Evaluation Platform of Platoon Control Algorithms in Complex Communication Scenarios

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***Abstract*—Cooperative Adaptive Cruise Control (CACC) extends the Adaptive Cruise Control with ~~the~~ additional information exchange between vehicles over vehicle-to-everything (V2X) communications in an ad-hoc network at 5.9 GHz band (ITS-G5) in Europe. Using ~~the~~ beyond line-of-sight information provided by V2X, the platoon control algorithms realize a shorter safe inter-vehicle distance. Nevertheless, the platoon performance (e.g., the safe inter-vehicle distance) ~~can~~ be ~~easily~~ impacted by the imperfectness of wireless communications. Specifically, in congested traffic scenarios Decentralized Congestion Control algorithms ~~(~~e.g., Transmit Rate Control ~~(TRC)~~ ~~that~~ regulates message rate based on congestion level~~)~~ may negatively influence the platoon performance. In this work, we propose an evaluation platform for platoon control algorithms based on industrial V2X nodes operating in the ITS-G5 channels. The real car is simulated by a longitudinal vehicle dynamic model. The model-in-the-loop test results demonstrate that ~~the~~ performance of CACC goes down significantly when the message rate is restricted and reduced by TRC. Our evaluation results further conclude that the effect of such complex communication scenarios imposed by the existing standards should be explicitly modeled in the future platoon control algorithms.**

***Index Terms*—ITS-G5, V2X, V2V, DCC, CACC, Platooning**

I. Introduction

Intelligent Transport Systems (ITS) have recently attracted considerable attention, due to their potential to improve traffic flow stability, throughput, fuel efficiency [1] and on-road safety. As a representative application of ITS, Cooperative Adaptive Cruise Control (CACC) extends the Adaptive Cruise Control (ACC) with additional information exchange between vehicles through vehicle-to-everything (V2X) communications in an ad-hoc network at the 5.9 GHz frequency band (ITS-G5) allocated in Europe [2].

Nevertheless, with increasing number of ITS-stations (ITS-S) transmitting in the ITS-G5 channels, the channel can be congested in peak-time traffic. In a congested channel, most messages collide with each other and cannot be correctly received by receivers [3]. Decentralized Congestion Control (DCC) is therefore proposed by European Telecommunications Standards Institute (ETSI) for Europe [4] and by the SAE [5] for the USA, to regulate and control the message dissemination. As a method of DCC, Transmit Rate Control (TRC) prevents the excessive use of the ITS-G5 channels by restricting the message transmitting rate of each ITS-S, which changes the update rate of the platoon controller input and creates complex communication scenarios for CACC. However, most of DCC methods are not application-aware; hence, they cannot meet specific application requirements. To achieve a small inter-vehicle distance the platoon control algorithm requires a high and fixed message exchange frequency [6], and the existing platoon control algorithms are mostly designed with such communication requirements [7] [8] [9] [10]. Therefore, use of TRC can negatively influence the platooning performance. The V2X communication community has recently started to investigate the impact of communication characteristics on platooning performance. A set of communication strategies which explicitly takes the requirements of the CACC controller into account is proposed in [11].

In this work, we develop an evaluation platform and conduct model-in-the-loop experiments to analyze the influence of TRC on a state-of-the-art platoon control algorithm.

II. Related Work

A number of Platoon Control Algorithms (PCAs) and their variants have been designed over the last decade. A majority of them are tested and validated in computer simulation environments [10] before road tests.

Typically, a simulator is composed of a network simulator, a road traffic simulator and vehicle models with the control algorithm integrated. Through simulations, the performance of different network setups can be compared, making it possible to recognize and resolve performance problems without conducting expensive field tests [12]. In Vehicular Ad-Hoc Network studies, network simulators (NS-3 and OMNeT++) are often used for simulating the message exchange between vehicle nodes and computing the packet reception status (packet delivery ratio and delay) of V2X communications.

In the 2011 Grand Cooperative Driving Challenge (GCDC2011) organized in the Netherlands, teams from different European universities have realized basic functionalities of CACC systems on the modified production vehicles [13] [14]. In GCDC2016, advanced platoon operations such as the cooperative platoon merge and the cooperative intersection passing were investigated [7] [8]. However, the platooning members were allocated an exclusive channel during the

GCDCs, and no complex communication scenario was considered in the events. It is in fact difficult to study complex communication scenarios using GCDC's setup due to the strict safety requirements. In other words, tuning the CACC control system with the real vehicles and making the vehicles follow or merge as expected were sufficiently challengeable. The safety of human and properties could not be promised when additional interferences were introduced, and V2X communications became unpredictable.

To summarize, both simulative and experimental studies have their limitations, which motivated us to develop the proposed PCA evaluation framework that costs less but is more flexible than the experimental studies. As opposed to the simulation environments, the platform we developed based on commercial embedded ITS devices operates in real ITS-G5 channels. The state-of-the-art PCA reported in [9] is implemented in our evaluation platform.

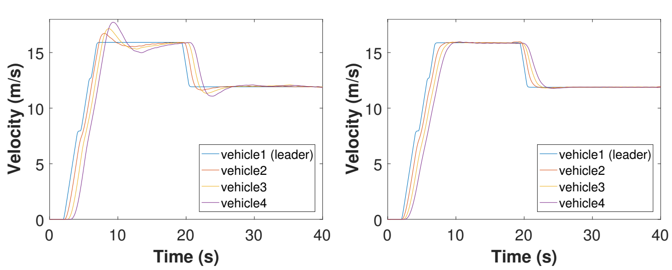
III. PLATOON PERFORMANCE METRICS

A. String Stability

String stability considers the propagation of disturbance generated at one vehicle in a string. In a stable string, the disturbance shall not be amplified in the upstream direction, i.e., from the leading vehicle to the followers. String stability is not only a requirement of a platoon control algorithm design, but also a metric to evaluate the platooning performance.

In [15] and [16], the string stability is quantified by the magnitude of the string stability transfer function. However, this frequency-domain approach has shown its limited capability in terms of analyzing real experiments data where various nonlinearities in the real world, such as variable transmission delays and actuation delay are introduced.

In this work, the string stability is evaluated based on time-domain logs retrieved from the vehicles, by directly checking the propagation of the disturbance. The disturbance shall not be amplified in the upstream direction [17]. Fig. 1a depicts the time-domain velocity response of a string unstable case. Overshoots can be observed in the response of Vehicle 2, 3 and 4, and the overshoots (disturbance) are amplified along the vehicle string. A similar behavior can be found in the time of deceleration. On the contrary, no overshoot occurs in the string stable case (Fig. 1b).



(a) (b)

Fig. 1: The velocity response of each platoon member in two simulations. (a) String unstable (disturbance amplification). (b) String stable (disturbance attenuation).

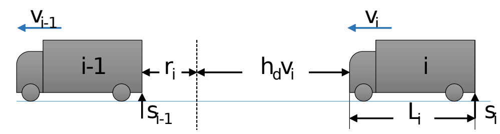


Fig. 2: Time headway in vehicle platooning

Specifically, in order to evaluate the string stability of a platoon, we consider the velocity curves with an acceleration period and a deceleration period. A straightforward way to analyze the string stability is to compare the overshoots of the responses of each platoon member. We consider the string is stable if

$$\frac{A_i - A_{i-1}}{V_{final}} \times 100\% \leq \delta_m,\ \ i = 2, \ldots, n \tag{1}$$

where i is the platoon member index and n is the string length; V_{final} is the steady-state response of the leader, while A_i is the amplitude of the overshoot of the i_{th} vehicle, taking the steady-state of the leader as the reference. δ_m is the maximum allowable relative error. For a strict stability criterion, we allow a small amplification ($\delta_m = 3\%$) along the string. δ_m is a design parameter that is chosen according to the platoon size and headway.

B. Minimum Allowable Time Headway (MinATH)

Time headway indicates the desired inter-vehicle distance, the control objective of CACC, which can be computed by:

$$d_{r,i}(t) = r_i + h_d v_i(t), \qquad i \geq 2 \tag{2}$$

where r_i is the desired stand-still distance of the i_{th} vehicle from its predecessor (Fig. 2). h_d is the time headway which indicates the time in seconds it takes to cover the gap between vehicles when the predecessor is standstill. $v_i(t)$ is the velocity of the i_{th} vehicle.

A shorter inter-vehicle distance is desired due to less air-drags and better road throughput. However, it is difficult for the platoon controllers to safely maintain a short inter-vehicle distance (ensuring string stability) since it imposes stricter requirements on both communication and control design. There exists a minimum feasible inter-vehicle distance that a platoon can safely maintain with a certain setting. The minimum feasible inter-vehicle distance can be modeled by the time headway h_d. Thus, in this study, we consider the Minimum Allowable Time Headway (MinATH) as a metric of platooning performance.

IV. EVALUATION PLATFORM DESIGN

The evaluation platform is composed of multiple Cohda wireless MK5 onboard units [18], each emulating one platoon vehicle by executing a control algorithm and integrating a Longitudinal Vehicle Dynamic Model (LVDM). The software architecture of a follower platoon member in Fig. 3 consists of a platoon control loop and several basic services. A number of buffers (dashed blocks) are used to connect the functional units executing at different rates.

A. Platoon Control Loop

1) Sensing: The control loop starts with a sensing period, where different types of sensors sense the surrounding environment and store the sensed signal in the RAM (buffers).

To achieve a better compatibility, the evaluation platform should provide multiple types of sensors that can be potentially required by different PCAs. The sensors are categorized into the non-line of sight sensors (V2X receiver), the line of sight sensors, and onboard motion sensors which measure the ego vehicle states. In our proposed platform, onboard motion sensors, a long-range Radar sensor, and a V2X transceiver are supported. In this study, we focus on model-in-the-loop tests where the real vehicles are replaced by the LVDM, so that the sensors except the V2X receiver are all simulated.

2) Computing: In the computing phase, a high-level controller computes the control goal by (2) based on the information input from the sensing period, obtains the error (e) and plans a trajectory for the vehicle to eliminate the error. In some CACC systems, the sensor fusion is performed for providing more accurate and reliable input to the PCA, by fusing the information obtained by different sensors. The PCA proposed in [9] uses the raw sensor measurement data, which takes into account the ego vehicle state parameters (position, velocity, acceleration and desired acceleration) and the predecessor state. The trajectory is planned and represented by a series of desired accelerations.

In [9], the desired acceleration of the i_{th} vehicle $a_{des,i}$ is computed (sample time T_s) by

$$\begin{aligned} a_{des,i}(k+1) = a_{des,i}(k) + T_s(-\frac{1}{h_d}a_{des,i}(k) \\ + \frac{1}{h_d}(k_p e_i(k) + k_d \dot{e}_i(k)) \\ + \frac{1}{h_d}a_{des,i-1}(k)), i \geq 1 \end{aligned} \tag{3}$$

where $a_{des,i}(k)$ is high-level controller output of the last cycle, and the errors in discrete time are

$$\begin{aligned} e_i(k) &= s_i(k) - s_{i-1}(k) - L_i - (r_i + h_d v_i(k)), i \geq 1 \\ \dot{e}_i(k) &= v_i(k) - v_{i-1}(k) - h_d a_i(k), i \geq 1 \end{aligned} \tag{4}$$

where $s_i(k)$ and $v_i(k)$ are the position and velocity of the i_{th} vehicle (Fig. 2) in discrete time.

3) Actuating: The actuating phase is where the desired acceleration is realized by the LVDM and the output (acceleration) can be computed by

$$a_i(k+1) = a_i(k) + T_{ls} \cdot (-\frac{1}{\tau}a_i(k) + \frac{1}{\tau}a_{des,i}(k)) \tag{5}$$

where T_{ls} is the sampling period of the plant and it should be much smaller than T_s. τ is the engine lag time constant. Position and velocity are computed by integral calculus.

B. Basic Services

The provided basic services include logging, a (virtual) Radar, the handler of the IEEE 802.11p receiver and a CACC Dissemination Basic Service (DBS) which determines the timing of each transmission and forwards the transmission request

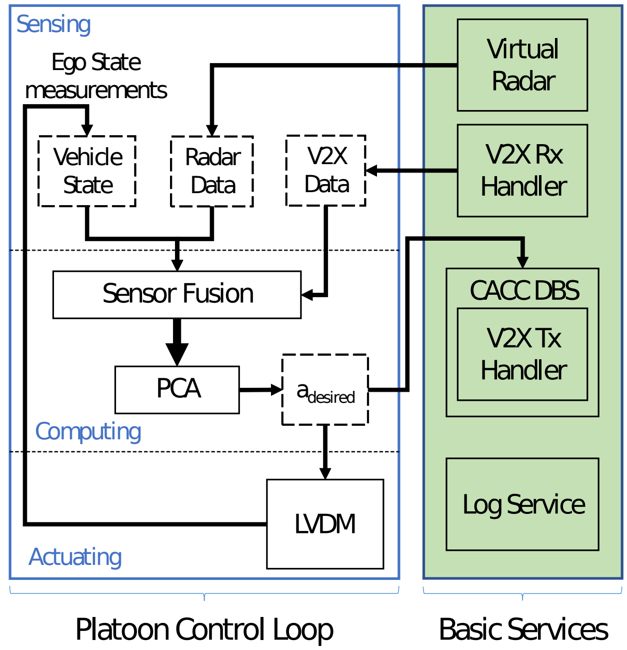


Fig. 3: Software architecture of a follower platoon member

and packet to the transmitter through Tx handler. CACC DBS is where the DCC algorithms shall be implemented. During the experiments, the data logging service executes at 100 Hz, saving the information stored in the buffers into a log file. The log files from different devices can be retrieved, processed and analyzed on an X86 PC with MATLAB.

V. EXPERIMENTS

A. Experiment Design

Fig. 4 illustrates the experiment setup composed by four MK5 nodes, each emulating an ITS-S and transmitting on the ITS-G5 channel. The leader is the reference vehicle of the platoon while the followers are supposed to follow the leader with a desired distance.

In this phase, we are more interested in the static performance of the PCA, meaning the MinATHs that the vehicle platoon can safely maintain under different message rates (controlled by TRC). In order to reduce the complexity of the experiments, instead of having one more MK5 node emits

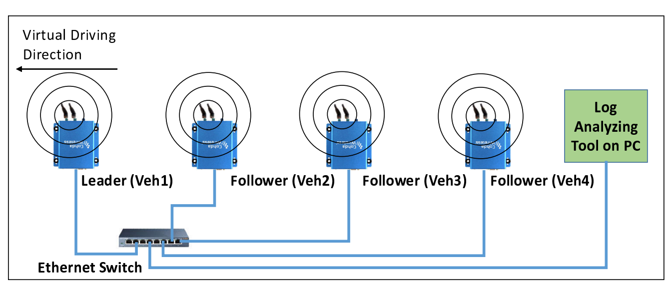
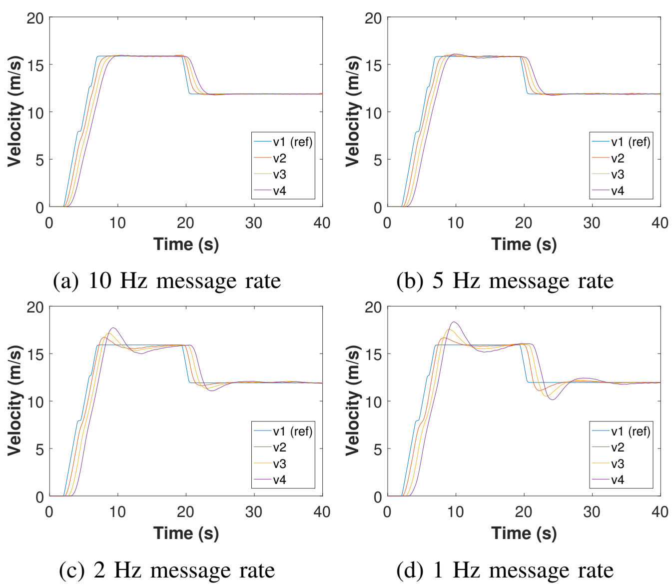


Fig. 4: Experimental setup with four MK5 nodes (1 leader + 3 followers).

at very high rate, triggering the TRC implemented in the DBS of the platoon member nodes, we manually configured the platoon with fixed beacon rates (1 Hz, 2 Hz, 5 Hz, and 10 Hz) which are often considered in DCC state machines [4] [19]. (The channel load levels triggering these beacon rates have been proven to be feasible in [20].) The velocity trajectory of the leading vehicle was designed so that the reference vehicle performs exactly the same during each test. Therefore, we can compare the platoon performance under different message rates. The experiment has been repeated a number of times, but the performance of each message rate is derived with one test, because the variance between each experiment is negligible.

B. Experimental Results

In Fig. 5, CACC performance under different message rates are compared. The leader, representing the vehicle driven by the human, has the same behavior during these tests, whereas the followers perform differently due to the different communication settings. The desired inter-vehicle distance is 0.5 s time headway, which applies to the four tests shown below. A reference is given in Fig. 5a, where the vehicles in the platoon exchange message at 10 Hz and the vehicle string is stable. However, the platoon becomes string unstable (TABLE I) in Fig. 5b, 5c, 5d (with lower message rate scenarios). The reason has been explained in Section III, i.e., more (ITS-G5) channel resources are required to realize vehicle platooning at lower h_d.



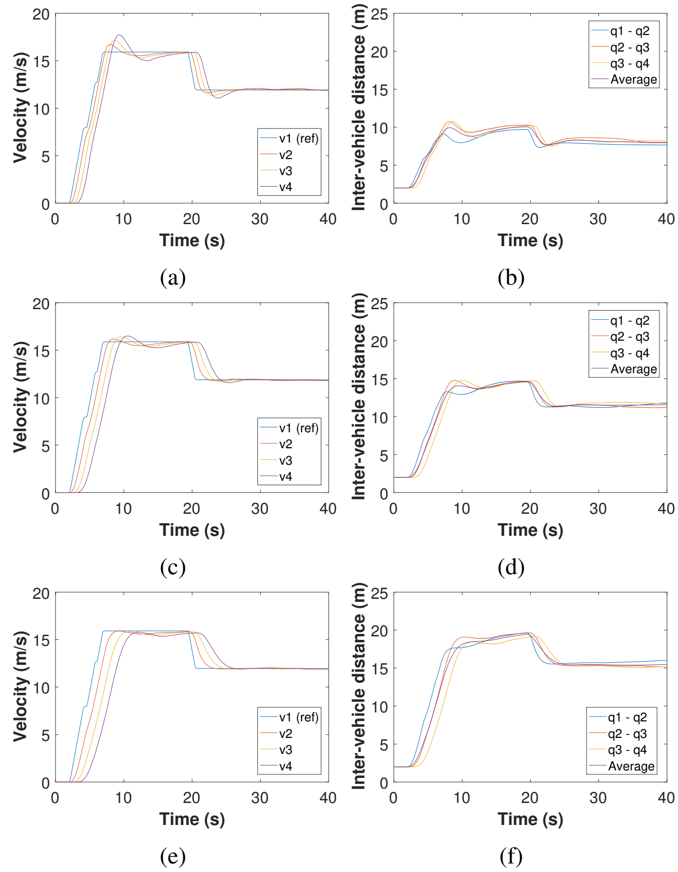
(a) 10 Hz message rate (b) 5 Hz message rate

(c) 2 Hz message rate (d) 1 Hz message rate

Fig. 5: CACC performance with 0.5 s time headway under different message update rate.

TABLE I: Overshoot measurement

	A_1	A_2	A_3	A_4	V_{final}	String stability
10 Hz	0	0.3778	0.4093	0.5479	15.88	stable
5 Hz	0	0.7891	1.1616	1.6288	15.88	unstable
2 Hz	0	5.0628	7.7513	11.3505	15.88	unstable
1 Hz	0	4.6985	10.3643	15.2827	15.88	unstable



(a) (b)

(c) (d)

(e) (f)

Fig. 6: String behavior with an increased headway with 2 Hz message rate: (a)(c)(e) velocity response of the platoon vehicles for 0.5 s, 0.8 s, and 1.1 s headway; (b)(d)(f) inter-vehicle distance for 0.5 s, 0.8 s, and 1.1 s headway.

In order to satisfy the string stability requirement of the low-message-rate CACC, the control objective (abstracted as h_d) needs to be adjusted. For instance, 2 Hz message rate does not promise string stable with h_d = 0.5 s, but the string stability requirement can be satisfied with a larger headway (less aggressive control objective). The MinATH for 2 Hz message rate is obtained by iterative tests with different h_d (Fig. 6a, 6c, 6e). The string stability condition (1) is examined by a log analyzing tool.

Although the string stability of the low-message-rate CACC can be reached by increasing the time headway, the road capacity has to be compromised since the inter-vehicle distance increases as a consequence (Fig. 6b, 6d, 6f).

We repeated the iterative test shown in Fig. 6 for each message rate (1 Hz, 2 Hz, 5 Hz, and 10 Hz) and obtained the MinATH for these message rates respectively. Fig. 7 clearly shows that MinATH increases with a decreasing message rate. Thus, for dealing with the varying message rates brought by DCC (TRC), an adaptive h_d must be considered as the control objective of platoon controllers.

Additionally, the CACC outperforms ACC in terms of the MinATH. Messages exchanged at 1 Hz still makes differences:

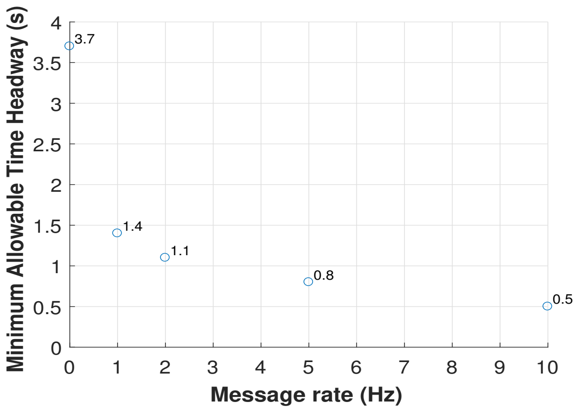


Fig. 7: MinATH for common message rates in V2X communications. (0 Hz stands for ACC).

CACC with only 1 Hz message rate can realize over twice shorter headway (1.4 s) than that of ACC (3.7 s). This allows us to make an important conclusion – although DCC may reduce the message exchange rate of CACC down to 1 Hz, CACC still performs better than ACC or human driving vehicles when cruising. On the other hand, DCC intends to keep order in the ITS-G5A channels, preventing CACC to degrade to traditional ACC due to the high packet dropouts caused by the congested channels.

VI. CONCLUSIONS AND FUTURE WORK

We consider the impact of varying message rate imposed by the Transmit Rate Control (TRC) mechanism on the vehicle platooning control performance. For studying this effect, an evaluation platform has been developed. Our experimental result clearly shows that the performance of vehicle platooning control goes down when the message rate is restricted and reduced by TRC. Our study suggested that an adaptive headway dynamic controller may adapt better to complex communication scenarios.

Our future work will focus on the following three aspects:

1) Deploying a jammer node emitting at a very high rate, letting the TRC taking over the control of the message rate of the platoon nodes, and investigating the dynamic performance of the platooning.
2) Integrating more platoon control algorithms on the platform and developing an adaptive headway control strategy.
3) Setting more 802.11p communication nodes for emulating realistic scenarios.

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