicles [20], [21].
- Improvements in driving safety could occur, given that system malfunctions may be less frequent than human errors, currently the predominant cause of vehicular accidents [22], [23], [24].
- Increased customer satisfaction is anticipated as vehicles in a platoon navigate autonomously, offering a smoother and safer ride while preventing the cutting in of other vehicles due to shorter inter-vehicle distances.

A platoon of CAVs functions as a Cyber-Physical System (CPS), merging computation, communication, and physical processes in both cyber and physical domains [2]. Within such platoons, the physical dimension is tied to vehicular motion, while the cyber dimension encompasses communication among vehicles and between vehicles and infrastructure [25], [26], [27]. The foundation of these distributed systems is the exchange of information, which is essential to achieve cooperative situational awareness. This exchange process outlines the method by which platoon vehicles communicate, primarily through broadcasting or beaconing protocols, which have been extensively explored within the vehicular networking community. The prevailing approach involves regular beacon broadcasts to all vehicles in range, enhancing cooperative awareness. Model-Based Communication (MBC) emerges as an innovative approach for enhancing communication scalability and alleviating channel overload [28]. Its main objective is to use a more adaptable broadcasting packet content structure, presenting the parameters of the combined vehicle dynamics and driver behavior models, diverging from the rigid Basic Safety Message (BSM) format specified by the J2735 standard [29]. For representing vehicle dynamics in the MBC framework, various modeling techniques are available, with non-parametric Bayesian inference methods, especially Gaussian Processes (GPs), showing potential for accurately representing the combined dynamics of vehicle motion and driver behavior.

Due to the constraints imposed by sensing and communication technologies, each vehicle controller typically has access to information only from its immediate vicinity. Consequently, controllers rely on localized data to achieve platoon-wide outcomes. Effective platoon management relies on seamless transmission of data between adjacent vehicles and from the lead vehicle down the chain. Numerous studies have explored strategies to enhance the communication reach from the platoon leader to its followers, especially beneficial for long platoons [30]. Although small platoons may experience minimal packet delays and losses even at high data transmission rates, longer platoons face increased risks of these issues under the same conditions due to the inherent limitations of wireless communication over extended distances [31]. The effectiveness of wireless communication diminishes as the length of the platoon increases, imposing a cap on the maximum number of vehicles that can be effectively connected [32]. Consequently, devising efficient communication protocols or algorithms is critical to ensure the effective dissemination of information within the platoon system [33], [34]. Despite advancements in optimizing network configurations for Multi-Agent Systems (MASs), the development of a V2V based framework is crucial for the fast and reliable distribution of critical safety messages throughout a long platoon. For the preservation of control system integrity, the wireless V2V network must ensure that the maximum Inter Packet Gap (IPG) does not exceed a predefined limit. Understanding packet propagation dynamics and identifying the principal determinants of delay within such a network are essential for accurately assessing communication latencies in platoon settings.

The size of the platoon significantly influences the efficacy of its communications. Our objective is to maximize platoon size, facilitating the efficient transit of a greater number of vehicles. This research employs distributed relaying through multi-hop communication for enhancing the broadcast link, enabling platoon members to relay packets from the leader to the rest of the platoon members [35]. This paper's core technical contributions are centered on examining how different communication information structures and Information Flow Topology (IFT) affect the scalability of homogeneous vehicular platoons in fixed formations, alongside the integration of this communication strategy with vehicular control mechanisms to consistently preserve inter-vehicle distances, irrespective of the platoon's length. Our key contributions include:

- Assessing and benchmarking the performance of extended platoons with respect to various communication strategies, considering both operational efficacy and network-centric metrics.
- Introducing a method for selecting distributed relays that incorporates the quality of the communication links and spatial parameters to minimize packet delivery times.
- The proposed approach seeks to diminish latency while considering the channel's capacity constraints.

II. RELATED WORK

The management of collective dynamics within a network of CAVs hinges on the vehicles' capability to perceive their own and each other's states, like the distance between vehicles and their velocities. These insights are garnered through inter-vehicle sensing and communication mechanisms. The effectiveness of cooperative applications is directly linked to the success rate of vehicular information exchange and the extent of the network that receives this information. This section focuses on CACC and its dependence on V2V communication.

A. COOPERATIVE ADAPTIVE CRUISE CONTROL (CACC)

During the 1990s, the concept of vehicle platooning gained widespread interest across both academic and industrial sectors, especially after the launch of the California Partners for Advanced Transit and Highways (PATH) program [36]. The primary objective in managing an autonomous vehicle platoon involves ensuring uniform speed across the platoon while maintaining a specified distance between each vehicle. For the n^{th} vehicle, characterized by its position $x_n(t)$, velocity $v_n(t)$, and gap with the vehicle in front d_n, as shown in Figure 1, the goal is to achieve the desired separation d_n^*.

$$\lim_{t\to\infty} |x_n(t) - x_{n-1}(t)| = d_n^* , \quad \text{for } n = 1, \ldots, N_v - 1 \quad (1)$$

where N_v is the number of platoon members. Another critical objective is the mitigation of disruptions or shock waves within the platoon, ensuring vehicles move at the same speed:

$$\lim_{t\to\infty} |v_n(t) - v_0(t)| = 0, \quad \text{for } n = 1, \ldots, N_v - 1 \quad (2)$$

with $v_0(t)$ representing the lead vehicle's speed. Detecting variations in the velocities of leading vehicles is crucial to diminish traffic shock waves, which result in "stop-and-go" patterns [23]. The goal of minimizing variations in acceleration is in line with the objectives in terms of fuel efficiency and ride comfort.

$$\lim_{t\to\infty} |a_n(t) - a_0(t)| = 0, \quad \text{for } n = 1, \ldots, N_v - 1 \quad (3)$$

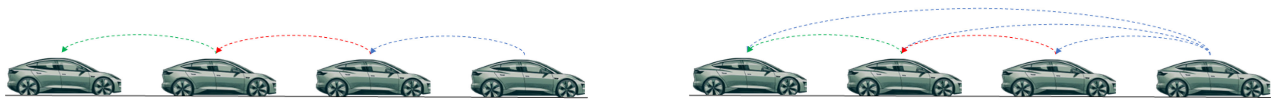
with $a_0(t)$ representing the lead vehicle's acceleration.

Direct transmission of precise state data allows vehicles to maintain closer proximity without endangering safety. Studies have established that platoons can attain both asymptotic and string stability, provided that time headway exceeds a certain minimum threshold. Moreover, it has been found that increasing the count of leading vehicles a vehicle responds to can lower this threshold [37]. Simulation results reveal that employing velocity feedback significantly improves platoon dynamics by reducing members' acceleration rates. Incorporating position feedback further smooths out reactions to changes in the leader's acceleration. The findings suggest that feedback from the vehicles that precede directly, rather than only from the leading vehicle, may also be effective [38]. In essence, the efficacy of platoon-based cooperative driving hinges on the network configuration and the control mechanisms in place, which integrate communication, computational, and physical elements.

1) INFORMATION FLOW TOPOLOGY (IFT)

In distributed MASs, IFT critically influences the communication links among agents, significantly affecting data sharing dynamics. The incorporation of wireless communication in CAV systems has introduced a variety of IFTs, posing unique challenges and opportunities for the design and analysis of such systems [39]. The selection from this broad spectrum of design options necessitates meticulous evaluation to enhance system efficacy. It has been identified that implementing CACC significantly boosts traffic flow and safety, independent of the chosen IFT.

In real-world applications, IFT often varies over time due to the dynamic nature of communication links and the changing presence of vehicles in the network. Figure 2 illustrates two IFTs commonly used in CAVs, Predecessor Following (PF) and Predecessor Leader Following (PLF). Additionally, more complex topologies like r-Predecessor Following (rPF) and r-Predecessor-Leader Following (rPLF) are applicable, as shown in Figure 1, where r indicates the number of directly communicated predecessors. In comparative terms, PLF and rPLF demonstrate superior performance over PF, with the choice between PLF and rPLF hinging on the availability of communication links. PF's limitation



(a) PF (b) PLF

FIGURE 2. Typical IFTs for a platoon: (a) Predecessor Following (PF); (b) Predecessor Leader Following (PLF).

in accessing information from distant vehicles restricts its communication benefits. By contrast, PLF enables CACC-equipped vehicles to receive advance traffic updates from the leader, enhancing anticipatory responses for traffic flow stabilization. rPLF, expanding on the communicative reach of CACC, allows following vehicles to leverage the data of preceding vehicles for improved traffic management. However, given communication constraints, there's a limit to platoon scalability, making platoon management essential. rPLF serves as a preferable choice with ample communication resources or in lower vehicle density settings, whereas PLF is deemed more suitable under restricted conditions [23], [40].

2) FORMATION GEOMETRY

Within the framework of platoon systems, the Formation Geometry aspect refers to the preferred spacing between vehicles, frequently referred to as the gap policy in various studies. Predominantly, three gap policies are widely adopted: Constant Distance (CD), Constant Time Headway (CTH), and Non-Linear Distance (NLD) policies [41]. The selection among CD, CTH, and NLD policies hinges on the criterion of vehicle speed affecting the desired inter-vehicle spacing. The CD method is effective for its capacity to boost traffic throughput by maintaining a reduced, fixed gap between vehicles, in contrast to the CTH approach.

B. VEHICLE-TO-VEHICLE (V2V) COMMUNICATION

In this work, we examine the mode-4 operation that facilitates direct communication among adjacent users equipped with Cellular Vehicle-to-everything (C-V2X) technology, through periodic transmissions of BSM. Generally, BSMs range from 180 to 300 bytes, with the potential to extend up to 1400 bytes for specific service messages. The emphasis on communication stems from the critical requirements for low latency and high reliability, as communications have shown to surpass sensors in significantly improving platoon safety. Enhancing traffic flow stability can be achieved by accessing detailed information from vehicles further ahead [40]. The distributed nature of these systems means that the following vehicles experience varying communication delays and are connected through different numbers of V2V links within V2V-based platooning frameworks. Such disparities in communication quality can markedly affect the functionality of CACC systems. Specifically, excessive communication delays or insufficient transmission rates can compromise string stability and other critical performance metrics for designated time gaps [31], [42]. Vehicular network topologies are inherently dynamic and complex, marked by diverse uncertainties such as communication delays, packet losses, and transmission errors [43]. These factors collectively influence the efficacy of CACC systems [44], [45], [46]. Interestingly, packet loss can effectively be seen as introducing randomness into the IFT, altering the communication dynamics within the platoon.

In the context of vehicular networks, the relay of traffic data across multiple hops necessitates scalability solutions to mitigate network congestion and minimize the transmission of unnecessary data, thus optimizing network capacity. A promising method for disseminating traffic information involves embedding compressed data within regularly transmitted BSMs, a technique known as piggybacking. However, this approach does not guarantee packet delivery as the broadcast mode lacks an acknowledgment (ACK) mechanism, leaving the broadcasters unable to detect collisions, leading to potential data loss without notification.

Addressing issues of channel congestion and packet loss in V2V communication has inspired various strategies aimed at maintaining network load at manageable levels and minimizing packet losses to acceptable rates. Yet, many of these solutions do not account for the distinct demands of specific applications, which may necessitate customized IFT. This oversight could particularly disadvantage applications like platooning, where a consistent and dependable exchange of information is crucial for operational integrity. In light of this, there have been efforts to devise methods that enhance the communication reach from the platoon leader to its members, with the aim of strengthening the cohesive functionality of the platoon [47]. However, these solutions often require mechanisms such as handshakes, which may not be feasible for all vehicular network applications [48], [49], [50].

1) MODEL-BASED COMMUNICATION (MBC)

To address packet losses in wireless vehicular communication, one strategy is to minimize dependency on V2V communications by smoothly transitioning to alternative solutions. For instance, the development of a velocity estimation algorithm aims to compensate for communication disruptions by leveraging transmitted models. Instead of simply sending beacon messages with updates on their position, vehicles can send a comprehensive situational awareness map to their neighbors. To compensate for packet losses, Ploeg et al. have leveraged onboard sensors for estimating the acceleration of the vehicle ahead, a measure typically reliant on V2V exchanges. In their work, for periods of brief communication disruptions, techniques such as the Kalman filter

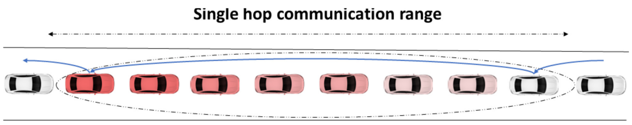


FIGURE 3. Desired multi-hop forwarder.

have been employed to estimate this acceleration, enhancing CACC management [51]. Implementing these strategies has shown to significantly improve string stability. However, these CACC design strategies generally do not incorporate the uncertainties associated with vehicle states, behaviors, and communications [9], [28], [52]. Despite acknowledging the uncertainty in communication delays, the possibility of messages not reaching their intended recipients has not been explicitly considered. The adoption of GP for predicting vehicle positions offers a novel approach by modeling the variability within a driver's behavior and the overall driving environment [53], [54], [55], [56]. Additionally, GPs have been proposed for planning overtaking maneuvers in autonomous racing scenarios [57]. GP, which generalizes multivariate Gaussian distributions to an infinite dimensionality, presents several advantages for system identification, including:

- The simplification of physics-based models thanks to GP's data-driven approach
- The use of Bayesian inference, which leverages marginal likelihood to mitigate the risk of overfitting
- GP models are particularly suited for situations where the data is scarce relative to the number of variables, effectively managing data insufficiency and measurement noise

2) RELAYING

In the realm of vehicular communication, single-hop transmission is predominantly employed for safety-critical applications where low latency is essential, such as in collision-avoidance systems that require instantaneous situational awareness [15]. Conversely, multi-hop communication serves applications necessitating the propagation of vehicle or road data over distances exceeding the limitations of single-hop transmissions. This includes a range of safety and efficiency related applications, from emergency vehicle and post-crash warnings to traffic information dissemination, vehicle tracking, traffic management, and road monitoring. Given the paramount importance of time-sensitive safety applications, research has predominantly concentrated on single-hop communication paradigms. However, multi-hop communication, despite its broad applicability, has often been overlooked in discussions surrounding the distinct requirements and characteristics of both efficiency and safety operations. This study specifically addresses the challenge of integrating vital safety communications within a framework that also accommodates the multi-hop transmission of general traffic information and other non-critical data [58].

The efficacy of tracking applications and their tracking precision depend on the volume of vehicle data successfully transmitted and the extent of the network coverage that receives these data [59]. Information pivotal to multi-hop safety and efficiency applications, such as details on traffic jams, vehicular density, movement patterns, or obstructions, varies in relevance according to the distance of the recipient from the data source. For these applications, which can accommodate certain delays, the expedited relay of data across vast distances does not present a clear advantage. Employing piggyback techniques on beacon signals for data forwarding, though not the fastest method, significantly reduces network congestion by circumventing the need to generate additional packet overhead. In the context of relay selection algorithms, the existing methodologies can essentially be grouped into three categories:

- Centralized: leveraging data from all agents
- Decentralized: depending solely on an agent's individual data
- Distributed: incorporating data from the agent as well as its immediate neighbors.

Given the logistical challenges associated with harnessing state information from all agents for relay selection, decentralized and distributed approaches are deemed more feasible for MASs.

Within the framework of a single relay approach, the Platoon Member (PM) that accurately identifies the Platoon Leader's (PL) signal and is situated nearest to the platoon's end is designated as the relay. This method optimizes the channel quality between the chosen relay and the receiving PMs, facilitating superior reception capabilities compared to other potential relays. Initial findings indicate that the communication of data related to objects at the sensory boundaries notably enhances tracking efficacy [60]. In [61], the effectiveness of various distance-based content selection strategies for vehicular map dissemination was examined. The studies revealed that adopting a probabilistic method, prioritizing distant objects within the transmitter's perception map for message inclusion significantly improves tracking precision.

Limitations of current state-of-the-art algorithms include the necessity for handshake mechanisms and the aging of broadcasted information. Yet, there's a pressing demand for the fast broadcasting of aggregated traffic data across multiple hops. A notable study on side-link relays for platooning introduced two relay strategies that leverage geographical data, necessitating handshake protocols in which each recipient must acknowledge receipt or non-receipt (ACK / NACK) from the sender [62]. An improvement to the relay selection process was suggested, identifying the optimal relay as the node capable of reaching every intended recipient within a specified destination zone [38]. Another approach considered relay selection based on reception likelihood [47], though this method incurred additional delay. Importantly, when a Road Side Unit (RSU) serves as a broadcast relay, it operates without expecting or processing any feedback, so it doesn't engage in re-transmissions in the event of packet loss. This work concentrates on evaluating the effects of packet relay via RSUs on application-level outcomes, specifically focusing on maintaining inter-vehicle distances within platoons, which requires both infrastructure support and the exchange of time-sensitive information [63]. A scheme for platoon-centric cooperative retransmission has been devised, using a 4-D Markov chain to enable senders to correct errors in previous transmissions for their platoon neighbors [64]. Additionally, a fundamental strategy for achieving scalable platooning involves employing information topologies with a consistent tree depth [65].

From the given illustration, it becomes apparent that selecting the most distant vehicle within the communication range as the next relay might seem ideal for retransmission tasks. Nevertheless, the reality that vehicles beyond a certain range might suppress their broadcasts, anticipating that subsequent vehicles will propagate the message, is complicated by the fact that Packet Error Ratio (PER) invariably escalates with distance. This situation requires that the vehicle chosen for the ensuing transmission must consider both its proximity to the initial sender and the likelihood of successful message receipt by vehicles further afield. To satisfy these criteria, a distance-dependent probabilistic method is suggested. Consequently, the selection of the next relay does not automatically favor the most remote vehicle; instead, it is based on a calculated probability, taking into account the specific circumstances of potential forwarders.

III. PRELIMINARIES AND PROBLEM FORMULATION

The significance of communication topology in coordinating MASs forms the basis of our exploration in this paper, where we delve into the role and attributes of a fixed communication network topology on distributed consensus efficacy across six distinct network models. The study examines the impact of various IFTs on the performance of CACC systems. A comprehensive analysis comparing different IFTs is essential for guiding their selection, applicable regardless of the platoon size. In standard vehicular communication frameworks, message loss tends to escalate with distance from the source, adversely affecting tracking performance. Various strategies have been proposed to enhance the signal reach from the PL to other members, especially when managing platoons at the limit of the C-V2X capacity. Platoon management is essential when the CACC system approaches the maximum number of vehicles that can be supported by stable C-V2X communication range. This paper details efforts to reduce Information Age (IA) using a network-aware approach that incorporates probabilistic and distance-dependent strategies.

We define the actors as follows.

- Platoon Leader (PL): This CAV controls the platoon's speed.

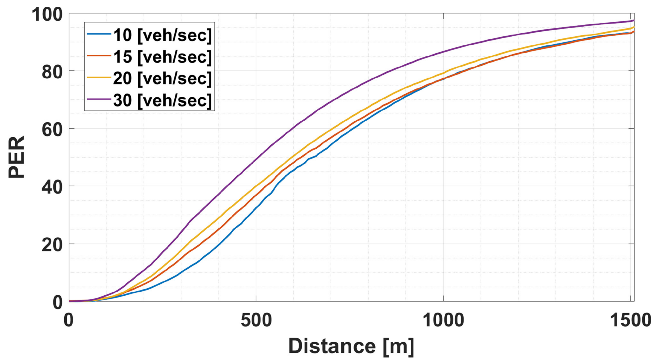


FIGURE 4. Packet Error Rate (PER) for different traffic flows at various distances.

- Platoon Member (PM): A CAV following the PL's directives. It also communicates with adjacent vehicles and relays messages to the next vehicle.

As illustrated in Figure 1, platoon vehicles can simultaneously transmit and receive data, acting as relays. We categorize communications into two types:

- PL's broadcasts: Broadcasting by PL enables transmission of information to PMs within range.
- Direct V2V interactions among PMs: It's assumed that PMs communicate through one-hop V2V connections.

A. CHANNEL MODEL

Researchers adopt a basic communication framework to examine how factors such as actuation delay, message frequency, and communication latency influence the minimal viable spacing between vehicles. For instance, analyses incorporate a comprehensive IEEE 802.11p simulation model, which, for specific application needs, allows for the substitution of different link quality estimators [60], [66], [67], [68]. The need for multiple hops increases as the distance between the lead and the last vehicle in the platoon increases, a scenario more common in long platoons [69]. For the purposes of channel modeling in this study, we rely on PER data derived from prior research [27], [70], utilizing PER as the channel model [71]. Figure 4 illustrates the PER for different vehicle densities at various distances. As expected, the PER increases with both an increase in distance and density.

B. VEHICLE MODEL & MODEL PREDICTIVE CONTROL DESIGN

At the heart of these vehicular systems lies the objective to compute the vehicle's control inputs through solving an optimization problem framed within a Model Predictive Control (MPC) framework, which accounts for the future driving pattern of the vehicle ahead. Within these MPC-driven systems, the forthcoming state of the vehicle ahead is anticipated, and by solving an optimization problem, the necessary control inputs for the following vehicle are determined. Consequently, this approach facilitates a predictive car-following pattern, enhancing vehicular efficiency by adaptively adjusting the distance and velocity [72].

1) VEHICLE MODEL

In this study, we consider a platoon of N_v vehicles, where $n \in \{0, 1, \ldots, N_v - 1\}$ denotes the n^{th} vehicle in the platoon, and $n = 0$ represents the platoon leader. As shown in Figure 1, d_n denotes the gap between n^{th} and $(n-1)^{th}$ vehicles and is defined as

$$d_n = x_{n-1} - x_n - l_n^v, \tag{4}$$

where x_n denotes the longitudinal position of the rear bumper of the n^{th} vehicle, and l_n^v its length. The strategy adopted here employs a fixed time headway for spacing between vehicles to enhance string stability and safety. This desired spacing is articulated as

$$d_n^*(t) = \tau_n\, v_n(t) + d_n^s. \tag{5}$$

where $v_n(t)$ is the speed of the n^{th} vehicle, τ_n the time headway, and d_n^s the standstill distance. The deviation in spacing from its desired value is $\Delta d_n(t) = d_n(t) - d_n^*(t)$, and the difference in speed between the n^{th} vehicle and the one preceding it is $\Delta v_n(t) = v_{n-1}(t) - v_n(t)$. Consequently, the change in this spacing becomes $\Delta \dot{d}_n(t) = \Delta v_n(t) - \tau_n a_n(t)$ and the velocity difference evolves as $\Delta \dot{v}_n = a_{n-1} - a_n$, where a_n indicates the acceleration of the n^{th} vehicle. Incorporating the driveline dynamics f_n, the acceleration rate for vehicle n is formulated as $\dot{a_n}(t) = -f_n a_n(t) + f_n u_n(t)$, with $u_n(t)$ serving as the control input. Defining $S_n = [\Delta d_n, \Delta v_n, a_n]^T$ as the state vector for the n^{th} vehicle, its dynamic behavior is captured by the state-space model

$$\begin{aligned}\dot{S}_n(t) &= A_n\, S_n(t) + B_n\, u_n(t) + D\, a_{n-1}(t) \\ &= \begin{bmatrix} 0 & 1 & -\tau_n \\ 0 & 0 & -1 \\ 0 & 0 & -f_n \end{bmatrix} S_n(t) + \begin{bmatrix} 0 \\ 0 \\ f_n \end{bmatrix} u_n(t) + \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} a_{n-1}(t).\end{aligned} \tag{6}$$

For the leading vehicle $(n = 0)$, the term $a_{n-1}(t)$ is considered to be zero. Transitioning to a discrete-time model using a first-order forward approximation results in

$$S_n(k+1) = (I + t_s\, A_n)\, S_n(k) + t_s\, B_n\, u_n(k) + t_s\, D\, a_{n-1}(k), \tag{7}$$

with t_s denoting the sampling time.

2) MODEL PREDICTIVE CONTROL (MPC)

This research incorporates various constraints related to the system's state and inputs, which include limitations on acceleration, control inputs, the maximum speed allowed, and the spacing between vehicles (with the understanding that negative spacing implies a collision scenario, which is unacceptable). These constraints are formalized as follows:

$$a_n^{min} \le a_n(k) \le a_n^{max}, \tag{8a}$$
$$u_n^{min} \le u_n(k) \le u_n^{max}, \tag{8b}$$
$$v_n(k) \le v^{max}, \tag{8c}$$
$$d_n(k) > 0. \tag{8d}$$

TABLE 1. The value of the parameters used in the model and optimization in the simulations.

Parameter	Value	Parameter	Value
N	10	t_s	$0.1\,s$
l_n^v	$5\,m$	d_n^s	$2\,m$
a_n^{max}	$3\,m/s^2$	a_n^{min}	$-4\,m/s^2$
u_n^{max}	$3\,m/s^2$	u_n^{min}	$-4\,m/s^2$
f_n	$10\,s^{-1}$		

Furthermore, to ensure passenger comfort, the variation in system inputs is constrained by

$$t_s\, u_n^{min} \le u_n(k+1) - u_n(k) \le t_s\, u_n^{max}. \tag{9}$$

The objective of the MPC for each vehicle involves minimizing the control inputs over a predictive horizon, stated as

$$\min_{u_n} \sum_{k=0}^{N-1} \Big[(\mathbf{S}_n(k) - R_n)^T\, Q_n\, (\mathbf{S}_n(k) - R_n) \Big] \tag{10}$$
subject to: System Constrains,

where $\mathbf{u}_n$ encompasses the control inputs from $k = 0$ to $k = N - 1$, where N is prediction horizon (refer to Table 1), Q is the state weighting matrix, used to penalize deviations from the desired trajectory. It is typically a symmetric positive semi-definite matrix and R is the reference trajectory or setpoint for the state, ensuring that control efforts are minimized.

Remark 1: The MPC framework employed here adopts a single look-ahead approach. Altering the cost function in (10) allows for the incorporation of an r look-ahead strategy, detailed as

$$\begin{aligned}&\sum_{k=0}^{N-1} \Big[(\mathbf{S}_n(k) - R_n)^T\, Q_n\, (\mathbf{S}_n(k) - R_n) \\ &\quad + \sum_{i=n-r}^{n-1} \mathbf{I}_{i>0} \times \Bigg[c_i^d \Bigg(x_i(k) - x_n(k) - \sum_{j=i+1}^{n} \Big(d_j^*(k) + l_j^v \Big) \Bigg)^2 \\ &\quad + c_i^v\, (v_i(k) - v_n(k))^2 \Bigg]\Bigg],\end{aligned} \tag{11}$$

where c_i^d and c_i^v are positive scalars, and r indicates the count of predecessors sharing information with the n^{th} vehicle. This approach enables a vehicle to adjust its velocity and spacing in relation to its r preceding vehicles. Notably, if the number of available predecessors is fewer than r, the vehicle adjusts its calculations based on Indicator function $\mathbf{I}_{i>0}$ which is defined as

$$\mathbf{I}_{i>0} = \begin{cases} 1 \text{ if } i \ge 0 \\ 0 \text{ if } i < 0 \end{cases} \tag{12}$$

C. STOCHASTIC MODEL-BASED COMMUNICATION

In this paper, the velocity of each cooperative vehicle over time, indicated as $v_n(t)$, is modeled as a GP. This process is characterized by a mean function, $m_n(t)$, and a covariance kernel function, $\kappa_n(t, t')$, as follows:

$$v_n(\mathbf{t}) \sim \mathcal{GP}\Big(m_n(\mathbf{t}), \kappa_n\big(\mathbf{t}, \mathbf{t}'\big)\Big). \tag{13}$$

Our focus is on integrating the insights derived from the observed velocity data regarding the underlying function, $v_n(t)$, and its future projections. We assume that for each cooperative vehicle, the mean of the process is zero, $m_n(t) = 0$. We use a Radial Basis Function (RBF) as the covariance kernel and consider the measurement noises to be independent and identically distributed (*i.i.d.*) following a Gaussian distribution, $\mathcal{N}(0, \gamma_{n,noise}^2)$. Under these assumptions, the covariance matrix for the observed velocity of the n^{th} cooperative vehicle can be expressed as follows:

$$K_n\big(\boldsymbol{t}, \boldsymbol{t'}\big) = \kappa_n\big(t, t'\big) + \gamma_{n,noise}^2 I \tag{14}$$

In this context, I represents the identity matrix, whose dimension matches that of the training (measured) data. Calculation of $\kappa_n(t, t')$ can be performed on the basis of the definition of the RBF, as follows:

$$\kappa_n\big(t, t'\big) = \exp\left(-\frac{\|t - t'\|^2}{2\gamma_n^2}\right). \tag{15}$$

Under the assumptions mentioned above, we can represent $\mathcal{V}_n^{obs}$, and the future values, $\mathcal{V}_n^*$, in the following way:

$$\begin{bmatrix} \mathcal{V}_{\mathbf{n}}^{\mathbf{obs}} \\ \mathcal{V}_{\mathbf{n}}{}^* \end{bmatrix} \sim \mathcal{N}\left(\mathbf{0}, \begin{bmatrix} K_n(\boldsymbol{t}, \boldsymbol{t}) & K_n(\boldsymbol{t}, \boldsymbol{t^*}) \\ K_n(\boldsymbol{t^*}, \boldsymbol{t}) & K_n(\boldsymbol{t^*}, \boldsymbol{t^*}) \end{bmatrix}\right), \tag{16}$$

In this formulation, $\boldsymbol{t}$ and $\boldsymbol{t^*}$ represent the time stamps associated with the sets of observation and future values, respectively. The function $K_n(.,.)$ is derived as per the kernel matrix described in (14). Therefore, the predictive distribution of future velocity values, $\mathcal{V}_n^*$, conditioned on having observed velocity values $\mathcal{V}_n^{obs}$ on time stamps $\boldsymbol{t}$ can be derived as;

$$\begin{aligned} &\left(\mathcal{V}_{\mathbf{n}}{}^* \mid \mathbf{t}^*, \mathbf{t}, \mathcal{V}_{\mathbf{n}}^{\mathbf{obs}}\right) \sim \mathcal{N}\left(\mu_n^*, \Sigma_n^*\right), \\ &\mu_n^* = K_n\left[\left(t^*, t\right)|\Theta_n\right] K_n^{-1}[(t, t)|\Theta_n]\, \mathcal{V}_{\mathbf{n}}^{\mathbf{obs}}, \\ &\Sigma_n^* = -K_n\left[\left(t^*, t\right)|\Theta_n\right] K_n^{-1}[(t, t)|\Theta_n]\, K_n\left[\left(t, t^*\right)|\Theta_n\right] \\ &\qquad +K_n\left[\left(t^*, t^*\right)|\Theta_n\right]. \end{aligned} \tag{17}$$

where Θ_n is the set of parameters, e.g., $\Theta_n = \{\gamma_n, \gamma_{n,noise}\}$. Each PM will receive information from preceding vehicles if communication is successful, or they will update the information with the stochastic model estimator if data is not received. For more information, refer to [9], [23], [33], [34].

D. NETWORKING AND RELAYING STRUCTURES

When communication stability is compromised, CAVs autonomously disengage from the PL, reverting to ACC while initiating a new platoon formation. To counteract this, employing relay techniques for long platoons becomes crucial. Furthermore, signals from the PL undergo significant path loss over extended distances, impeding the ability of PMs to accurately decode the leader's signals. Relay technologies serve as a vital solution to mitigate path loss challenges.

The effectiveness of communication systems is evaluated based on three primary criteria:

- *Reliability and Reachability:* In scenarios where a network maintains full connectivity alongside frequent dissemination of single-hop safety beacons (BSMs), techniques leveraging piggybacking on these beacons can attain 100% reachability.
- *Scalability:* The forwarder ratio, indicative of the proportion of vehicles retransmitting a message against the total number of vehicles within a single-hop range, is critical. Scalability ensures that the concept of string stability remains unaffected by variations in platoon size, allowing for the seamless integration or disengagement of vehicles.
- *Information Age (IA):* Defined as the time elapsed since the last update received from vehicle j in vehicle i, IA reflects the freshness of the information. Upon receiving new data on the vehicle j, IA temporarily equals the message delivery latency, then increases until the next update. Maximum IA is influenced by both broadcast frequency and forwarding delays, with our forwarding algorithm aiming to minimize IA while considering channel and network conditions to prevent congestion.

Addressing the challenge of minimizing status update delays is complex, given that beacons are disseminated via broadcast without support for acknowledgments or retransmissions. Adjustments to the transmission rate or range are typically managed by single-hop safety protocols. However, our approach allows for control over message size by including BSM and additional data within each packet. Studies on Dedicated Short-Range Communications (DSRC) indicate that augmenting a DSRC beacon by 100 bytes barely affects its overall performance. The relationship between the augmentation of piggybacked data volume and the increment in forwarding delay follows a logarithmic pattern [73], and employing piggybacking rather than expanding single-hop beacon coverage effectively reduces channel congestion [74], [75].

Research shows that the Information Dissemination Ratio (IDR) initially increases with channel load up to a certain optimal point before drastically declining [76]. This phenomenon highlights the negative implications of overloading the communication channel, such as elevated packet loss rates, which increase IA and diminish network reachability. Ideally, without channel load constraints, the simplistic flood broadcasting technique would emerge as superior, characterized by immediate retransmission of all received messages by each vehicle, promising the utmost reachability and minimal IA, assuming channel capacity isn't exceeded. Consequently, an optimal communication strategy should not only achieve extensive reachability and minimal IA but also regulate the channel load to hover near the peak IDR value. Nonetheless, due to bandwidth inefficiencies and the risk of generating duplicate packets, flooding is impractical for vehicular networks. Consequently, vehicular broadcast protocols typically impose limits on the number of data-forwarding participants to ensure system scalability.

Given the dynamic nature of network conditions that may vary for each vehicle, the determination of whether a vehicle should act as the next forwarder is made on an individual basis, following a probabilistic approach. Upon receiving a message for the first time, a vehicle undergoes a Bernoulli trial with a predetermined probability of success to decide on the rebroadcast of the message. In the case of a uniform probabilistic rebroadcast strategy, this probability remains constant across all vehicles. Hence, each vehicle, performs a Bernoulli trial with a success probability $p_i = \delta/M$, where M denotes the count of vehicles within a single-hop communication vicinity, and $\delta \in [1, M]$ established in accordance with the specific demands of the multihop safety or traffic applications, serves as the reliability factor of the approach. The logic dictates that an increased δ enhances the probability of message rebroadcast across vehicles, as the success probability is uniformly applied. Consequently, a higher δ not only boosts the forwarder ratio and the network's load but also augments the probability of beacon retransmission, thereby enhancing reliability at the cost of increased network load. This underscores why δ is referred to as the reliability factor.

All algorithms for multi-hop broadcasting in vehicular networks share two fundamental procedures: broadcasting a message to all nearby vehicles and identifying the subsequent forwarder for further message propagation. These processes aim to maximize reachability and minimize both the IA and network congestion. Broadly, vehicular multicast protocols fall into two categories: topology-based and position-based methods. The former selects forwarders based on network topology, whereas the latter depends on geographic information, such as the positions of the source, destination, and neighboring nodes, along with the coordinates defining the multicast area [77]. An exemplary position-based method is the ETSI Geo-networking geo-broadcast, a straightforward form of flooding, known for achieving high packet delivery rates but potentially leading to a broadcast storm issue. To ensure high packet delivery while reducing the number of transmitting nodes, certain nodes are chosen based on topological and connectivity criteria. The node predicted to have the highest reception probability is designated as the relay. This selection method has been shown to provide greater reliability than location-based relaying, albeit at the cost of increased latency.

In our approach, vehicles probabilistically include the messages received from the PL in their subsequent beacons. Specifically, the success probability is calibrated such that, within each beacon interval, at least one vehicle is guaranteed to rebroadcast the message, ensuring the mean number of rebroadcasts exceeds one. To underscore the effectiveness of our method, it's crucial to assess how the selection of the next relay within the single-hop range influences IA. For instance, within a counter-based rebroadcast strategy, imagine k sequentially aligned vehicles within the same communication range (refer to Figure 3). If the foremost vehicle rebroadcasts a message received from a previous hop, the decision of the remaining $(k-1)$ vehicles to relay this message or defer to others significantly impacts IA. In particular, IA is affected differently if the rearmost vehicle, as opposed to one immediately behind the leader, rebroadcasts the message, as the former scenario extends the information further, whereas the latter limits dissemination to a shorter range, potentially inhibiting subsequent relays. Hence, the probability that vehicle i includes a message from vehicle j in its next beacon is given by

$$p_i(j) = \min\left(\frac{\text{ISPF}(d(i,j))}{1 - \text{PER}_i(j)}, 1\right) \tag{18}$$

where ISPF$(d(i,j))$ denotes the Ideal Success Probability Function for vehicle i rebroadcasting [60]. Assuming perfect channel conditions and no packet loss, the success rate would mirror the ISPF output, calculated solely on the vehicular distance since the denominator would consistently be one. However, in practice, as attenuation and the likelihood of collisions increase with distance, leading to a higher PER, the rebroadcast probability is adjusted to counteract reduced transmission chances. The use of the minimum function ensures that the success probability does not exceed one. It's noteworthy that despite the variation in success probability in (18), the Bernoulli trials remain independent, aligning with the Poisson binomial distribution across N trials in probability theory.

Initially, the ISPF could align with uniform probabilistic approaches, assigning identical chances of success across all vehicles. Yet, this model would inherently favor nearer vehicles due to their lower PER, as the numerator in (18) remains constant while the denominator decreases as PER increases by distance. Although PER's behavior is contingent upon network conditions, our protocol adjusts the ISPF to counteract PER's influence significantly. Preferably, the protocol aims to select the most distant vehicle within a single-hop range for message forwarding. By appropriately increasing the ISPF's numerator with distance, the adverse impact of PER is neutralized, enhancing the forwarding probability for distant vehicles. Our proposed ISPF is defined as

$$\text{ISPF}(d(i,j)) = \frac{1 - \exp\left(\lambda_i \times \frac{d(i,j)}{D(P_{tx})}\right)}{1 - \exp(\lambda_i)}, \quad \lambda_i > 0, \tag{19}$$

where $d(i,j)$ represents the Euclidean distance between vehicles i and j, and $D(P_{tx})$ symbolizes the single-hop communication range (in meters), with P_{tx} indicating transmission power. The scale parameter λ_i is adaptively modified based on the density and average velocity of vehicles within vehicle i's single-hop range. Notably, for $\lambda_i > 0$, $(1 - exp(\lambda_i)) < 0$, the function shows a monotonically increasing trend with distance. In scenarios of free-flow traffic, λ_i mirrors traffic flow (vehicles per second), with inter-arrival times following an exponential distribution of parameter λ_i and average speed $(\bar{v})$ is independent of the traffic flow and density. The calculation of λ_i thus becomes $\lambda_i = \bar{v}\rho$, integrating average speed and density metrics [69], [78].

Specifically, ISPF is designed to evaluate a PM's potential as a relay, focusing on its ability to extend communication range and sustain robust connectivity with the PL. The rebroadcast probability hinges not solely on ISPF and distance but also on PER and prevailing channel conditions. Thus, the farthest vehicle may not always be chosen as the next forwarder if other vehicles present a higher forwarding probability under their specific conditions. Thus, any PM that decodes the leader's message is considered a potential relay, adhering to a decode-forward relay strategy (refer to Figure 3, where the more red cars have a greater likelihood of relay).

For effective platoon management and vehicle coordination, we introduce six schemes dedicated to updating information among vehicles. Furthermore, through the utilization of MBC strategies that incorporate predictive information, it is feasible to neutralize the delays encountered by receivers. The development of these novel protocols is driven by the unique demands of their application context.

1) PREDECESSOR-FOLLOWER (PF)

The initial scheme, termed PF, serves as the foundational benchmark against which the subsequent proposed schemes are evaluated. This approach is depicted in Figure 2(a).

2) PREDECESSOR-LEADER FOLLOWER (PLF)

Adopting a unidirectional leader topology, where information from the leader is disseminated to every follower, enhances platoon scalability by ensuring a stability margin that remains positive and unaffected by the size of the platoon. This arrangement allows for an agile platoon response in emergency situations by dynamically prioritizing the leader's data in influencing follower behavior, as depicted in Figure 2(b).

3) TEN LOOK-AHEAD IFT

Exploring an approach where each vehicle in the platoon leverages data from a limited number of vehicles directly ahead, as opposed to relying solely on the PL, presents promising outcomes, as depicted in Figure 1. Such a methodology, focusing on communication with immediate predecessors rather than the PL, has demonstrated efficacy. It is established that adopting a strategy that involves the input of multiple preceding vehicles for local control can effectively reduce the time headway gap, ensuring string stability [79]. The result is a platoon that exhibits faster reaction times and greater reliability, especially in the face of communication delays. Specifically, the approach is designed to interact with up to ten directly preceding vehicles; if fewer vehicles are ahead, it communicates with all available ones.

4) VIRTUAL LEADER PREDECESSOR-FOLLOWER (VLPF) WITH TEN VEHICLE LENGTH

Investigations of the r look-ahead IFT, as depicted in Figure 1, where 'r' denotes the count of predecessor vehicles

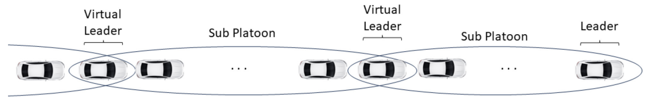


FIGURE 5. Depiction of a VLPF platoon showcasing the arrangement of virtual leaders.

considered in the control strategy, indicate limitations in expanding platoon sizes without increasing the gap between vehicles. This restriction comes from reduced reception rates for vehicles located far from the PL [80]. The strategy involves designating certain PMs as "virtual leaders," enabling direct communication with members beyond the reach of the original platoon leader's signal, circumventing the need for multi-hop communications. Essentially, vehicles following a virtual leader perceive it as their immediate lead, aligning their speed and acceleration accordingly to maintain optimal spacing. The essence of VLPF lies in segmenting extensive platoons into smaller and more manageable units under the guidance of appointed virtual leaders, ensuring short distances between vehicles and their designated leaders for robust communication and facilitating longer platoon configurations. Evidence suggests that an increase in virtual leader allocation correlates with reduced collision incidences [81], as conceptually depicted in Figure 5.

5) LEADER DATA RELAYING

Opting for the most distant node within the sender's communication range as the relay may compromise message reception due to propagation losses. A viable strategy to ensure that platoon members beyond the leader's communication reach can still access messages from the leader involves embedding these messages within beacon broadcasts during subsequent intervals. In the probabilistic distance-dependent model we propose, the success probability of message re-broadcast, determined through Bernoulli trials, varies across vehicles. For any given vehicle i, the decision to rebroadcast the received leader message from vehicle j is influenced by the distance separating the two vehicles and the PER associated with that distance. PER quantifies the fraction of packets lost relative to the total expected packets within a given interval, calculated locally by vehicle i for messages from vehicle j, as indicated by $PER_i(j)$ in (18). Tracking the sequence numbers of received packets can help determine the extent of packet loss during the assessment period. Studies show that probabilistic methodologies yield superior mapping precision compared to deterministic strategies [61]. Our formulation employs a hybrid probabilistic model that prioritizes rapid propagation at each relay point, integrating network conditions and the criticality of the data into the decision-making process. Thus, it allows for decentralized, collaborative decisions on retransmissions, emphasizing the role of packet forwarding, as facilitated by beacon piggybacking, in enhancing platoon performance by minimizing inter-vehicle distances.

6) LEADER RELAYING WITH TEN LOOK-AHEAD IFT

Incorporating predictive data from both the PL and preceding vehicles can substantially enhance the string stability of the platoon [23]. Additionally, the platoon demonstrates an improved string stability margin even with increased communication delays [31]. Establishing connectivity between one vehicle and a broad network of others is crucial to minimize the propagation of spacing errors. A key benefit of the described communication protocols is their facilitation of cooperative awareness among vehicles without imposing excessive demands on network capacity. This is achieved through a network design that integrates numerous direct V2V connections alongside a piggybacking relayer, which distributes the leader's messages across the entire platoon.

IV. EXPERIMENTAL RESULTS

In this analysis, we delve into the operational efficacy of cooperative platoon systems in a mass network environment, analyzing the impact of various IFTs on the dimensions and effectiveness of platoons. To benchmark our approach, which integrates broadcasting by the PL with V2V communications, a comparison is drawn against other approaches listed above. This relaying scheme permits direct communication between adjacent vehicles via one-hop links, while those not directly connected rely on multi-hop communication, with intermediate vehicles facilitating message transmission. This method is prevalent in decentralized vehicular networks, such as Vehicular Ad Hoc Networks (VANETs). Comparing our relaying communication strategy with the broadcast-centric approach is a logical step to highlight the merits of the proposed system. Simulations serve as a valuable method for validation, considering the substantial costs and extensive efforts required for real-world deployments [15]. With a particular emphasis on cooperative safety, our analysis aims to link communication patterns with the extent of tracking errors. It is understood that tracking performance improves with faster delivery of information to tracking estimators. Therefore, our objective is to measure the volume of data each vehicle successfully transmits to its intended recipients, a metric crucial to the precision of the tracking application.

A. IMPLEMENTATION DETAILS

Within a platoon, the PL sets the speed (V_0), acting as the velocity benchmark for the PMs. PL's adjustments in speed, either through acceleration or deceleration, act as perturbations within the platoon system. The simulations run at a step interval of 100 ms, identified as the standard period for communication exchanges. To concentrate on evaluating the effectiveness of our method, we standardize the transmission frequency and maximum range at 10Hz and $D(Ptx) = 500\ m$, respectively. Consequently, the transmission of a piggybacked message by any PM requires no more than 100 ms. Therefore, conveying a message from the lead to a member situated n hops away incurs a maximal delay of $100 \times n\ ms$. This latency impacts the platoon's capacity to maintain precise and stable spacing between vehicles. In the realm of broadcasting and multicasting routing, transmission efficiency and data throughput emerge as critical factors, especially relevant to vehicle tracking within Cooperative Vehicle Safety Systems (CVSS). Here, the new messages will make the previous messages in the queue obsolete, so only the most up-to-date message is transmitted.

Multiple metrics, such as Channel Busy Ratio (CBR), delay, PER, and Inter-Transmit Time (ITT) are indicative of communication reliability challenges. Specifically, CBR and ITT influence communication quality as evidenced by their impact on PER, with the probability of communication success being derivable from an empirical channel model documented in [71]. Furthermore, to evaluate the implications of unreliable communication, we reference PER values corresponding to traffic densities of 10, 15, 20, and 30 vehicles per second from prior research [27], [31], [70] as our comparative benchmarks. Figure 4 illustrates the PER associated with the specified traffic densities. For solving the optimization problem, we employ the CVXPY package within Python, with the Gurobi optimization suite serving as the solver for mixed-integer programming problems [82], [83]. The system's resilience is tested in a scenario where the PL encounters a speed disturbance. Table 1 contains the parameters utilized in the simulations. Each simulation scenario lasts for 180 seconds, during which the platoon's goal is to maintain a desired gap time of 0.6 seconds with the preceding vehicle.

B. ANALYSIS AND RESULTS

Our research primarily assesses application-specific performance metrics, notably inter-vehicular spacing within a platoon, to gauge the effectiveness of communication protocols. In contrast to a baseline approach that uses direct V2V connections, our study explores the benefits of implementing a relay-based communication strategy. Our protocol requires just the timestamp, location, and speed data from PL. We characterize performance in terms of latency and IA, crucial metrics for delay-sensitive applications. Each act of message forwarding introduces latency, incrementally delaying the message's arrival at its intended recipient. IA is defined as the time elapsed between the message's creation and its reception with respect to a unique time reference. Subsequently, we assess the resilience of our CACC system across various communication links, using inter-vehicle distance as the primary measure of service quality. During packet loss episodes, the MBC approach serves as a control signal estimator.

Figure 6 shows the dynamics of a 100-vehicle platoon over time, illustrating error, speed, and acceleration for each vehicle. Initially, there is significant error in inter-vehicle distances, but this decreases as vehicles adjust their positions, indicating stabilization. The speed and acceleration graphs also show large initial variations that converge over time, reflecting synchronized movements. This convergence

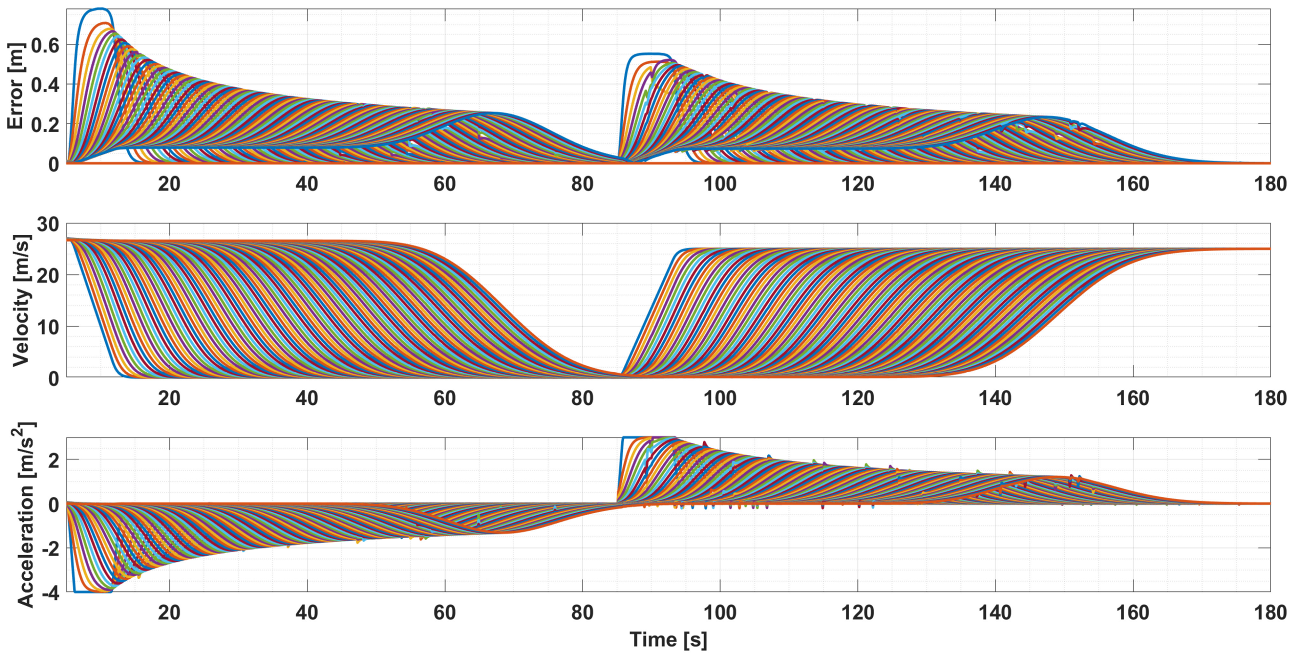


FIGURE 6. Performance of a 100-vehicle platoon. Each line shows the error, speed, and acceleration of an individual vehicle over time.

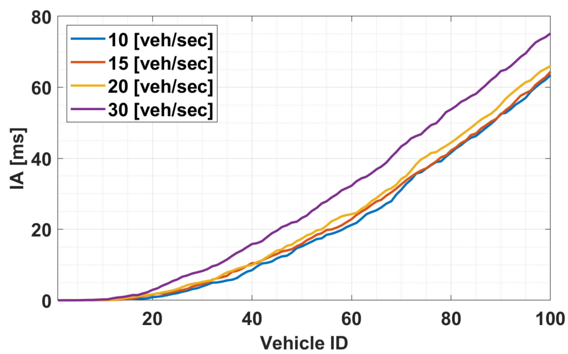


FIGURE 7. IA for each vehicle ID at different traffic flow rates.

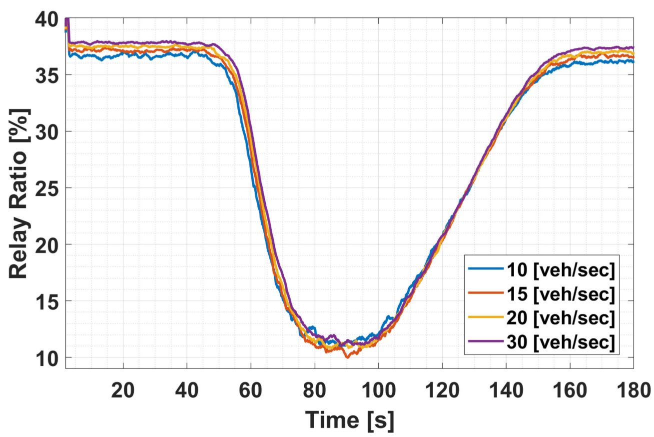


FIGURE 8. Relay ratio over time for different traffic flow rates.

ensures uniform speed and acceleration, maintaining overall stability and safety in the platoon. A notable finding was that the establishment of appropriate spacing by platoon members is sequentially dependent on their preceding vehicles achieving this metric, as the driving control mechanism relies on the leading vehicle's velocity and acceleration.

Figure 7 shows the IA for each vehicle ID at different traffic flow rates. IA, the time since the last update, increases with both the distance from the source and the traffic flow rate. As messages pass through more hops, delays accumulate, resulting in older information for vehicles further from the source. Higher traffic flow rates further increase IA due to network congestion and more frequent packet losses. Thus, greater distances and higher traffic flows lead to older and potentially less reliable information for vehicles further down the platoon.

Figure 8 shows the relay ratio over time for different traffic flow rates. The relay ratio, indicating the percentage of vehicles choosing to relay messages, decreases when vehicles are close together and stationary (around 60-100 seconds in Figure 6) because the need for relays diminishes. As vehicles move apart, the relay ratio increases, reflecting more frequent message relays. While the increase in traffic flows slightly increases the relay ratio, its impact is less significant than the effect of vehicle spacing. Thus, the relay ratio is mainly influenced by vehicle spacing and secondarily by traffic flow rate, with notable changes during transitions between stopped and moving states.

Figure 9 shows the relay ratio versus vehicle ID for different traffic flow rates. The relay ratio, indicating the percentage of vehicles successfully relaying messages, decreases progressively towards the end of the platoon. Notably, beyond vehicle ID 80, the relay ratio drops to nearly

TABLE 2. Statistics for various IFT approaches with varying traffic flow.

Traffic Flow	10 veh/sec	15 veh/sec	20 veh/sec	30 veh/sec
	Error $(m,\ m/s,\ m/s^2)$	Error $(m,\ m/s,\ m/s^2)$	Error $(m,\ m/s,\ m/s^2)$	Error $(m,\ m/s,\ m/s^2)$
PF	0.1025, 17.1040, 1.5802	0.1022, 17.1043, 1.5914	0.1025, 17.1043, 1.5816	0.1024, 17.1043, 1.5909
PLF	0.0774, 17.0912, 1.5765	0.0773, 17.0918, 1.5883	0.0775, 17.0916, 1.5798	0.0773, 17.0917, 1.5858
Ten look-ahead	0.0714, 17.0527, 1.5409	0.0710, 17.0550, 1.5533	0.0714, 17.0535, 1.5468	0.0713, 17.0539, 1.5521
VLPF	0.0725, 17.0537, 1.5749	0.0722, 17.0542, 1.5954	0.0725, 17.0542, 1.5762	0.0725, 17.0542, 1.5840
Relaying	0.0543, 17.0498, 1.4852	0.0540, 17.0503, 1.4957	0.0542, 17.0503, 1.4886	0.0542, 17.0503, 1.4914
Relaying + Ten look-ahead	0.0460, 17.0431, 1.4892	0.0457, 17.0438, 1.4968	0.0460, 17.0436, 1.4916	0.0458, 17.0436, 1.4953

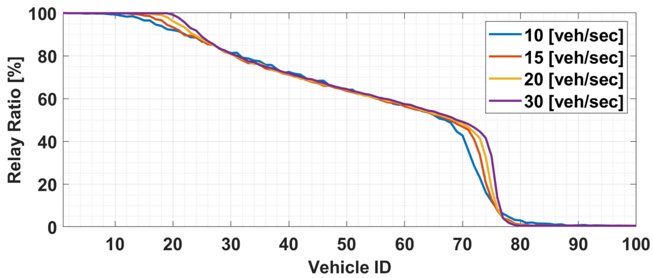


FIGURE 9. Relay ratio versus vehicle ID for different traffic flow rates.

zero, indicating that relaying messages further becomes useless. While an increase in traffic flow slightly increases the relay ratio due to more frequent retransmissions needed to ensure message delivery, its impact is less significant compared to the distance from the platoon leader.

Table 2 compares errors in distance, speed, and acceleration for various IFT approaches under different traffic flow rates. The PF approach shows consistent errors, with slightly higher acceleration errors at higher flows. The PLF method reduces errors slightly compared to PF, especially in higher traffic flows, indicating better stability. The ten look-ahead strategy, where each vehicle considers data from up to ten vehicles ahead, shows further error reduction, improving platoon stability. The VLPF approach, which uses virtual leaders to extend communication range, improves error metrics, especially in acceleration. Implementing a relaying strategy reduces errors in all metrics, particularly acceleration, indicating more stable communication and control. The combination of relaying and ten look-ahead yields the lowest errors across all metrics and traffic flows, demonstrating the highest stability and efficiency.

V. CONCLUSION

This study develops a management strategy for CACC-equipped long platoons, addressing the constraints posed by the limited range of C-V2X communications. Within such MPC-driven systems, control inputs are derived by optimizing based on predicted states of preceding vehicles, thereby enabling anticipatory following behavior that enhances vehicular efficiency through adaptive speed and spacing adjustments. Unlike ACC systems, CACC platoon controllers that use different IFTs achieve narrower desired time gaps without compromising stability, thus significantly enhancing traffic capacity and safety through effective communication. Research indicates that while ACC systems offer negligible improvements in traffic flow and stability, CACC systems present substantial benefits. It is thus essential to restrict the degradation of CACCs to ACCs to maintain these advantages, with an emphasis on expanding platoon sizes and communication scopes. This paper introduces a CACC model based on specific IFTs, underscoring the need to minimize intervehicle distances through reliable and low-latency relaying of safety messages, thus addressing the dissemination of such messages within the platoon.

The stability and safety of the platoon, pivotal in platooning applications, hinge on the vehicles' capability to share status updates via beacon exchanges. High CBR can precipitate significant PER and IA, signaling unreliable communications. This underscores the necessity for meticulously designed communication strategies in long platoons. The paper outlines an algorithm for rebroadcasting aggregated traffic data across vehicular networks, leveraging piggybacking on existing network beacons for enhanced latency and scalability. This approach employs a network-aware, dual-layer, distance-dependent protocol combined with a mixed probabilistic rebroadcast method that ensures higher rebroadcast probabilities for vehicles further from the sender and in optimal communication conditions, aiming for rapid hop-to-hop forwarding. Additionally, it has been discovered that an expanded communication range can mitigate disturbances, and introducing more communication dimensions can prevent string instability, commonly associated with shock waves that detrimentally affect driver and passenger comfort.

Limitations and Future Work: The redundancy in beacon reception due to other vehicles' retransmissions can diminish efficiency, particularly in larger platoons. The study reveals that reducing update delays grows more beneficial as platoon size increases, necessitating further investigation into this effect. The influence of different topologies on control inputs suggests that distributed control is inherently topology-dependent. Additionally, the impact of topology on disturbance propagation requires thorough examination.

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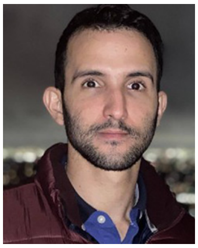

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