# Security of Distributed Cyber-Physical Systems with Connected Vehicle Applications


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## Project objective

This project focuses on connected vehicle applications where vehicles share information via dedicated short-range communication (DSRC), with the goal of improving fuel efficiency of the system and avoiding collision.

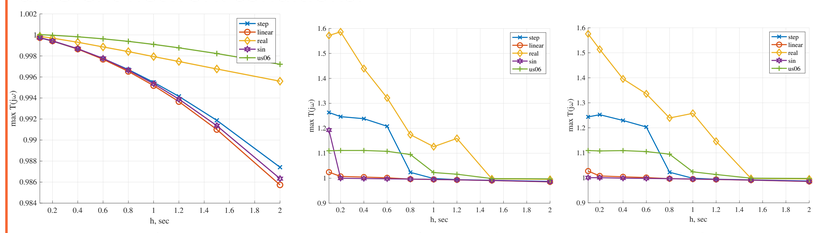
## Motivation

- Increasing the security of vehicles;
- Increasing the traffic throughput;
- Reducing fuel consumption and emission;
- Reducing the human failure and accident.

## CACC Performance Metrics

### *String Stability*

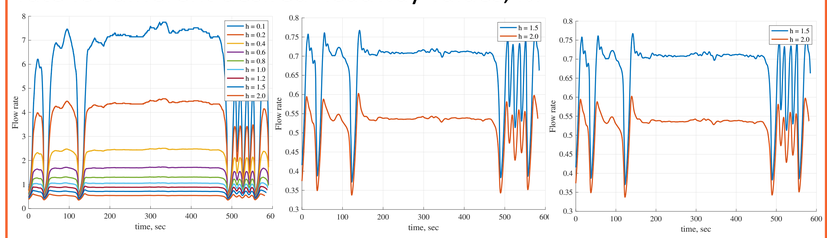
String stability defines how disturbance in the front of the platoon propagates to the rear of the platoon for a given headway value $h$. A system is string stable if $\max T(j\omega) \leq 1$. The graphs below shows string stability for different acceleration profiles under different network conditions.




No Packet Loss | Network Congestion | Denial of Service

### *Traffic Flow*

Traffic flow rate is calculated as the number of vehicles passing over a point on the road per unit second. The following graphs shows the effect of network congestion and DoS attacks on flow rate for different desired headway values, $h$.




No Packet Loss | Network Congestion | Denial of Service

Results show the traffic flow rates are greatly impacted by network impairment.

## Mitigation Strategies

The headway time value $h$ impacts the safe and efficient operation of a CACC platoon. We define an adaptive $h$ value that adapts to network reliability.

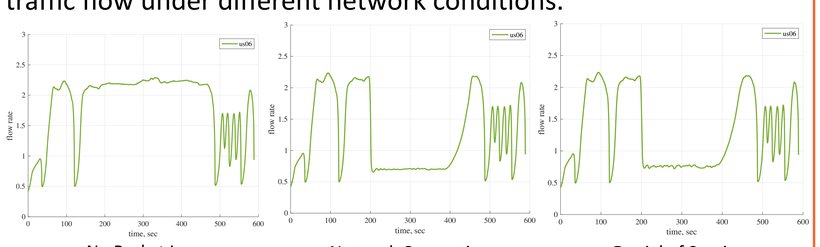
### *Network Reliability Metric*

Reliability metric of the communication network is defined as the ratio of packets that were successfully received to the total number of packets that were expected.

$$Reliability = 1 - \frac{N_{failed}}{N_{total}}$$

### *Dynamic headway assignment*

Adapting headway values to network reliability yields improved traffic flow under different network conditions.



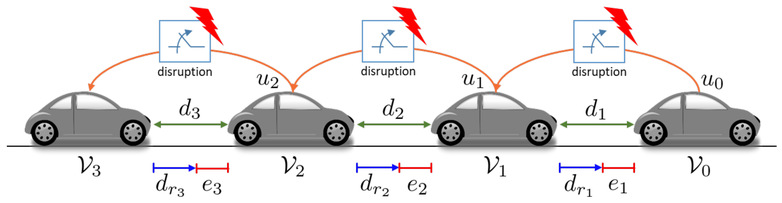

No Packet Loss | Network Congestion | Denial of Service

Adapting headway value $h$ improves traffic flow rate over using fixed $h$ value under unexpected network conditions.

## DoS-Resilient Hybrid Controller for String-Stable Connected Vehicles

Radio jamming with unknown strategy

Energy and geography constrained



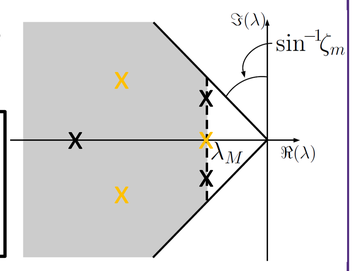

The attacker generates DoS with the purpose of disrupting the network for the longest time possible.

Design a controller to be resilient to the longest possible sequence of packet drop out, under certain performance constraints and satisfying string stability.

### *Performance Requirements*

The "networked-free" error dynamics must satisfy given performance

$$\mathbb{P}(\lambda_M, \zeta_m) := \{A \in \mathbb{R}^{n\times n} | \Lambda_{\max}(A) = \lambda_M, \; \zeta_{\min}(A) \geq \zeta_m\}$$




Case C1

$k_d = f_{C1}(k_p)$

$k_p \in [\underline{k}_{p_{C1}}, \bar{k}_{p_{C1}}]$

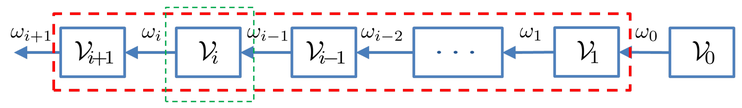
Case C2

$k_d = f_{C2}(k_p)$

$k_p \in (\underline{k}_{p_{C2}}, \bar{k}_{p_{C2}}]$

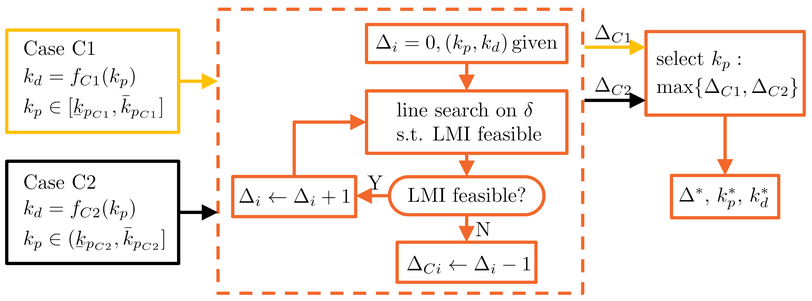
### *String Stability*

String stability of the whole vehicle platoon can be studied as input-output stability of the single vehicle.




$\frac{\|\omega_0\|_{\mathcal{L}_2}}{\|\omega_{i-1}\|_{\mathcal{L}_2}} \leq 1$ ⇨ $\mathcal{L}_2$ stability ⇨ LMI-based analysis

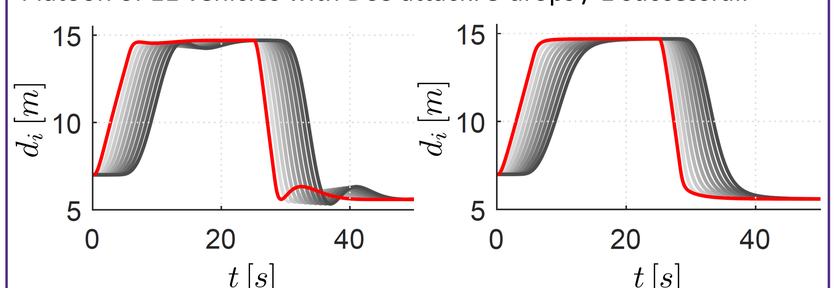
### *Design Algorithm*




### *Numerical Results*

Comparison between tuning in [Ploeg ea CITS '11] [1] and tuning with proposed approach.

Platoon of 11 vehicles with DoS attack: 5 drops / 1 successful.




Tuning as in [Ploeg ea CITS '11] [1] | Tuning as the proposed approach

[1] J. Ploeg et al., "Design and experimental evaluation of cooperative adaptive cruise control," in 14th IEEE Intelligent Transportation Systems Conference, 2011.

## Robust Control For Distributed Automotive System

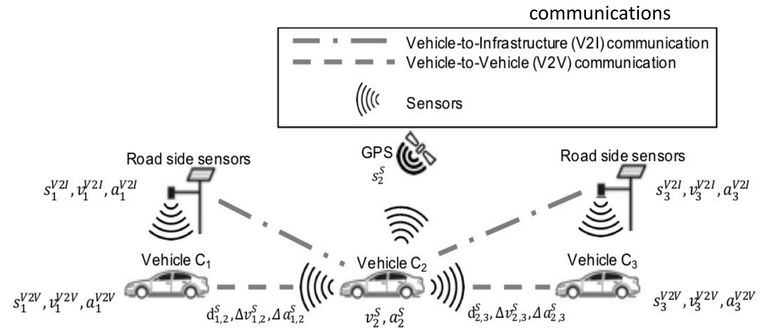
### *Sensor Measurements of a Distributed Automotive System*

| Description | Sensor Type | Symbol |
|---|---|---|
| $C_2$'s local measurement of its position | Raw GPS data | $s_2^S$ |
| $C_2$'s local measurement of its velocity | Wheel rotation speed | $v_2^S$ |
| $C_2$'s local measurement of its acceleration | Accelerometer data | $a_2^S$ |
| Distance between $C_1$ and $C_2$ | Laser distance sensor | $d_{1,2}^S$ |
| Speed difference between $C_1$ and $C_2$ | Doppler radar | $\Delta v_{1,2}^S$ |
| Acceleration difference between $C_1$ and $C_2$ | Lidar | $\Delta a_{1,2}^S$ |
| Distance between $C_2$ and $C_3$ | Laser distance sensor | $d_{2,3}^S$ |
| Speed difference between $C_2$ and $C_3$ | Doppler radar | $\Delta v_{2,3}^S$ |
| Acceleration difference between $C_2$ and $C_3$ | Lidar | $\Delta a_{2,3}^S$ |

Local sensor measurements of C2

| Description | Sensor Type | Symbol |
|---|---|---|
| $C_1$'s position sent by RSU at $t$ | V2I | $s_1^{V2I}$ |
| $C_1$'s velocity sent by RSU at $t$ | V2I | $v_1^{V2I}$ |
| $C_1$'s acceleration sent by RSU at $t$ | V2I | $a_1^{V2I}$ |
| $C_1$'s position sent by $C_1$ at $t-1$ | V2V | $s_1^{V2V}$ |
| $C_1$'s velocity sent by $C_1$ at $t-1$ | V2V | $v_1^{V2V}$ |
| $C_1$'s acceleration sent by $C_1$ at $t-1$ | V2V | $a_1^{V2V}$ |
| $C_3$'s position sent by RSU at $t$ | V2I | $s_3^{V2I}$ |
| $C_3$'s velocity sent by RSU at $t$ | V2I | $v_3^{V2I}$ |
| $C_3$'s acceleration sent by RSU at $t$ | V2I | $a_3^{V2I}$ |
| $C_3$'s position sent by $C_3$ at $t-1$ | V2V | $s_3^{V2V}$ |
| $C_3$'s velocity sent by $C_3$ at $t-1$ | V2V | $v_3^{V2V}$ |
| $C_3$'s acceleration sent by $C_3$ at $t-1$ | V2V | $a_3^{V2V}$ |

Data inputs to C2 via V2X communications




### *Faults*

**Physical**
- Sensor malfunctions.
- Actuator malfunctions

**Cyber**
- Denial of service
- Packet dropping
- Code/data insertion, etc.

### *Fault-tolerant Control Schemes*

- **Naive Averaging:** Simply uses the arithmetic average of all the different ways to estimate a parameter as its estimate.
- **Averaging Without Maximum and Minimum:** Input is very similar to the naive averaging, except that the maximum value and the minimum value are excluded in the calculating the average values of each parameter.
- **Kalman filter:** Takes inputs from multiple sources to correct the estimate from the previous time step, and then make a prediction for the next step.

### *Design Approach*

1. Automotive system (Platoon) integrated with fault conditions and countermeasures is simulated.
2. Simulation information is collected (fuel performance & no crashes).
3. Game between fault conditions and fault-tolerant control schemes is established. Payoff matrix is prepared.
4. Z-test is conducted. Dominance strategies are identified.
5. Solution of the game is identified from dominance strategies.
6. Solution is used to improve controller robustness.

## Benefits

### Scientific Impacts

- Potential improvement in traffic conditions, vehicle and personal safety, and energy consumption.
- Collision avoidance.
- More security is valuable for car makers and auto insurances.

### Broader Impacts

- General approach for distributed networked CPSs.
- This method makes CPSs more resilient and secure to cyber attacks.
- Research data is useful for public and private agencies responsible for providing infrastructure side of the connected vehicle system.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