Platooning With IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow

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Abstract—Intraplatoon information management strategies for dealing with safe and stable operation are proposed in this paper. New algorithms to mitigate communication delays are presented, and Matlab/Simulink-based simulation results are reported. We argue that using anticipatory information from both the platoon's leader and the followers significantly impacts platoon string stability. The obtained simulation results suggest that the effects of communication delays may be almost completely canceled out. The platoon presents a very stable behavior, even when subjected to strong acceleration patterns. When the communication channel is subjected to a strong load, proper algorithms may be selected, lowering network load and maintaining string stability. Upon emergency occurrences, the platoon's timely response may be ensured by dynamically increasing the weight of the platoons' leaders data over the behavior of their followers. The simulation results suggest that the algorithms are robust under several demanding scenarios. To assess if current intervehicle communication technology can cope with the proposed information-updating schemes, research into its operation was conducted through a network simulator.

Index Terms—Autonomous vehicles, intervehicle communication (IVC), network simulation, platooning, traffic information management, traffic simulation.

I. INTRODUCTION

URBAN traffic congestion is becoming an unmanageable problem. Its consequences span from economics, public health, and energy consumption to pollution, among others. Traffic regulation through dynamic tolls may temporarily mitigate its impact, but new long-term solutions are required.

As concerns urban transportation, it seems likely that demand tends to always surpass supply. Nevertheless, mobility of urban inhabitants and goods should be granted and improved. However, more road network construction is not always viable and might not even ensure sound benefits. The problem to tackle resides on how to improve road capacity while reducing both travel time and traffic congestion. Platooning may help

to improve lane capacity, if constant spacing is used [1]–[3]. However, to be effective with respect to traffic flow, platooning should be performed with vehicles evolving on dedicated tracks and operating on a nonstop basis from origin to destination [4]. As such, by eliminating the stop-and-go problem of common car and transit systems, platooning could contribute to a faster and more comfortable mobility with higher energy efficiency.

Intervehicle communication (IVC) is emerging as a prominent technology for helping in reducing traffic congestion. Recent technological advances on communications, such as dedicated short-range communications (DSRC) [5]–[7] and long-term evolution advanced (LTE-Advanced) [8], as well as on cooperative adaptive cruise control (CACC) [9], personal rapid transit (PRT) [4], and autonomous vehicles, such as cybercars [10], are opening new research avenues that might show the usefulness of platooning in urban mobility improvement, when applied to automated vehicles. Moreover, since the vehicles in platooning are expected to be allowed to move very close to each other, a considerable reduction on energy consumption might be possible [4], once each follower vehicle would benefit from a reduced air drag due to their precedent vehicle.

In the present stage of our research, some assumptions are made. First, only longitudinal control of vehicles is assumed. Second, we consider only autonomous vehicles platooning. Third, we consider a platoon dimension up to 31 m long (a maximum of eight vehicles 3 m long and 1 m apart). Next, line-of-sight (LOS) communication between each leader and its followers is assumed. Then, our communication algorithm uses time slots, aiming to avoid intraplatoon packet collisions. Finally, the vehicles' dynamics are considered identical. These assumptions aim to isolate the effects of communication delays on the platoon's behavior. However, they must be assessed to find if they are acceptable with respect to communication constraints. For that purpose, the NS-3 [11] network simulator is used in testing several demanding platoon scenarios.

Among others, the following problem can be formulated: How can platoon stability be ensured under the negative effects of communication delays? Control methods for ensuring platoon string stability exist [3], however, under the assumption of the use of IVC without delays. This is not a realistic assumption, and communication delays are known to create hardly manageable string instability [12]. Intraplatoon information management strategies to deal with this problem are proposed in this paper. Our main goal is to ensure platoon string stability under the unavoidable presence of communication delays. To achieve
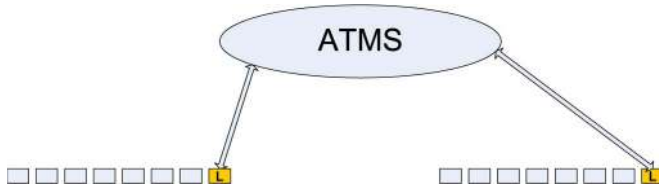
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Fig. 1. Hierarchical ATMS (partial view).

TABLE I
FIELDS OF KNOWLEDGE TO CONSIDER

Field	Some relevant topics
Traffic	Theory, fundamental diagram, traffic flow
Communications	DSRC/WAVE, LTE-Advanced (4G)
Simulation	Traffic and communication networks
Control	Constant spacing platooning, string stability
Autonomous vehicles	Communicant, cooperative
Computer Science	C++, Python, Java, application architecture
Energy	Consumption, efficiency, EV's

our goal, we aim to enclose the communication, computation, and actuation delays within an upper bound delay, which is managed at a higher level in a way that presents no significant effect on platoon string stability.

An appropriate scenario for a platoon-based mobility system consists of its implementation with autonomous electric vehicles (EVs) in a network of dedicated tracks with offline stations and nonstop trips from origin to destination, managed by a hierarchical multilayered advanced traffic management system (ATMS) [13], [14]. As such, traffic of conventional vehicles is not considered in this scenario. Fig. 1 shows a partial view of the proposed ATMS. This study focuses on the appropriate operation of each platoon, dealing with its string stability when facing communication delays. Nevertheless, this work is part of a more vast research, where other important problems are also the subject of study, such as the rules to construct a platoon and leaders' election. For a more detailed description, see [13] and [14]. A brief summary of those rules follows: All leaders are elected by an upper level of the ATMS, receiving from it their acceleration patterns in predetermined time periods; a vehicle is only allowed to enter the track to evolve isolated, if it will occupy a leader's vacant location at precise positioning, and it will perform as leader; a set of up to eight vehicles may be admitted to the track, despite not joining other vehicles evolving in the track, as long as the first vehicle occupies a leader's vacant position and performs as leader, whereas the remaining vehicles perform as followers, under the control law (6) of Section IV; an isolated vehicle, or a set of vehicles, may enter the track just behind other evolving vehicles, performing as follower(s), if the total number of vehicles is ≤ 8; when a leader leaves the track, the lead vehicle of the platoon's remaining vehicles must assume leadership; should some unforeseeable event occur, leaders are allowed to perform emergency stops, under the information-updating algorithms described in Section VI.

The upper levels of the proposed ATMS should control the whole system, including platoon leaders' appropriate operation and admission of vehicles into the system, to avoid congestion, even when operating close to its maximum capacity. The management of free vehicles to deal with asymmetrical transportation demand should also be ensured by the ATMS.

Since communication failures are of considerable importance in such scenarios, we further explore communication algorithms that might ensure that communication errors do not occur or are minimized. For that purpose, network simulations were performed with NS-3, and results are reported.

In the succceeding sections, we present the applied platoon control models, communication and information-updating schemes, and simulation models and results.

II. RELATED WORK

This research encompasses several fields of knowledge (as shown in Table I). A great number of research studies and results have been published in the last years, concerning the aforementioned fields. Many of them are related with autonomous vehicles [15], adaptive cruise control [16], CACC [9], cooperative active safety system [17], among other research topics.

In [18], Shladover reviewed the history of the founding of the California Partners for Advanced Transit and Highways (PATH) program and of the national intelligent transportation system program in the U.S., providing perspective on the changes that have occurred during the past 20 years. In [19], Varaiya discussed key issues related to a highly automated intelligent vehicle and highway system (IVHS) and proposed an IVHS control system architecture. Swaroop *et al.* [1], [2] investigated various platooning control strategies. Alvarez and Horowitz [20] researched the conditions to achieve safe platooning under a normal mode of operation. Horowitz and Varaiya described in [21] a five-layer automated highway system control architecture, involving the infrastructure and the vehicles. Rajamani *et al.* [22] developed a controller of platoons with constant spacing, concluding that autonomous control is not enough to ensure string stability. He found that only with IVC is the string stability of vehicle platoons achieved. The method was experimentally evaluated in field tests. Kato *et al.* [23] described the technologies of the cooperative driving with automated vehicles and IVCs in the Demo 2000 cooperative driving. Global control strategies for vehicle platooning systems are addressed in [24]. Recently [25], Broggi's team completed a 3-month journey of 13 000 km, with four autonomous EVs equipped to drive in leader–follower configuration.

The effects of communication delay on the string stability of platoons were researched by Mahal [12]. The main conclusion was that the string stability of platoons is compromised in the presence of communication delays. A simple method to deal with string instability due to communication delays was proposed in [26]. The solution consisted of a simultaneous update of all vehicles' controllers with the delayed information. However, it did not deal with anticipatory information from the leaders or the followers.

PRT experimental testing and field applications have been reported [27]. However, the benefits of such novel transportation system with regard to light rail or conventional cars are yet to be clearly demonstrated. Simulators more focused on PRT systems

have been proposed [28], [29]. However, it is not clear how they model both communications and cooperation.

In [30], we addressed the implementation of IVC-enabled autonomous vehicle platooning capabilities in the Simulation of Urban MObility (SUMO) traffic simulator [31]. Dold and Stursberg [32] proposed an approach to robust model predictive control for distributed systems with chain structure, which includes a scheme for communicating predicted control trajectories between the subsystems. Wang and Pham [33] developed a high-fidelity cosimulation platform to study the motion and control of a vehicle platooning system, in MSC ADAMS and Matlab/Simulink.

Safety-based IVC is crucial for appropriate platooning operation. However, DSRC broadcasting performance does not present enough reliability to ensure safe vehicle operation in such scenarios. Several proposals have recently been made, aiming to improve its features. In this context, Yu and Biswas [34] presented a novel medium access control (MAC) protocol for IVC using DSRC, which consists of a self-configuring time-division multiple-access protocol with short and deterministic delay bound capabilities. Torrent-Moreno *et al.* [35] proposed a distributed transmit power control method to control the load of periodic messages on the channel. Bi *et al.* [36] presented a cross-layer broadcast protocol to allow efficient and reliable message dissemination in IVC systems. Palazzi *et al.* [37] proposed a novel IVC architecture that adapts its functionalities to efficiently serve applications by quickly propagating their messages over a vehicular network. Tabatabaei *et al.* [38] presented an improvement on simpler propagation models for simulations by augmenting ray-tracing-derived models of wireless propagation. However, there are few approaches concerning the analysis of DSRC use in a constant spacing platooning environment, presenting specific problems with which to deal.

III. TRAFFIC FLOW LIMITS

Maintaining a desired intervehicle spacing in platoons demands a tight control of each vehicle. In case of human-driven vehicles, intervehicle spacing is defined through a constant time headway, which means that increasing speed implies increased spacing. According to [39], the "desired minimum gap" s^* between two vehicles under the intelligent driver model (IDM) [40] is given by

$$s^*(v, \Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}} \qquad (1)$$

with $\Delta v := v_\alpha - v_{\alpha-1}$, where α denotes the follower vehicle and $\alpha - 1$ denotes the leading vehicle, s_0 is the minimum distance in congested traffic, a is the maximum acceleration, and b is the "comfortable deceleration." The last term of (1) is only significant in nonstationary traffic, when $\Delta v \neq 0$. Term vT is the most relevant one to the resultant spacing in stationary traffic, where T denotes the "safety time gap." When speed increases, s^* proportionally increases, which means that the road vehicle density decreases. With human drivers, it is not possible to avoid this performance pattern, even with IVC, because human reaction time is the main reason for the need of the safety gap proportional to the vehicle speed. That reaction

TABLE II
LANE CAPACITY USING PLATOONS

v	n	d (m)	D (m)	C (ve/h)	SUMO	k (veh/km)
36 km/h	1	–	15	2000	2400	55
	5	1	30	3674	3675	102
	8	1	30	4721	4730	131
	15	1	30	6067	6070	169
	20	1	30	6606	6600	183
72 km/h	1	–	25	2571	2800	36
	5	1	30	7347	7340	102
	8	1	30	9443	9450	131
	15	1	30	12135	12140	169
	20	1	30	13211	13210	183

time of about 1 s leads to the lack of string stability in vehicle platooning. This means that, if the lead vehicle decelerates, the spacing between vehicles may decrease toward the end of the platoon, leading to possible collisions.

According to [19], road capacity may be increased by using platoons with tightly spaced vehicles. The formulation to determine road capacity is given as follows:

$$C = v\frac{n}{ns + (n-1)d + D} \qquad (2)$$

where C represents the number of vehicles (in vehicles per second), d is the intraplatoon spacing (in meters), D is the interplatoon spacing (m), s is the vehicle length (in meters), v is the steady-state speed (in meters per second), and n is the number of cars in each platoon.

Based on (2), Table II presents lane capacity values for $s = 3$ m, and velocities of 36 and 72 km/h. Parameter k represents the vehicle density in vehicles per kilometers. The spacing of free vehicles $(n = 1)$ is consistent with the minimum gap obtained from the IDM model (1), in which human drivers, presenting reaction times of approximately 1 s, need about 15 m of safety gap at a speed of 36 km/h. Note the significant improvement of lane capacity with platoons of eight vehicles each, when compared with the free vehicle case, even with an interplatoon spacing of 30 m, which is double the spacing of individual vehicles (15 m). It is also worth mentioning, that, for the free vehicle case, the values were obtained under ideal conditions, i.e., without traffic lights, intersections, or other obstacles usually present in an urban environment. Doubling the velocity in Table II leads to a slight improvement of the lane capacity (28.5%) in the case of free vehicles. However, the capacity doubles with platoons of eight vehicles, when compared with the analogous case at the speed of 36 km/h, resulting in more than three times the capacity of the lane with free vehicles, with the same speed considered. Table II also presents the traffic flow results of simulations of constant speed platoons, performed on the SUMO traffic simulator. In Table II, SUMO results for $n = 1$ were obtained using the Krauß car-following model [41]. The platooning results $(n \geq 5)$ were obtained with the modified SUMO reported in our previous work [30], which consists in a novel car-following implementation allowing to simulate platooning of autonomous vehicles with constant spacing. The simulation scenario consisted of a several-kilometers-long straight lane, where a large sequence
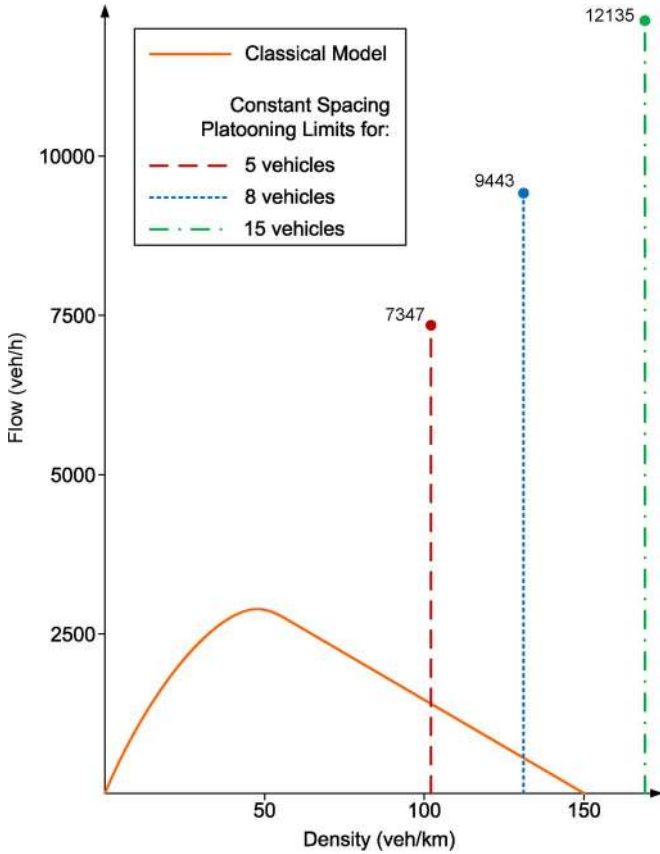
Fig. 2. Fundamental diagram of traffic flow. Limits for platoons of five, eight, and 15 vehicles each, separated by 30 m, with vehicles 3 m long and 1 m apart from each other, are depicted in dashed lines, with upper values for the speed of 72 km/h.

of platoons evolved in formation. At some defined points of the lane, E1-type loop detectors were installed in SUMO, allowing to obtain the aggregate results of traffic flow. Although slightly higher in the case of free vehicles, these results are consistent with those theoretically drawn from (2).

In Fig. 2, we represent the fundamental diagram of traffic flow [42]. By the fundamental relation of traffic flow theory

$$q = u \times k \quad (3)$$

where q represents traffic flow (in vehicles per hour), u the vehicle speed (in kilometers per hour), and k the vehicle density (in vehicles per kilometer). The classical model states that, above a critical density k_c (approximately 50 veh/km in Fig. 2), the traffic state begins to enter in a congestion phase, where vehicles are closer to each other and moving slower, until traffic comes to a full stop, at a jam density k_j, at about 150 veh/km. The data obtained with SUMO for the conventional traffic are consistent with the continuous line. In Fig. 2, we further represent three upper limits of density values, by vertical dashed lines, for the cases of platoons with 5, 8, and 15 vehicles each, corresponding to the following values of k: 102, 131, and 169 veh/km, respectively. These are the upper bounds at which a constant spacing platooning system could operate. Once the platoons' formation is already in place, lane capacity is proportional to the speed. The flow is equal to lane capacity, if the vehicle density is maintained. The top of each dashed line

is the theoretical flow limit with respect to a given density and speed values. For example, 9443 veh/h is the lane capacity for the case of a density of 131 veh/km, with a platoon featuring $v = 72$ km/h, $n = 8$, $d = 1$ m, and $D = 30$ m (see Table II). However, for a traffic system to operate with a traffic flow close to 9443 veh/h (under the aforementioned conditions), the admittance of vehicles should be limited, to ensure that the correspondent maximum density of 131 veh/km would never be surpassed. Otherwise, congestion would occur, lowering the traffic flow value. Moreover, such traffic system should be based on constant spacing platooning of autonomous vehicles and managed by an ATMS. Based on Table II, we find $n = 8$ as the best compromise between traffic flow improvement and platoons' dimension.

IV. BASE MODEL OF VEHICLE CONTROL

It becomes clear that one way to effectively improve road capacity consists of the use of vehicle platoons with constant spacing. However, constant spacing platooning requires string stability, which means that the spacing errors do not amplify down the platoon from vehicle to vehicle. To ensure string stability between vehicles in a constant spacing platoon, IVC is required [1], [3].

According to Fig. 3 and considering the desired ith vehicle position defined by

$$x_{i\_des} = x_{i-1} - L_i \quad (4)$$

where $L_i = l_{i-1} + g_{i\_des}$, with l_{i-1} being the length of the preceding vehicle and g_{i_des} being the intervehicle desired gap, the spacing error is defined as

$$\varepsilon_i = x_i - x_{i-1} + L_i. \quad (5)$$

Using a sliding-mode approach, Rajamani [3] designed a controller with vehicles' desired acceleration expressed as

$$\ddot{x}_{i\_des} = (1 - C_1)\ddot{x}_{i-1} + C_1\ddot{x}_l$$
$$- \left(2\xi - C_1(\xi + \sqrt{\xi^2 - 1})\right)\omega_n\dot{\varepsilon}_i$$
$$- (\xi + \sqrt{\xi^2 - 1})\omega_n C_1(V_i - V_l) - \omega_n^2\varepsilon_i. \quad (6)$$

The parameters of (6) are described in Table III. With this control method, the spacing error will converge to zero, and the system is string stable, under the conditions $\xi \geq 1$ and $C_1 < 1$ [3]. To each follower in a platoon of vehicles, parameter C_1 represents the weight factor of the leader's information with respect to the preceding vehicle. When $C_1 = 0$, the following second-order system is attained:

$$\ddot{x}_{i\_des} = \ddot{x}_{i-1} - 2\xi\omega_n\dot{\varepsilon}_i - \omega_n^2\varepsilon_i \quad (7)$$

and only the precedent vehicle's information becomes relevant to each vehicle behavior. From (6), we can conclude that, to determine the desired acceleration of each vehicle, wireless communications are needed to allow each vehicle to receive the speed and acceleration values from both the preceding vehicle and the platoon leader. It is assumed that vehicles have precise
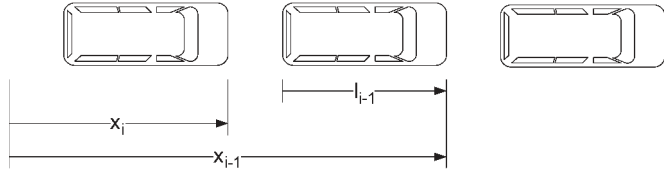
Fig. 3.   String of platoon vehicles.

TABLE III
NOMENCLATURE OF MATHEMATICAL FORMULATIONS

Symbol	Description
$\ddot{x}_{i\_des}$	desired acceleration of the ith vehicle
$\ddot{x}_{i-1}$	acceleration of the vehicle preceding the ith vehicle
$\ddot{x}_l$	acceleration of the vehicle leader of the platoon
V_i	velocity of the ith vehicle
V_l	velocity of the vehicle leader of the platoon
C_1	control gain used in longitudinal controller (weight factor of the leader with respect to the preceding vehicle, with values $0 \leq C_1 < 1$)
ξ	damping ratio (equal to 1 for critical damping)
ω_n	bandwidth of the controller

self-position information in real time, whether obtained from Global Positioning System (GPS)/differential GPS, or from other sensing means. Moreover, the distance from each vehicle to its precedent is assumed to be determined by the use of a lidar or radar installed in each vehicle. Additionally, it is assumed that platoon formation and leader's election are dealt with by the ATMS at a higher level [13], [14]. The control model does not integrate air drag nor the coefficient of friction effects. As such, the focus of this research is on communication delay effects over an identical set of vehicles and strategies to mitigate them.

V. COMMUNICATIONS

We consider IVC supported by wireless communications from the leader to all followers and from each vehicle to its immediate follower and the leader. The communication scheme uses time-division multiple access with token passing [26]. All vehicles transmit their data at each token cycle tc, in their respective time slot ts. For that purpose, $tc = 10 \times ts_j$, $j = 1, \ldots, 10$. We also consider $tc = 100$ ms and $ts = 10$ ms as appropriate reference values.

VI. INFORMATION MANAGEMENT ALGORITHMS

To exchange information between vehicles, allowing an appropriate platoon behavior, five information-updating schemes are proposed.

Table IV presents the parameters of the information-updating schemes. The delay bounds used in these algorithms are much higher than those obtained through simulation, with respect to packet transmission delays. The idea of these algorithms is to operate under an upper bound delay while continuing to ensure a stable platoon behavior. Consequently, lower delay effects over string stability may then be mitigated or even almost canceled out. Additionally, by managing information at an upper level, with anticipatory information, delays per-

TABLE IV
INFORMATION UPDATING SCHEMES' PARAMETERS

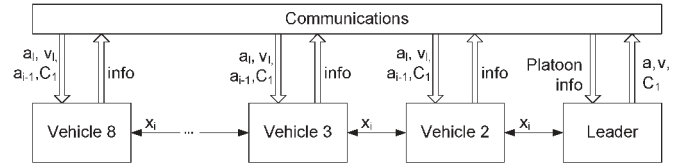| Algorithm	Anticipation	C_1	Apparent Delay (leader, followers)	Updating Cycle uc
I	none	static	$100\,ms$, $100\,ms$	$100\,ms$
II	leader	static	$0\,ms$, $100\,ms$	$100\,ms$
III	leader	dynamic	$0\,ms$, $100\,ms$	$100\,ms$
IV	all	static	$0\,ms$, $0\,ms$	$100\,ms$
V	all	static	$0\,ms$, $0\,ms$	$800\,ms$

Fig. 4.   Platoon's information flow diagram.

ceived by receivers may be canceled out (null apparent delays), as presented in Table IV, and explained throughout the next sections, where the proposed information-updating schemes are described. All of them use the platoon's information flow architecture, which diagram is shown in Fig. 4.

A. Information-Updating Scheme I

This first scheme is presented as a work base, to which the other proposed schemes II, III, IV, and V will be compared with. Moreover, it also makes possible the study of the influence that C_1 parameter presents over the platoon stability. The platoon's leader transmits its data to all followers in its time slot ts_1. Each vehicle j, in sequence, transmits its data to the respective follower, in each ts_j, in sequence. After all vehicles have obtained the data, they proceed to the computation of the next acceleration they must apply through their actuators. However, all vehicles are synchronized and simultaneously update their operation parameters at the end of each information-updating cycle uc to improve platoon stability [26]. We will designate that instant by vehicle actuation moment vam. We adopt an updating cycle $uc = 100$ ms. With n being the number of vehicles per platoon, with $1 \leq n \leq 8$, and $ts = 10$ ms, condition $uc \geq n \times ts$ is verified.

Fig. 5 shows a temporal diagram of the packet data exchange between the platoon vehicles in two consecutive 100-ms time frames. Different colors represent different data content. First, the leader broadcasts its present data to all followers. Each of them, in turn and in their respective time slot, transmits the acceleration computed in the previous 100-ms time frame. At the end of the frame, all vehicles compute their next acceleration, based on the measured distance to the respective precedent vehicle, and the data received from that vehicle and the leader. At the same time, the leader computes the acceleration value to apply in the next frame. Then, all vehicles simultaneously perform the actuation of the obtained data in each vehicle. The information of the leader and also of all vehicles to each of their followers is 100 ms old.

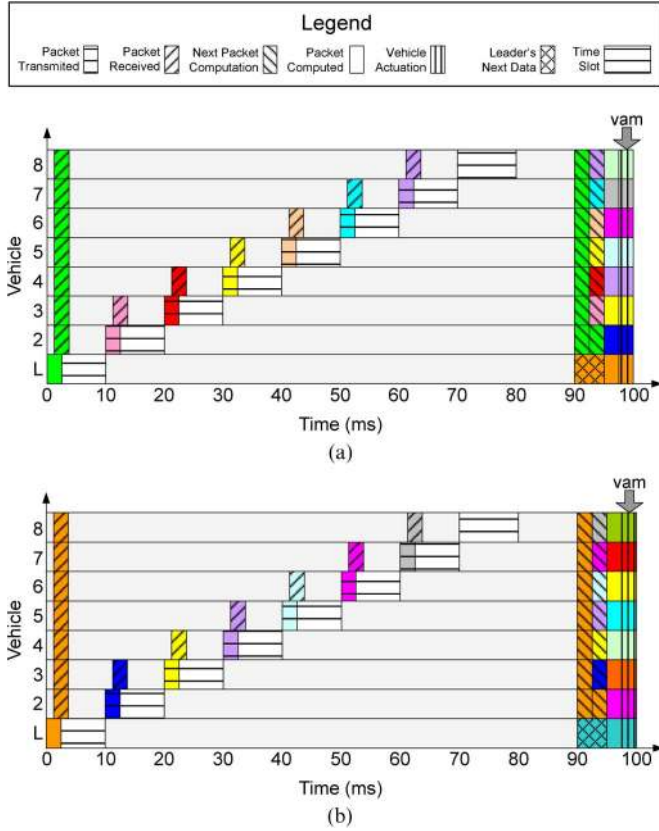Table V defines the parameters used in the following algorithms:

Fig. 5. Algorithm I: Without anticipatory information. (a) First 100-ms time frame. (b) Second 100-ms time frame.

TABLE V
ALGORITHM PARAMETERS

Parameter	Definition
uc_i	updating cycle i
ts_j	time slot j
a_c	current acceleration
a_n	next acceleration
v_c	current speed
v_p	predicted speed
vam	vehicle actuation moment

Algorithm 1 presents the leader's behavior in this information-updating scheme, whereas Algorithm 2 presents the behavior of a follower, both represented in pseudocode.

B. Information-Updating Scheme II

In this information-updating scheme, the platoon's leader announces the plan for the next frame at each tc, in its ts_1 but waits before actuating with the computed values to allow the followers to be able to update their data before their own actuation. This waiting step is a key feature to improve platoon stability and may be interpreted as an "anticipatory information" that all vehicles receive from the leader to allow them timely and simultaneous actuation, at the vehicle actuation moment vam. The information that each follower emits to the subsequent vehicle is 100 ms old, as in Scheme I. Each updating cycle is $uc = tc = 100$ ms.

Fig. 6 shows a temporal diagram of the packet data exchange between the platoon vehicles in two consecutive 100-ms time frames. First, the leader broadcasts the data to all their followers. However, differently from the previous scheme, the information broadcasted by the leader has not yet been applied to the vehicle. Instead, the leader waits until all the remaining vehicles receive and transmit their data. Each vehicle, in turn and in the respective time slot, transmits its actual acceleration (which was computed in the previous 100-ms time frame, considering the leader's anticipatory information). With this updating scheme, it is possible, at the cost of an increase of 100 ms in the reaction time of the leader, to considerably improve the platoon stability, in the direct proportion of the leader's information weight, as represented by parameter C_1 in (6).

Algorithm 1 Leader in Information-Updating Scheme I

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for all uc_i **do**

     At ts_1, the leader broadcasts its current acceleration a_c and speed v_c.

     At ts_{10}, the leader gets from ATMS or computes its next acceleration a_n.

     At vam, the leader actuates with a_n.

end for

Algorithm 2 Follower in Information-Updating Scheme I

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for all uc_i **do**

     At ts_1, vehicle v_j receives the acceleration and speed from the leader.

     At ts_{j-1}, vehicle v_j receives the acceleration from its precedent vehicle.

     At ts_j, vehicle v_j transmits its current acceleration a_c to its follower.

     At ts_{10}, vehicle v_j compute its next acceleration a_n under the control law of (6)

     At vam, vehicle j actuates with a_n

end for

Algorithm 3 Leader in Information-Updating Scheme II

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for all uc_i **do**

     At ts_1, leader *computes its predicted speed v_p at vam, based on its current acceleration a_c*

     At ts_1, leader broadcasts its *next acceleration a_n and predicted speed v_p*

     At ts_{10}, leader gets from ATMS or compute *the next acceleration to use at the next updating cycle uc_{i+1}*

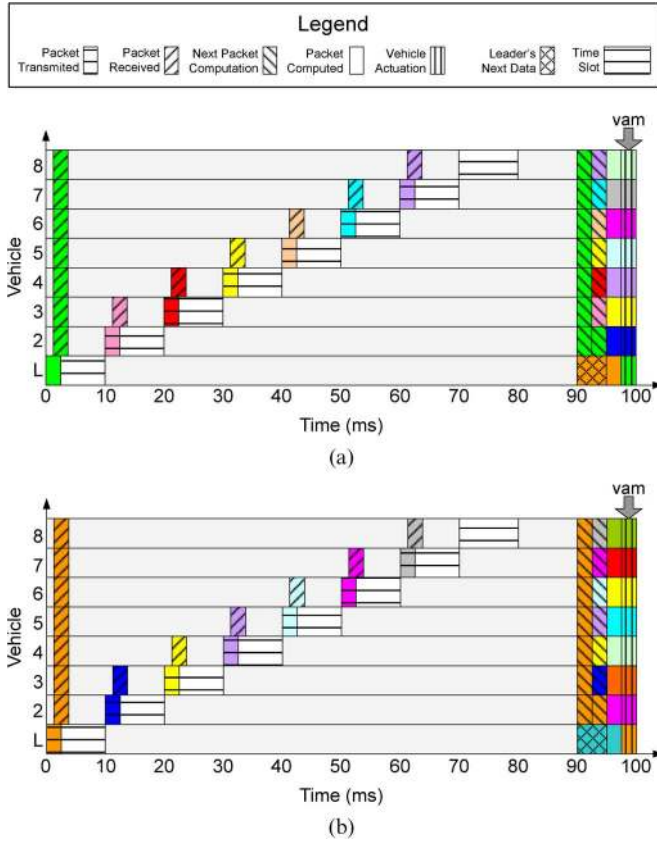   At vam, leader actuates with a_n

end for

Fig. 6. Algorithm II: With leader's anticipatory information, using the vehicle actuation moment vam. (a) First 100-ms time frame. (b) Second 100-ms time frame.

Algorithm 3 presents the leader's behavior in this information-updating scheme, whereas the behavior of a follower is the same as in Scheme I (see Algorithm 2). The main differences from Algorithm 1 are presented in italic text.

C. Information-Updating Scheme III

All vehicles in the platoon receive information from the leader at all uc, as in Scheme II. Parameter C_1 in (6), which represents the weight of the leader's data, is dynamically changed to cope with some potential dangerous conditions (e.g., in the presence of a unexpected strong deceleration of the leader). In such cases, the leader warns its followers to increase their C_1. We introduce here a new parameter C_2 that will serve as a base value, whereas the C_1 parameter will dynamically vary, which we will designate by $C_{1_{\mathrm{dyn}}}$, where $C_1 = C_{1_{\mathrm{dyn}}}$, with $C_2 \leq C_{1_{\mathrm{dyn}}} < 1$. This parameter is used when strong accelerations (both positive or negative) are determined by the leader. In these cases, $C_{1_{\mathrm{dyn}}}$ immediately assume a value close to 1 (without reaching it, since string stability requires that $C_1 < 1$ [3]), for a very short period of time, after which, the value rapidly decays to the C_2 base value again. Nevertheless, all vehicles use the same C_1 value in each uc. With this algorithm, very conservative C_2 values may be maintained, whereas a very stable platoon behavior is achieved. As we will see in the results (Section VII-C), the behavior of the platoon is even better than the obtained behavior with a fixed $C_1 = 0.9$.

D. Information-Updating Scheme IV

This information-updating scheme extends the key feature of Scheme II (anticipatory information) from the leader to all vehicles. The platoon leader announces the plan for the next frame at each tc, in its ts_1. Each follower, in sequence, determines its own plan for the next tc and transmits it to their respective follower, in their own time slot. As such, at each tc, both the leader and each of the followers, in sequence, transmit their data. Each vehicle j transmits in its time slot ts_j to allow all vehicles to transmit without packet collisions. It is important to note that, although both the leader and all the remaining platoon vehicles transmit their next acceleration value, they all hold their actuation, until all vehicles receive their information. Only then, all vehicles simultaneously update their operation parameters, at the vehicle actuation moment vam, in the end of each information-updating cycle uc. Each updating cycle $uc = 100$ ms. Since this updating scheme transmits data to use on the next uc, the platoon stability significantly improves in comparison with the other schemes. The timings at which this algorithm operates are appropriate to demanding dynamic operations, where vehicles are required to be more responsive and adaptive. However, it is very demanding with respect to both communication and timely computation of vehicle parameters.

Fig. 7 shows a temporal diagram of the packet data exchange between the platoon vehicles in a 100-ms time frame. This scheme consists of an evolution of Scheme II. In this case, all vehicles in the platoon announce the acceleration value before the moment at which it will be used to act on the vehicle. For that purpose, a tight synchronization and very short timings must be ensured. Note in Fig. 7(a) that each vehicle has to compute its next acceleration value within the time it received the data of its precedent vehicle and the beginning of its own time slot, where it must be able to transmit the computed value to its own follower. In Fig. 7, we admit that less than one third of the time slot is used to receive the precedent vehicle's data, which leaves enough remaining time to perform the needed computations.

Algorithm 4 Follower in Information-Updating Scheme IV

---

for all uc_i **do**

    At ts_1, vehicle j receives the acceleration and speed from the leader.

    At ts_{j-1}, vehicle j receives the acceleration from its precedent vehicle.

    At ts_{j-1}, vehicle j compute its predicted speed v_p at vam, based on its current acceleration a_c.

    At ts_{j-1}, vehicle j compute its next acceleration a_n at vam, under the control law of (6).

    At ts_j, vehicle j transmits its next acceleration a_n to its follower.

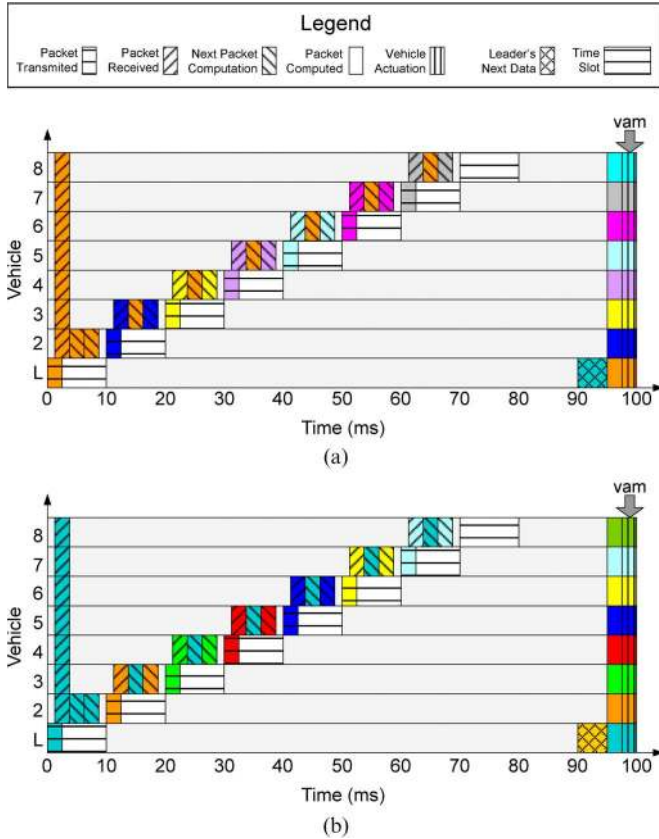   At vam, vehicle j actuates with a_n.

end for

Fig. 7. Algorithm IV: With all vehicles' anticipatory information, using vehicle actuation moment vam. (a) First 100-ms time frame. (b) Second 100-ms time frame.

Fig. 8. Leader's actuation. (a) Acceleration pattern. (b) Velocity pattern.

Algorithm 4 presents the follower's behavior in this information-updating scheme, whereas the behavior of a leader is the same as in Scheme II (see Algorithm 3).

E. Information-Updating Scheme V

At the first tc, the leader transmits its data to the followers. At each subsequent tc, each of the followers, in sequence, transmits their data to the vehicle behind them. As on Scheme IV, the vehicles hold their actuation, until all vehicles receive their information. Only then, all vehicles simultaneously update their operation parameters, at the vehicle actuation moment vam, in the end of each information-updating cycle uc. With an n-vehicle platoon, each uc should attain the condition $uc \geq n \times tc$. For an eight-vehicle platoon, with $tc = 100$ ms, $uc \geq 800$ ms. This updating scheme is proposed for a stable and foreseeable traffic state. Its major advantage consists of the significant low communication channel load it presents.

VII. RESULTS

To assess the appropriate operation of the proposed models, several simulations were carried out in Matlab/Simulink [43]. All models include an eight-vehicle platoon of IVC-enabled autonomous vehicles, aiming to maintain a 1-m distance to their precedents. The operational part of the model is implemented in Simulink. Fig. 4 shows the platoon's information flow diagram. The applied acceleration profile and the resultant velocity are
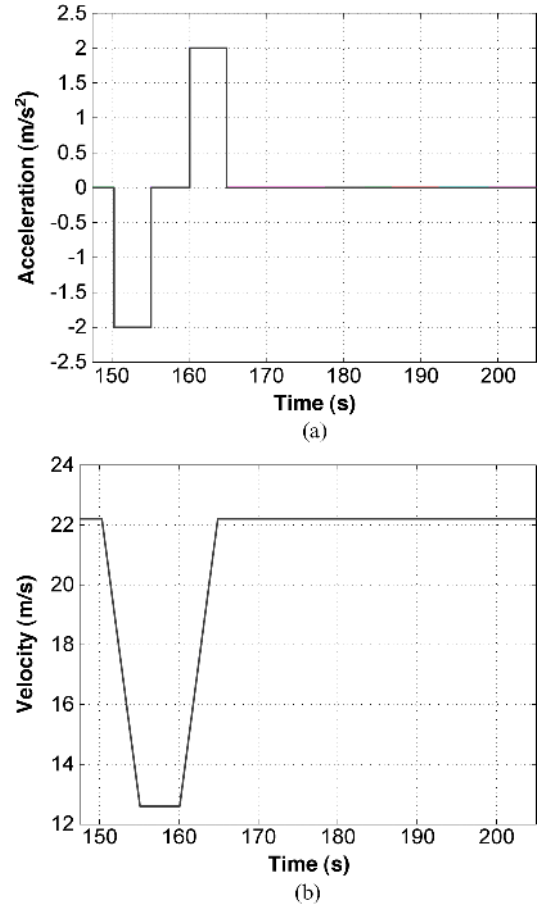
TABLE VI
PARAMETERS OF THE SIMULATION MODEL

Parameter	Symbol	Value
Time step	T_s	$1\,ms$
Bandwidth of the controller	ω_n	0.2
Damping ratio	ξ	1
Leader's weight (fixed)	C_1	$0 \leq C_1 < 1$
Leader's weight base value	C_2	$0 \leq C_2 < 1$
Leader's weight (dynamic)	$C_{1_{dyn}}$	$C_2 \leq C_{1_{dyn}} < 1$
Maximum acceleration	a_{max}	$3\,ms^{-2}$
Leader's acceleration	a_{upp}	$2\,ms^{-2}$
Leader's deceleration	a_{low}	$-2\,ms^{-2}$
Maximum deceleration	a_{min}	$-4\,ms^{-2}$
Communication time slot	ts	$10\,ms$
Communication token cycle	tc	$100\,ms$
Information updating cycle	uc	$100\,ms$, $800\,ms$

shown in Fig. 8. Table VI presents the simulation parameters used in the Matlab/Simulink simulations.

In this section, we present the results obtained from simulations performed with Matlab/Simulink for the five information-updating schemes previously proposed.

A. Information-Updating Scheme I

The first simulation corresponds to Scheme I (Section VI-A). It is assumed that all vehicles operate with transmitted information 100 ms old. As such, their response will present a delay

with respect to each precedent vehicle. In Fig. 9(a), the increase in the absolute values of the followers' acceleration with respect to the leader is presented. Fig. 9(b) shows a detailed region of Fig. 9(a), where we can observe the discrete values of the acceleration, with a 100-ms sample period. Fig. 9(c) shows the resultant velocity of each vehicle, with all of them approaching their precedent vehicle and subsequently falling behind it, as Fig. 9(d) clearly shows. All vehicles reach to a point (at about 155 s) where they are only 60 cm apart from the respective precedent vehicle. In this first simulation, we used $C_1 = 0$, which means that the leader's information has no effect on the behavior of all the platoon followers, except on the second vehicle, since this is the leader's immediate follower.

A second simulation was performed using $C_1 = 0.999$. Fig. 10 shows the acceleration, velocity, and spacing error of this case. Note that the second vehicle is noticeably affected by the 100-ms communication delay, presenting a worse response than that of the previous case. Equation (6) may enlighten this issue. When $C_1 = 0$, the computation of the next acceleration value does not consider the difference of the velocity values between the vehicle and the leader. However, as C_1 increases, that difference is used. Unfortunately, the second vehicle is using 100-ms-old information, from both the leader's acceleration and the velocity values. As such, the result is worse when compared with the case of $C_1 = 0$ since the spacing error in the later case was only caused by 100-ms-old acceleration value from the precedent vehicle (which is the leader in this case). The response is also more abrupt than before. Since the remaining vehicles receive the same information from the leader at the same time, the spacing error toward their precedent vehicles is softened. (It is worth remembering that they are operating with $C_1 = 0.999$.)

B. Information-Updating Scheme II

This scheme differs from the previous scheme by a feature that is of the most importance to the stability of the platoon: the transmission of leader's anticipatory information. As explained in Section VI-B, this is due to the leader's waiting step, until the vehicle actuation moment vam is reached, allowing its followers to timely use the transmitted information in their own next acceleration computation. The simulation of this scheme presents several relevant results: as we can observe from Fig. 11(a), independently of the value of C_1, the second vehicle mimics the behavior of the leader, as it is also its precedent. The third vehicle response is shown in Fig. 11(b). The response is identical of that of Scheme I when $C_1 = 0$, as expected. However, as C_1 increases, the vehicle's response is considerably improved. As C_1 approaches 1, the tracking error approaches zero. The same behavior is presented by all the remaining vehicles [the eighth vehicle's response is shown in Fig. 11(c). These results show that the leader's anticipatory information has a major impact on the platoon stability, and apart from the second vehicle, its effect is proportional to C_1. Ideally, platooning with this operating scheme and a very high C_1 value would assure a very stable platoon behavior. However, it would be also problematic in the long run since vehicles would be considering the leader's data almost exclusively,
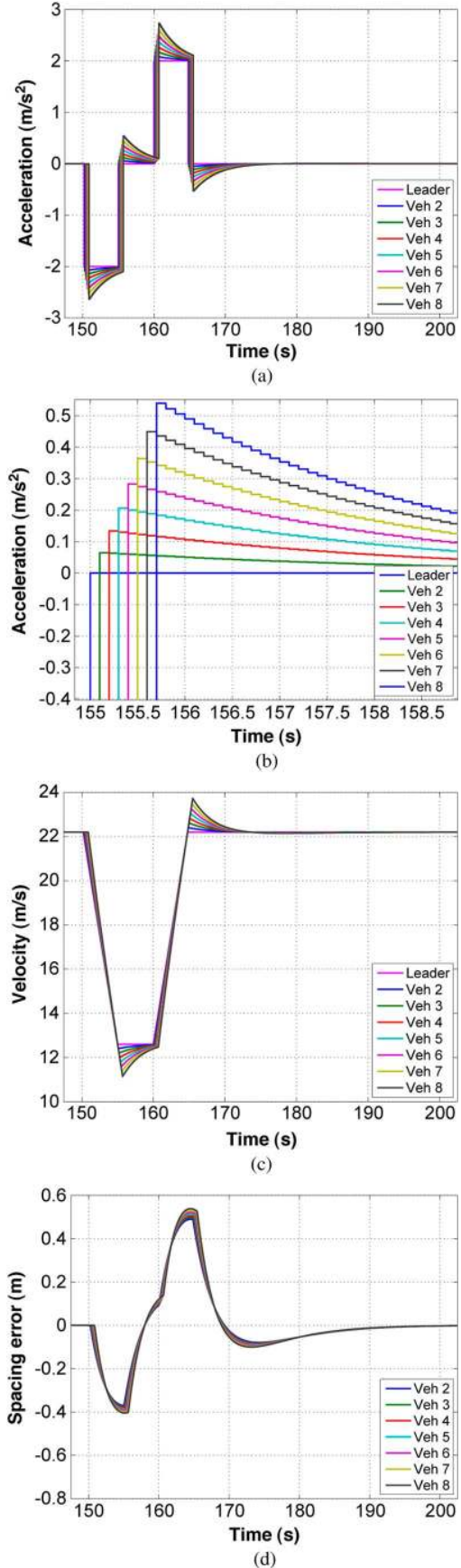

Fig. 9. Algorithm I with $C_1 = 0$. (a) Acceleration of the platoon. (b) Acceleration of the platoon (zoomed). (c) Velocity of the platoon. (d) Spacing error of the platoon.
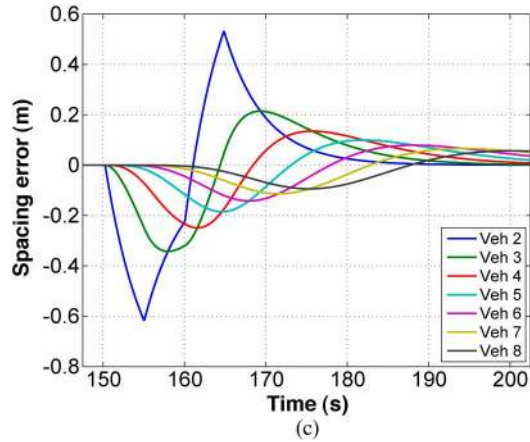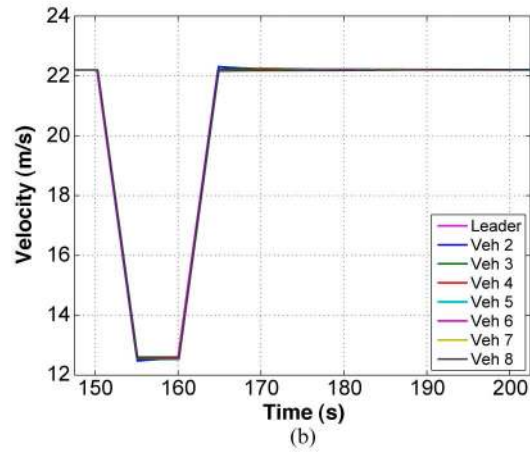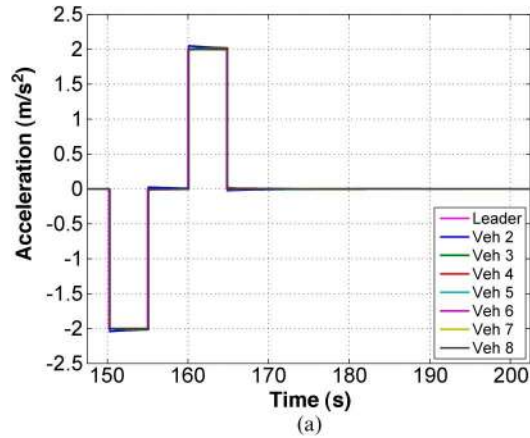
Fig. 10. Algorithm I with $C_1 = 0.999$. (a) Acceleration of the platoon. (b) Velocity of the platoon. (c) Spacing error of the platoon.

Fig. 11. Algorithm II: Leader's anticipation. (a) Vehicle 2. (b) Vehicle 3. (c) Vehicle 8.

which is neither secure nor reliable. As such, a scheme that could entangle a balance between stability and safety would be preferable. The platoon operating with a fixed C_1 value between 0.5 and 0.7 has shown to be an acceptable compromise. However, it is not adaptive.

C. Information-Updating Scheme III

In the simulation of this updating scheme, we analyze the adaptive value for the leader's information weight $C_{1_{\text{dyn}}}$, discussing in detail the effects of this dynamic parameter on the platoon stability. Table VII presents the spacing errors of
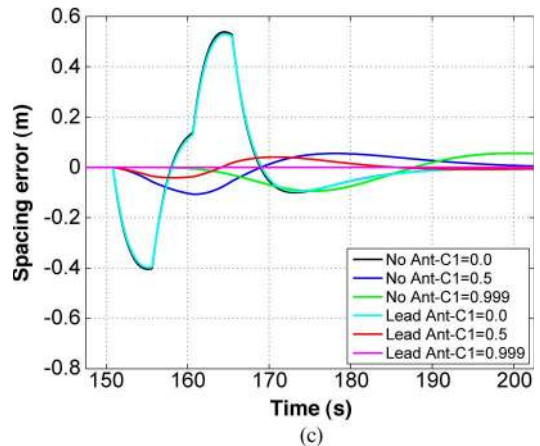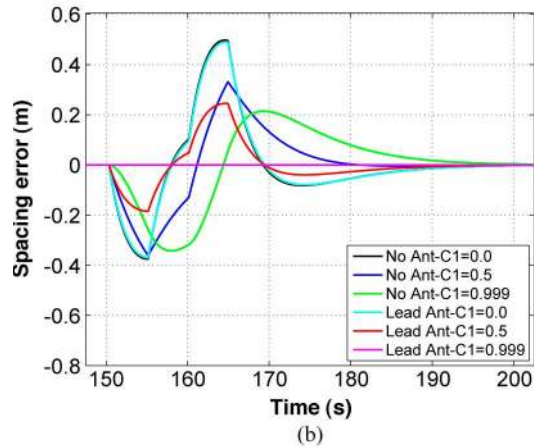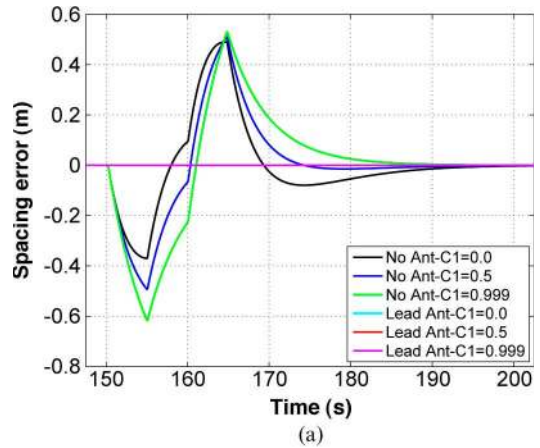
algorithms I and II, when performed with several different C_1 parameter values. The lines in bold represent the spacing error values when the vehicles approach their precedent, with respect to the 1-m objective distance (negative error values), whereas the other lines represent the spacing error when the vehicles have fallen behind its 1-m objective (positive error values). We can observe that the C_1 value is crucial to platoon stable behavior.

When operating with $C_1 = 0.5$, the spacing error data of the vehicles in positions 4, 5, and 6 seem to be contradictory. Therefore, a more detailed analysis is required. In fact, these vehicles seem to present no behavior improvement from the

TABLE VII
INFLUENCE OF C_1 ON THE SPACING ERROR

Veh.	$C_1 = 0$			$C_1 = 0.5$			$C_1 = 0.9$		
	NA	LA	%	NA	LA	%	NA	LA	%
2	**-0.370**	**0.000**	**100**	**-0.493**	**0.000**	**100**	**-0.592**	**0.000**	**100**
	0.490	0.000	100	0.509	0.000	100	0.526	0.000	100
3	**-0.375**	**-0.370**	**1**	**-0.360**	**-0.185**	**49**	**-0.327**	**-0.037**	**89**
	0.497	0.490	1	0.330	0.245	26	0.213	0.049	77
4	**-0.381**	**-0.375**	**2**	**-0.257**	**-0.139**	**46**	**-0.238**	**-0.020**	**91**
	0.505	0.497	2	0.190	0.180	5	0.131	0.026	80
5	**-0.386**	**-0.381**	**1**	**-0.187**	**-0.101**	**46**	**-0.177**	**-0.012**	**93**
	0.513	0.505	2	0.120	0.123	−3	0.095	0.015	85
6	**-0.392**	**-0.386**	**2**	**-0.151**	**-0.073**	**52**	**-0.135**	**-0.009**	**94**
	0.521	0.513	2	0.087	0.079	9	0.075	0.010	87
7	**-0.398**	**-0.392**	**2**	**-0.128**	**-0.052**	**59**	**-0.108**	**-0.006**	**94**
	0.529	0.521	2	0.068	0.055	19	0.062	0.007	89
8	**-0.404**	**-0.398**	**1**	**-0.107**	**-0.041**	**62**	**-0.089**	**-0.005**	**95**
	0.538	0.529	2	0.055	0.041	25	0.053	0.005	90
LEGEND: Veh.-Vehicle position		NA-No Anticipation			LA-Leader Anticipation			%-Improvement		

leader's anticipatory information with respect to the case where no anticipation exists. In Fig. 12, we can see the behavior of the platoon with $C_1 = 0.5$. Fig. 12(a) shows the spacing error with no anticipatory information, whereas Fig. 12(b) shows the case when anticipation exists. We can observe that, in the later case, since the second vehicle mimics the behavior of the leader, the remaining vehicles are unable to so promptly respond when acceleration occurs. Therefore, the response of the vehicles in positions 4, 5, and 6 is not as good as expected, resulting in similar values of the former case, in the absence of anticipatory information, as can be seen in Fig. 12(c). However, it is important to notice that this only happens when vehicles accelerate. During braking maneuvers, the improvement is always above 45%, which assures a safe operation of the system.

Although higher values of C_1 prove to be generally beneficial in the presence of leader's anticipatory information, they should not be maintained for a long time. In fact, a high C_1 value is only required when a considerable difference of the acceleration, in absolute terms, occurs between consecutive uc intervals. When facing strong accelerations and/or decelerations, a prompt platoon response is required to maintain stability. However, as the acceleration stabilizes, C_1 may then be relaxed to a more conservative value. These are the premises of the present scheme. For this purpose, we introduced the aforementioned parameter C_2, representing the base value above which the dynamic C_1, which is represented by $C_{1_{dyn}}$, will vary, when strong accelerations are determined by the leader. Fig. 13 shows the comparison of the results for equal values of a fixed C_1 and a base value C_2 with dynamic $C_{1_{dyn}}$. We consider only fixed C_1 values of 0.7 and 0.9 since the difference of results using low fixed C_1 with respect to equally low C_2 with dynamic $C_{1_{dyn}}$ is so high that the resultant graph scale does not allow accurate visualization of the spacing errors corresponding to the $C_{1_{dyn}}$ values. Fig. 14 shows the spacing error results showing better response of dynamic $C_{1_{dyn}}$ with a base value C_2 of zero, when compared with fixed $C_1 = 0.99$. Note that this is one of the most unfavorable case for $C_{1_{dyn}}$ and an extremely favorable case for the fixed C_1. Even so, the dynamic scheme presents a considerable stability improvement. Fig. 15 shows both the acceleration patterns of the third vehicle and the

values of dynamic $C_{1_{dyn}}$ with a base value $C_2 = 0$, and a fixed $C_1 = 0.99$.

D. Information-Updating Scheme IV

The results of this scheme are extremely favorable. We already observed, in Scheme II, the beneficial results of the leader's anticipatory information over the platoon behavior, even operating with 1-uc-old information from precedent vehicles. However, with Scheme IV, we took a step further with respect to information anticipation. In this scheme, all vehicles announce the acceleration value that they will use on the next updating cycle uc before their followers compute their own predictable values in an ordered chain of events. Then, all the platoon's vehicles simultaneously actuate at the vehicle actuation moment vam, resulting in a very stable behavior. In this updating scheme, C_1 may present a near zero value, as far as no communication failures occur. This happens because the leader's information is already incorporated into the precedent vehicles' own information, which is anticipatively received. The results of this algorithm, for different C_1 values, present a spacing error virtually null.

E. Information-Updating Scheme V

This scheme is analogous of the precedent, with one major difference: uc is now of 800 ms, instead of 100 ms, as in the previous case. This means that only one vehicle transmits at each $tc = 100$ ms. This scheme is intended to be used in the presence of stable and foreseeable traffic conditions and is very benign in what concerns communication network load. Despite a uc value eight times greater than before, the results are very favorable. The results of this algorithm, for different C_1 values, present a spacing error virtually null, similarly to the previous scheme case.

VIII. NETWORK SIMULATIONS

Some of the information-updating schemes used in previous simulations are very benign where communication network
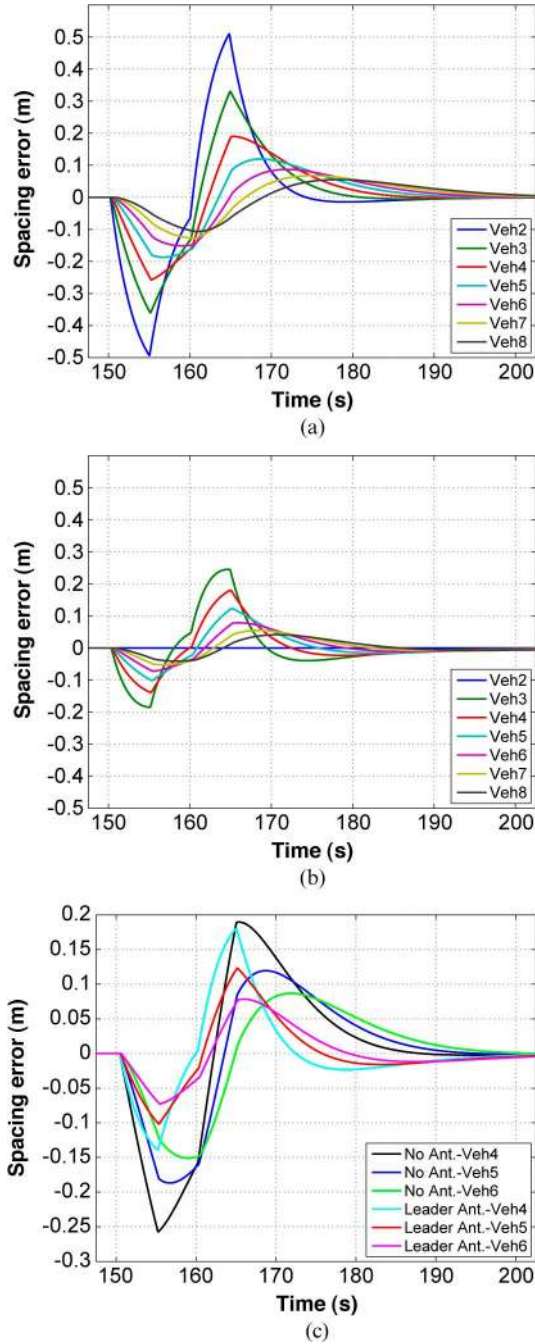
Fig. 12. Analysis of the influence of $C_1 = 0.5$ on the platoon behavior. (a) No anticipation with $C_1 = 0.5$. (b) Leader's anticipation with $C_1 = 0.5$. (c) Vehicles 4, 5, and 6 comparison, with $C_1 = 0.5$.

Fig. 13. Algorithm III: Comparison of a fixed and a dynamic C_1. (a) Vehicle 3. (b) Vehicle 8.

TABLE VIII
DSRC SYSTEM PARAMETERS

Parameter	Value
Frequency Spectrum	$5.9\,GHz$
Channel Size	$10\,MHz$
Max Range	$\leq 1\,Km$
Data Rate	$3\,Mbps$ to $27\,Mbps$
Latency	$\leq 50\,ms$
Slot Time ST	$16\,\mu s$
$SIFS$	$32\,\mu s$
$AIFS$	$64\,\mu s$

load is concerned. However, the current IVC technologies and protocols rise some concerns of whether they can cope with the involved timings of the information-updating schemes, when all vehicles communicate within 100 ms. To assess current IVC operation in such scenarios, we chose to test DSRC since it is conceived to deal with high-mobility patterns, presenting very low latencies and a large-enough range. However, its intrinsic operating characteristics require a more throughout analysis to assess its behavior when a large number of vehicles are involved. For that purpose, we used the NS-3 network simulator.
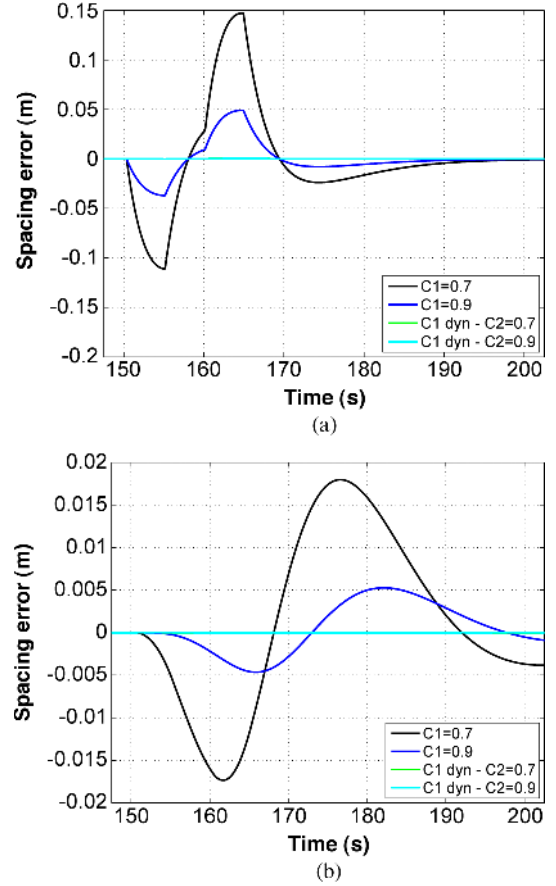
A. DSRC Operating Parameters

DSRC/Wireless Access in Vehicular Environments are defined in the IEEE 802.11p and 1609.x standards [5]–[7], [44]. The lower layers are defined in IEEE 802.11p, and its MAC protocol uses an improved version of the distributed coordination function, which is named enhanced distributed channel access (EDCA), with quality-of-service (QoS) capabilities. The DSRC system parameters are presented in Table VIII.

B. NS-3 Simulation Setup and Parameters

A scenario of ten platoons of eight vehicles each was implemented in NS-3. Each platoon is separated by 30 m. Each vehicle is 3 m long and is separated from the precedent vehicle by 1 m. The antennas are defined at 1.5 m above the ground.
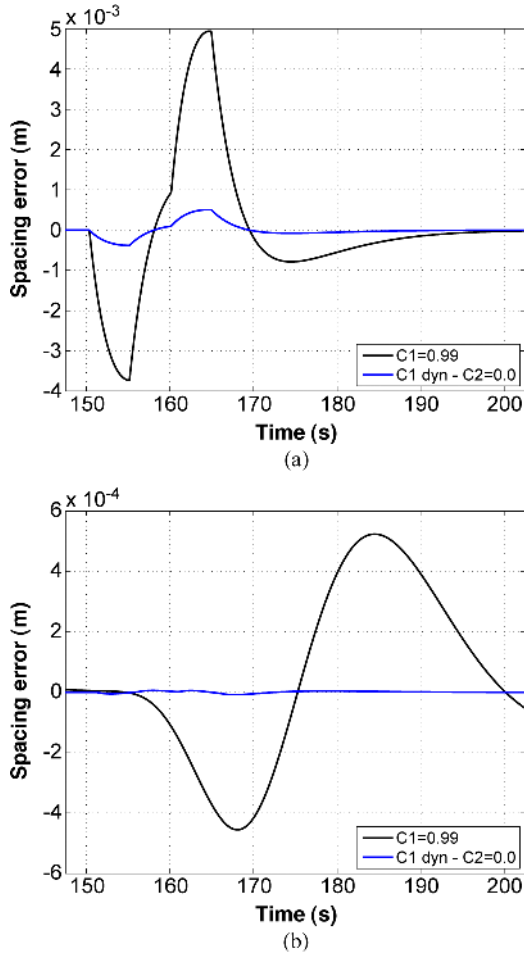
Fig. 14. Algorithm III: High fixed versus dynamic C_1 with low C_2. (a) Vehicle 3. (b) Vehicle 8.

Fig. 15. Algorithm III: Leader's acceleration and dynamic C_1. (a) Vehicle 3: Acceleration. (b) Vehicle 3: Dynamic C_1 with $C_2 = 0$.

The platoons' leaders broadcast messages to their followers at 3-Mb/s data rate and in LOS. Each follower communicates to its own follower using unicast at 27-Mb/s data rate. Each data packet has a 100-B payload, and explicit acknowledgement (ACK) packets have 10 B. The communication is performed through the DSRC control channel (CCH) since CCH is dedicated to safety and control messages, whereas service channels (SCHs) are reserved for more general-information purposes. The CCH intervals are active for 50 ms of each 100-ms interval. A 4-ms guard interval (GI) was reserved at the beginning of each CCH to allow proper synchronization and channel switching of all vehicles [45]. Of the remaining 46 ms, we reserved a time slot of 11 ms for the leader and 5-ms time slots for each one of the seven followers. Fig. 16 shows the proposed logical division of the CCH, aiming to avoid packet collisions within each platoon. Nevertheless, data packets continue to contend for the transmission media access between each ith vehicle of near platoons.

The main concern that this setup poses is related to proper reception of leaders' broadcasted messages by the vehicles in eighth position at each platoon. In fact, the distance to their respective leaders is 28 m, and the leaders of the platoons behind them are only 33 m apart (considering antenna-to-antenna distances). To assess proper communication flow, a

Fig. 16. DSRC CCH leaders' and followers' time slots.

ten-platoon setup of eight vehicles each was implemented. The main simulation parameters are presented in Table IX.

C. NS-3 Simulation Results

Several simulations were performed. In the beginning of each one, a warm-up process was conducted to proceed to the fulfillment of the MAC/Internet Protocol address association tables

TABLE IX
PARAMETERS OF THE NS-3 NETWORK SIMULATION

Parameter	Value
Number of nodes	80
Guard interval	$4\,ms$
Time slot (leader)	$11\,ms$
Time slot (follower)	$5\,ms$
Node spacing (intra-platoon)	$4\,m$
Node spacing (inter-platoon)	$33\,m$
Propagation delay model	Constant speed
Propagation loss model	Log distance
Data rate (leader)	$3\,Mbps$
Data rate (follower)	$27\,Mbps$
AC	$3\,(VO)$
AIFSN	2
CW_{min}	3
CW_{max}	7

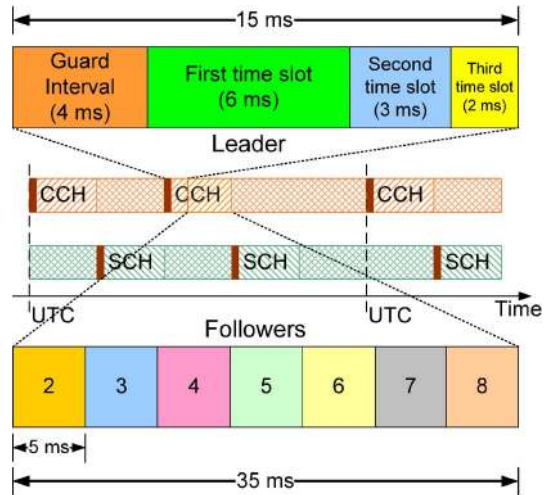(among other actions). This procedure intends to avoid the overhead that such packet exchange would produce during the first superframe of data transmission. DSRC protocol defines that each CCH start time is synchronized with the coordinated universal time (UTC). Additionally, we divided each CCH in time slots to avoid intraplatoon collisions. These two features could lead to an interplatoon transmission synchronism, which might increase first packet collisions in the beginning of each time slot, even when using the arbitration interframe space number (AIFSN) and contention window (CW) mechanisms, of the IEEE 802.11e EDCA QoS enhancements [46]. In fact, when a node detects that the media is busy, a new CW is computed, and the corresponding backoff time is applied, i.e.,

$$CW_{\mathrm{new}} := min\left\{2 \times (CW_{\mathrm{old}} + 1) - 1, CW_{\mathrm{max}}\right\}. \qquad (8)$$

However, at the beginning of each time slot, only the $AIFS[AC]$ interval is used, with

$$AIFS[AC] = AIFSN[AC] \times ST + SIFS \qquad (9)$$

with the access category $AC = 3(AC\_VO)$, the arbitration interframe space $AIFS[AC] = 64$ μs, $AIFSN[AC] = 2$, DSRC slot time $ST = 16$ μs, and the short interframe space $SIFS = 32$ μs. Since all platoons' vehicles use this same value, collisions are prone to occur. To minimize the probability of these early collisions, an additional application-level random backoff between CW_{min} and CW_{max} was inserted.

The presented data of Figs. 17 and 18 were obtained from statistically noncorrelated simulations of 100 frames of 100 ms each.

Fig. 17 shows the aggregate data of average, minimum, and maximum values of reception delays from precedent vehicles, per platoon, using unicast. Higher average delay values are presented by the middle platoons. These results are in concordance with what would be expected since these platoons receive transmissions from both the platoons upfront and the platoons behind. (The DSRC range limit may be higher than the length of a ten-platoon chain like this one.) We see that the average values are all under 1 ms, and no failures occurred over the entire simulation. Since the time slots of the followers are 5 ms long, they have enough remaining time to perform
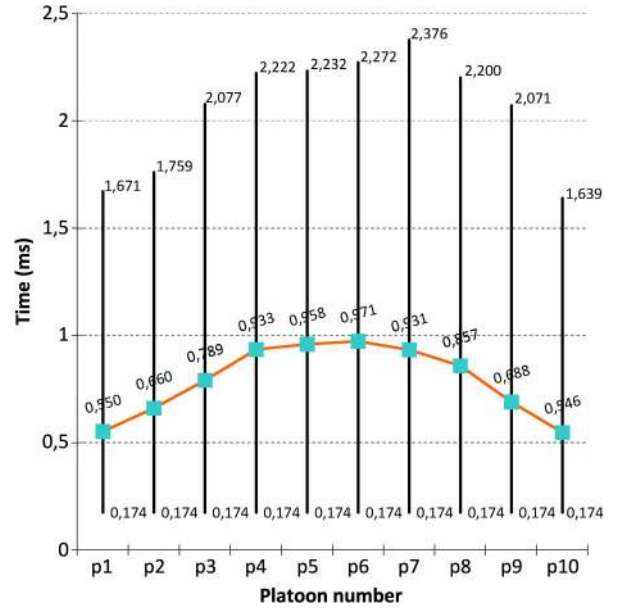
Fig. 17. Platoons' follower reception delays of messages from their precedent vehicles, using unicast.
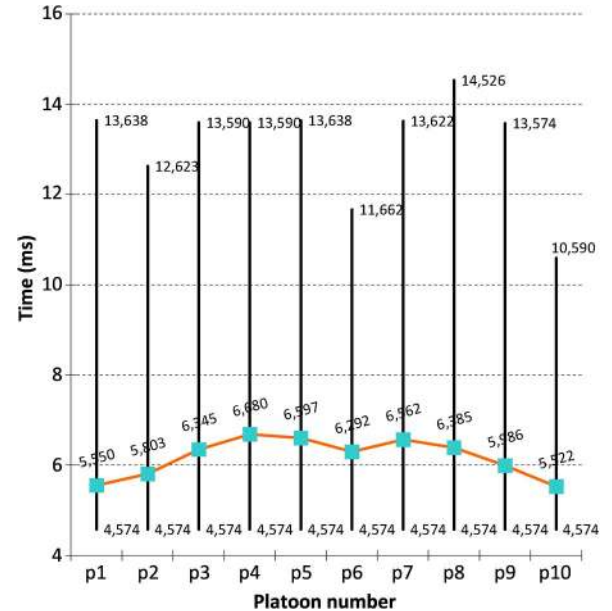
Fig. 18. Platoons' follower reception delays of messages broadcasted by their leaders.

all the required computations, which validates the assumptions made when information-updating Scheme IV was presented and simulated (see Sections VI-D and VII-D, respectively). Even the maximum detected delay of 2.376 ms is below half the time slot value.

Although unicast communication between followers is reliable, the broadcasted communication between the leaders and their followers is not very resilient. There is no packet delivery guarantee since the ACK mechanism does not exist in broadcasting. Moreover, even if a collision occurs, the broadcast emitter has no means of detecting it since the MAC of IEEE 802.11p uses carrier sense multiple access with collision avoidance. Therefore, an explicit ACK mechanism had to be

implemented to ensure proper reception of broadcasted messages from each platoon's leader to all its followers. Although several strategies to improve reliable broadcasting in vehicular environment have been proposed by the research community, this is a problem that has yet to be completely tackled. After several experimental simulations, we decided to implement a selective ACK mechanism. Since all performed simulations revealed that the vehicles in the eighth position had always failed to receive its message when transmissions failure occurred, we used those vehicles as referees to acknowledge successful platoons' leader transmissions. As such, they became the sole followers to emit ACKs upon proper reception of their own leader's messages, in the right time slots. Using this scheme, several subdivisions of the leader's time slots, and two or three transmissions were thoroughly tested. The most favorable results were obtained with the leader's time slot subdivision shown in Fig. 16. Considering the 4 ms of the GI, the first transmission occurs at 4 ms from the beginning of each CCH interval, at the beginning of the 11-ms leader's time slots, and is 6 ms long; the second one occurs at 10 ms, if necessary, and is 3 ms long; and the third one occurs at 13 ms, for 2 ms long. The obtained results with this time slot subdivision, and the parameters presented in Table IX suggest that this communication scheme is reliable.

Fig. 18 shows the aggregate results of the simulations performed, with the average, minimum, and maximum values of reception delays of the followers, from leaders' broadcasted messages, per platoon position. Higher average delay values are presented by the middle platoons, due to the same aforementioned reason. As such, the platoons at the top of the chain present better average delay results, around 5.5 ms, whereas the platoons in the middle present average delay results at about 6.7 ms. Simulation also showed that the first leaders' transmissions were mostly successful. When the corresponding ACK did not arrive in time, a second transmission took place. When the second transmission's ACK was not timely received by the leader, a third transmission occurred. Quantitatively, 89.4% of the first transmissions were successful; 9.8% reached their destiny at the second transmission; and only 0.8% required three transmissions to be properly received.

Since platoon leaders' time slots were augmented by 50% with respect to previous Matlab/Simulink simulations and the followers' time slots were reduced to half its previous value, a new set of simulations were performed with these different timings. The results are similar to those obtained previously, confirming the appropriate performance of the proposed algorithms.

IX. CONCLUSION

A simulation engine for platoons of IVC-enabled autonomous vehicles has been implemented in Matlab/Simulink. Several information-updating schemes have been proposed and assessed through simulation scenarios. The simulation results suggest that the proposed information-updating algorithms are appropriate to the problem under study.

To assess whether DSRC could cope with the tight time constraints of the simulation models, a set of simulations has been performed with the NS-3. The results suggest that the proposed algorithms may operate using the present technology, although some concerns remain with respect to broadcast performance of the DSRC protocol. Moreover, the selected Log Distance signal propagation model used in the NS-3 simulator may be simplistic. Other models (e.g., Three Log Distance or Nakagami with different m-parameter values) might probably present less favorable results with respect to leaders' broadcasting since the reliability of this protocol is still an open issue in the research community. Thus, more demanding network scenarios with more complex mobility patterns should also be assessed.

Nevertheless, when using the information-updating Scheme IV proposed and simulated in Sections VI-D and VII-D, respectively, the leader's anticipatory information is already incorporated in the information that each vehicle receives from its precedent and transmits to its own follower, allowing a safe operation with parameter $C_1 = 0$. As such, an all-unicast intraplatooning transmission scheme is feasible, leaving broadcasting for leaders to communicate with other platoons and infrastructure. Moreover, unicast messages are resilient and timely delivered under the simulated scenarios.

Since constant spacing platooning may enable a considerable increase in traffic flow, more simulation results of IVC-enabled autonomous vehicles are required, aiming at the comprehension of new possible representations of the fundamental diagram of traffic flow applied to such scenarios.

Considering the favorable performance presented by the proposed information-updating algorithms in the very demanding scenario of constant spacing platoons, they might also allow important safety and efficiency improvements when applied to different scenarios involving other type of IVC-enabled vehicles.

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