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Cooperative Platoon Control of Heterogeneous Vehicles Under a Novel Event-Triggered Communication Strategy

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ABSTRACT This paper investigates the cooperative platoon control problem of heterogeneous vehicles. Under a leader and predecessor following communication structure, each following vehicle tracks the state of the leader while maintaining a constant spacing between successive vehicles. To reduce the utilization of communication resources, a new event-triggered communication strategy (ETCS) is proposed, where the current data of the following vehicle is transmitted to its direct successor only when the difference between the current data and the last transmitted data exceeds a state-dependent threshold. By properly designing the threshold, the number of data transmissions near the steady state is greatly reduced. The tracking errors of all vehicles are shown to be bounded while Zeno behavior can be avoided under the ETCS. The advantages of the proposed ETCS are discussed by comparing with the existing strategies. Moreover, to deal with the heterogeneity of the vehicles' dynamics, a decentralized and computationally efficient method is presented to solve the non-identical control gains of all the vehicles. The numerical simulations have been conducted to illustrate the effectiveness of the proposed approach.

INDEX TERMS Cooperative platoon control, decentralized controller, event-triggered communication, heterogeneous vehicle platoon.

I. INTRODUCTION

The continuously growing land freight transportation and urban traffic promote the development of intelligent transportation systems (ITSs), which are expected to achieve accurate traffic control, increase roadway throughput, and improve safety. The benefits of ITSs rely, to a large extent, on the technique of vehicular platoon control, namely, organizing vehicles in the same lane to autonomously follow a leading vehicle while maintaining appropriate longitudinal spacing between successive vehicles [1]. After decades of research and development efforts from both the academia and the industry, the adaptive cruise control (ACC) system is being mounted in more and more cars so that a vehicle can autonomously track its predecessor by using measured relative state information via onboard sensors [2]–[4]. To further enhance the performance of a platoon, cooperative adaptive cruise control (CACC) systems are proposed so that tighter inter-vehicle distances can be achieved by allowing the vehicles to share their real-time state information (e.g., positions, velocities and accelerations) over wireless communication channels (e.g. DSRC networks [5], [6]). Under different

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communication structures and properly designed control laws, CACC is extensively studied by both theoretical analysis and experiments [7]–[15].

Since the performances of CACC systems are inevitably affected by the capacity and quality of a wireless communication channel, vehicular platoon control problems subject to communication imperfections are receiving more and more attentions. For examples, the issues of data transmission losses [16], delays [17], irregular data transmission intervals [18], and channel fading and media access constraints [19] have been investigated in vehicular platoon control problems. Note that most of these issues emerge only when the communication channels are extensively used by massively many vehicles. Therefore, to alleviate these destructive effects, one promising way is to reduce the amount of data transmissions requested by the vehicles. This goal can be achieved by applying event-triggered communication schemes (ETCSs), where the data of a system is sent out only when certain condition is satisfied [20]–[22]. In the past decade, various event-triggered schemes (ETSs) have been proposed for purposes such as reducing the executions of control actions or avoiding continuous sensing of a sensor [23].

The ETSs have also been widely applied in distributed or decentralized control systems such as sensor actuator networks [24]–[26], networked control systems [27], [28], and multi-agent systems [29]–[34]. In these systems, each sensor or each control unit runs an individual event generator based on local information of the system. For example, in wireless sensor actuator networks, decentralized ETCS is proposed in [24] so that each sensor determines independently the time of sending out its sensed system state to the central controller. In [25], the central controller also runs an ETCS to enlarge the average inter-event time used for data transmission from every sensor to the controller. In [26], the ETCS of each sensor is based on the periodically sampled multiple outputs of the system, and output-based control law is designed to ensure asymptotic stability and dissipativity of a linear system under external disturbances. In the stabilization of a networked control system that contains multiple interconnected subsystems, decentralized ETCSs are proposed for each subsystem to determine the time of transmitting local information to the connected subsystems [27], [28]. In [27], the decentralized ETCS of each subsystem relies on its own current state and the last successfully transmitted state, while the decentralized ETCS proposed in [28] has a dynamic structure and is dependent on the output and control value of a single subsystem. In multi-agent systems where distributed agents exchange information with neighbors to reach agreements on their system states, there exist plenty of publications on event-triggered schemes (see the recent survey papers [29], [35] and the references therein). However, a large amount of those ETSs can only reduce control executions while require continuous communications among neighboring agents. To resolve this problem, some proposed approaches include the distributed ETCSs that rely on the intermittently transmitted states from all neighbors [30], [31], and the decentralized ETS that uses model-based estimations of all neighbors' states [32]. The ETCSs in [33] and [34] avoid using neighbors' information by applying state-independent thresholds such as a positive constant [33] or a time-decreasing function [34].

To prevent the ETCS from degrading to continuous communications, the inter-event times are required to be strictly positive. This is also known as the task of avoiding the occurrence of Zeno behavior (the behavior of triggering infinite number of events in a finite time interval). In [24], [25], [27], [28], [30], an additional dwell time is imposed before triggering the next event so that the minimum inter-event time can be forced to be larger than a positive value. In [20], [26], [35]–[37], the sampled-data-based methods are applied where the event-triggering conditions are checked only at periodic sampling instants. Including positive state-independent terms in the thresholds of event-triggering conditions can also help to avoid Zeno behavior subject to external disturbances [22] or inter-system interferences [31]–[34]. Considering that inter-connected vehicular systems would interfere with each other, the last approach is applied in this paper to avoid Zeno behavior.

Motivated by the above results, event-triggered schemes are receiving more and more attentions in vehicular platoon control problems [36]–[39], either for the purpose of reducing control executions or saving communication resources. In [36], each vehicle applies a local ETS to reduce control executions. However, each ETS needs continuously communicated states of all vehicles and thus is centralized. In [37], the event generator of each vehicle depends on the states of its own and that from its predecessor, and thus is distributed. However, the linear feedback control gains still need centralized computation. Note that the event-triggered control laws in [36] and [37] are based on periodically sampled system states, and thus are likely to reduce to periodic control strategies when the system states are heavily disturbed. In [38], state-independent thresholds are used to design decentralized ETCSs for vehicles with heterogeneous nonlinear dynamics. However, state-independent thresholds are insensitive to state variations and cannot guarantee the positivity of the inter-event times for arbitrarily large states [22]. In [39], the dynamic ETCS in [28] is applied for platoon control of vehicles with homogenous linear dynamics, and is observed to have larger inter-event times than static schemes. However, it is structurally complicated for computation, and may suffer from security issues since the private control value of a preceding vehicle is required to be transmitted on the network.

In this paper, a new decentralized ETCS is proposed for platoon control of heterogeneous vehicles under a leader predecessor following (LPF) communication structure where each following vehicle receives information from both its predecessor and the leader [4], [9], [12]. The LPF structure can result in smaller tracking error overshoots, and is less sensitive to disturbances compared with the predecessor following (PF) structure in which each following vehicle only receives information from one preceding vehicle [9]. The ETCS of each following vehicle depends on its own tracking error with respect to the leader without using other following vehicle's information. Hence, it is a distributed scheme which is superior to the centralized scheme in [36] that required all-to-all continuous communications. Motivated by the methods in [22], [31], [32] of avoiding Zeno behavior, the threshold of each vehicle's event-triggering condition in this paper is composed by a state-dependent term to handle cases where the tracking errors are large, and a constant term to handle cases where the tracking errors are small. This kind of mixed threshold can ensure positive minimum inter-event time for all system states [22] compared with the state-independent thresholds used in [33], [34], [38] which only ensure this for finite states. It can also prevent inter-vehicle communications from degrading to periodic transmissions as in [36], [37]. As a compromise of using such thresholds, the tracking errors of the vehicles are shown to be bounded rather than asymptotically stable. This paper also has the following contributions.

Firstly and most importantly, the proposed distributed event-triggering condition imposes a smaller order on the state-dependent term than that on the state updating error. This ensures larger inter-event times near the steady state compared with existing state-dependent event-triggering schemes that use equal orders on both terms [23]–[32], [35]–[37]. Both theoretical analysis and simulation examples have been justified this contribution.

Secondly, compared with the study of homogeneous linear vehicle models in [39] and the centralized computation method of control gains for heterogeneous vehicles in [37], we studied heterogeneous vehicles and offered a distributed and efficient method to compute the non-identical control gains of heterogeneous vehicles by transforming centralized nonlinear matrix inequalities into distributed linear matrix inequalities.

The remainder of this paper is organized as follows. Section II presents the vehicle platoon model and the event-triggered strategy. Section III shows the sufficient condition for parameters of the ETCS under a centralized control design so that the tracking error of each vehicle is bounded. In section IV, the control gains for the heterogeneous vehicles are derived by using a decentralized method. Numerical simulation results are given in Section V, and concluding remarks are presented in Section VI.

II. VEHICEL PLATOON MODELING

A vehicle platoon is generally composed by a battery of vehicles as shown in Fig. 1, where there are one leading vehicle (indexed by 0) and n following vehicles (indexed by $F := \{1, \cdots, n\}$). The states of the ith ($i \in F \cup \{0\}$) vehicle are position, velocity and acceleration which are denoted by z_i, v_i and a_i, respectively. These states can be measured by the vehicle via onboard sensors [12], [13]. In this paper,

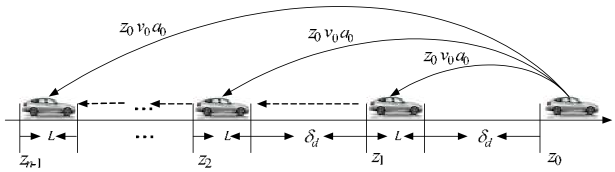

FIGURE 1. A platoon of vehicles with a leader predecessor following (LPF) communication structure.

vehicle platoon is supposed to have the leader and predecessor following (LPF) communication structure ([4], [9], [12]), in which the leader vehicle broadcasts information to all followers through a wireless network such as the VANET [6], while each following vehicle $i \in F\backslash\{n\}$ except the last one only transmits data to its direct follower $i+1$.

A. BASIC MODEL OF VEHICEL PLATOONING

Define the spacing error between a following vehicle $i \in F$ and the leading vehicle 0 as follows

$$\delta_i = z_0 - z_i - i\delta_d - iL, \quad i \in F \tag{1}$$

where δ_d is the desired spacing between two neighboring vehicles, and L is the length of a vehicle. The evolution of δ_i is described by the following linearized differential equations [13]

$$\dot{\delta}_i(t) = \dot{z}_0(t) - \dot{z}_i(t) = v_0(t) - v_i(t), \tag{2}$$
$$\dot{v}_i(t) = a_i(t), \tag{3}$$
$$\dot{a}_i(t) = -\frac{1}{\varsigma_i}a_i(t) + \frac{1}{\varsigma_i}u_i(t), \tag{4}$$

where ς_i is the characteristic time constant, and $u_i(t)$ is the control input of each following vehicle $i \in F$.

The continuous-time controllers usually take the following state feedback forms [2], [13]

$$u_1(t) = k_1^{\delta}\delta_1(t) + k_1^{ve}\Delta v_{0,1}(t) + k_1^{ae}\Delta a_{0,1}(t), \tag{5}$$
$$u_i(t) = k_i^{\delta}\delta_i(t) + k_i^{ve}\Delta v_{0,i}(t) + k_i^{ae}\Delta a_{0,i}(t) + k_i^{v}\Delta v_{i-1,i}(t) + k_i^{a}\Delta a_{i-1,i}(t), \quad i \in F\backslash\{1\}, \tag{6}$$

where k_i^{δ}, k_i^{v}, k_i^{a}, k_i^{ve} and k_i^{ae} are the control gains, and$\Delta v_{i-1,i}(t) = v_{i-1}(t) - v_i(t)$, $\Delta a_{i-1,i}(t) = a_{i-1}(t) - a_i(t)$, $\Delta v_{0,i}(t) = v_0(t) - v_i(t)$, and $\Delta a_{0,i}(t) = a_0(t) - a_i(t)$.

Remark 1: The control law in this paper is in the form of state feedback control by following exiting literature, e.g. [2], [13], [18], under the consideration that vehicular systems (either manufactured in factories or developed in the lab) usually have the ability to measure their own states by using onboard sensors. For instance, positions can be measured by GPS, while velocities and accelerations can be measured by encoders and accelerometers [13] (or a LIDAR [12]). In cases that some of these sensors are not available or fail to work, output feedback control techniques such as those in [28], [41] and [42] would be helpful.

Let $x_i(t) = [\delta_i(t), \Delta v_{0,i}(t), \Delta a_{0,i}(t)]^T$, $i \in F$ be the tracking error of each following vehicle with respect to the leader. Then the tracking error dynamics of all following

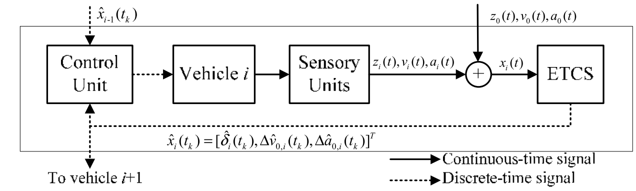

FIGURE 2. Control structure and information flows of a following vehicle $i \in F\backslash\{n\}$ under the event-triggered communication strategy.

vehicles can be described in the following unified form: for all $i \in F$,

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t), \tag{7}$$

$$\begin{aligned} u_i(t) &= K_{oi}x_i(t) + K_{ci}(x_i(t) - x_{i-1}(t)) \\ &= K_i x_i(t) - K_{ci}x_{i-1}(t), \end{aligned} \tag{8}$$

where $A_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1/\varsigma_i \end{bmatrix}$, $B_i = \begin{bmatrix} 0 \\ 0 \\ -1/\varsigma_i \end{bmatrix}$, $K_{oi} = [k_i^{\delta}, k_i^{ve}, k_i^{ae}]$, $K_{ci} = [0, k_i^v, k_i^a]$ with $K_{c1} = 0$, and $K_i = K_{oi} + K_{ci}$.

B. MODELING UNDER THE EVENT-TRIGGERED TRANSMISSION SCHEME

To implement the feedback control law (8) by each following vehicle $i \in F$, the tracking error $x_i(t)$ can be computed by the vehicle i based on its own state information measured continuously by onboard sensors and the broadcast information received from the leading vehicle, whereas the tracking error $x_{i-1}(t)$ has to be received from the predecessor. In this paper, the control structure and information flows of a following vehicle are illustrated in Fig. 2, in which the leader is supposed to continuously transmit its state information z_0, v_0 and a_0 to all followers through a dedicated high-speed wireless channel; each follower $i \in F\backslash\{n\}$ transmits data to its successor $i+1$ based on an event-triggered communication scheme (ETCS) so as to save communication resources.

To introduce the ETCS, we need to define some variables. Let $\{b_i[k]\}_{k=0}^{\infty}$, $i \in F\backslash\{n\}$ denote the sequence of data transmission time instants of vehicle i, where k counts the number of transmissions starting from the initial time 0. It is assumed that $b_i[0] = 0$. Denote $\hat{z}_i(t_k) = z_i(b_i[k])$, $\hat{v}_i(t_k) = v_i(b_i[k])$, and $\hat{a}_i(t_k) = a_i(b_i[k])$, for all $i \in F\backslash\{n\}$. Define $\hat{x}_i(t_k) = [\hat{\delta}_i(t_k), \Delta\hat{v}_{0,i}(t_k), \Delta\hat{a}_{0,i}(t_k)]^T$, $i \in F\backslash\{n\}$ as the tracking error state at time instant $t = b_i[k]$, where $\Delta\hat{v}_{0,i}(t_k) = v_0(b_i[k]) - \hat{v}_i(t_k)$, $\Delta\hat{a}_{0,i}(t_k) = a_0(b_i[k]) - \hat{a}_i(t_k)$, and $\hat{\delta}_i(t_k) = z_0(b_i[k]) - \hat{z}_i(t_k) - i\delta_d - iL$. At each time instant $b_i[k]$, vehicle $i \in F\backslash\{n\}$ transmits $\hat{x}_i(t_k)$ to its subsequent vehicle $i+1$. Since the last vehicle n doesn't need to transmit any message, we let $\hat{x}_n(t_k) = x_n(t)$ for all t to unify notation. Then, the difference between the current tracking error $x_i(t)$ and the previously transmitted tracking error $\hat{x}_i(t_k)$ is defined as follows:

$$e_i(t) = x_i(t) - \hat{x}_i(t_k), \quad b_i[k] \le t < b_i[k+1], \; \forall i \in F. \tag{9}$$

It is clear that $e_n(t) = [0, 0, 0]^T$ for all $t \in [b_i[k], b_i[k+1])$.

The vehicle $i \in F\backslash\{n\}$ transmits its own tracking error $x_i(t)$ to its successor $i+1$ as soon as the following condition is violated

$$\|e_i(t)\|^2 \le \beta_i \left\|\hat{x}_i(t_k)\right\| + c_i, \tag{10}$$

where β_i is a positive number to be designed, and c_i is a positive constant. Since $\|e_i(t)\|$ represents the information updating error of a vehicle, the right-hand side of (10) is regarded as a threshold for information updating errors. Note that the event-triggering condition (10) is decentralized in the sense that it can be computed locally by each following vehicle without using information from any other following vehicle.

Remark 2: Note in (10) that the state-dependent term $\beta_i \left\|\hat{x}_i(t_k)\right\|$ can ensure positivity of the minimum inter-event time when $\left\|\hat{x}_i(t_k)\right\|$ is large, while the constant term c_i can help to exclude Zeno behavior when $\left\|\hat{x}_i(t_k)\right\|$ is small [22], [31], [32]. It is worth mentioning that the order of $\left\|\hat{x}_i(t_k)\right\|$ on the right-hand side of (10) is one half of the order of the information updating error $\|e_i(t)\|$. Thus, the decreasing speed of the threshold is slower than the converging rate of the information updating error when $\left\|\hat{x}_i(t_k)\right\|$ is small. Therefore, inter-event times near the steady state where $\left\|\hat{x}_i(t_k)\right\|$ is small can be larger than that using existing triggering conditions in which $\left\|\hat{x}_i(t_k)\right\|$ have the same order with $\|e_i(t)\|$ (e.g., see [23]–[32], [35]–[37]). This point will become clear as will be presented in the sequel. We would like to assert that other fractional orders smaller than one can also be imposed on $\left\|\hat{x}_i(t_k)\right\|$. The order chosen in (10) is for the purpose of simplifying analysis and for ease of computation.

Based on the ETCS, the control input of a following vehicle $i \in F$ is written as follows:

$$u_i(t) = K_i\hat{x}_i(t_k) - K_{ci}\hat{x}_{i-1}(t_k), \, b_i[k] \le t < b_i[k+1]. \tag{11}$$

Denote $x = [x_1, \cdots, x_n]^T$, $u = [u_1, \cdots, u_n]^T$, $\hat{x} = [\hat{x}_1, \cdots, \hat{x}_n]^T$. The error dynamics of the platoon system (2)-(4) under an ETCS is written compactly as follows

$$\dot{x}(t) = Ax(t) + Bu(t), \tag{12}$$

$$u(t) = K\hat{x}(t_k), \tag{13}$$

where $A = blkdiag\{A_1, \ldots, A_n\}$, $B = blkdiag\{B_1, \ldots, B_n\}$, and

$$K = \begin{bmatrix} K_1 & 0 & 0 & 0 & 0 \\ -K_{c2} & K_2 & 0 & 0 & 0 \\ 0 & -K_{c3} & \ddots & 0 & 0 \\ 0 & 0 & -K_{c(n-1)} & K_{n-1} & 0 \\ 0 & 0 & 0 & -K_{cn} & K_n \end{bmatrix}. \tag{14}$$

The objective of this paper is to design the parameters of the event-triggering condition in (10) and the control gains in (14) so that the tracking errors of all vehicles in the platoon are bounded for all the initial tracking error states.

III. PLATOON CONTROL UNDER ETCS

In this section, we present some sufficient conditions for the tracking errors of the following vehicles to be bounded. To do so, we provide the following lemma for later use.

Lemma 1 [32]: For arbitrary vectors $\xi \in R^m$, $\ell \in R^m$, and positive definite matrix $\Theta \in R^{m\times m}$, there holds the following inequality $2\xi^T\ell \le \xi^T\Theta\xi + \ell^T\Theta^{-1}\ell$.

The following theorem shows that the error states of all following vehicles are bounded under the event-triggering condition (10).

Theorem 1: For any initial state $x(0)$, the state of the error system in (12)-(13) with event-triggered communication by violating (10) is bounded if there exist positive definite matrices $P \in R^{3n\times 3n}$, $Q \in R^{3n\times 3n}$ and $W_i \in R^{3\times 3}$, $M_i \in R^{3\times 3}$, $\forall i \in F$, such that

$$P(A+BK)+(A+BK)^TP \le -Q, \tag{15}$$

$$\begin{bmatrix} -Q+W & PBK \\ K^TB^TP & -M \end{bmatrix} \le 0, \tag{16}$$

$$P, Q, M_i, \quad W_i > 0, \tag{17}$$

where $M = blkdiag\{M_i\}_{i\in F}$, $W = blkdiag\{W_i\}_{i\in F}$, and each parameter β_i, $i \in F\backslash\{n\}$ in (10) satisfies

$$0 < \beta_i < \frac{\lambda_{\min}(W_i)}{\lambda_{\max}(M_i)}. \tag{18}$$

In addition, Zeno behavior will not occur in the transmissions.

Proof: For the system in (12) and (13), choose the Lyapunov candidate function $V(x(t)) = x^T(t)Px(t)$, for all $t > 0$ where $P > 0$. The derivative of $V(x(t))$ along the evolution of $x(t)$ is as below

$$\dot{V}(x(t)) = x^T(t)(PA+A^TP)x(t) + 2x(t)^TPBK\hat{x}(t_k). \tag{19}$$

Using (9), we can obtain that

$$\dot{V}(x(t)) = x^T(t)[P(A+BK)+(A+BK)^TP]x(t) - 2x^T(t)PBKe(t). \tag{20}$$

Using (15)-(17) and Lemma 1, we can have that

$$\begin{aligned}\dot{V}(x(t)) &\le -x^T(t)Qx(t) + x^T(t)PBKM^{-1}K^TB^TPx(t) \\ &\quad + e^T(t)Me(t) \\ &= -x^T(t)(Q - PBKM^{-1}K^TB^TP)x(t) \\ &\quad + e^T(t)Me(t) \\ &\le -x^T(t)Wx(t) + e^T(t)Me(t) \\ &\le -\sum_{i\in F}\lambda_{\min}(W_i)\|x_i\|^2 + \sum_{i\in F}\lambda_{\max}(M_i)\|e_i\|^2. \end{aligned} \tag{21}$$

According to the condition in (10), we can obtain that

$$\begin{aligned}\|e_i(t)\|^2 &\le \beta_i\left\|\hat{x}_i(t_k) - x_i(t) + x_i(t)\right\| + c_i \\ &\le \beta_i\|e_i(t)\| + \beta_i\|x_i(t)\| + c_i \end{aligned} \tag{22}$$

which gives the following

$$\|e_i(t)\| \le \left(\beta_i\|x_i(t)\| + \frac{\beta_i^2}{4} + c_i\right)^{\frac{1}{2}} + \frac{\beta_i}{2}. \tag{23}$$

Taking squares on both sides of (23), one has

$$\begin{aligned}&\|e_i(t)\|^2 \\ &\le \beta_i\|x_i(t)\| + \frac{\beta_i^2}{2} + c_i + \beta_i\left(\beta_i\|x_i(t)\| + \frac{\beta_i^2}{4} + c_i\right)^{\frac{1}{2}} \\ &\le \beta_i\|x_i(t)\| + \frac{\beta_i^2}{2} + c_i \\ &\quad + \beta_i\left(\frac{\beta_i^2}{\beta_i^2+4c_i}\|x_i(t)\|^2 + \beta_i\|x_i(t)\| + \frac{\beta_i^2}{4} + c_i\right)^{\frac{1}{2}} \\ &= \beta_i\|x_i(t)\| + \frac{\beta_i^2}{2} + c_i \\ &\quad + \beta_i\left(\sqrt{\frac{\beta_i^2}{\beta_i^2+4c_i}}\|x_i(t)\| + \sqrt{\frac{\beta_i^2+4c_i}{4}}\right) \\ &\le 2\beta_i\|x_i(t)\| + \sigma_i \end{aligned} \tag{24}$$

where $\sigma_i = c_i + \frac{\beta_i^2}{2} + \beta_i\sqrt{\frac{\beta_i^2+4c_i}{4}}$. It follows from (21) and (24) that

$$\begin{aligned}\dot{V}(x(t)) &\le -\sum_{i\in F}\lambda_{\min}(W_i)\|x_i\|^2 \\ &\quad + \sum_{i\in F}\lambda_{\max}(M_i)(2\beta_i\|x_i(t)\| + \sigma_i) \\ &\le \sum_{i\in F}[-\lambda_{\min}(W_i) + \beta_i\lambda_{\max}(M_i)]\|x_i\|^2 \\ &\quad + \sum_{i\in F}\lambda_{\max}(M_i)(\beta_i + \sigma_i). \end{aligned} \tag{25}$$

Define

$$\gamma = \min_{i\in F}[\lambda_{\min}(W_i) - \beta_i\lambda_{\max}(M_i)]. \tag{26}$$

One sees that $\gamma > 0$ by (18). It follows from (25) that

$$\begin{aligned}\dot{V}(x(t)) &\le -\gamma\sum_{i\in F}\|x_i\|^2 + \sum_{i\in F}\lambda_{\max}(M_i)(\beta_i+\sigma_i) \\ &\le -\frac{\gamma}{\lambda_{\max}(P)}V(x(t)) + \sum_{i\in F}\lambda_{\max}(M_i)(\beta_i+\sigma_i) \end{aligned} \tag{27}$$

where the second inequality is due to the definition of $V(x(t))$ and the Courant-Fischer's Theorem that

$$\lambda_{\min}(P)\sum_{i=1}^n\|x_i(t)\|^2 \le V(x(t)) \le \lambda_{\max}(P)\sum_{i=1}^n\|x_i(t)\|^2. \tag{28}$$

Using the Comparison Lemma (see [40]) to (27), one gets

$$\begin{aligned}V(x(t)) &\le V(x(0))e^{\frac{-\gamma t}{\lambda_{\max}(P)}} + \frac{1}{\gamma}\lambda_{\max}(P) \\ &\quad \times \sum_{i\in F}\lambda_{\max}(M_i)(\beta_i+\sigma_i)\left(1 - e^{\frac{-\gamma t}{\lambda_{\max}(P)}}\right) \end{aligned} \tag{29}$$

Combing (29) with the left-hand side of (28), we have

$$\begin{aligned}\|x(t)\| &= \sqrt{\sum_{i=1}^n\|x_i(t)\|^2} \\ &\le \sqrt{\frac{V(x(0))}{\lambda_{\min}(P)} + \frac{\lambda_{\max}(P)}{\gamma\lambda_{\min}(P)}\sum_{i\in F}\lambda_{\max}(M_i)(\beta_i+\sigma_i)} \equiv \kappa. \end{aligned} \tag{30}$$

That is, for all $t > 0$, $\|x(t)\|$ is upper bounded by a constant related to the initial state $\|x(0)\|$. Moreover, (29) implies that for all initial state values the state $x(t)$ will converge exponentially to the following set

$$\left\{x \in R^n : \|x\| \leq \sqrt{\frac{1}{\gamma} \sum_{i \in F} \lambda_{\max}(M_i)\,(\beta_i + \sigma_i)}\right\}. \tag{31}$$

Next, we show that Zeno behavior will not occur. For an arbitrary $i \in F\backslash\{n\}$, let t_1 and t_2 ($b_i[k] \leq t_1 < t_2 \leq b_i[k+1]$) be two adjacent time instants such that $\|e_i(t_1)\| = 0$ and $\|e_i(t_2)\| = 0$. Thus, $\|e_i(t)\| > 0$ for all $t \in (t_1, t_2)$, and

$$\frac{d}{dt}\|e_i\| = \frac{d}{dt}(e_i^T e_i)^{1/2} = \frac{e_i^T \dot{e}_i}{\|e_i\|} \leq \frac{\|e_i\|\,\|\dot{e}_i\|}{\|e_i\|} = \|\dot{e}_i\|. \tag{32}$$

Notice that $\hat{x}_i(t_k)$ is a constant for all $b_i[k] \leq t < b_i[k+1]$. It follows that

$$\dot{e}_i(t) = \dot{x}_i(t) = A_i x_i + B_i K_i \hat{x}_i - B_i K_{ci} \hat{x}_{i-1}, \quad \forall t \in [b_i[k], b_i[k+1]). \tag{33}$$

Combing (32), (33) with (12), (13), we obtain that $\forall t \in (t_1, t_2)$

$$\begin{aligned}\frac{d}{dt}\|e_i\| &\leq \|\dot{e}_i\| = \left\|A_i x_i + B_i K_i \hat{x}_i - B_i K_{ci} \hat{x}_{i-1}\right\| \\ &= \left\|A_i e_i + (A_i + B_i K_i)\hat{x}_i - B_i K_{ci} \hat{x}_{i-1}\right\| \\ &\leq \|A_i\|\,\|e_i\| + \|A_i + B_i K_i\|\,\left\|\hat{x}_i\right\| + \|B_i K_{ci}\|\,\left\|\hat{x}_{i-1}\right\|.\end{aligned} \tag{34}$$

By the Comparison Lemma and the fact that $e_i(t_1) = 0$, (34) gives that $\forall t \in (t_1, t_2) \subset [b_i[k], b_i[k+1])$

$$\begin{aligned}\|e_i(t)\| &\leq \|A_i\|^{-1}\left(\|A_i + B_i K_i\|\,\left\|\hat{x}_i\right\| + \|B_i K_{ci}\|\,\left\|\hat{x}_{i-1}\right\|\right)\left(e^{\|A_i\|(t-t_1)} - 1\right) \\ &\leq \rho_i \kappa \left(e^{\|A_i\|(b_i[k+1]-b_i[k])} - 1\right).\end{aligned} \tag{35}$$

where

$$\rho_i = \|A_i\|^{-1}\left(\|A_i + B_i K_i\| + \|B_i K_{ci}\|\right). \tag{36}$$

The above also holds for $t = b_i[k+1]^-$, i.e., the time instant just before $b_i[k+1]$. Since a new event is triggered at $b_i[k+1]$, it must hold that

$$\left\|e_i(b_i[k+1]^-)\right\| > \left(\beta_i \left\|\hat{x}_i(t_k)\right\| + c_i\right)^{1/2}.$$

Combining the above with (35) yields that

$$\left(\beta_i \left\|\hat{x}_i(t_k)\right\| + c\right)^{1/2} < \rho_i \kappa \left(e^{\|A_i\|(b_i[k+1]-b_i[k])} - 1\right) \tag{37}$$

which further implies that

$$b_i[k+1] - b_i[k] > \|A_i\|^{-1} \ln\left(\rho_i^{-1}\kappa^{-1}\sqrt{\beta_i \left\|\hat{x}_i(t_k)\right\| + c_i} + 1\right). \tag{38}$$

It is clear that the right-hand side of (38) is strictly positive. Therefore, Zeno behavior will not occur. This completes the proof.

Remark 3: Regarding the feasibility of the LMIs in Theorem 1, we would like to point out that if there exist positive definite matrices P and Q such that (15) holds, then there always exist positive definite matrices W_i and M_i, $\forall i \in F$ that satisfy (16). For example, for any positive constant number $\varepsilon \in (0, \lambda_{\min}(Q))$, the matrices $W_i = \varepsilon I_{3\times 3}$ and $M_i = (\|PNK\|_2^2)$ clearly satisfy (16).

Remark 4: As every β_i decreases, the exponential convergence rate γ of the overall tracking error $\|x(t)\|$ increases (see (26) and (29)), and meanwhile the ultimate bound of the tracking error state decreases (see (31)). That is, faster tracking speed and better tracking accuracy can be achieved by using a smaller β_i. In addition, smaller β_i and c_i (and thus smaller σ_i) imply a smaller bound for $\|x(t)\|$ for all $t > 0$ as seen from (30). Hence, inter-vehicle collision can be avoided when (30) is made smaller than the desired spacing distance δ_d starting with a small initial tracking error $\|x(0)\|$. However, the decreases of β_i and c_i will also reduce the lower bounds of inter-event times as seen from (38). Hence, there exists a trade-off between improving tracking performances and reducing the utilization of communication resources.

Remark 5: Note that the triggering thresholds on the right-hand side of (10) are state-dependent. Thus each vehicle's inter-event time intervals can vary differently along with the tracking errors compared with state-independent thresholds ([33], [34], [38]) which have a fixed minimum inter-event time interval. State-dependent thresholds are also used for platoon control of discrete-time vehicular systems in [36], [37]. However, Zeno-freeness is ensured purely by the boundedness of the sampling time period, and the transmission intervals are likely to reduce to the periodic sampling period in the presence of state disturbances.

In the literature, the following form of event-triggering conditions (ETC) is frequently used (e.g., see [31], [32])

$$\|e_i(t)\|^2 \leq \alpha_i \left\|\hat{x}_i(t_k)\right\|^2 + d_i, \tag{39}$$

where α_i and d_i are positive constants. Note that in (39) the orders of $\|e_i(t)\|$ and $\left\|\hat{x}_i(t_k)\right\|$ are equal while in (10) their orders are different. In the following, the event-triggering condition in (39) is called E-ETC while that in (10) is called F-ETC for short. Before comparing their performances, we present the following result for the system (12)-(13) under (39).

Proposition 1: For any initial state $x(0)$, the state of the error system in (12)-(13) with event-triggered communication by violating (39) is bounded if there exist positive definite matrices P, Q and W_i, M_i, $\forall i \in F$, such that (15)–(17) are satisfied and each parameter α_i, $i \in F\backslash\{n\}$ in (39) satisfies

$$\begin{cases}2\alpha_i(1+\sqrt{\alpha_i})^2/(1-\alpha_i)^2 < \lambda_{\min}(W_i)/\lambda_{\max}(M_i) \\ 0 < \alpha_i < 1.\end{cases} \tag{40}$$

In addition, Zeno behavior will not occur.

Proof: Since $\left\|\hat{x}_i(t_k)\right\|^2 = \|x_i(t) - e_i(t)\|^2 \leq (\|x_i(t)\| + \|e_i(t)\|)^2$, one can obtain from (39) that

$$(1-\alpha_i)\|e_i(t)\|^2 - 2\alpha_i\|x_i(t)\|\,\|e_i(t)\| - \alpha_i\|x_i(t)\|^2 - d_i \leq 0.$$

Solving the above quadratic inequality about $\|e_i(t)\|$ and using $0 < \alpha_i < 1$, one can have

$$\|e_i(t)\| \le \frac{1}{1-\alpha_i}\left(\alpha_i \|x_i(t)\| + \left(\alpha_i \|x_i(t)\|^2 + (1-\alpha_i)d_i\right)^{\frac{1}{2}}\right) \le \frac{1}{1-\alpha_i}\left(\alpha_i \|x_i(t)\| + \sqrt{\alpha_i}\,\|x_i(t)\| + \sqrt{(1-\alpha_i)d_i}\right).$$

Taking squares on both sides of the above yields that

$$\begin{aligned}\|e_i(t)\|^2 &\le \frac{1}{(1-\alpha_i)^2}\Big[(\alpha_i+\sqrt{\alpha_i})^2\|x_i(t)\|^2 + (1-\alpha_i)d_i \\ &\quad + 2(\alpha_i+\sqrt{\alpha_i})\|x_i(t)\|\sqrt{(1-\alpha_i)d_i}\Big] \\ &\le \frac{1}{(1-\alpha_i)^2}\Big[2(\alpha_i+\sqrt{\alpha_i})^2\|x_i(t)\|^2 + 2(1-\alpha_i)d_i\Big] \\ &= \frac{2\alpha_i(1+\sqrt{\alpha_i})^2}{(1-\alpha_i)^2}\|x_i(t)\|^2 + \frac{2d_i}{1-\alpha_i}.\end{aligned}$$

Plugging the above into the last inequality of (21), one gets

$$\dot V(x(t)) \le -\sum_{i\in F}\left(\lambda_{\min}(W_i) - \frac{2\alpha_i(1+\sqrt{\alpha_i})^2}{(1-\alpha_i)^2}\lambda_{\max}(M_i)\right)\|x_i\|^2 + \sum_{i\in F}\lambda_{\max}(M_i)\frac{2d_i}{1-\alpha_i}. \tag{41}$$

Note that

$$\gamma_1 = \min_{i\in F}[\lambda_{\min}(W_i) - 2\alpha_i(1+\sqrt{\alpha_i})^2 \big/ (1-\alpha_i)^2\lambda_{\max}(M_i)]$$

is positive according to the first inequality in (40). Then, following similar proof procedures as that in the proof of Theorem 1, one can show that $x(t)$ is bounded and will ultimately converge to the following set

$$\left\{x \in R^n : \|x\| \le \sqrt{\frac{1}{\gamma_1}\sum_{i\in F}\lambda_{\max}(M_i)\frac{2d_i}{1-\alpha_i}}\right\}. \tag{42}$$

In addition, the lower bound of inter-event times under (39) is given as follows

$$b_i[k+1] - b_i[k] > \|A_i\|^{-1}\ln\left(\rho_i^{-1}\kappa_1^{-1}\sqrt{\alpha_i\left\|\hat x_i(t_k)\right\|^2 + d_i} + 1\right) \tag{43}$$

where $\kappa_1 = \sqrt{\frac{V(x(0))}{\lambda_{\min}(P)} + \frac{\lambda_{\max}(P)}{\gamma_1\lambda_{\min}(P)}\sum_{i\in F}\lambda_{\max}(M_i)\frac{2d_i}{1-\alpha_i}}$, and ρ_i is defined in (36). Since the right-hand side of (43) is strictly positive, Zeno behavior will not occur. This completes the proof.

Remark 6: For the E-ETC in (39) and the F-ETC in (10), we would like to compare their effects on the performances of the control system (12)-(13). Firstly, as observed from (25) and (41), the least convergence rates of the control system under the two event-triggering conditions are equal when $\beta_i = 2\alpha_i(1+\sqrt{\alpha_i})^2/(1-\alpha_i)^2$, or equivalently, when

$$\alpha_i = \beta_i \Big/ \left(\sqrt{2} + \sqrt{\beta_i}\right)^2 \tag{44}$$

for all $i \in F\backslash\{n\}$. Secondly, the ultimate bound in (42) is equal to that in (31) if (44) is satisfied and

$$d_i = (\beta_i + \sigma_i)(1-\alpha_i)\big/2, \quad \forall i \in F\backslash\{n\}. \tag{45}$$

Therefore, the F-ETC in (10) and the E-ETC in (39) can result in comparable convergence performances for the system states. At last, we compare the minimum inter-event times resulted by these two event-triggering conditions under equivalent control performances. Note that $\gamma_1 = \gamma$ and $\kappa_1 = \kappa$ under (44) and (45). It follows that the lower bound in (38) will be larger than that in (43) when $\beta_i\left\|\hat x_i(t_k)\right\| + c_i > \alpha_i\left\|\hat x_i(t_k)\right\|^2 + d_i$, or equivalently when $\left\|\hat x_i(t_k)\right\| < \left(\beta_i + \sqrt{\beta_i^2 + 2\alpha_i(c_i - d_i)}\right)\Big/2\alpha_i$ which will become $\left\|\hat x_i(t_k)\right\| < 1 + \sqrt{1 + c_i/\beta_i}$ for a small enough β_i (Recall in Remark 4 that a smaller β_i implies faster tracking rate and better tracking accuracy). Note that the value of $1 + \sqrt{1 + c_i/\beta_i}$ can quite large when β_i is smaller than c_i. On the other hand, when $\left\|\hat x_i(t_k)\right\|$ is sufficiently large the lower bound in (38) will be smaller than that in (43). Thus, the new event-triggering condition in (10) is superior in scenarios where the tracking errors are kept small. This observation will be demonstrated by simulation examples in the sequel.

IV. DECENTRALIZED DESIGN OF CONTROL GAINS

The last section presents the sufficient conditions in (15)-(17) to solve the control gain matrices of all following vehicles. However, since the control gain matrix K defined in (14) is not block diagonal, the computation complexity of solving these inequalities will increase geometrically as the number of vehicles in the platoon increases. To tackle this problem, we present in the following theorem a method modified from [27] such that (15) and (17) can be solved in a decentralized manner.

Theorem 2: The state of the error system in (12)-(13) with event-triggered communication by violating (10) is bounded if there exist matrices $P_i \in R^{3\times3}$, $Q_i \in R^{3\times3}$, and $W_i \in R^{3\times3}$ for all $i \in F$ such that the following matrix inequalities are solved for some given positive constants μ and η:

$$P_1(A_1 + B_1K_1) + (A_1 + B_1K_1)^T P_1 + Q_1 \le 0, \tag{46}$$

$$\begin{bmatrix} -Q_1 + \mu I_{3\times3} + W_1 & P_1B_1K_1 \\ (P_1B_1K_1)^T & -\eta I_{3\times3}\end{bmatrix} \le 0, \tag{47}$$

and $\forall i \in F\backslash\{1\}$,

$$\begin{bmatrix} -\mu I_{3\times3} & -(P_iB_iK_{ci})^T \\ -P_iB_iK_{ci} & P_i(A_i + B_iK_i) + (A_i + B_iK_i)^T P_i + Q_i\end{bmatrix} \le 0, \tag{48}$$

$$\begin{bmatrix} -Q_i + \mu I_{3\times3} + W_i & -P_iB_iK_{ci} & P_iB_iK_i \\ -(P_iB_iK_{ci})^T & -\eta I_{3\times3} & 0 \\ (P_iB_iK_i)^T & 0 & -\eta I_{3\times3}\end{bmatrix} \le 0, \tag{49}$$

$$Q_i > \mu I_{3\times3}, \quad P_i > 0, \ W_i > 0, \tag{50}$$

and each parameter β_i in (10) satisfies

$$0 < \beta_i < \frac{\lambda_{\min}(W_i)}{\eta}, \quad i \in F\backslash\{n\}. \tag{51}$$

Proof: Expanding matrices in (46) and (48) into $3(n-1)\times 3(n-1)$ dimensions by appropriately adding zeros, and summing up both sides of the expanded matrix inequalities, one can get (15) with

$$P = blkdiag\{P_i\}_{i\in F},\ Q = blkdiag\{Q_i - \mu I_{3\times 3}\}_{i\in F}. \quad (52)$$

Similarly, the matrix inequality (16) can be derived from (47) and (49) with

$$\begin{aligned} W &= blkdiag\{W_i\}_{i\in F}, \\ M &= blkdiag\{2\eta I_{3\times 3}, \ldots, 2\eta I_{3\times 3}, \eta I_{3\times 3}\}. \end{aligned}$$

Further considering (50) and (51), we see that the conditions (15)-(18) in Theorem 1 are all satisfied. This completes the proof.

Note that the conditions in (46)-(51) can be solved in a decentralized manner by each agent. However, the matrix inequalities (46)-(49) are nonlinear in the variables P_i, K_{ci} and K_i. Hence, in the following theorem, we further convert these matrix inequalities into linear matrix inequalities so that the control gains can be solved efficiently.

Theorem 3: The matrix inequalities in (46)-(50) are solvable if for all $i \in F$ there exist real matrices $P_i = \begin{bmatrix} P_{i1} \in R^{2\times 2} & \\ & P_{i2} \in R \end{bmatrix}$, $Q_i \in R^{3\times 3}$, $W_i \in R^{3\times 3}$, $\Phi_i \in R^{1\times 3}$, and $\Phi_{ci} \in R^{1\times 3}$ such that

$$P_1A_1 + B_1\Phi_1 + (P_1A_1 + B_1\Phi_1)^T + Q_1 \leq 0, \quad (53)$$

$$\begin{bmatrix} -Q_1 + \mu I_{3\times 3} + W_1 & B_1\Phi_1 \\ (B_1\Phi_1)^T & -\eta I_{3\times 3} \end{bmatrix} \leq 0, \quad (54)$$

and $\forall i \in F\backslash\{1\}$,

$$\begin{bmatrix} -\mu I_{3\times 3} & -(B_i\Phi_{ci})^T \\ -B_i\Phi_{ci} & P_iA_i + B_i\Phi_i + (P_iA_i + B_i\Phi_i)^T + Q_i \end{bmatrix} \leq 0, \quad (55)$$

$$\begin{bmatrix} -Q_i + \mu I + W_i & -B_i\Phi_{ci} & B_i\Phi_i \\ -(B_i\Phi_{ci})^T & -\eta I_{3\times 3} & 0 \\ (B_i\Phi_i)^T & 0 & -\eta I_{3\times 3} \end{bmatrix} \leq 0, \quad (56)$$

$$Q_i > \mu I_{3\times 3}, \quad P_i > 0, \ W_i > 0. \quad (57)$$

Furthermore, the control gains are given by

$$K_i = P_{i2}^{-1}\Phi_i, \quad K_{ci} = P_{i2}^{-1}\Phi_{ci}, \ \forall i \in F. \quad (58)$$

Proof: Note the following equalities:

$$P_iB_i = \begin{bmatrix} P_{i1} & \\ & P_{i2} \end{bmatrix} \begin{bmatrix} 0 \\ -\frac{1}{\varsigma_i} \end{bmatrix} = \begin{bmatrix} 0 \\ -\frac{1}{\varsigma_i} \end{bmatrix} P_{i2} = B_iP_{i2}. \quad (59)$$

It follows that

$$P_iB_iK_i = B_iP_{i2}K_i = B_i\Phi_i \quad (60)$$

and

$$P_iB_iK_{ci} = B_iP_{i2}K_{ci} = B_i\Phi_{ci}. \quad (61)$$

With the above equivalent quantities, the matrix inequalities (53)-(57) imply (46)-(50) respectively. This completes the proof.

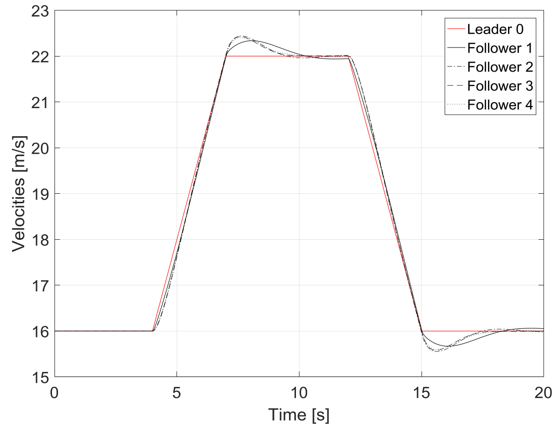

FIGURE 3. Velocities of all vehicles under the F-ETC in (10).

V. NUMERICAL SIMULATIONS

In this section, we conduct simulations to illustrate the effectiveness of the cooperative platoon control method under the proposed event-triggered communication strategy and the designed controllers. In the simulations, the platoon consists of five vehicles including one virtual leading vehicle 0 and four following vehicles with time constants being $\varsigma_i = 0.2$ for $i = 1, 4$ and $\varsigma_i = 0.25$ for $i = 2, 3$. The initial and desired spacing between any two neighboring vehicles is set as $\delta_d = 10m$. The initial speeds are $16m/s$ for all vehicles, and their initial accelerations are all zero.

Setting $\mu = 0.016$ and $\eta = 0.46$ in (54)-(57) of Theorem 3, we can derive the values of the matrices P_i, W_i, Φ_i, and Φ_{ci} for $i = 1, \ldots, 4$ by using LMI solvers in MATLAB. The derived values are omitted for simplicity of presentation. The control gains of the follower vehicles are derived according to (58) and given as $K_1 = [-4.2, -4, -3]$, $K_i = [-3.3892, -3.47, -1.5]$, $K_{ci} = [0, -3.99, -0.6]$ for i =2,3, and $K_4 = [-3.38, -3.48, -1.5] K_{c4} = [0, -4, -0.6]$.

We have also obtained that $\lambda_{\min}(W_1) = 0.0098$, $\lambda_{\min}(W_2) = \lambda_{\min}(W_3) = 0.0037$, which give the values of $\lambda_{\min}(W_i)/\eta$ in (51) as 0.0213, 0.008, 0.008 for i =1,2,3. We set $\beta_1 = 1.06\times 10^{-6}$, $\beta_2 = \beta_3 = 1.04\times 10^{-6}$, which all satisfy (51), and we choose $c_i = 1\times 10^{-4}$ for all $i = 1, 2, 3$, so that the bound in (30) is $\kappa = 1.1574 < \delta_d = 10$. These parameters ensure that the spacing between any two successive vehicles will be larger than $\delta_d - \kappa = 8.8426$ all the time, i.e., no collision will occur among the vehicles.

Simulations have been conducted for a scenario as shown in Fig. 3, where the leading vehicle's speed is 16m/s initially, and then increases to 22m/s during time interval 4s − 7s. It decelerates to 16m/s during time 12s − 15s, and maintains at this speed afterward. Simulation results in Fig. 3 and Fig. 4 show that all the following vehicles' velocities and accelerations can effectively track those of the leading vehicle. Moreover, Fig. 5 shows that each vehicle's spacing error with respect to the leader is kept in a relatively small level.

The simulation period is set to be 0.1ms, which is a practically realizable time period for vehicle-to-vehicle communications (e.g., using DSRC that supports high data rates

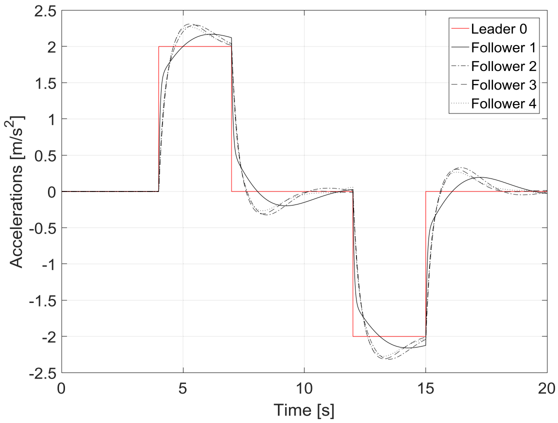

FIGURE 4. Accelerations of all vehicles under the F-ETC in (10).

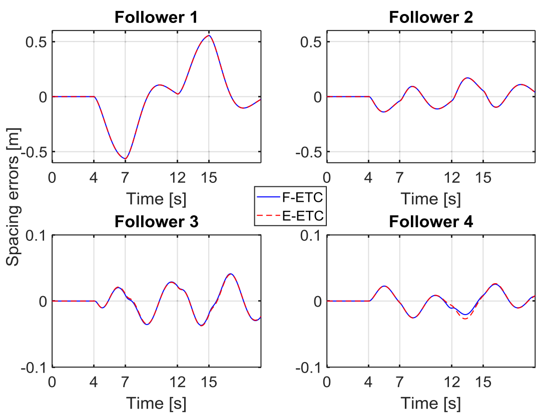

FIGURE 5. The spacing errors with respect to the leader under the F-ETC in (10) and E-ETC in (39).

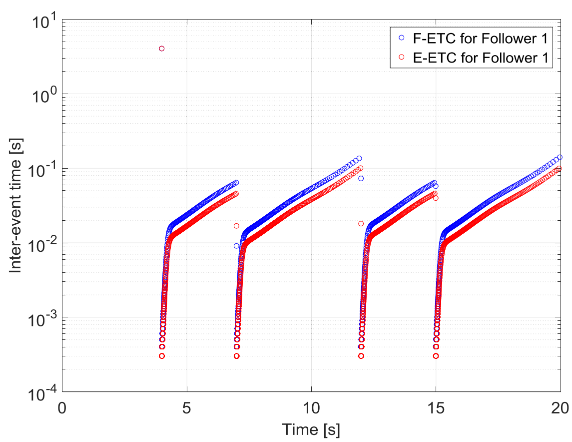

FIGURE 6. The inter-event times of follower vehicle 1 under the F-ETC in (10) (blue circles) and the E-ETC in (39) (red circles).

up to 12Mbps [5]). Under the event-triggering condition in (10), the inter-event times of data transmissions for the vehicles 1 to 3 are larger than the simulation period as shown by the blue circles in Fig. 6 to Fig. 8, respectively. Hence, Zeno behavior didn't occur. In addition, the number of triggered transmissions of the vehicles 1 to 3 are counted as 1089, 1227 and 1179, respectively, which are greatly smaller than the total number of 2×10^5 simulation periods.

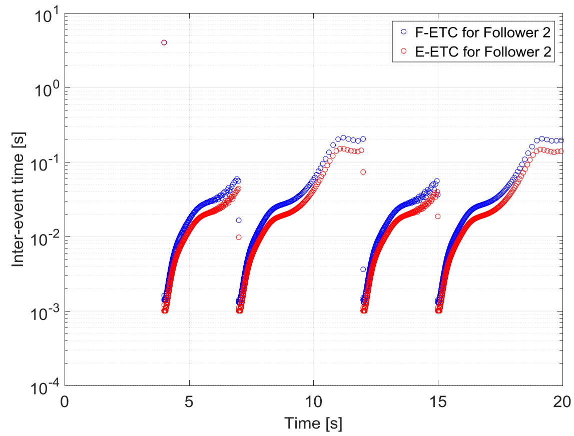

FIGURE 7. The inter-event times of follower vehicle 2 under the F-ETC in (10) (blue circles) and the E-ETC in (39) (red circles).

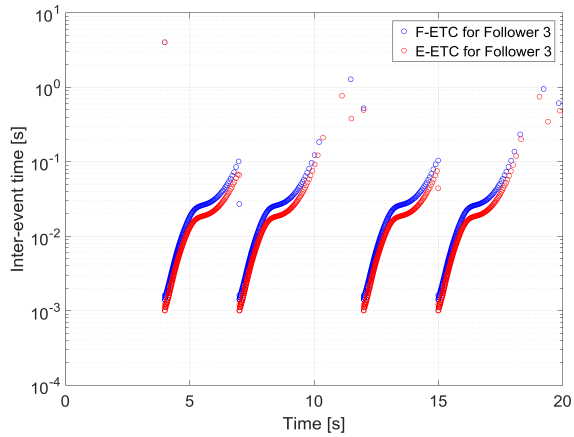

FIGURE 8. The inter-event times of follower vehicle 3 under the F-ETC in (10) (blue circles) and the E-ETC in (39) (red circles).

Therefore, substantial savings of communication resources were achieved by using the F-ETC in (10). Moreover, the minimum inter-event times of the following vehicles 1 to 3 are observed as 0.4ms, 1.3ms, 1.4ms, respectively in the simulation results, which are all larger than the lower bounds computed according to (38) (which are 0.31ms, 0.26ms, 0.23ms for vehicles 1 to 3, respectively).

We also conducted simulations for the platoon system under the event-triggering condition in (39). According to (44) and (45), we set $\alpha_1 = 5.3 \times 10^{-7}, \alpha_2 = \alpha_3 = 5.2 \times 10^{-7}$, and $d_1 = 5.0536 \times 10^{-5}$, $d_2 = d_3 = 5.0526 \times 10^{-5}$, so that the least converging rate and the ultimate bound of the vehicles' tracking errors are equivalent to those under F-ETC. Simulation results in Fig. 5 show that the tracking performances under both triggering conditions can be hardly distinguished. However, the F-ETC has larger inter-event times than the E-ETC as shown in Fig. 6 to Fig. 8. This is because $\|\hat{x}_i(t_k)\| \leq \kappa < \left(\beta_i + \sqrt{\beta_i^2 + 2\alpha_i(c_i - d_i)}\right) \Big/ 2\alpha_i$ ($\kappa = 1.1574$ while the values of the rightmost formula are 10.74, 10.83, 10.83, for $i = 1, 2, 3$). These simulation results validate the advantages of the new ETC as stated in Remark 6.

VI. CONCLUSIONS

This paper has proposed a distributed event-triggered communication strategy (ETCS) for cooperative platoon control of heterogeneous vehicles. To reduce data transmissions, each following vehicle except the last one transmits its tracking error with respect to the leader to its direct successor only when its own information updating error exceeds a threshold which is sum of a state-dependent term and a constant. It is proved that the proposed ETCS doesn't exhibit Zeno behavior. The control gains of all vehicles are designed by applying a decentralized method. Numerical simulations have shown the effectiveness of the proposed method and the applicable scenarios of the proposed ETCS. The simulation results also motivate us to combine the ETCS with that in (39) so as to further reduce the number of triggered events in different situations.

This paper has focused on reducing data transmissions for the vehicles while ignored other communication imperfections such as communication delays and the media access capacities of communication channels which are important factors that can affect control performances [17], [19]. For realistic applications of the proposed ETCS in platoon control, it is interesting to conduct further investigations under these communication imperfections. In addition, string stability (i.e., the property of attenuating disturbances along the vehicle string) is also an important issue for vehicular platoon control [11], [39]. Under the ETCS proposed in this paper, although a rigorous mathematical proof for string stability is hard to give, we observed this property in simulation studies by imposing extra constraints used in [36] on the existing control gains. Inspired by these observations, controllers with guaranteed string stability will be designed in the future.

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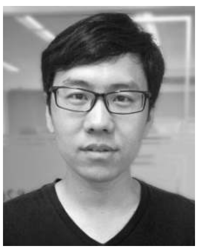

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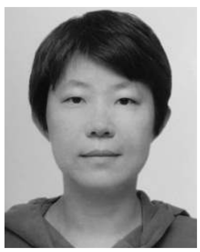

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