On the resilience of Autonomous Connected Vehicles Platoon Under DoS Attacks: a predictor-based sampled data control.

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PROBLEM STATEMENT AND CONTROL GOAL

Consider a group of N autonomous connected vehicles sharing their state information through a not reliable vehicular ad hoc networks, whose communication topology is modeled via a direct graph $\mathcal{G}_N$.

Vehicle Dynamics

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t-\mu_i(t)), \quad i = 1,\dots,N,$$

$$x_i(t) = [p_i(t),\ v_i(t),\ a_i(t)]^\top$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{T} \end{bmatrix} \quad B = [0\ 0\ 1/T]^\top$$

$T\ [s]$: powertrain time constant

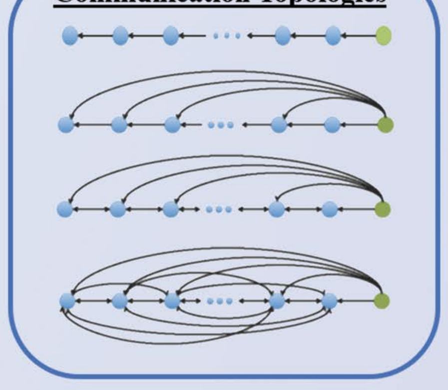
$\mu_i(t)$ s.t. $0 \le \mu_i(t) < \mu^\star, \forall i$
Accounting for **computation and processing latencies** required to actuate the vehicle.

Leader Dynamics

$$x_0(t) = Ax_0(t)$$

$$x_0(t) = [p_0(t),\ v_0(t),\ a_0(t)]^\top$$

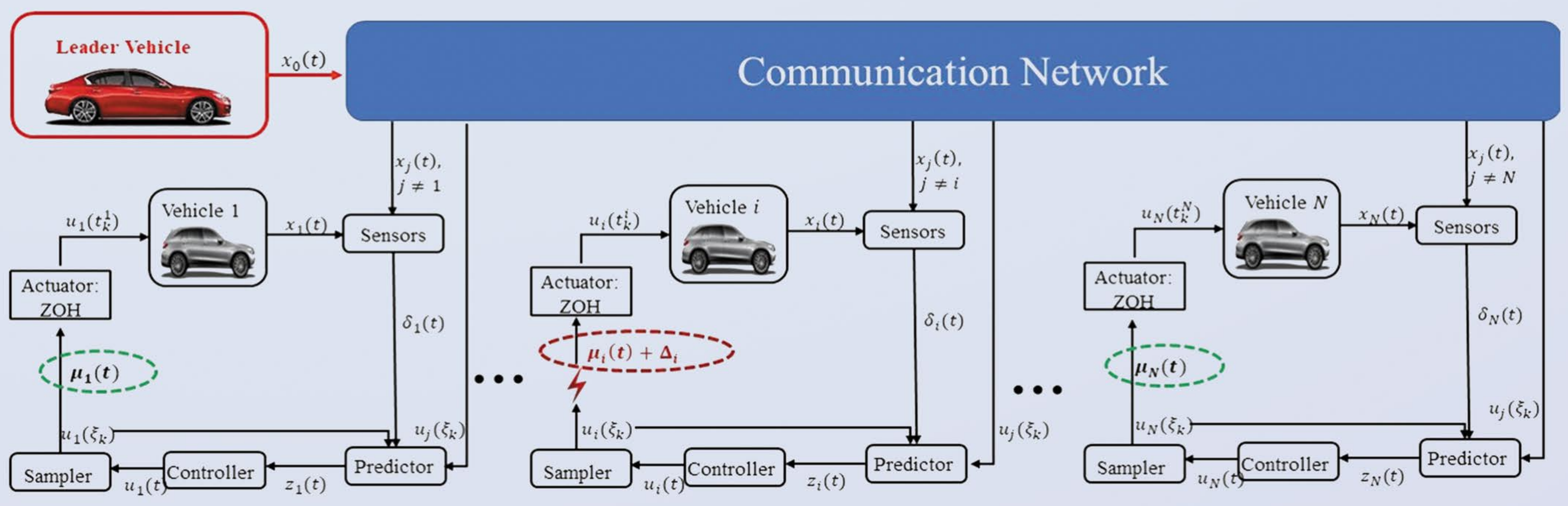
Communication Topologies



- A digital implementation of the distributed controller is considered: for each vehicle, the onboard sensors can continuously measure its state $x_i(t)$, while the control input $u_i(t)$ is sampled at $\xi_k, k \in \mathbb{N}_0, \xi_{k+1} - \xi_k = h$, with $h > 0$.
- A not-reliable communication network from controller-to-actuator is considered: besides processing delay $\mu_i(t)$, a DoS attack can corrupt the controller-to actuator channel. In this case the updating instant of the corresponding actuator satisfies

$$t_k^i = \xi_k + D_i, \qquad D_i = \mu^\star + \Delta_i \ \rightsquigarrow \text{large delay}$$

The objective is to design a distributed resilient sampled-data controller able to solve the platooning formation control problem despite the occurrence of both controller-to-actuator DoS attacks and communication delays.



Control goal

$$\lim_{t\to\infty} \|p_i(t) - p_0(t) - d_{i0}\| = 0,$$

$$\lim_{t\to\infty} \|v_i(t) - v_0(t)\| = 0,$$

$$\lim_{t\to\infty} \|a_i(t) - a_0(t)\| = 0,$$

where d_{i0} $[m]$ is the desired inter-vehicle distance between vehicle i and the leader indexed with 0.

Vehicle Dynamics Under DoS Attack

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(\xi_k),$$

$$t \in [t_k^i, t_{k+1}^i),\ k \in \mathbb{N}_0.$$

The time interval is paralyzing for the i-th vehicle.

CONTROL DESIGN

The distributed sampled-data predictor-based controller is designed as:

$$u_i(t) = Kz_i(t)$$

$$z_i(t) = e^{AD_i}\psi_i(t) + \int_{t-D_i}^{t} e^{A(t-\tau)}B\Big(c_iu_i(\tau) - \sum_{i=1}^{N} a_{ij}u_j(\tau)\Big)d\tau.$$

Predictor–based change of variable

$$\psi_i(t) = \sum_{j=1}^{N} a_{ij}(x_i(t) - x_j(t) - \bar{d}_{ij}) + a_{i0}(x_i(t) - x_0(t) - \bar{d}_{i0})$$

global synchronization error for the $i-th$ vehicle

$$\bar{d}_{ij} = [d_{ij},\ 0,\ 0]^\top,\ \forall j = 0,1,\dots,N, j \neq i,$$

d_{ij} is the desired distance between vehicles i and j

$$K = [k_1,\ k_2,\ k_3] \in \mathbb{R}^{1\times 3}$$

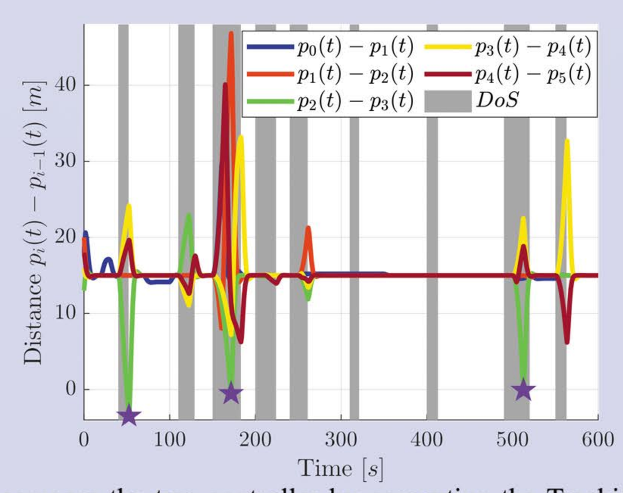
Control gains vector

$$a_{ij}\ :\ c_i = \textstyle\sum_{j=1}^{N} a_{ij} + a_{i0} > 0,\ \forall i$$

Communication topology such that there exists a directed spanning tree rooted at the leader node.

COMPARISON

Comparison with predictor-free controller $u_i(t) = K\psi_i(t), \forall i \in \mathcal{V}_N$. The predictor-free controller is not able to counteract the involved large input delays, even causing collisions during DoS attacks occurrence (star symbols).



We also compare the two controller by computing the Tracking Index TI_i for each vehicle according to the following formula:

$$TI_i = \frac{1}{T_s}\int_0^{T_s}\Big(|(v_i(t) - v_j(t))\cdot SDE| + |(p_i(t) - p_j(t) - d_{ij})\cdot SVE|\Big)dt$$

TABLE III: Comparison w.r.t. predictor-free control strategy $u = K\psi_i(t)$: Tracking Index value.

Control Strategy	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5
Controller (8)	1.398	1.527	1.701	2.039	1.432
Predictor-free controller	1.854	4.895	5.814	6.751	5.868

NUMERICAL RESULTS

To validate the theoretical derivation, we exploit Matlab/Simulink simulation platform, while Yalmip Toolbox with MOSEK solver is used to solve the LMI problem.

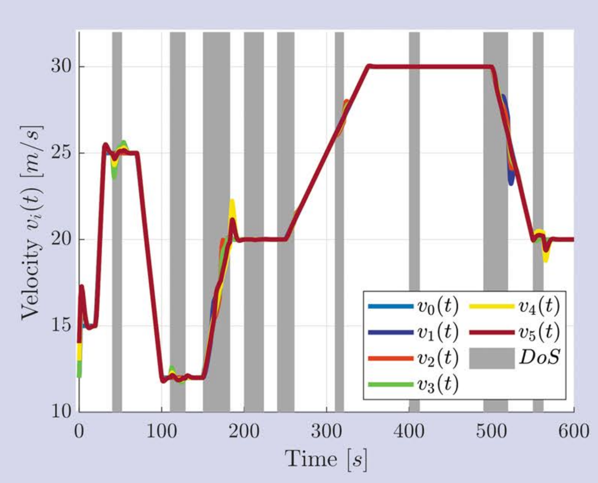
- A fleet of $N = 5$ autonomous connected vehicles traveling on a straight road is considered, plus a leader acting as a reference.
- The connectivity among vehicles undergoes the Leader-Predecessor-Follower (LPF) topology.
- The control gain vector K is selected as $K = [k_1,\ k_2,\ k_3] = [-0.5,\ -1.5,\ -1.5]$.
- Desired spacing gap $d_{i,i-1} = 15\ [m]$.

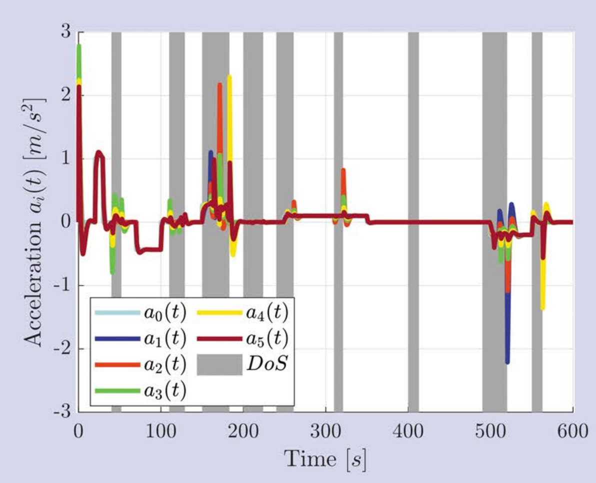
TABLE I: Simulation Parameters.

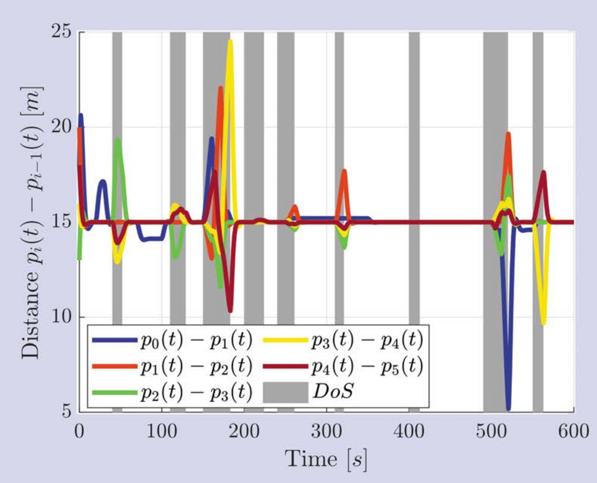
Initial position $[p_0(0), p_1(0), \dots, p_5(0)]^\top$ $[m]$	$[225, 207, 187, 174, 158, 140]^\top$
Initial speed $[v_0(0), v_1(0), \dots, v_5(0)]^\top$ $[m/s]$	$[15, 12, 14, 12, 13, 14]^\top$
Desired spacing policy $d_{i,i-1}$ $[m]$	15
Power train constant T $[1/s]$	0.5

TABLE II: DoS Attacks.

Vehicle	Dos Occurrence		
Vehicle 1	$t \in [150;160]$	$t \in [205;215]$	$t \in [510;520]$
Vehicle 2	$t \in [160;171]$	$t \in [250;261]$	$t \in [310;321]$
Vehicle 3	$t \in [40;52]$	$t \in [110;122]$, $t \in [500;512]$	$t \in [200;212]$
Vehicle 4	$t \in [170;183]$	$t \in [240;253]$, $t \in [550;563]$	$t \in [400;413]$
Vehicle 5	$t \in [115;129]$	$t \in [150;164]$, $t \in [490;504]$	$t \in [210;224]$







Leader-tracking maneuver under sampled-data predictor based controller: for a decay rate $\alpha = 0.1$ and a sampling period $h = 0.01$ the feasibility of LMI is ensured till $D_p = 16\ [s], \forall p$.
It means that the proposed controller is able to counteract large delays accounting for the occurrence of a DoS attack whose maximum length is equal to 16 [s].