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Event-triggered Scheduling for Infrastructure-supported Collaborative Vehicle Control ⋆

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Abstract: This paper investigates the design of event-triggered scheduling and medium access control for the real-time coordination of multiple vehicles through an infrastructure node. The key motivation of our proposed event-triggered mechanism is to concurrently address safety aspects of the vehicle control and the efficient usage of network resources of the vehicle-to-infrastructure (V2I) protocol. While the real-time guarantees needed for safety are achieved by a novel coordination scheme in the medium access layer, the event-triggered mechanism improves the real-time performance of the control task. The coordination scheme enabled through the topology of the V2I network limits the number of successive data dropouts and we prove stability of the estimator at the infrastructure that monitors the state of the vehicle group. Numerical studies on a platooning case study validate our theoretical results.

Keywords: Networked Control, Event-triggered Scheduling, Vehicle-to-Infrastructure Communications, Medium Access Control, Platooning

1. INTRODUCTION

In this paper, we envision a scenario where multiple autonomous vehicles are controlled through the infrastructure that coordinates their collective behavior by fusing the available sensor information of each vehicle illustrated in Fig. 1 for 3 vehicles. Typical application areas include the coordination of traffic at intersections and autonomous parking lot management. Our study will mainly focus on aspects of vehicle-to-infrastructure communications (V2I) that enable real-time guarantees while providing an efficient usage of network resources for contention-based carrier sense multiple access (CSMA) over the wireless medium. Prioritizing data packets based on their content will help us to ensure delivery of important packets with shorter latencies while filtering out redundant messages from the network. The idea of content-based prioritization is realized by an event-triggered mechanism in the vehicle-to-infrastructure link, while the infrastructure sends messages periodically. Each vehicle determines the importance of providing its information to the infrastructure. If the obtained value exceeds a threshold, it will request to transmit the information to the infrastructure. In order to resolve contention among concurrent requests, the medium access is coordinated by the infrastructure that assigns priorities in a predefined periodic fashion. In this way, we are capable to retain real-time properties for our strategy similarly as for time-triggered contention-free schemes, while still having the benefits of event-triggered medium access in terms of efficiency and average latency.

There exist several works that give suggestions on the implementation of state-based scheduling algorithms in wireless networks. The work in Christmann et al. (2014) develops an implementation of the Try-Once-Discard protocol (TOD) proposed by Walsh et al. (1999), for wireless networked control systems. The methodology is based on the arbitration phase in the CAN bus., while the work in Mamduhi et al. (2014) suggests a randomized version of TOD. By considering an event-triggered architecture similar to ours, Muehlebach and Trimpe (2015) propose an LMI-based synthesis approach.

The MAC layer of our V2I scheme is related the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) Quality of Service (QoS) extension, also found in Vehicular Ad Hoc Networks, Bilstrup et al. (2008). As EDCA is not capable for providing real-time guarantees, we give a modified version that has some parallels to Barradi et al. (2010). Moreover, initial ideas on event-triggered beaconing for position tracking in vehicular environments are proposed in Rezaei et al. (2010).

While our work targets the interaction of control and communications at the level of the medium access control (MAC) layer, there also exist approaches, such as in Gatsis et al. (2014) and Gatsis et al. (2015), that focuses on the synthesis of networked controllers at the physical layer of the communication protocol. In this work, we however do not consider effects arising from imperfections at the physical layer.

The salient feature of our proposed MAC protocol is its bound on the number of successive data dropouts depending on the number of vehicles and contention-free slots available. This makes the method attractive also for other

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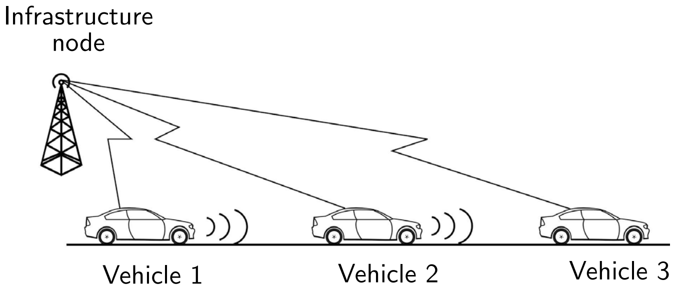

Fig. 1. Illustration of the evisioned infrastructure-supported collaborative vehicle coordination.

event-triggered controllers that impose a constraint on the maximum allowable number of successive dropouts, e.g. see Wang and Lemmon (2011) and Dolk and Heemels (2015).

The contributions of this paper can be summarized as follows. First, we propose a novel data scheduling scheme for distributed linear quadratic control systems based on event-triggered medium access with centrally coordinated prioritization. While the event-triggering mechanism considers the discrepancy between locally and remotely state estimations, the priority assignment scheme coordinated by the infrastructure node yields a time-varying periodic pattern. Second, we investigate the real-time guarantees of our approach. By relating our event-triggered scheme to a time-triggered scheduling strategy, we are able to give bounds on the worst-case transmission latency and show boundedness of the mean square error of the global state estimate at the infrastructure node. The latter makes use of results of our recent work in Molin et al. (2015b). Third, we give a design guideline that allows an implementation of our proposed scheme in the wireless MAC layer which only needs slight modification of existing protocols that are based on IEEE 802.11 with Quality-of-Service (QoS) capabilities. Finally, we demonstrate our method numerically on a infrastructure-supported vehicle platooning task.

The system model is introduced in Sec. 2, while its real-time properties are analyzed in Sec. 3. Sec. 4 gives a guideline for the implementation of the transmission scheme and Sec. 5 evaluates the obtained results on a numerical case study.

2. SYSTEM MODEL

2.1 Dynamical system

For the sake of generality, we introduce the system model in its most generic form while it will be specialized to the collaborative vehicle control setting in further sections. We consider a linear discrete-time system

$$x_{k+1} = Ax_k + Bu_k + w_k \tag{1}$$

with (A, B) being controllable and A invertible – the latter is satisfied for most sampled-data systems due to the properties of the matrix exponential,

$$x_k \in \mathbb{R}^n,\ u_k \in \mathbb{R}^p,\ A \in \mathbb{R}^{n\times n},\ B \in \mathbb{R}^{n\times p}$$
$$x_0 \sim \mathcal{N}(0, R_0), \quad R_0 \in \mathbb{R}^{n\times n}, R_0 > 0$$
$$w_k \sim \mathcal{N}(0, R_w), \quad R_w \in \mathbb{R}^{n\times n}, R_w > 0.$$

Assuming M agents, each agent $j \in \mathcal{M} = \{1, \dots, M\}$ takes measurements y_k^j,

$$y_k^j = C^j x_k + v_k^j \tag{2}$$

with $(A, [C_k^{1\mathsf{T}}, \dots, C_k^{M\mathsf{T}}]^\mathsf{T})$ being observable and

$$y_k^j \in \mathbb{R}^{m_j},\ C^j \in \mathbb{R}^{m_j\times n}$$
$$v_k^j \sim \mathcal{N}(0, R_v^j), \quad R_v^j \in \mathbb{R}^{m_j\times m_j}, R_v^j > 0.$$

The control input u_k is composed of $u_k = [u_k^{1\mathsf{T}}, \dots, u_k^{M\mathsf{T}}]^\mathsf{T}$ with $u_k^j \in \mathbb{R}^{p_j}$ being the control input at agent j. The control law is given by

$$u_k = -L\hat{x}_{k|k-1} \tag{3}$$

with stabilizing gain L, i.e., $A - BL$ being Hurwitz, and $\hat{x}_{k|k-1}$ being the state estimate at the infrastructure node that is broadcasted to each agent at the beginning of each sampling period. Furthermore, we assume that there are $N_\mathrm{T} \le M$ slots available within the sampling period, in which agents can transmit data to the infrastructure node.

2.2 Local filtering

In this section, we define the local filtering structure in each sensor node. It is not presumed that the state can be fully recovered at one sensor node by its local measurements, i.e., (A, C^j) is not observable in general. Similar as in Battistelli et al. (2012), we aim at a representation in which a sensor node focuses on the estimation of its observable subspace of the state x_k. For time-invariant linear systems, it is well known, e.g., Antsaklis and Michel (2006), that there exists a non-singular state transformation T^j that separates the state space into an observable and unobservable subspace, such that

$$(T^j)^{-1}AT^j = \begin{bmatrix} A_1^j & 0 \\ A_{21}^j & A_2^j \end{bmatrix}, \quad C^jT^j = \begin{bmatrix} C_1^j & 0 \end{bmatrix}$$
$$T^j = \begin{bmatrix} T_1^j & T_2^j \end{bmatrix}, \quad (T^j)^{-1} = \begin{bmatrix} D_1^j \\ D_2^j \end{bmatrix}$$

with (A_1^j, C_1^j) being observable. Let n_o^j be the dimension of the observable subspace of agent j. Then, the local filter at agent j estimates the state $x_k^j = D_1^j x_k \in \mathbb{R}^{n_o^j}$ of the subsystem evolving by

$$\begin{aligned} x_{k+1}^j &= A_1^j x_k^j + D_1^j w_k \\ y_k^j &= C_1^j x_{k+1}^j + v_k^j. \end{aligned} \tag{4}$$

The minimum mean square error (MMSE) estimator $\hat{x}_{k|k}^j$ of x_k^j is given by the Kalman filter

$$\hat{x}_{k|k}^j = \hat{x}_{k|k-1}^j + K_k^j(y_k^j - C_1^j\hat{x}_{k|k-1}^j) \tag{5a}$$
$$P_{k|k}^j = (I_{n_o^j} - K_k^jC_1^j)P_{k|k-1}^j \tag{5b}$$
$$\hat{x}_{k+1|k}^j = A_1^j\hat{x}_{k|k}^j + D_1^jBu_k \tag{5c}$$
$$P_{k+1|k}^j = A_1^jP_{k|k}^j(A_1^j)^\mathsf{T} + D_1^jR_w(D_1^j)^\mathsf{T} \tag{5d}$$

where $K_k^j = P_{k|k-1}^j(C_k^j)^\mathsf{T}(C_1^jP_{k|k-1}^j(C_1^j)^\mathsf{T} + R_v^j)^{-1}$ and $\hat{x}_{0|-1}^j = 0$, $P_{0|-1}^j = D_1^jR_0(D_1^j)^\mathsf{T}$. I_n denotes the identity matrix in $\mathbb{R}^n$. As the state estimate $\hat{x}_{k|k-1}$ is broadcasted to all agents, u_k is available at each agent.

At the infrastructure node, there runs an estimator that predicts $\hat{x}_{k|k}^j$, which is implemented by the recursion

$$\tilde{x}_{k|k}^j = \begin{cases} \hat{x}_{k|k}^j & \text{data sent from agent } j \\ \tilde{A}_1^j\tilde{x}_{k|k}^j + D_1^jBu_k & \text{otherwise} \end{cases} \tag{6}$$