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Relay-assisted platooning in wireless networks: a joint communication and control approach

Tiago R. Gonçalves, Vineeth S. Varma, and Salah E. Elayoubi

Abstract

This paper addresses the problem of the joint design of the mobile communication system and the control scheme for enabling vehicle platooning applications. Vehicles communicate essential information for platooning control through multi-hop vehicle-to-vehicle (V2V) communications and are assisted in this task by Road Side Units (RSU), when available. While classical approaches, adopted in previous and current mobile systems, consider the application needs solely as requirements for the communication network, we advocate a bi-directional interaction of application and communication network. We first study the impact of different communication strategies on the application-level performance, namely the inter-vehicle distance in the platoon. Such schemes introduce a tradeoff between the packet delivery rate and the additional delay introduced by relaying. In order to assess the impact of both metrics, we start by developing a Markov model for the different communication links (inter-vehicle and vehicle-to-RSU). We then propose a cross-layer approach that adapts the application layer (platoon control parameters) to the observed Medium Access Control (MAC) layer performance. We demonstrate via simulations the benefit of the proposed relaying scheme, and that a joint design of application and communication systems is essential for enabling the integration of industrial applications in future generation networks.

Index Terms

Vehicle platoons, relaying, cooperative adaptive cruise control (CACC).

I. INTRODUCTION

Vehicle platoon is a particular formation of a group of coordinated vehicles, where a short inter-vehicle distance is maintained by automation and Vehicle-to-Vehicle (V2V) communication technologies [1]. Vehicle platooning is expected to improve fuel efficiency [2]–[4] and reduce traffic congestion [5]–[7] by gathering vehicles close together, thus reducing the air resistance of the platoon’s members. Experimental analysis have shown that with such particular convoy formation, a bus, following another one, is able to reduce 40% in aerodynamic drag at 80km/h when 10m of inter-vehicular distance is maintained [8], [9]. However, the feasibility and the deployment of platoons require a reliable and fast exchange of information between vehicles so that control actions are based on the most up-to-date information about the road and traffic status. Nevertheless, such an exchange of information occurs over unreliable wireless communication channels subject to inherent characteristics such as delay and packet loss. A careful design of the communication schemes for platoons is thus essential, but the focus in this design must shift from the objective Quality of Service (QoS) measures (delay, packet loss) to the application-layer performance, essentially the minimum achievable inter-vehicle distance without any risk of vehicle collisions.

In this paper, we investigate the joint design of the Vehicle to Everything (V2X) network and the platooning control scheme. We specifically consider relay-assisted vehicle-to-vehicle (V2V) communications for conveying essential platooning information. When a vehicle (platoon leader or member) sends a packet, it is overheard by the other vehicles and the Road Side Units (RSU) that may relay the packet, increasing thus the packet delivery ratio but introducing an additional delay. We propose analytical models for the network and application sides and then use them for joint optimization.

On the network side, we propose a novel model for the channel access schemes with the presence of relaying links through V2V and the RSU. In particular, we model the presence of a large number of point-to-point V2V links, coexisting with a broadcast relaying link that conveys the leader’s packets to the rest of the platoon. Our model also integrates the impact of radio errors resulting from the physical layer (link performance) within the Medium Access Control (MAC) layer model (packet collision estimation).

Tiago R. Gonçalves, and Salah E. Elayoubi are with Université Paris-Saclay, CentraleSupélec - CNRS - L2S, Gif-sur-Yvette, France. E-mail: {tiago.rochagoncalves; salaheddine.elayoubi}@centralesupelec.fr.

Vineeth S. Varma is with Université de Lorraine, CRAN UMR 7039 and the CNRS, Nancy, France. E-mail: vineeth.satheeskumar-varma@univ-lorraine.fr.

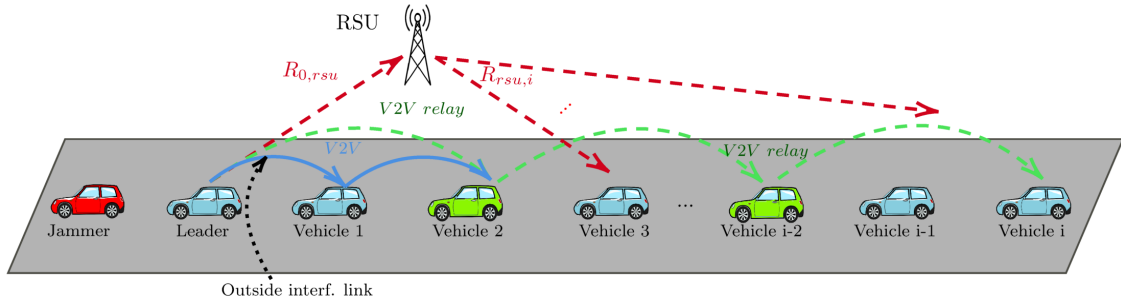


Fig. 1. Arrangement of a platoon with V2V and V2I relaying communication technologies. The solid blue lines are the vehicle to neighbor links, the dashed green and red lines are the broadcast links for V2V and RSU relaying, respectively, and the dotted black lines are the outside interference links from outside the platoon.

For the application layer, we consider the Predictive Cooperative Adaptive Cruise Control (PCACC) controller [10] and extend it by introducing a dynamic control mechanism where some of the parameters of the controller are adapted based on the expected quality of the radio system. We assess the performance of this proposed control scheme under the different relaying strategies. We specifically integrate the resulting Packet Error Rate (PER) and delay distribution and evaluate their impact on the platoon performance. To the best of our knowledge, no prior studies addressed the analysis of the network performance with a comprehensive comparison between different relaying schemes while considering the coexistence of communication and control aspects.

In view of the above, the main contributions of this paper are summarized as follows.

- Proposition and analytical modeling of V2V relaying scheme and a study of the impact of RSU relaying. These models integrate the impacts of link and system levels.
- Evaluation of the impact of network QoS (errors and delay) on the controller performance under V2V and RSU relaying.
- Offline optimization of the platoon control parameter, namely inter-vehicular distance, for a given communication scenario.
- Joint optimization of the network and application as we show that the communication performance is impacted by the control performance and vice versa leading to behavior that can not be easily predicted by a "silo-based" approach.

Many research works look at platooning formation, of which several have proposed different approaches to extend the coverage range of the leader message to other platoon members using relaying systems. In particular, two main factors are the motivation behind relaying in platooning systems: (i) large path loss fading caused by extensive platooning; (ii) external interference that substantially reduces the probability to decode the signal correctly. In opposition to existing works, we do not aim to propose new relaying schemes for platooning but use the existing relaying methods through V2V relaying and RSU to study the performance from an end-user perspective with a bi-directional interaction between control and communication parameters. The advantage of our approach is that we exploit the existing packets and add the relayed information within them to avoid overload conditions. The relevance surges due to the requirement of periodic messages from the application layer. Therefore, exploiting the information from the application side to make the relaying without an overload is a substantial improvement in our cross-layer scheme between the application and MAC layers.

II. PLATOONING CONTROL SYSTEM

This paper considers a longitudinal platoon of N vehicles, arranged as 1 platoon leader and $N - 1$ platoon members. The platoon members are distributed as non-relaying and $N_r - 1$ relaying vehicles as depicted in Fig. 1 in blue and green colors, respectively. The vehicles in all other lanes are not necessarily in platoons, and a jammer (in red) precedes the platoon leader. In order to stabilize the platoon under the presence of the jammer, while reducing the distance between the platoon members, the platoon leader communicates data about its acceleration and velocity to all the members of the platoon, as does also each vehicle to its following one. If packets are lost or delayed, the platoon performance may be adversely affected. Therefore, communication link reliability is imperative to the deployment of controlled platoons. We introduce in this section a brief overview of the system with the proposed dynamic control and the considered communication scenarios specific to platooning.

A. Vehicle dynamics

In order to simplify the system analysis, the vehicle dynamics are modeled as a first-order low pass filter due to the actuator lag, which has been widely adopted in the literature [11]–[13] in the continuous-time dynamics as:

$$\dot{x}_i(t) = v_i(t) \quad (1)$$

$$\dot{v}_i(t) = a_i(t) \quad (2)$$

$$\dot{a}_i(t) = -\frac{1}{\tau_a}a_i(t) + \frac{1}{\tau_a}u_i(t) \quad (3)$$

with x_i , $\dot{x}_i = v_i$, and $\ddot{x}_i = a_i$ being the longitudinal position, velocity and acceleration of vehicle i , respectively. The subscript i is the vehicle platoon member index where $i \in \{1, \dots, N-1\}$ and 0 the platoon leader index. u_i is the control input of vehicle i , i.e., its desired acceleration. τ_a is the time constant of the first-order low pass filter, i.e., the actuator lag. In other words, it is the delay between the acceleration signal and its actual realization in the vehicle as a result of inertial and mechanical constraints. The rationale is to approximate the dynamics of the throttle body and vehicle inertia in order to avoid instantaneous response. Furthermore, control input constraints were applied to avoid unpractical acceleration signals as $u_{min} \leq u_i(k) \leq u_{max}$ where u_{min} and u_{max} are the minimum and maximum acceleration signals admitted that compass the control signal. In this paper, we assume a lag of $\tau_a = 0.5$ s as in [13] in order to be conservative. A smooth behavior of a platoon is important, so to ensure passenger comfort, the control input constraints are bounded by $u_{min} = -3$ m/s² and $u_{max} = 2$ m/s² as in [14], [15].

B. Objective of platoon control

The objective of platoon control is to allow the platoon members to track the leader's speed, while maintaining a desired constant distance gap D_{des} between preceding vehicles in the absence of any disturbance in the leader's vehicle, i.e., no acceleration nor braking. The constant spacing condition being satisfied can be written as

- 1) $\lim_{t \rightarrow \infty} |\dot{x}_i(t) - \dot{x}_0(t)| = 0$
- 2) $\lim_{t \rightarrow \infty} |x_i(t) - x_{i-1}(t) + L_i + D_{des}| = 0$

where the first limit aims to mimic the leader's speed while the second aims to keep a desired distance D_{des} between preceding vehicles in the platoon where L_i is the length of vehicle i . Note that in order to maintain the coordinated behavior of the platoon, we assume that all platoon members follow the same constant spacing policy where the objective is to keep a constant and stable distance D_{des} between vehicles. Because from the perspective of fuel saving and traffic efficiency, a constant spacing policy is preferred over a constant time-gap policy.

C. Platoon controller and information flow topology

We describe briefly the application level control schemes and the information flow topology for the evaluated platooning scenario. A thorough understanding of the dynamics of the controller is indeed essential for the design of relevant communication schemes. Similar to [14], [10], [16] and [17] we adopt a platoon scenario with the well-known sliding-surface longitudinal control proposed by [13] where certain network-induced issues such as time delay and packet dropout are evaluated. More precisely, we adopted a modified version introduced by Sybis *et al.* [10], and adapted it here to incorporate packet delays. Such a scheme implies that the control effort, the desired acceleration, of the leader (\ddot{x}_{0_des}) and of the preceding vehicle ($\ddot{x}_{(i-1)_des}$) are available to the following vehicle, and its control law is given by

$$\begin{aligned} \ddot{x}_{i_des}(t) &= (1 - C)\ddot{x}_{(i-1)_des}(t - \Delta) + C\ddot{x}_{0_des}(t - \varphi) \\ &\quad - (2\xi - C(\xi + \sqrt{\xi^2 - 1}))\omega_n \dot{\epsilon}_i(t - \rho) \\ &\quad - (\xi + \sqrt{\xi^2 - 1})\omega_n C(\dot{x}_i - \dot{x}_0)(t - \varphi) - \omega_n^2 \epsilon_i(t - \rho) \end{aligned} \quad (4)$$

where

$$\epsilon_i = x_i - x_{i-1} + L_i + D_{des} \quad (5)$$

$$\dot{\epsilon}_i = \dot{x}_i - \dot{x}_{i-1}. \quad (6)$$

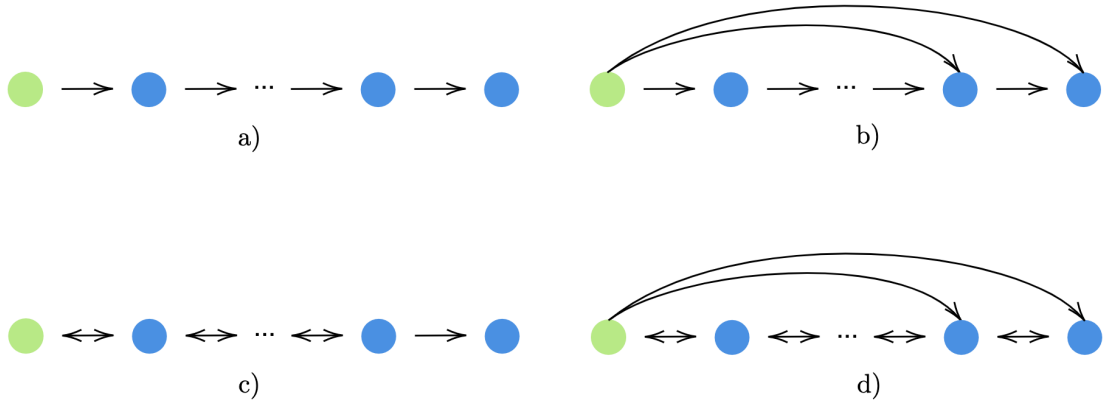


Fig. 2. Typical information flow topology of platooning systems. The vehicle in green is the leader, while the blue ones are the platoon members.

where L_i is the length of the vehicle and D_{des} is the desired inter-vehicular distance that we want to minimize. The spacing error is defined in (5). The control parameters to be tuned are C , ξ , and ω_n . The parameter C takes on values $0 \leq C < 1$ and is responsible for weighting the contribution of the leader's speed and acceleration. ξ is the controller damping ratio and ω_n is the controller bandwidth. Therefore, the most up-to-date values of the $(\ddot{x}_{0_des}, \dot{x}_0, \ddot{x}_{(i-1)_des})$ in (4) are subject to wireless inherent characteristics such as packet dropouts or delay as follows. ρ consists the delay in sensor measurement and disturbs preceding radar information of position and velocity as in (5) and (6), respectively. Δ is the delay in V2V wireless communication from $(i, i + 1)$ vehicles, and affects the preceding vehicle acceleration $(\ddot{x}_{(i-1)_des})$. Lastly, φ describes the delay in wireless communication from $(0, i)$ link, and it affects the acceleration and velocity of the leader $(\ddot{x}_{0_des}, \dot{x}_{0_des})$ packet. Based on the class of controllers and the wireless communication technologies, different information flow topologies are possible in platooning systems, as shown in Fig. 2. In this work, we adopt the predecessor-following-leader topology, as shown in Fig. 2b, since it exploits communication features and it is suitable with our controller (4). The reader is referred to [18] for further discussions about information flow topology. Note that the leader vehicle information corresponds to only a partial component between many factors needed to design the control signal for each vehicle. Nevertheless, this information is of utmost importance in order to maintain string stability for a platoon under constant spacing policy [13], [19]. This means that in the absence of the leader information, each follower vehicle is still able to compute its own acceleration, but the accordion effect might appear. Note that we assume emergency braking systems to avoid collisions in practical settings. A broader explanation of different types of communication links is explained next.

III. COMMUNICATION MECHANISMS FOR PLATOONING

In order for the platoon control to be efficient, there is a need for a reliable exchange of information between neighboring vehicles and from the leader to the rest of the platoon as discussed in section II-C and shown in Fig. 2b. We introduce in this section the communication solutions considered in this paper.

A. Baseline scheme with V2V communications only

In this baseline, vehicles use direct communication links without any relay-assisted method. Without loss of generality, we consider an IEEE 802.11p-like access on the unlicensed spectrum. The model can be easily extended to other contention-based mechanisms. There are essentially three types of links, as follows:

- Vehicle to neighbor links, where each vehicle conveys its acceleration and velocity to its preceding one. For a platoon of N vehicles, there are $N - 1$ such links. We denote by $(i, i + 1)$ the link between vehicle number i and its preceding. Following the CSMA/CA mechanism, a packet on this link is repeatedly transmitted until an ACK is received from vehicle $i + 1$, or the maximum number of transmissions, say m is reached. Such links are displayed in (blue) solid lines in Fig. 1 for the first two and omitted for the rest for simplicity.

- Broadcast link, where the platoon leader (or the assigned relaying vehicles) communicates its information to the rest of the platoon. As there is no native broadcast channel design in CSMA/CA, it cannot be expected that an ACK is received from each vehicle. The leader, therefore, do not wait for an ACK to retransmit but attempt a fixed number of repeated transmissions denoted by m_l . We denote the broadcast link from the leader to vehicle i as $(0, i)$. Note that such approach is also known as “blind” retransmission scheme, see [20], [21].
- Outside links, that correspond to signals from an interfering source that does not belong to the platoon. We consider M broadcast links and model them as interference as shown in (black) dotted lines in Fig. 1.

B. Relaying of the leader’s packets

Looking back at the control mechanism defined in (4), the $(i, i + 1)$ links convey local control information that is weighted by the parameter $(1 - C)$, while link $(0, i)$ is responsible for carrying information of the leader, weighted by the parameter C . Knowing that the distance on link $(0, i)$ is generally large and that it is subject to larger shadowing (because of the existence of cars in between the leader and the vehicle i), it is of utmost importance to enhance its quality. Therefore, we adopt relaying through V2V and RSU as solutions for the broadcast channel, where the relaying vehicles in the platoon and RSU relay the packet received from the leader, in a broadcast manner to all other vehicles. We consider two flavors of relaying as follows.

1) *V2V relaying*: This scheme has the advantage of not employing extra infrastructure. Certain vehicles in the platoon are able to relay the leader’s message, namely relaying vehicles, which act like additional contending nodes in the channel. Furthermore, it introduces delays in the system that can not be neglected, and its impact is evaluated in the next section. Among the entire platoon, there are N_r relaying vehicles (including the leader vehicle). As each vehicle acts as a node, such links are arranged as $N_r - 1$ for relaying platoon members and one for the leader with m_r and m_l fixed number of transmissions, respectively (without waiting for an ACK). This communication can be received by any other vehicle in the platoon but the control packet may be outdated due to the delay induced by the relaying. We denote the broadcast link from selected relays V2V vehicles r_z , $z \in \{0, \dots, N_r - 1\}$ to vehicle i by (r_z, i) . Such links are visible in dashed lines in Fig. 1.

We propose a novel system of relaying the leader packets by exploiting the V2V communications already used in the baseline scheme for vehicle-to-neighbor communication. The main idea is that the assigned relaying vehicles will communicate with their neighbors only after receiving information from the leader, either directly from the leader or via another relay. Since the schedule of the leader’s packet generation is fixed, the only variable is the delay to transmit due to the access delay caused by the CSMA protocol. Let’s denote the mean access delay by Δ , which is computed later in Section 4. Therefore, each relay node waits for a maximum time of twice this delay multiplied by the relay index before generating its own packet so that it can receive the leader information from the leader or a previous relay. Then, it will include the information from the leader on the vehicle-to-neighbor communication packet. This implies that the relaying is done *without excessive addition of packets into the network*, and therefore not increasing the network load or generating interference. This procedure is detailed in Algorithm 1.

We will next describe the information management of the presented V2V relaying scheme. Algorithm 1 is based on a round-robin scheduling or a token-based protocol, in which the relay waits for a packet from the previous relay or leader before communication. This type of sequential relay helps minimize the delay induced by the relay. The delay here refers to the time between the measurement of the leader information (velocity and acceleration) to the time at which this information is received by a vehicle in the platoon. If all the relays communicate randomly, the average delay induced per hop can be of the order of 50 ms plus the waiting time in the CSMA/CA queue. However, when the relays communicate sequentially, this delay can be reduced to just the waiting time.

In the V2V relaying information scheme, described in Algorithm 1, the leader of the platoon broadcast m_l times its desired acceleration and velocity to the rest of the platoon at each cycling period t_c . Then, each vehicle in the sequence transmits its data to the corresponding follower one. Moreover, if a particular vehicle is a relaying vehicle that successfully decoded the leader’s signal, it will incorporate the latest leader packet it has and broadcast its own data with m_r retransmission attempts. Note that we look at the expected or average delay, and we set the maximum waiting time by a relay to be twice this value in Algorithm 1.

Algorithm 1: V2V relaying information scheme

for all t_c **do**
Leader broadcast m_l times its acceleration and velocity $(\ddot{x}_{0_des}, \dot{x}_0)$;
 for all non relaying vehicles i **do**
 Vehicle i receives the acceleration and velocity $(\ddot{x}_{0_des}, \dot{x}_0)$ from leader or overhear it from certain relay, if any;
 Transmit its desired acceleration and velocity to its successor vehicle;
 for all V2V relays r_z **do**
 Vehicle r_z receives the leader acceleration and velocity $(\ddot{x}_{0_des}, \dot{x}_0)$ from the leader or another previous relay;
 After the max. waiting time of $2z\Delta$, vehicle r_z broadcast m_r times its acceleration jointly with leader's acceleration and velocity $(\ddot{x}_{r_z_des}, \ddot{x}_{0_des}, \dot{x}_0)$;
 end for
 end for
end for

Remark 1. *The sequential scheme and the waiting time proportional to z are utilized to ensure that the latest leader information is propagated with minimal delay. This implies that relay r_z communicates before relay r_{z+1} , and therefore can not listen to the message of r_{z+1} . We are thus able to estimate the packet error rates and delays of the leader packet at each relay by causality checks. For non-relaying vehicles, no extra information management logic is enforced since such vehicles can overhear any broadcast messages from the leader or relaying vehicles without a directional distinction.*

Algorithm 2: RSU relaying information scheme

for all t_c **do**
Leader broadcast m_l times its acceleration and velocity $(\ddot{x}_{0_des}, \dot{x}_0)$;
 for all vehicles i **do**
 Vehicle i receives the acceleration and velocity $(\ddot{x}_{0_des}, \dot{x}_0)$ from leader or RSU relay;
 Transmit its desired acceleration and velocity to its successor vehicle;
 for closest RSU relay from leader **do**
 RSU receives the acceleration and velocity $(\ddot{x}_{0_des}, \dot{x}_0)$ from leader;
 After the delay Δ , the RSU broadcast only once leader's acceleration and velocity $(\ddot{x}_{0_des}, \dot{x}_0)$;
 end for
 end for
end for

2) *RSU relaying:* The second form is the RSU relaying, where the RSU is considered as an additional node in the system; it overhears the packet sent by the leader to vehicle 1 (let $(0, RSU)$ be this link), and then retransmits it in a broadcast manner, without expecting feedback. We denote the broadcast link from the RSU to vehicle i by (RSU, i) . Note that since the RSU acts as a broadcast relay, it does not

next vehicle in the platoon, which is the input of the V2X block of the following vehicle $i + 1$ (not shown), which closes the loop.

Therefore, the communication system's overall purpose is to grant the exchange of information between vehicles, not necessarily consecutive ones, in the platoon, which is done via a wireless medium. The reason behind such an obligation is that we adopt a cooperative controller, which requires external control information of other platoon members, that can not be captured by on-board sensors. For instance, looking back at the control mechanism of equation (4), there are essentially three terms concerned. First, the desired acceleration of the preceding vehicle ($\ddot{x}_{(i-1)_des}$) weighted by parameter $(1 - C)$, the desired acceleration of the leader ($\ddot{x}_{(0)_des}$) vehicle weighted by parameter C , and the leader's velocity (\dot{x}_0). Note that both packet delay and packet loss impact the aforementioned three control variables as they rely on wireless communication. In this work, we adopt a zero-order hold mechanism as the holding strategy for the control signal during network-induced issues. Therefore, the control performance is affected according to the delay and losses based on the communication mechanism for platooning adopted.

V. COMMUNICATION PERFORMANCE ANALYSIS

In this section, we identify the main performance metrics on the different links, and we introduce the mean access delay computation. Then, we propose an analytical model adapted to different platooning scenarios while integrating both link and channel access levels. We first devise a Markov chain to model the CSMA/CA protocol with retransmissions for point-to-point V2V links. Next, we introduce the broadcast channel analysis and derive the probability that a given vehicle, numbered i , receives the packets of the leader. Finally, we extend the model to consider the V2V and RSU relaying cases for unlicensed spectrum.

Regarding the main performance metrics on the different links, consider the following. We differentiate between link and system levels. At the link level, performance is characterized by the average packet error rate, i.e., the probability that a particular packet transmission fails, due to fast fading and interference from other links. Note that PER is usually employed for losses at the physical layer, we use for simplicity the term PER to express packet losses due to collisions at the MAC layer or bad radio conditions. This PER takes two different values when the packet is conveyed alone, compared to the collision case when it is transmitted on an occupied channel. Let $f_{0,(k,l)}$ and $f_{c,(k,l)}$ be the PER for the collision-free and collision case, respectively, for links (k, l) defined above (k and $l \in \{RSU, 0, \dots, N - 1\}$). At the system level, the main performance metric is the packet loss, which incorporates the PER on the link level but also considers the m possible retransmissions and the CSMA/CA mechanism. In the next section, we develop a performance model on the system level (channel access) that takes into account the link-level metrics.

A. Modeling aspects

In this section, we aim to introduce the model adopted, named baseline, with the corresponding description. Before focusing on the analytical modeling of the proposed V2V relaying scheme, notice that vehicle to neighbor links, i.e., the link between a vehicle i and its preceding ($i + 1$), are modeled as unicast transmission following the CSMA/CA protocol described next. Differently, for broadcast transmissions, there is no acknowledgment frame, therefore, we consider a simpler systematic "blind" retransmission as in [20], [21], where important safety messages are retransmitted a fixed number of times regardless of the event at the receiver side. In this paper, we model the CSMA/CA channel access procedure using a discrete-time Markov chain, as illustrated in Fig. 4. We aim to develop an analytical model to describe the relationship between the access performance and the resulting packet error rate and delay distribution to evaluate their impact on the platoon performance. Similarly to the authors in [22]–[26], we adapt the Bianchi [27] model for unsaturated sources to better cope with vehicular networks. However, different from them, we consider, in addition to losses due to collisions between packets, losses that are due to imperfections on the radio channel, while the existing models neglect radio imperfections and path loss.

Message reception errors are evaluated through the computation of the Signal to Interference plus Noise Ratio (SINR). More precisely, the SINR of a packet transmitted on the link (k, l) can be computed as:

$$SINR_{(k,l)}(P_T) = P_{Tx} - P_{PL}(d_{(k,l)}) - 10 * \log_{10}(10^{P_I/10} + 10^{P_N/10}) \quad (7)$$

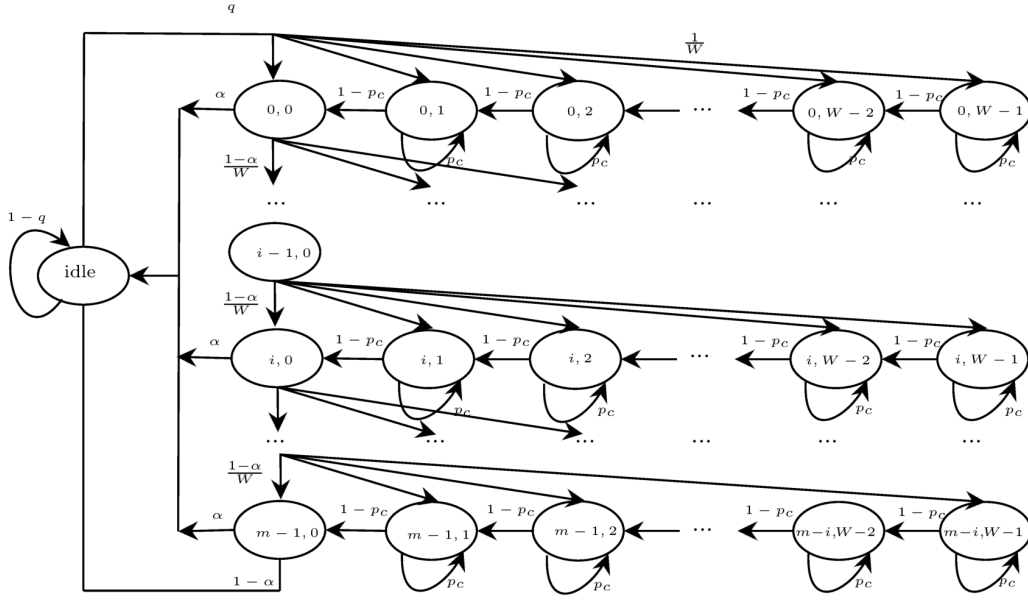


Fig. 4. Proposed Markov chain for baseline scheme.

where P_{Tx} is the transmission power in dBm, P_N denotes the noise floor in dBm and it is given by $P_N = -174 + 10 \cdot \log_{10}(BW)$ where BW is the bandwidth allocated for the V2V channel. $P_{PL}(d_{(k,l)})$ consists the path loss in dB between the link (k,l) given by the distance $d_{(k,l)}$ in meters. We have adopted the Winner-II Path Loss Model (B1 scenario) that is given by $P_{PL}(d_{(k,l)}) = 22.7 \cdot \log_{10}(d_{(k,l)}) + 41 + 20 \cdot \log_{10} \frac{f_c [GHz]}{5}$ [28]. The last component (P_I) corresponds to the total interference coming from other vehicles outside of the platoon and/or from within as well. Further explanation is given in the next section. In (7), the numerator represents the received power, whereas the denominator means the noise power contribution, the path loss, and the average interference with all other vehicles if any.

Focusing on the vehicle to neighbor channel, and more precisely on the link (k,l) , the packet is correctly decoded with probability

$$\alpha_{(k,l)} = (1 - p_c) \cdot (1 - f_{0,(k,l)}) + p_c \cdot (1 - f_{c,(k,l)}) \quad (8)$$

at each transmission attempt, where p_c is the probability that the channel is busy during a slot (collision probability), f_0 is the probability of loss without collision, and f_c is the probability of loss with collision, introduced previously and computed in the numerical applications under a vehicular channel environment given by (7). In the sequel, we drop the link identification (k,l) for convenience, except when needed. The real impact of packet collision due to interference in the system is of enormous complexity due to the vehicle's mobility. Nevertheless, it can not be neglected, and we consider the following to be true.

Assumption 1 (Probability of loss with collision). *Regarding the probability of loss with a collision between link (k,l) , we assume the following influence on the model's reliability.*

$$f_{c,(k,l)} = \mathbb{E}_{P_I}[\phi(SINR_{(k,l)}(P_I))] \quad (9)$$

where $\phi(\cdot)$ is a function that models the quality of the link (k,l) based on $SINR_{(k,l)}$.

Remark that such probability fluctuates over the distance between link (k,l) and the considered external interference. In fact, concerning the latter, we consider a uniform distribution where certain external vehicles contend for the medium with equal probability. Moreover, we may introduce the probability of loss without collision over the same function that models the quality of the link (k,l) based on $SINR_{(k,l)}$ that yields

$$f_{0,(k,l)} = \phi(SINR_{(k,l)}(0)) \quad (10)$$

Assumption 2 (Poisson process for packet arrival). *In order to capture the bursty nature of the traffic where small packets are generated by each vehicle following a Poisson process of intensity λ , we have*

included one inactive state in the Markov chain to model the probability to remains idle on a slot, taken equal to a packet duration T . This is given by $1 - q = e^{-\lambda T}$.

B. Mean access delay

In the proposed V2V relaying scheme, a heterogeneous delay rises as each relaying vehicle waits a certain maximum time for the preceding relay's packet, after which it generates a packet to broadcast, including the latest leader information it has. Once this packet is generated, it must wait for the contention window to expire before transmitting it. Note that different contention window sizes are possible, e.g., using the four access categories (AC) in IEEE 802.11p (AC0 indicates the highest priority with the lowest contention window, whereas AC3 indicates the lowest priority with the largest contention window). Different from the other works, we aim to evaluate its impact on the control performances in addition to the network performance. Such an evaluation is achievable due to the inclusion of the estimated average delay caused by different access categories in the dynamic control scheme for V2V relaying approach. More precisely, we evaluate the mean access delay (Δ) based on the estimation of an average time interval between consecutive successful channel access attempts. Formally, it can be computed by the expected hitting time (η_{ij}) from state i until we hit state j , as in [29].

Define the Backoff Timer (BOT) as a random number chosen in the range $(0, W - 1)$ where W is the contention window (CW) size¹ for a generic access category. Next, define the Backoff Stage (BOS), as the stage to attempt to transmit the packet. Let $s(t)$ be the stochastic process representing the BOS $\{0, \dots, m - 1\}$ and $\Pi(t)$ representing BOT at time t . Let $\Pi_{i,j} = \lim_{t \rightarrow \infty} P\{s(t) = i, \Pi(t) = j\}$, $i \in \{0, m - 1\}$, $j \in \{0, W - 1\}$ be the stationary distribution of the chain. Therefore, recursively, one can calculate the hitting time from any state $0 \leq j \leq W - 1$ to reach the second attempt stage ($i = 1$) that translates to the Markov state set $A = \{(1, 0)\}$, which is given by

$$\eta_{(1,j)A} = \frac{j}{1 - p_c} \quad \text{for } j \in \{0, 1, \dots, W - 1\} \quad (11)$$

Therefore, now considering the mean hitting time after the first transmission attempt $i = \{(0, 0)\}$ to the set $A = \{(1, 0)\}$, we have

$$\begin{aligned} \eta_{(0,0)A} = & 1 + \frac{1}{W} \eta_{(1,0)A} + \frac{1}{W} \eta_{(1,1)A} + \frac{1}{W} \eta_{(1,2)A} + \dots \\ & + \frac{1}{W} \eta_{(1,W-1)A} \end{aligned} \quad (12)$$

where with (11) and considering a constant packet length, it yields to

$$\Delta = \left(\frac{1}{1 - p_c} \frac{W + 1}{2} \right) \cdot T \quad (13)$$

where $(W + 1)/2$ is the average contention window, T is the packet period in the channel access, and p_c is the probability that the channel is busy during a slot. Note that we assume that the packet length is constant, which is reasonable when the data frame is short in contrast to the protocol overhead. The backoff interval is calculated as a random number of slot times uniformly selected from $[0, W - 1]$. As for the introduced delay by each approach, we have considered the following.

- Baseline introduces a minimal delay in the system as we assume that once a certain node is ready to transmit in the queue, it will send its most updated information measured just before transmitting. Also, due to the lack of relaying mechanism information, we assume a maximum link delay of 1 ms.
- In the presence of V2V relaying systems, we have considered the following delay computation for each active relaying vehicle

$$\varphi_z = \Delta \cdot z \quad \forall z \in \{1, \dots, N_r - 1\} \quad (14)$$

where Δ is the delay coefficient introduced by each relaying hop whose value corresponds to the average waiting time for a certain contention window size introduced in (13). z is the vehicle index of the effective selected relay vehicle that forwards the leader's message in the platoon.

- RSU relaying selects and manages the radio resources centrally and, therefore, a minimum delay is introduced. In this paper, the RSU is considered as an additional node that contends with the medium by broadcasting only once, and therefore, the delay is computed as in (13).

¹The CW may change from one stage to another, but we adopt here, without loss of generality, a constant CW, as advocated for delay-sensitive services using LBT cat3.

C. Packet loss probability for V2V links

In this subsection, we aim to derive the performance models for the baseline scheme with V2V communications only.

1) *Vehicle to neighbor channel*: In order to attain the probability of loss for point-to-point V2V links we must calculate the steady-state probability of the Markov chain of Fig 4.

Proposition 1. *The steady-state probability of the proposed Markov chain shown is computed by:*

$$\Pi_{idle} = \left[1 + \frac{q(1 - (1 - \alpha)^m)}{\alpha} \cdot \left(1 + \frac{W - 1}{2(1 - p_c)} \right) \right]^{-1}. \quad (15)$$

Proof. To calculate the loss, we have to calculate the stationary probabilities of the states. Given the BOS and BOT defined above, we can recursively calculate the probability of states for the first backoff stage $i = 0$ and for any timer $2 \leq j \leq W - 1$, given by

$$\Pi_{0,W-j} = \frac{jq}{(1 - p_c)W} \Pi_{idle}. \quad (16)$$

Now, evaluating the last state (timer expiration $j = W$) for the first stage ($i = 0$), we have the following

$$\Pi_{0,0} = \frac{q}{W} \Pi_{idle} + (1 - p_c) \Pi_{0,1} = q \Pi_{idle}. \quad (17)$$

Therefore, taking into account the probability of success transmission introduced in (8), we can define the following

$$\Pi_{1,W-1} = \frac{(1 - \alpha)}{W} \Pi_{0,0} + p_c \Pi_{1,W-1} = \frac{(1 - \alpha)q}{(1 - p_c)W} \Pi_{idle}. \quad (18)$$

Recursively, we can calculate the last state probability ($j = W$) for any backoff stage as

$$\Pi_{i,0} = (1 - \alpha)^i q \Pi_{idle}, \quad (19)$$

for $0 < i < m - 1$. Therefore, the probability of stationary states is given by

$$\Pi_{i,W-j} = \frac{jq(1 - \alpha)^i}{(1 - p_c)W} \Pi_{idle}, \quad (20)$$

for $0 \leq i \leq m - 1$ and $1 \leq j \leq W - 1$. Moreover, the steady-state probabilities must satisfy the normalization condition $\Pi' \Pi = 1$, that yields to (15) which concludes thus the proof. \square

The loss depends on the probability of finding the channel occupied during a slot. For the broadcast channel, the transmission attempt probability for a packet generated from the leader and the relaying vehicles is given by

$$\tau_{\#} = q \cdot m_{\#} \quad (21)$$

where $\# \in \{l, r\}$ for leader and relaying, respectively, as they attempt a constant number of transmissions. However, for the other V2V communications, the number of transmissions depends on the ACK, and we compute this using a fixed point approach as follows.

Proposition 2. *The channel occupation probability p_c is given by*

$$p_c = 1 - (1 - \tau_p)^{N - N_r - 1} (1 - \tau_e)^M (1 - \tau_r)^{N_r - 1} \cdot (1 - \tau_l)(1 - \tau_h)^H \quad (22)$$

where the following transmission attempt probabilities are investigated when different nodes contend for the medium to transmit a packet. First, the probability of trying to transmit for intraplatoon link is calculated by:

$$\tau_p = \sum_{i=0}^{m-1} \Pi_{i,0} = \frac{(1 - (1 - \alpha_{i,i+1})^m)}{\alpha_{i,i+1}} q \Pi_{idle} \quad (23)$$

while for hidden terminals and external links are given, respectively, by $\tau_h = q \cdot m$ and

$$\tau_e = \sum_{i=0}^{m-1} \Pi_{i,0} = \frac{(1 - (1 - \alpha_{ext})^m)}{\alpha_{ext}} q \Pi_{idle}. \quad (24)$$

Proof. The probability of a slot being busy is computed as the probability that at least one of the competing transmitters is active. More precisely, it encompasses the contribution for the neighbor, the interference from other vehicles here divided in-range and hidden nodes, and the broadcast links to contend for the channel. For the first and second components, we consider $N - 1$ links within the platoon, M external vehicles that do not belong to the platoon but generate nevertheless packets, and H hidden nodes, respectively. For the transmission attempt probability for a packet generated from a hidden terminal, we consider H hidden nodes following a Poisson process and transmitting λ [packets/sec] with m transmission attempts. For the broadcast component, we consider the leader and $N_r - 1$ relaying vehicles with distinct possible retransmissions. Therefore, we can thus compute the channel occupation probability as in (22) where τ_p (rep. τ_e) is the probability of trying to transmit for platoon and external vehicles, respectively, with the corresponding link decoding probability α as follows. For platoon vehicles, $\alpha_{(i,i+1)}$ is used, while for external vehicles and hidden nodes, the same proposed Markov chain model can be used, replacing the PER in (8) by the PER corresponding to a typical distance on a non-platoon link (α_{ext}) and (α_{hid}), respectively.

While for the broadcast component, the probability of trying to transmit the packet for the leader and relaying vehicles is computed as in (21) where $\# \in \{l, r\}$ for leader and relaying, respectively. While q is the probability of generating a packet, i.e., the probability of not remaining idle on a slot, and m_l and m_r are the broadcast retransmissions attempts for the leader and relaying vehicles for the broadcast component, respectively.

The channel occupation probability p_c can thus be obtained using a fixed point analysis that solves the set of equations (15, 22, 23, 24, 21). \square

Note that we have modeled the capture effect by assuming that only collisions from a certain distance lead to a loss, so only devices within a distance are taken in the analysis. Interference that comes from far vehicles does not account. Therefore, the probability that a packet is lost on link $(i, i + 1)$, i.e., neighbor link, despite the m possible retransmissions, is computed by:

$$L_{i,i+1} = (1 - \alpha_{(i,i+1)})^m, \quad i \in \{0, \dots, N - 1\} \quad (25)$$

2) *Broadcast channel:* The broadcast mode is introduced and detailed next. In addition to outside links and vehicle to neighbor links, certain vehicles, such as the leader and relaying vehicles, contend for the shared channel with broadcasting messages as in (22). We assume different transmissions attempt for leader and relaying vehicles as m_l and m_r , respectively. Such particular vehicles periodically broadcast critical safety messages containing their acceleration and velocity, for instance. Therefore, the probability of loss of the broadcast link $(0, i)$ is given by

$$L_{(0,i)} = (1 - \alpha_{(0,i)} \cdot \sigma_0)^{m_l} \quad (26)$$

$\forall i \in \{1, \dots, N - 1\}$ where σ_0 is the probability that the packet is correctly decoded by the leader, which is one by default and $\alpha_{(0,i)}$ is the probability for the leader message to be successfully decoded by the receiver vehicle i , considering packet collisions and path loss, as in (8). Moreover, note that vehicle mobility has not been neglected as the probability of loss with and without collision on a vehicular channel is taken into account. Furthermore, we assume m_l retransmission attempts, and due to the inherent feature of broadcast, no acknowledgment is possible. Finally, remark that for the broadcast channel, we consider a simpler broadcast chain with m_l systematic retransmissions (no backoff and no retransmission due to loss).

D. Performance analysis for V2V relaying

In Section 3.4, we have introduced a novel V2V relaying scheme in which we propose that certain platoon members are selected as relays, namely relaying vehicles r_z where $z \in \{0, \dots, N_r - 1\}$. These relays are capable of forwarding the packets of the platoon leader along with their regular vehicle-to-neighbor communication as a decoded-forward relay to preserve the quality of platooning communication with no extra infrastructure or additional packet generation needed. In this subsection, we study the performance of such a relay.

Proposition 3. *The probability that the packet is correctly decoded by each relaying vehicle r_z , where $z \in \{0, \dots, N_r - 1\}$, is given by*

$$\sigma_z = \begin{cases} 1 & z = 0 \\ 1 - (1 - \alpha_{r_0, r_1} \cdot \sigma_0)^{m_l} & z = 1 \\ 1 - (1 - \alpha_{r_0, r_z} \cdot \sigma_0)^{m_l} \prod_{k=1}^{z-1} (1 - \alpha_{r_k, r_z} \cdot \sigma_k)^{m_r} & \forall z \in \{2, \dots, N_r - 1\} \end{cases} \quad (27)$$

*The final probability of loss between the leader and a particular **non** relaying vehicle i in the presence of V2V relaying is thus calculated as*

$$L_i = (1 - \alpha_{r_0, i} \cdot \sigma_0)^{m_l} \prod_{z=1}^{N_r-1} (1 - \alpha_{r_z, i} \cdot \sigma_z)^{m_r} \quad (28)$$

$\forall i \in \{1, \dots, N-1\} \wedge i \neq r_z$. *While the final probability of loss between the leader and certain relaying vehicle r_z is*

$$L_{r_z} = 1 - \sigma_z \quad \forall z \in \{0, \dots, N_r - 1\} \quad (29)$$

Proof. In broadcast transmission, the leader sends packets to all platoon members simultaneously as in (26). Remark that relaying vehicles communicate only after receiving information from the leader either directly from it or from another previous relay. Once correctly decoded, they are able to hand over the information as a broadcast with m_r possible retransmissions to the posterior platoon members. For the V2V relaying link, we define the probability that the packet is correctly decoded by each relaying vehicle as (27). The reasoning for each line is as follows:

- 1) $\sigma_0 = 1$ because leader always has packet;
- 2) $\sigma_1 = 1 - (1 - \alpha_{r_0, r_1} \cdot \sigma_0)^{m_l}$ corresponds to the hop from the leader to the first relaying vehicle, which is broadcasted m_l times, i.e., it can be seen as the complement of (26) for link $(0, r_1)$ instead;
- 3) $\sigma_z = 1 - (1 - \alpha_{r_0, r_z} \cdot \sigma_0)^{m_l} \prod_{k=1}^{z-1} (1 - \alpha_{r_k, r_z} \cdot \sigma_k)^{m_r}$ as now we have the influence of $z - 1$ hops of the previous relaying vehicles that are broadcasted m_r times and calculated recursively for each $z \in \{2, \dots, N_r - 1\}$.

where $\alpha_{(r_0, r_z)}$ is the probability for the leader message to be successfully decoded by the receiver selected relaying vehicle r_z , considering packet collisions and path loss, as in (8). Remark that Algorithm 1 is required to guarantee the functional operation of the V2V relaying approach. More precisely, such specific order token ring alike between relays is essential to preserve causality, which explains the upper bound limit of the product operator in (27). In other words, it prevents that certain relay vehicle σ_{z+1} from handling and forwarding a message before relay vehicle σ_z , where $z \in \{0, \dots, N_r - 1\}$, by assuring certain maximum waiting time as described in Section III-B1. Moreover, for each hop, we consider independent events in which the product rules can be applied. Therefore, the final probability of loss between the leader and a particular *non* relaying vehicle i in the presence of V2V relaying is then computed by (28). However, note that no specific order is considered as any *non* relaying vehicle is able to overhear the broadcast relayed transmission, which explains the upper bound limit of the product operator in (28) that accounts for all possible $N_r - 1$ relaying vehicles in the platoon. Furthermore, the final probability of loss between the leader and certain relaying vehicle is given by (29) where with (27), we confirm that for relaying vehicles, the causality constrain was imposed. This completes the proof. \square

E. Performance with RSU relaying

In addition to the V2V relaying scheme, we aim to extend the Markov model to the RSU relaying case. Whenever the leader sends a packet to its platoon, this packet can be also received by the RSU closest to the leader, which then relays the packet as a broadcast.

Proposition 4. *The final probability of loss between the leader and the vehicle i in the presence of RSU is*

$$L_i = L_{(0, i)} \cdot (L_{(0, RSU)} + L_{(RSU, i)} - L_{(0, RSU)} \cdot L_{(RSU, i)}) \quad (30)$$

where the loss on the downlink is thus given by

$$L_{(RSU, i)} = p_c f_{c, (RSU, i)} + (1 - p_c) f_{0, (RSU, i)}, \quad (31)$$

while the uplink is given by the probability of loss of (26) considering the link $(0, RSU)$ accordingly.

Proof. A loss for a broadcast channel occurs here only if both the direct $(0, i)$ link and the relaying link fail, increasing the system's robustness. In other words, we consider independent events in which the product rule applies. As for the relaying link, it is composed of two links $(0, RSU)$ and (RSU, i) as shown in Fig. 1. Accordingly, with a simple additive rule of probability, we are able to compute the relaying factor through RSU. Therefore, the final probability of loss between the leader and the vehicle i in the presence of RSU is given by (30). To ease the comparison with the previous V2V relaying approach, we consider in this work the RSU relay link under an unlicensed spectrum. The RSU, in this case, is a node like the others in the IEEE 802.11p system. The RSU here overhears the transmission on the leader-follower link, and its probability of loss is computed as in (26), taking into consideration in $\alpha_{(0,RSU)}$ the PER on the uplink of the relay.

If the packet is correctly decoded, the RSU can broadcast it only once to the other platoon members. We model this downlink of the relay by a one-stage Markov chain (like the one in Fig. 4, with $m = 1$) where the loss on the downlink is thus given by (31), which concludes the proof. Remark that such results are in line with Algorithm 2, which describes the information handling agreement when adopting RSU as the relaying scheme. \square

VI. SIMULATION RESULTS

In this section, we present our numerical results, which compare the performance of the baseline scheme, the proposed V2V relay, and an RSU relay. The baseline consists of the case where vehicles communicate with V2V only, i.e. no use of relaying. We also illustrate the interaction between the proposed dynamic controller and the communication schemes in a realistic platooning simulation.

A. Simulation environment description

In our simulations, vehicles in the platoon move along a highway with 2 lanes per direction with 4 m widths each. An overview of the system diagram is given in Fig. 5. We used the Simulink environment to model the vehicle dynamics and to implement the control law, which corresponds to the "Platoon simulator". Therefore, it is responsible to provide periodic snapshots of the positions of the platoon vehicles to the communication simulator. As shown in Fig. 5, the communication framework is implemented with Matlab and its WLAN Toolbox, and some main parameters are highlighted as input/output. The first one is the ("Link simulator") which computes the PER for a given link quality based on the positions of vehicles obtained from the platoon simulator system. Finally, the ("Channel access model") is responsible for modeling the channel access, which is implemented as modeled using the Markovian model presented above, considering that vehicles broadcast a 500 bytes message under baseline, V2V, and RSU relaying conditions if applicable. In the simulation analysis, we use the 10 MHz channel with a 100 ms scheduling period corresponding to the 10 Hz CAM message generation frequency, as advocated by the ETSI EN 302 637-2 standard. The system parameters for both communication and control-traffic model are specified in Table I.

Remark 2. We make use of the *MATLAB WLAN ToolboxTM* for the simulation of the PHY layer of the IEEE 802.11p standard. More precisely, with this toolbox, we are able to compute the PER of an 802.11p link between a transmitter and a receiver, considering a V2V fading channel and for a given link quality (SNR/SINR), i.e., $\phi(\cdot)$ from Assumption 1. Note that such a toolbox does not include the competition between links to access the channel. Therefore, we also develop a "Channel access" module which models interference with other links, including V2V, broadcast transmissions by relays, and external interfering sources that contend for channel access.

When not stated otherwise, we have adopted the following framework. For the link $(0, i)$, we assume a shadowing that increases linearly with the number of vehicles in the platoon (2 dB per intermediate vehicle). As for the CSMA parameters, we have adopted $W = 32$ and $m = m_l = m_r = 2$ as the content window size and the retransmission attempts for the neighbor, leader, and V2V relay link, respectively. Additionally, note that there is no power transmission adjustment, as we adopt a fixed value of 22.5 dBm for all links. Furthermore, for the RSU relay scheme, we have implemented one RSU for each kilometer. As for the control parameters, the platoon members are equipped with the dynamic proposed controller. Unlike the literature, this paper evaluates the system performance under a strongly perturbed scenario as shown by the jammer profile in Fig. 6a, but repeated 50 times to seek robustness. The control strategy demands relative position and longitudinal velocity of the preceding vehicle so we assumed that

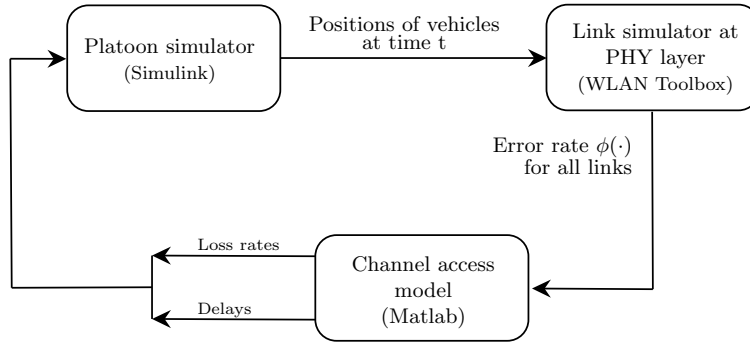


Fig. 5. System diagram with control and communication interaction.

TABLE I
COMMUNICATION AND CONTROL AND TRAFFIC SIMULATION PARAMETERS

Communication		Control and Traffic	
Parameter	Value	Parameter	Value
MAC protocol	802.11p	Leader factor (C')	0.5
Path loss	Winner+B1 LOS	Desired dist. (D_{des})	Adapt.
Noise power	-174 dBm/Hz	Damping ratio (ξ)	2
Tx power	22.5 dBm	Bandwidth (ω_n)	0.5 Hz
Shadowing	2dB/vehicle	Actuator lag (τ_a)	0.5 s
MCS	QPSK, R=1/2	Vehicle length (L)	16.5 m
Data rate	6 Mb/s	Max. acc. (u_{max})	+2m/s ²
Channel	Highway LOS	Min. acc. (u_{min})	-3m/s ²
Carrier frequency	5.9 GHz	Radar interval	60 ms
Bandwidth	10 MHz	Lanes per direction	2
CAM size	500 bytes	Lane width	5 m
CAM interval	100 ms	Max. traf. density (M)	Fig. 6b
BOT (W)	32	Simulation duration	1200 s
BOS (m)	2	Jammer profile	Fig. 6a
BOS leader (m_l)	2		
BOS relays (m_r)	2		
Hidden nodes (H)	0		

the measurements are sampled each 60 ms with a delay of $\rho = 1$ ms and done by a long-range radar. Simulations are performed with a platoon size of $N = 21$.

Another important simulation aspect is the traffic density profile. The maximum road traffic density that generates external interference to the platoon was considered as $M = 100$ cars/km/lane, and its profile is shown in Fig. 6b. We have implemented it as a uniformly distributed random parameter with a period of 60 s. Notice that the traffic density period is doubled when compared to the jammer incidents that occur each 30 s. Finally, our model could potentially cope with the hidden terminal case by setting the parameters H and τ_h accordingly in (22), e.g., it might follow a certain distribution. However, in the simulation scenario, no hidden terminal effect is considered, i.e., $H = 0$. Nevertheless, we still ensure

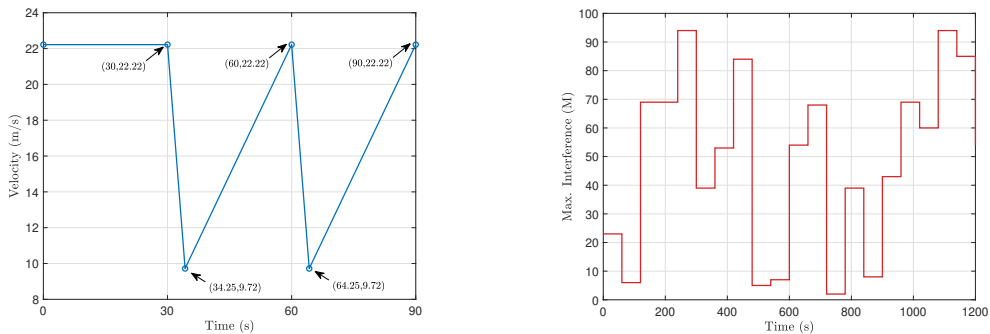


Fig. 6. Illustration of the jammer velocity profile on the left, and the traffic density profile on the right.

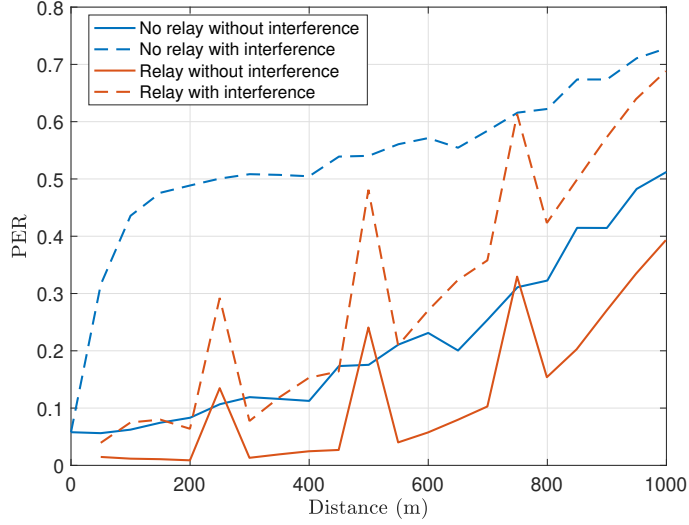


Fig. 7. PER in a Highway environment under NLOS condition with and without relaying, with or without interferences.

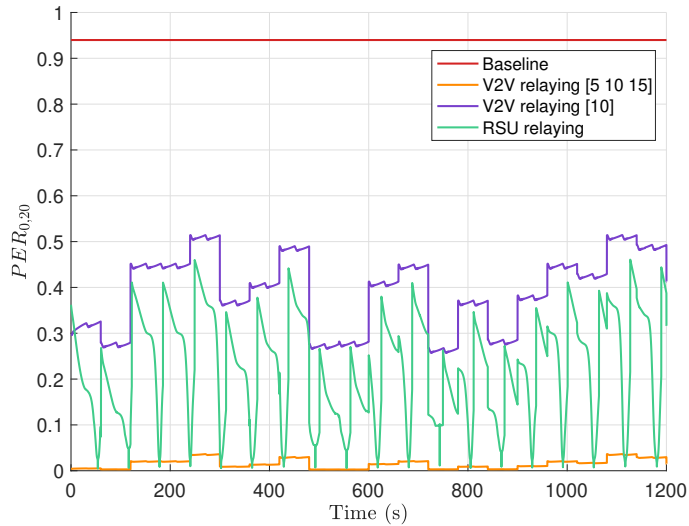


Fig. 8. PER for 20th vehicle for the different communication scenarios with $m = m_l = m_r = 2$ retransmission attempts.

the robustness of our dynamic control scheme under different communication quality links since we already considered a large number of competing nodes as the maximum number of external nodes that might cause interference is $M = 100$ vehicles/km/lane, which is significantly larger than [10], [14] and [30] that consider a traffic density only up to 20 cars/km/lane.

In order to cope with the information handling algorithm presented in the previous section, a simpler way is to consider the delay as a linear uniformly distributed random function for each V2V relaying vehicle. So, by each relaying vehicle's index, the delay increases linearly and, therefore, the causality imposition in the proposed handling algorithm is attended. From (13), the correspondent delay value for $W = 32$ is $\Delta = 9.8$ ms for each relaying vehicle hop.

B. Communication system performance

We next describe the performance from a communication perspective with platoon sizes of $N = 21$. Note that the reliability of the system-level performance is measured by the packet loss as defined in

TABLE II
PERFORMANCE METRICS OVER DIFFERENT COMMUNICATION SCHEMES FOR PLATOON SIZE $N=21$, $m = m_l = m_r = 1$.

Outputs	Baseline	V2V Relay		RSU Relay
		$r=[5 \ 10 \ 15]$	$r=[10]$	1RSU/km
Avg. Dist. (m)	32.6280	2.2476	21.4118	2.1350
Min. Obs. Dist. (m)	1.1163	1.4125	1.8963	1.2991
Max. Obs. Dist. (m)	63.2088	2.6910	34.2947	2.5584
Avg. PER (10th car)	0.9579	0.1779	0.8666	0.1033
Avg. PER (20th car)	0.9695	0.2088	0.9534	0.2222

TABLE III
PERFORMANCE METRICS OVER DIFFERENT COMMUNICATION SCHEMES FOR PLATOON SIZE $N=21$, $m = m_l = m_r = 2$.

Outputs	Baseline	V2V Relay		RSU Relay
		$r=[5 \ 10 \ 15]$	$r=[10]$	1RSU/km
Avg. Dist. (m)	32.4961	2.2455	2.6458	2.1357
Min. Obs. Dist. (m)	1.3476	1.4884	1.9203	1.3837
Max. Obs. Dist. (m)	60.9268	2.6045	3.1339	2.5501
Avg. PER (10th car)	0.9196	0.0184	0.2642	0.0555
Avg. PER (20th car)	0.9399	0.0150	0.3903	0.2227

(26), (28)-(29) and (30) for baseline, V2V relaying and RSU relaying, respectively. We start by showing the impact of relaying on the PER for motivating our study. Figure 7 plots the packet loss probability, without and with relaying, without and with interference. It shows that, for a communication distance of 500 m, the PER is not acceptable for critical vehicular applications, which calls for solutions such as relaying. Note that spikes correspond to relaying vehicles, in which they follow a specific order token ring alike between relays to preserve causality as described by Algorithm 1. While *non* relaying vehicles are able to overhear the broadcast relayed transmission which explains their lower probability of loss, as explained in the proof of Proposition 3.

We also specifically focus on the last car of a platoon of 21 vehicles and present a communication radio link comparison as shown in Fig. 8, where we present the average probability of loss between the leader and the last vehicle over time for each communication approach considered. We observe from Fig. 8 that V2V scenario without any V2I results in a very high loss rate compared to RSU relaying scheme and V2V relaying vehicles. This loss is expected to be even higher for larger platoons. Due to the very large inter-vehicular distance required to avoid a vehicular collision, the path loss and shadowing play a substantial role compared to the number of external interference vehicles, which explains the rough behavior of a straight line for the baseline in Fig. 8. In contrast, relay schemes exhibit a more cyclic behavior with respect to the closest RSU from the leader vehicle (recall that an RSU is deployed every 1 Km).

C. Platoon performance: inter-vehicle distance

We now move to the evaluation of the robustness of our dynamic control scheme under different communication links. To this aim, we have adopted the inter-vehicle distance as the end-service performance metric. We apply the zero-order hold mechanism as the holding strategy for the control signal during the periods of packet losses. In all simulations, we focus on minimizing the inter-vehicular distance with respect to a fixed value of all the other control parameters while ensuring that zero vehicle collisions occur. Note that we implemented a safety gap distance of 1 m for the emergency braking actuation to avoid collisions in practical settings.

1) *Platoon performance for different network configurations:* We first start by evaluating the performance of the platoon under different network configurations. We present in Table II and III the average inter-vehicular distance for 21 vehicle platoon over all the communication approaches considered for retransmission attempts $m = m_l = m_r = 1$ and $m = m_l = m_r = 2$, respectively. From the former table, we can observe large inter-vehicular distance for baseline and for V2V relaying with only one relaying member vehicle, i.e., vehicle 10 as the selected relay $r = [10]$. However, when the retransmission attempts increase, better platooning performances are obtained for the relaying vehicle $r = [10]$ as shown in Table III. That is due to substantial improvements on communication performances of around 70% for the average packet error rate for the 10th vehicle under V2V relaying $r = [10]$ produced by boosting m_l and m_r that allows forwarding the leader's message more reliably. Regardless of the retransmission

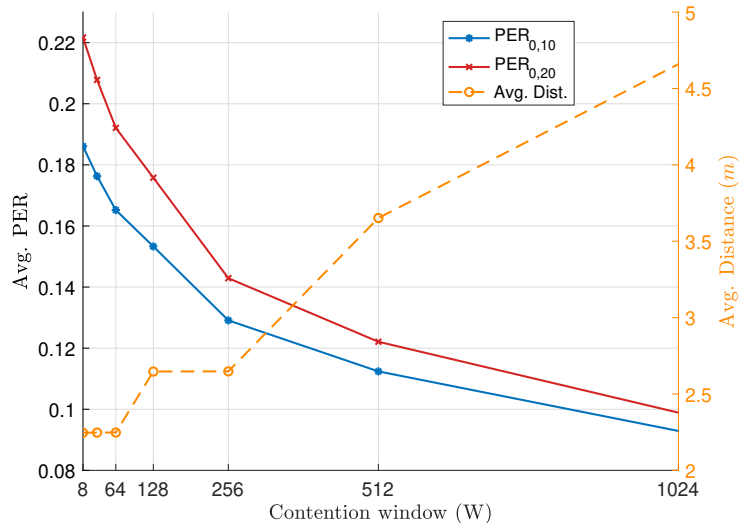


Fig. 9. Average packet error rate for 10th and 20th vehicle under V2V relay $r = [5 \ 10 \ 15]$ approach in solid blue and red lines, and average inter-vehicular distance of the platoon for different content window sizes in dashed yellow line, respectively.

attempts, the baseline scheme imposes higher inter-vehicular distances in the platoon, as much as 32 m, when compared to relayed schemes where the average distance is around 2 m. We also illustrate in Table II and III the minimum observed distance during the simulation (that must not go below 1 m to avoid emergency braking) and the maximal observed distance for their respective platoon size. When looking at the platoon performance with relaying, similar performances are observed for both relay schemes, despite the large difference in the loss rates, as recalled in the last rows of Table III. This similarity raises a question related to the necessity or not of RSU relaying and its additional infrastructure for platooning systems, when compared with V2V relaying that shows slightly larger inter-vehicular distances but with no extra cost required while satisfactory retransmission attempts are observed.

2) *Optimization of the communication protocol for the platoon:* We have observed above that the platoon performance highly depends on the parameters of the network and that there is no systematic correlation between the degradation of the packet success rate and the platoon performance. This indicates a certain robustness toward the packet loss rate. As control systems are known to be sensitive to packet delays and not only to packet losses, we investigate in this section the impact of delay on the platoon performance for a fixed retransmission attempt of $m = m_l = m_r = 1$. The network parameter that influences the most the delay is the backoff parameter (waiting time before retransmission that is a random number of slot times uniformly selected from $[0, W - 1]$). The results are shown in Fig. 9. We can observe that increasing W leads to considerable improvement of the average packet error rate in the platoon, as displayed in solid blue and red lines for the 10th and 20th vehicles, respectively. This is because increasing the backoff time reduces the collision probability p_c . However, considerable access delay is proportionally introduced, as in (14) by each selected relaying vehicle. Therefore, regarding the control performance, the results in the right axis of Fig. 9 show that more than doubled inter-vehicular distance is now required to avoid collision when considering the correspondent extremes content window values (8 and 1024, resp.), leading to an inter-vehicle distance of 2.24 m and 4.65 m, respectively. Therefore, the best trade-off is observed for $W = 64$, which significantly improves the average inter-vehicular distance of the platoon while achieving a lower average packet error rate (and therefore a lower retransmission probability and a lower interference to other systems).

VII. EXTENDED PERFORMANCE ANALYSIS

While the above performance analysis captures the essential features of the joint communication/control design, there is a myriad of parameters that impact the performance, and there are schemes in the literature that consider communication networks for platooning. We first compare in this section our scheme to the state of the art. We then explore the impact of these parameters, including the road-side unity density and the platoon size.

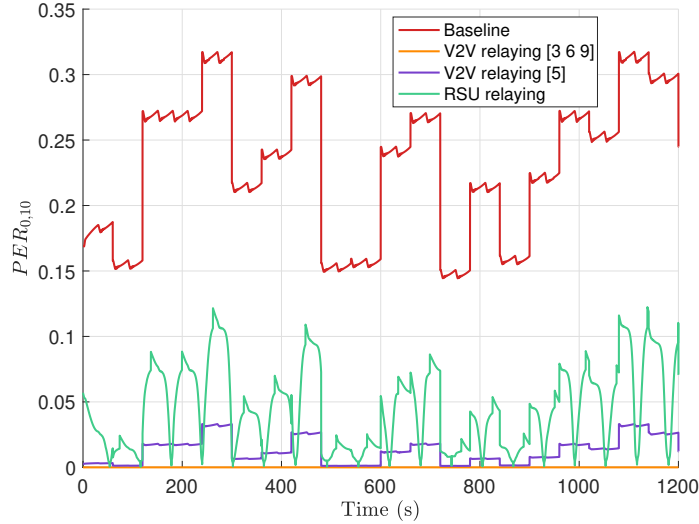


Fig. 10. PER for 10th vehicle for the different communication scenarios with $m = m_l = m_r = 2$ retransmission attempts.

A. Comparison with classical approaches

We now compare our scheme against the classical approaches [12], [23], [31], [32], that simply fix an inter-vehicular distance for the platoon and do not consider the bi-directional interaction between control and communication parameters. We present the following comparison with our baseline approach with $N = 21$ vehicles presented in Table III. We have set a fixing distance of $D_{des} = 5$ m between vehicles, as in [32], and we can indeed observe satisfactory packet error rate as $PER_{0,10} = 0.34$ and $PER_{0,20} = 0.89$ for the 10th vehicle and 20th vehicle in average, respectively. Note that such high values for the 20th vehicle are achieved due to the significant length of each vehicle as $L = 16.5$ m and the extensive size of the platoon with $N = 21$ vehicles. However, such a scenario does not guarantee a secure outcome as 9 collisions are detected. In fact, due to the interplay of control and communication system, the PER and distance blow up, and the safe distance becomes 32 m with $PER_{0,10} = 0.92$ and $PER_{0,20} = 0.94$ for the 10th vehicle and 20th vehicle in average, respectively, as shown in Table III. As it can be seen, a joint approach eliminates collisions and requires higher distances that result in a higher PER, which requires the vehicles to be even further apart and so on in a recursive loop. Therefore, a joint analysis is especially important as the communication performance is impacted by the control performance and vice versa leading to behavior that can not be easily predicted by a singular approach.

B. Impact of the platoon size

The system performance has been evaluated in the previous section for a platoon of 21 vehicles. However, one question we would like to answer in this section is if relaying schemes are useful when the platoons are much smaller. For this purpose, we consider a platoon of $N = 11$ vehicles and study its need in terms of system design. We observe in Fig. 10 substantially lower packet error rates for the last vehicle. Due to shorter platoon size, larger coverage, and consequently shorter inter-vehicular distances, the baseline approach varies accordingly with the external interference as the channel path loss plays a limited role now. Even though relaying approaches have smaller loss rates, similar control performances are obtained, which raises a question of relaying approach's requirement for smaller platoon sizes as shown in Section VI-C. However, it is essential to note that despite what the simulation results on the system-level performances indicate, these simulations have been run for a limited time, and the impact of packet bursts and improbable effects have not been studied. A lower packet error rate will result in a safer and more robust system-level performance due to smaller randomness in the dynamics. On the other hand, for platoon size of $N = 11$, similar control performances are obtained regardless of the communication approach adopted as shown in Table IV and V for $m = m_l = m_r = 1$ and $m = m_l = m_r = 2$, respectively. This indicates that for smaller platoons, no extra relaying approach is mandatory as even for the baseline, a satisfactory outcome is observed. This fact can be explained by the

TABLE IV
PERFORMANCE METRICS OVER DIFFERENT COMMUNICATION SCHEMES FOR PLATOON SIZE $N=11$, $m = m_l = m_r = 1$.

Outputs	Baseline	V2V Relay		RSU Relay
		$r = [3 \ 6 \ 9]$	$r = [5]$	
Avg. Dist. (m)	3.1058	1.7112	2.2104	1.6896
Min. Obs. Dist. (m)	2.1928	1.0758	1.5719	1.0355
Max. Obs. Dist. (m)	3.4987	2.0638	2.5826	2.0493
Avg. PER (5th car)	0.1706	0.0003	0.1666	0.0330
Avg. PER (10th car)	0.4979	0.0011	0.1494	0.0872

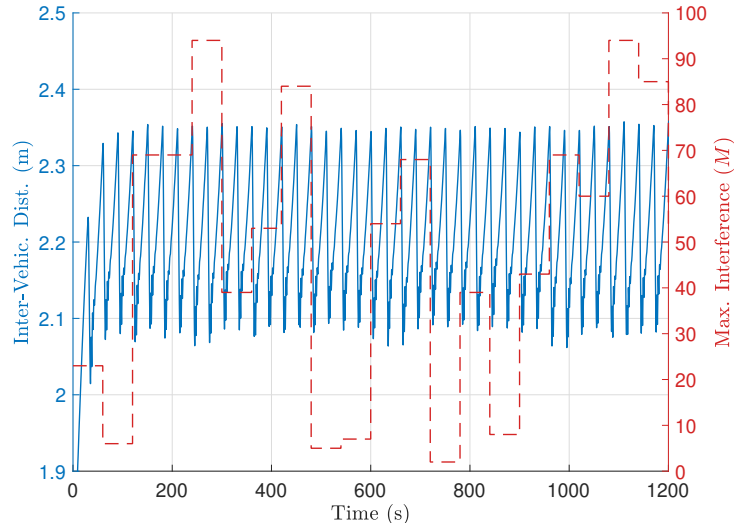


Fig. 11. Average inter-vehicular distance for platoon size of $N = 11$ under baseline approach in solid blue, and traffic density profile over time in dashed red lines.

robustness of the dynamic PCACC control for a sampling rate of 100 ms under moderate packet losses due to the limited path loss effect. Finally, Fig. 11 shows the average inter-vehicular distance of the platoon size $N = 11$ with the respective interference number of vehicles over time. We can observe that the average inter-vehicular decreases slightly for higher interference, and smooth control performance and spacing are observed overall.

VIII. RELATED WORK

A recent evaluation on side-link relay for platooning was done by [31], where the authors proposed two relay schemes that use geographic location information. In [33], a disturbance adaptive platoon architecture is proposed where they adopt V2V relaying to mitigate negative effects of traffic disturbance such as uncomfortable passenger experience and increased exhaust emission. Inspired by Bianchi's 2-D Markov chain [27], the authors in [22] proposed a platoon-based cooperative retransmission scheme by formulating a 4-D Markov chain so that one sender can retransmit blocks to its neighbors within the same platoon in case of a previous transmission error. However, they consider the RSU as the only destination receiving data from all vehicles, which may not be the case in real applications. The scheme proposed in [34] focuses on the performance of safety message broadcasting for the road-intersection scenario. The authors in [34] adopt different antenna configurations for the RSU relaying. Different from this work, the vehicle dynamics are neglected, and no V2V relaying is evaluated. The authors in [35] proposed a centralized method for joint power control and V2V relay selection. They assume a C-V2X communication where the leader performs the intra-platoon resource allocation for the platoon members after interacting with the eNB. However, the evaluation of the platoon's performance was left for future work. In [36], a relaying policy for platooning applications using a TDMA-based scheme is proposed. The authors focus on enhancing the probability of receiving event-driven messages, which translates to focus on hazardous environmental events messages over periodic vehicle awareness messages. The main novelty of the Markov chain model that we develop is that it includes losses that are due to imperfections

TABLE V
PERFORMANCE METRICS OVER DIFFERENT COMMUNICATION SCHEMES FOR PLATOON SIZE $N=11$, $m = m_l = m_r = 2$.

Outputs	Baseline	V2V Relay		RSU Relay
		$r = [3\ 6\ 9]$	$r = [5]$	
Avg. Dist. (m)	2.2124	2.2143	2.2122	1.6896
Min. Obs. Dist. (m)	1.5622	1.5099	1.5640	1.0714
Max. Obs. Dist. (m)	2.577	2.5635	2.5635	2.0318
Avg. PER (5th car)	0.0328	≈ 0	0.0343	0.0071
Avg. PER (10th car)	0.2313	≈ 0	0.0126	0.0443

on the radio channel, in addition to losses due to collisions between packets, while the existing models neglect radio imperfections and path loss. This is of utmost importance as path loss causes a significant loss even without interference.

An important body of works replaces the notion of delay in vehicular networks by the metric of Age of Information (AoI). [37] proposed an application-layer broadcast rate adaptation algorithm that adapts the messaging rate and showed that this reduces the congestion. [38] considered a dense platooning system and showed that, by considering AoI-based packet generation, the traffic load is decreased without degrading the platoon performance. In our work, we consider the classical delay metric because our system has a specific controller with a period packet generation, as advocated by the ETSI EN 302 637-2. However, as our controller adopts the zero-order hold mechanism during the periods of packet losses, an AoI-based broadcast rate adaptation should reduce the packet rate, but this would have a limited impact on the performance as we consider a single platoon and interference is mainly caused by external vehicles that would not follow the same rate adaptation, in contrast with the models in [37], [38].

Another significant contribution of our paper is associated with the heterogeneous communication delays analysis and its impact on the control and networking performance. One of the first papers that started considering a joint control/network analysis is the work in [11], where the authors perform a theoretical analysis of a CACC under different time headways and communication delays. However, a constant wireless communication delay is considered, and no control adaptation is performed. The design of control systems that explicitly considers network and vehicle performance is proposed in [39] where theoretical bounds on the minimum inter-vehicular distance are derived considering a network subject to packet losses. A few works evaluate the performance of platooning systems under heterogeneous wireless communication delays. The authors in [16] evaluated the effect of communication delay by considering packet dropout as a time delay chosen as multiple of the sampling period and upper bounded. All aforementioned works have evaluated low time-delay values of wireless communication such as 20-40 ms while IEEE 802.11p presents no fixed upper bound delays for a contention-oriented MAC scheme [23]. Furthermore, the authors in [23] have investigated the MAC access delay distribution by proposing an exponential distribution as a reasonable approximation for it. However, no multi-hop broadcast is evaluated.

In this paper, we study a joint system of periodic platooning communication and control to reduce inter-vehicular spacing while maintaining platoon safety. Several works evaluate the performance of platooning under different communication approaches [12], [14], [17], [30], [40]–[42]. For instance, [40] used the 802.11p technology to evaluate the communication performance under a CACC controller in platoons. Likewise, [14] has adopted both 802.11p and C-V2X wireless technologies and compared their performances in terms of the inter-vehicular distance of the platoon. Ploeg *et al.* [41] proposed a control strategy for graceful degradation based on estimating the preceding vehicle’s acceleration in case of packet losses, but it mainly deals with extreme cases like complete link failure or lack of a wireless device on one of the vehicles. Fernandes and Nunes [17] suggested different information management algorithms, including one with a dynamical control parameter where they simply suggest a lower bound value for it. In [12], certain control parameters and the radio resource allocation are jointly considered. However, they do not consider the impact of state variables (position, velocity, and acceleration) on the platooning control while the impact of vehicle mobility on reliability is considered in our model. In [42], the authors focused on emergency braking strategies for platooning based on the 802.11p protocol. Note that in a previous work [30], we proposed a centralized design for the controller under a simple radio model based on V2V only, while in this paper, we develop a joint communication/control model that considers sophisticated radio link and system models in the presence of V2V and RSU relaying methods.

While our work focuses on IEEE 802.11p, other competing technologies which exploit the existing cellular infrastructure and that are grouped within the Cellular V2X (C-V2X) family, are also of interest. Molina and Gonzalez [43] conducted simulations to show a comprehensive analysis of the advantages of the performance of C-V2X Mode 4 over the 802.11p. Similarly, [44] used a simulation environment to compare the communications performance of both modes 3 and 4 of C-V2X with the 802.11p standards. Recently, [45] adopted an analytic approach to describe the C-V2X Mode 4 performance. However, these works were limited to the communication aspects of vehicular networks and did not consider the control aspects of the platooning problem. Another set of works considered the platooning scenario under different communication approaches. More recently, Naik *et al.* [46] provide interesting thoughts about the next generation of both 802.11p and C-V2X access technologies, namely IEEE 802.11bd and 5G NR V2X respectively, while highlighting their beneficial features in platooning applications. An interesting extension of our paper would be to study how these technologies could be incorporated into our analytical model and how they impact the platoon's performance.

IX. CONCLUDING REMARKS

In this paper, we have proposed an integrated design of control and communication systems for future V2X networks, focusing on the platooning use case. We advocate that such integrated control is essential for enabling industrial applications in highly contended networks. We propose a novel analytical model to compute the probability of packet loss in a platoon with and without relay support through RSU or V2V relaying. An offline optimization of the control parameter, inter-vehicular distance, is then presented based on the computed loss rate. The numerical results show that the joint communication-control optimization scheme with V2V relaying can significantly reduce the inter-vehicular distance while guaranteeing the control and communication requirements. However, the best platoon performance is achieved when the content window is optimized so that the channel access delay is reduced without excessively increasing the packet error rate; this ensures a lower inter-vehicular distance while maintaining the robustness of the proposed control scheme to moderate communication errors.

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BIOGRAPHIES

Tiago Rocha Gonçalves received his B.S. degree (*summa cum laude*) in electrical engineering from the Federal University of Rio Grande do Norte, Brazil, in 2016. In 2018, he received his M.S. degree in Control from the University of Campinas - UNICAMP, Brazil. He is now a Ph.D. student at CentraleSupélec, France. His research interest includes intelligent vehicles, platooning systems, system modeling, and control and communication interaction.

Vineeth Satheeskumar Varma is a CNRS researcher at the Centre de Recherche en Automatique de Nancy (CRAN) in Nancy (France). He received his dual Master's degree in Science and Technology from Friedrich-Schiller-University of Jena in 2009 and Warsaw University of Technology in 2010. He obtained his Ph.D. degree from LSS-University of Paris Saclay in 2014. His areas of interest are energy efficiency in telecommunication, multi-agent systems and the interface of automatic control and communication.

Salah Eddine Elayoubi received his M.S. degree in telecommunications from the National Polytechnic Institute of Toulouse, France, in 2001, and his Ph.D. and Habilitation degrees in computer science from the University of Paris VI, France, in 2004 and 2009, respectively. From 2004 to 2013 he was with Orange Labs in France. Since January 2018, he is a full professor at CentraleSupélec, France. His research interests include radio resource management, modeling, and performance evaluation of mobile networks.