On Resilient Control for Secure Connected Vehicles

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Opportunities for Intelligent Transportation Systems

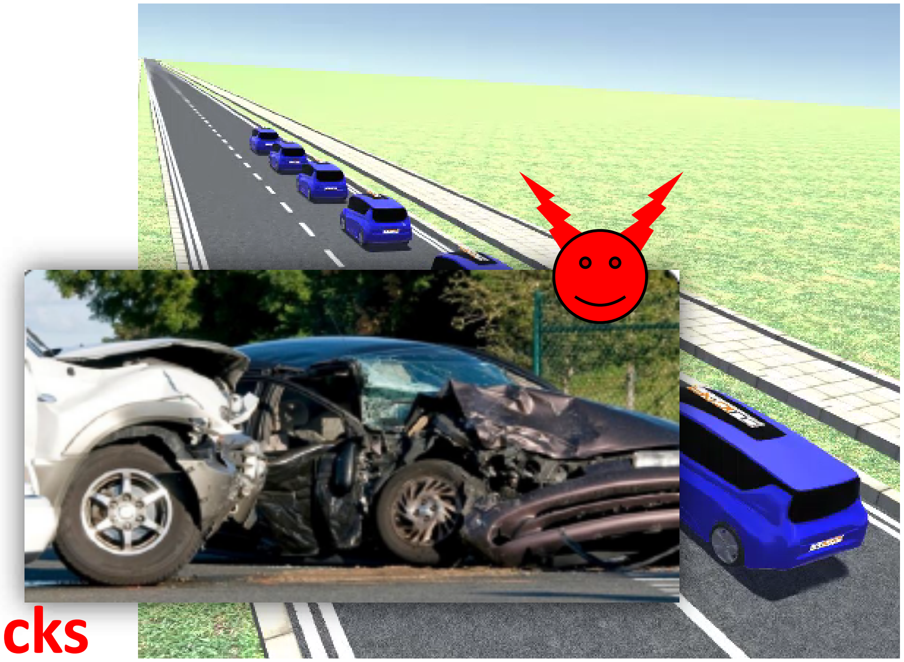
Connected vehicle image from:
https://www.geotab.com/blog/connected-vehicle-technology/

Connected Autonomous Vehicles[1,2,3,4] :

- Expected to improve:
  - Traffic throughput.
  - Safety.
  - Fuel economy.
- V2V and V2I communications through Dedicated Short-Range Communication (DSRC).

Famous application is Cooperative Adaptive Cruise Control (CACC):

- Relies on V2V.
- Employs on-board sensors.
- Autonomous vehicles



Vulnerable to Cyber-Attacks

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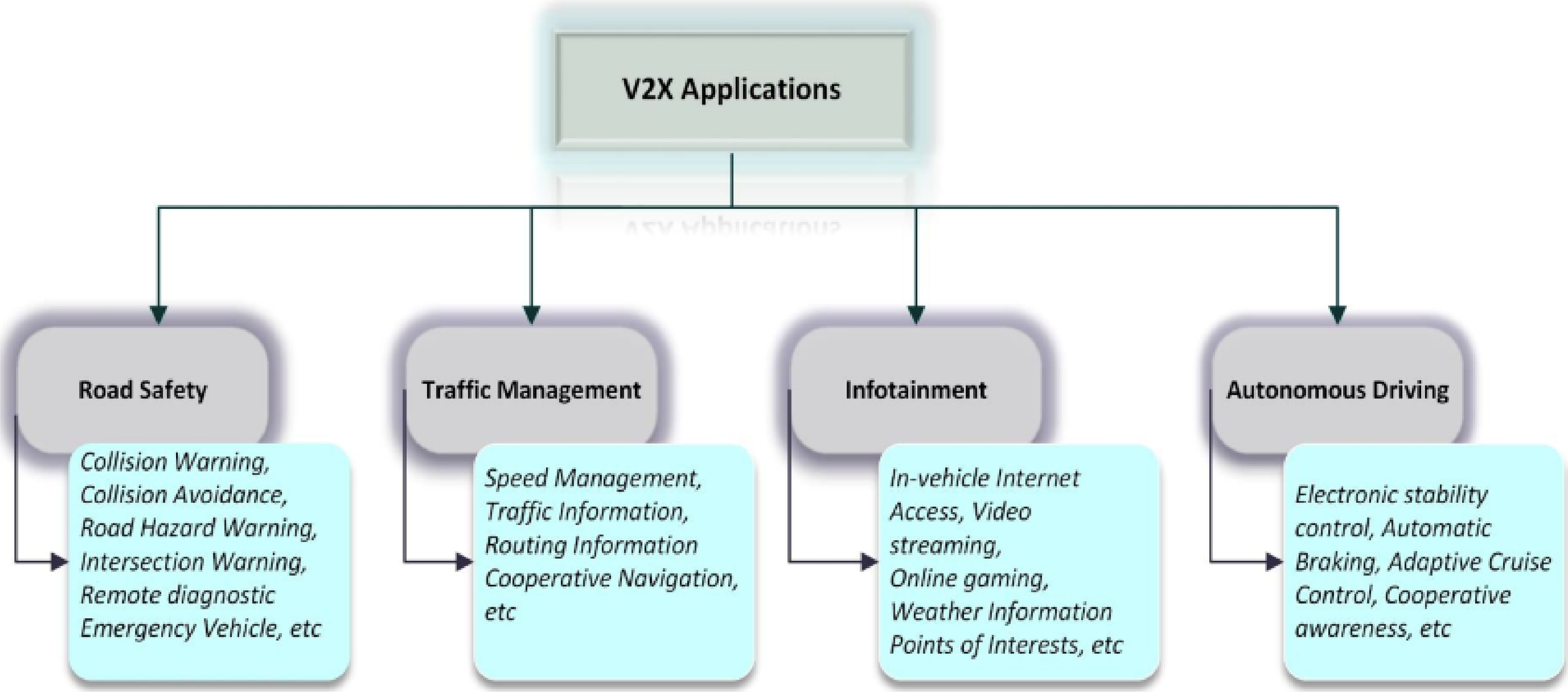
[1] Smart city challenge. https://www.transportation.gov/sites/dot.gov/files/docs/Smart%20City%20Challenge%20Lessons%20Learned.pdf.

[2] J. K. Hedrick, M. Tomizuka, and P. Varaiya. Control issues in automated highway systems. IEEE Control Systems, 14(6):21–32, 1994.

[3]]. N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark. Connected vehicles: Solutions and challenges. IEEE Internet of Things Journal, 1(4):289–299, 2014.

[4] B. Van Arem, C. J. G. Van Driel, and R. Visser. The impact of cooperative adaptive cruise control on traffic-flow characteristics. IEEE Trans on ITS, 7(4):429–436, 2006.

V2X Applications



V2X Applications

Road Safety

Collision Warning, Collision Avoidance, Road Hazard Warning, Intersection Warning, Remote diagnostic Emergency Vehicle, etc

Traffic Management

Speed Management, Traffic Information, Routing Information Cooperative Navigation, etc

Infotainment

In-vehicle Internet Access, Video streaming, Online gaming, Weather Information Points of Interests, etc

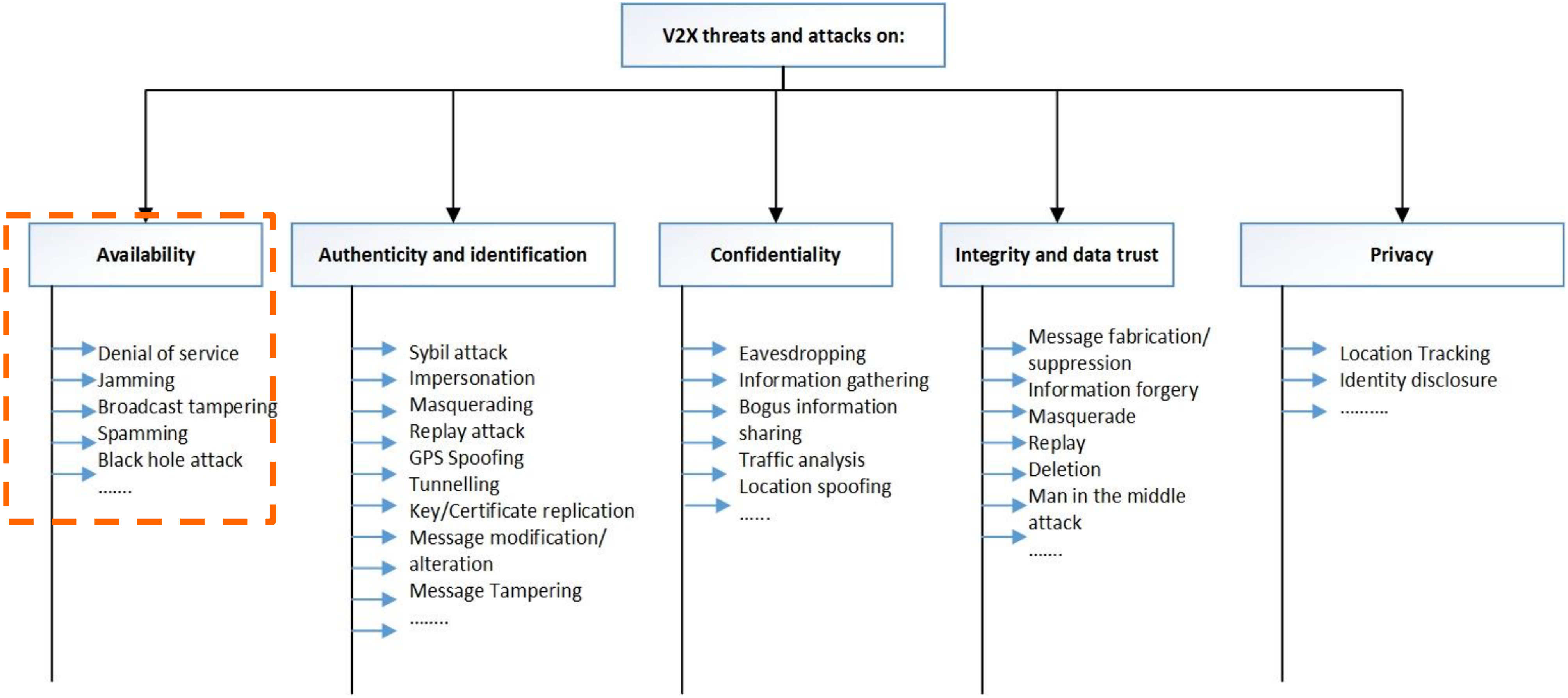
Autonomous Driving

Electronic stability control, Automatic Braking, Adaptive Cruise Control, Cooperative awareness, etc

M. Muhammad, “Security Issues in LTE-enabled V2X Communication Systems”, AESIN Conference 2017

V2X Connectivity Challenges

V2X Security: Types of Attacks on V2X



V2X threats and attacks on:

Availability
- Denial of service
- Jamming
- Broadcast tampering
- Spamming
- Black hole attack
- ....

Authenticity and identification
- Sybil attack
- Impersonation
- Masquerading
- Replay attack
- GPS Spoofing
- Tunnelling
- Key/Certificate replication
- Message modification/ alteration
- Message Tampering
- ....

Confidentiality
- Eavesdropping
- Information gathering
- Bogus information sharing
- Traffic analysis
- Location spoofing
- ......

Integrity and data trust
- Message fabrication/ suppression
- Information forgery
- Masquerade
- Replay
- Deletion
- Man in the middle attack
- ....

Privacy
- Location Tracking
- Identity disclosure
- ....

M. Muhammad, “Security Issues in LTE-enabled V2X Communication Systems”, AESIN Conference 2017

Review on V2X/CAV Security

Security threats have become more sophisticated, and cars already on the road require updated security mechanisms that address new risks.

Existing solutions

Bit commitment and signature → Availability (e.g. DoS)
Digital certification and zero knowledge → Identification and authenticity (e.g. Man in the middle, GPS spoofing replay attack)
Trusted hardware → Identification and authenticity
Group management system → Integrity and data trust (e.g. Message tampering)
Encryption of data and the corresponding positioning and vehicle identification → Confidentiality and privacy (e.g. Traffic analysis)

- Security must not come at the expense of performance.
- In traffic safety scenarios, security verification must be performed in real time.
- Queueing of V2V messages is not an option.
- Finally, security systems must be certified. Certification of the complete solution assures safety.

Hamida, Elyes Ben, Hassan Noura, and Wassim Znaidi. "Security of cooperative intelligent transport systems: Standards, threats analysis and cryptographic countermeasures." *Electronics* 4.3 (2015): 380-423.
Ivanov, I., et al. "Cyber security standards and issues in V2X communications for Internet of Vehicles." (2018)

Potential Ways to Lunch Cyber Attack

V2X Network Cyber Attack on Communication

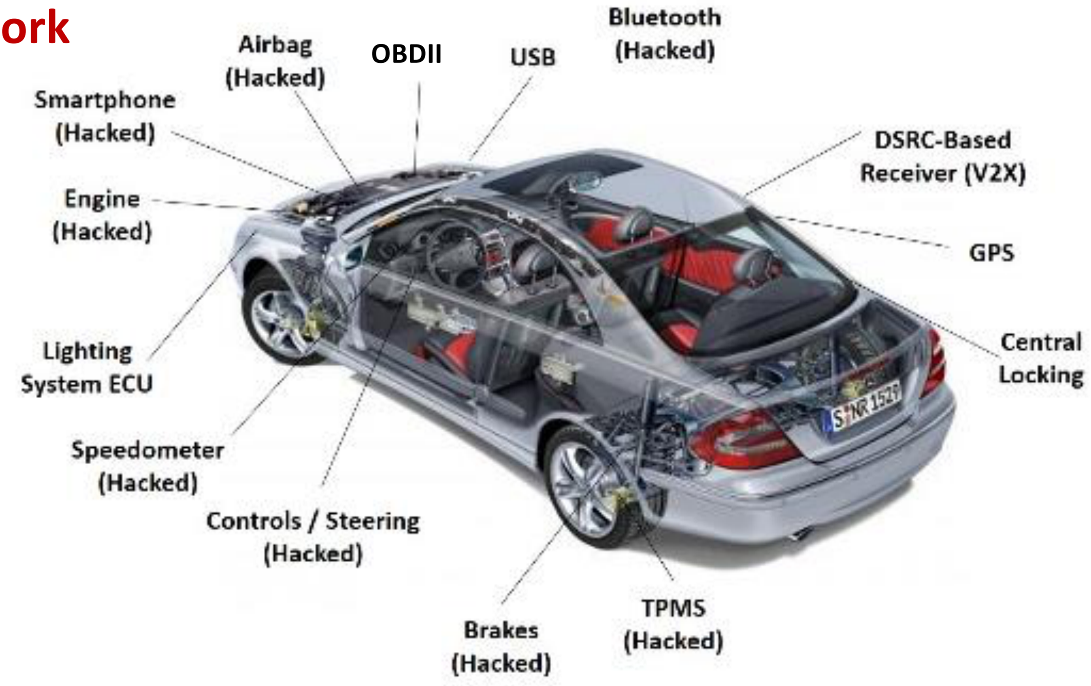
Network flooding, affecting the availability of the network

Changing the content and integrity of the package

V2X Cyber Attack on In-Vehicle Network

Hacking the equipment, sensors and actuators

Affecting CAN bus readings, messages and high level controls



Previous Work

Denial of Service

$$\begin{bmatrix}\dot{d}_i(t)\\ \dot{v}_i(t)\\ \dot{a}_i(t)\end{bmatrix} = \begin{bmatrix}0 & -1 & 0\\ 0 & 0 & 1\\ \frac{k_p}{h} & -\left(k_p+\frac{k_d}{h}\right) & \left(k_p+\frac{1}{h}\right)\end{bmatrix}\begin{bmatrix}d_i(t)\\ v_i(t)\\ a_i(t)\end{bmatrix} + \begin{bmatrix}1\\ 0\\ \frac{k_d}{h}\end{bmatrix} v_{i-1}(t) + \begin{bmatrix}0\\ 0\\ \frac{1}{h}\end{bmatrix}\boxed{a_{i-1}(t-\tau)}$$

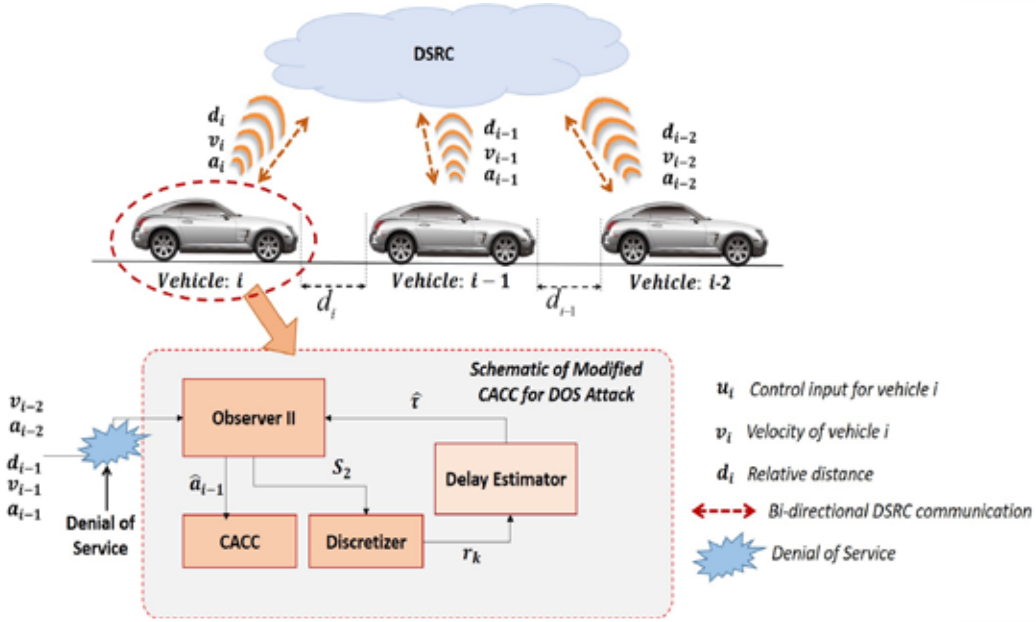
Packet drop out

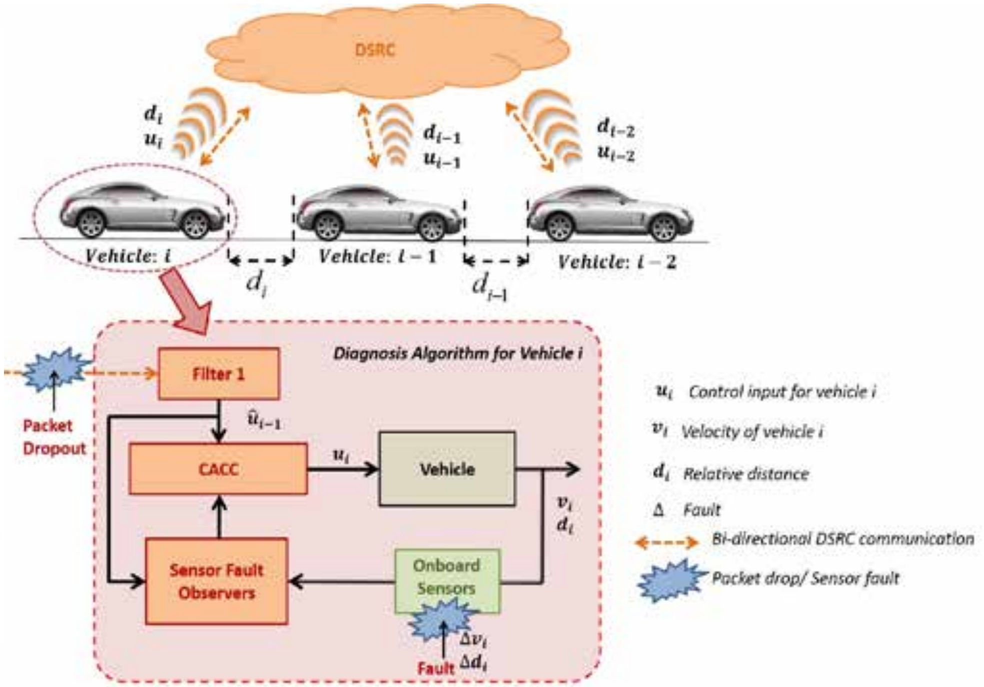
$$\chi(k) \in \{0,1\}$$

$$\begin{cases} p(\chi(k)=0)=\lambda \\ p(\chi(k)=1)=1-\lambda \end{cases}$$

$$k \times T_s \le t < (k+1) \times T_s$$

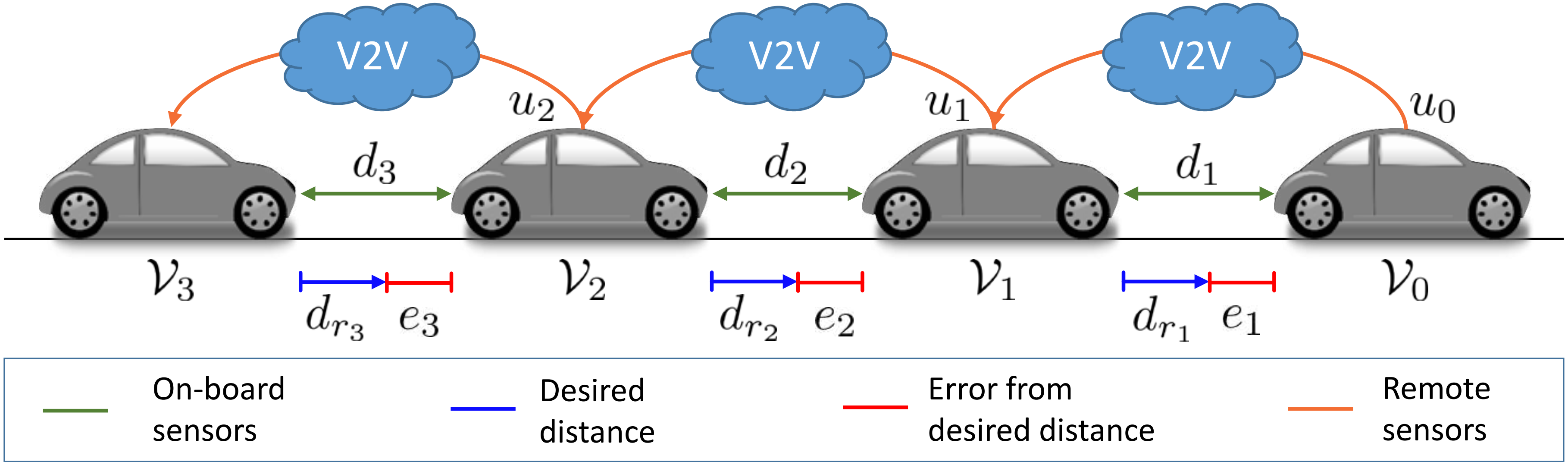
$$\dot{u}_i = -\frac{1}{h}u_i + \frac{1}{h}(k_p e_i + k_d \dot{e}_i) + \frac{1}{h} \times \boxed{\chi(k) \times u_{i-1}}$$





- Attacker provides several requests to access the network → communication network will be busy for real requests

Vehicle Platooning: Cooperative Adaptive Cruise Control (CACC)



Adaptive Cruise Control (ACC)

- Reference: $d_{r_i} = r + h\, v_i$
- Error: $e_i = d_i - d_r$

  $e_i(t) \to 0$
- String stability (shock waves attenuation)

Cooperative Adaptive Cruise Control (CACC)

- Shared information
- Closer inter-vehicle distance

Vehicle and Controller Dynamics[1]:

$$\mathcal{V}_i : \begin{pmatrix} \dot{e}_i \\ \dot{v}_i \\ \dot{a}_i \end{pmatrix} = \begin{pmatrix} v_{i-1} - v_i - h a_i \\ a_i \\ -\frac{1}{\tau_d} a_i + \frac{1}{\tau_d} u_i \end{pmatrix}$$

$$\dot{u}_i = -\frac{1}{h} u_i + \frac{1}{h}\left(\underbrace{k_p e_i + k_d \dot{e}_i}_{\text{on-board sensors}} + \underbrace{u_{i-1}}_{\substack{\text{V2V} \\ \text{one vehicle} \\ \text{ahead network} \\ \text{topology}}}\right)$$

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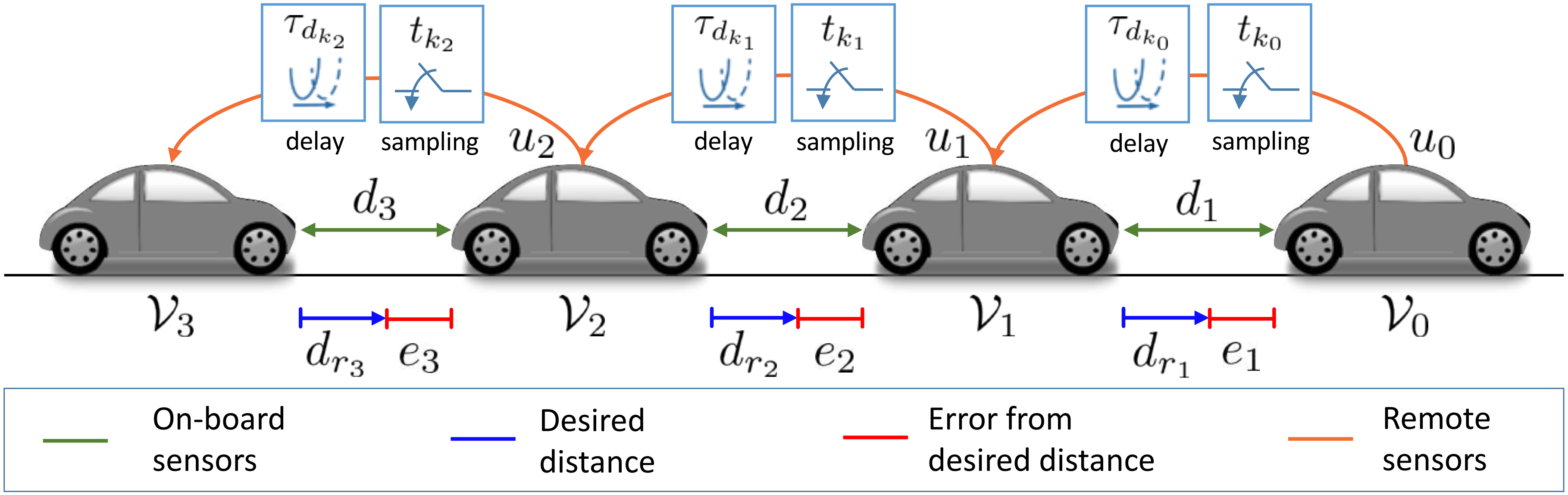
[1] J. Ploeg, B. T. Scheepers, E. Van Nunen, N. Van de Wouw, and H. Nijmeijer, “Design and experimental evaluation of cooperative adaptive cruise control,” in 14th International IEEE Conference on Intelligent Transportation Systems (ITSC), pp. 260–265, IEEE, 2011.

Vehicle Platooning with Sporadic Measurements



The presence of the network leads to network imperfections such as[1]:

Question:

How do we deal with these phenomena in our model?

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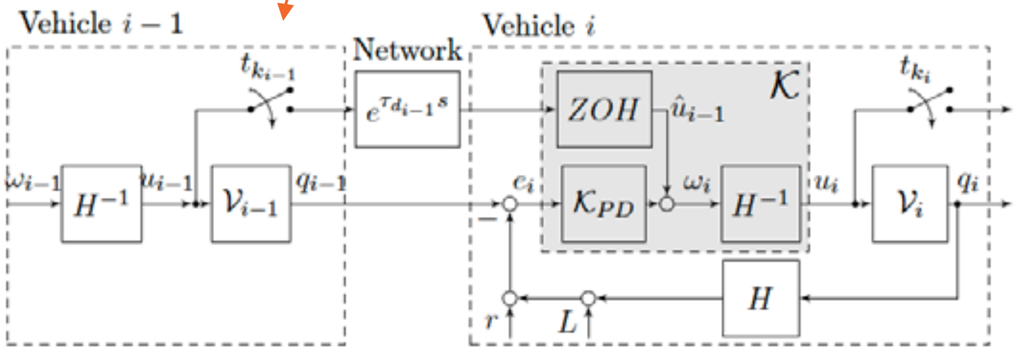
[1] W.P.M.H. Heemels, A. R. Teel, N. Van de Wouw, and D. Neˇsi´c. Networked control systems with communication constraints: Tradeoffs between transmission intervals, delays and performance. IEEE Transactions on Automatic Control, 55(8):1781–1796, 2010.

Vehicle Model with Networked Sporadic Measurements

Controller Dynamics:

$$\dot{u}_i = -\frac{1}{h}u_i + \frac{1}{h}\left(\underbrace{k_p e_i + k_d \dot{e}_i}_{\text{on-board sensors}} + \underbrace{u_{i-1}}_{\text{V2V}}\right)$$

sporadic measurements



Assumptions

maximum allowable transmission interval

1. Variable transmission intervals:

$$\delta_T \leq t_{k_{i-1}+1} - t_{k_{i-1}} < T_{mati}$$

2. Variable network delays

$$0 \leq \tau_{d_{k_i}} \leq T_{mad} \leq T_{mati}$$

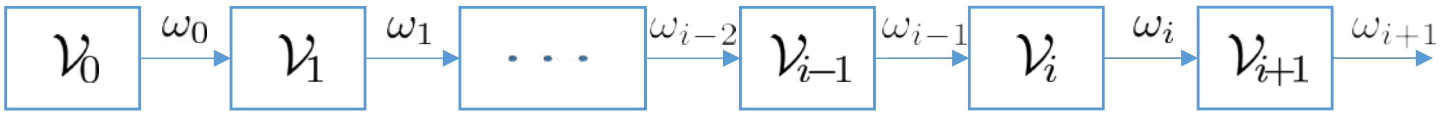
maximum allowable delay

Ensures transmitted output is received by controller before next sample is sent

The state of the error dynamics is modified such that the whole platoon is considered as a cascade of dynamical systems.

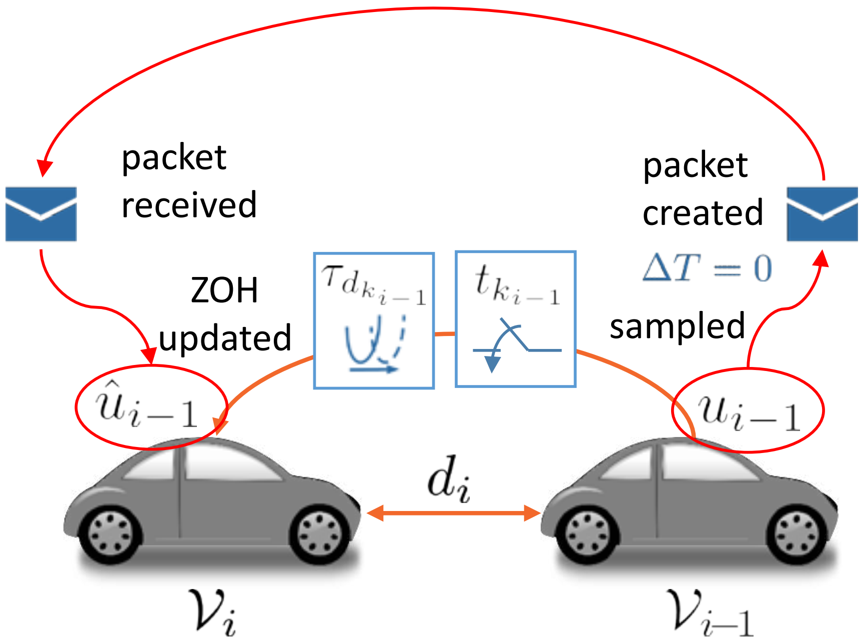
Benefits in achieving **by design**

- String stability
- Performance



Available at:
R. Merco, F. Ferrante, P. Pisu, “Network Aware Control Design for String Stabilization in Vehicle Platoons: An LMI Approach”, IEEE American Control Conference (ACC), 2019

Vehicle Model with Networked Sporadic Measurements



packet received

ZOH updated

packet created

$\Delta T = 0$

sampled

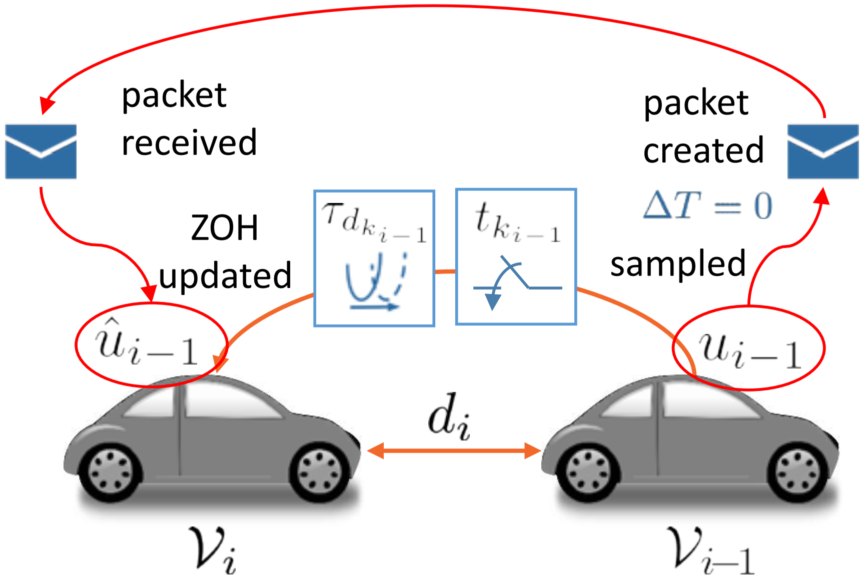
The controller relies on u_{i-1} is sampled and sent throughout the vehicle network

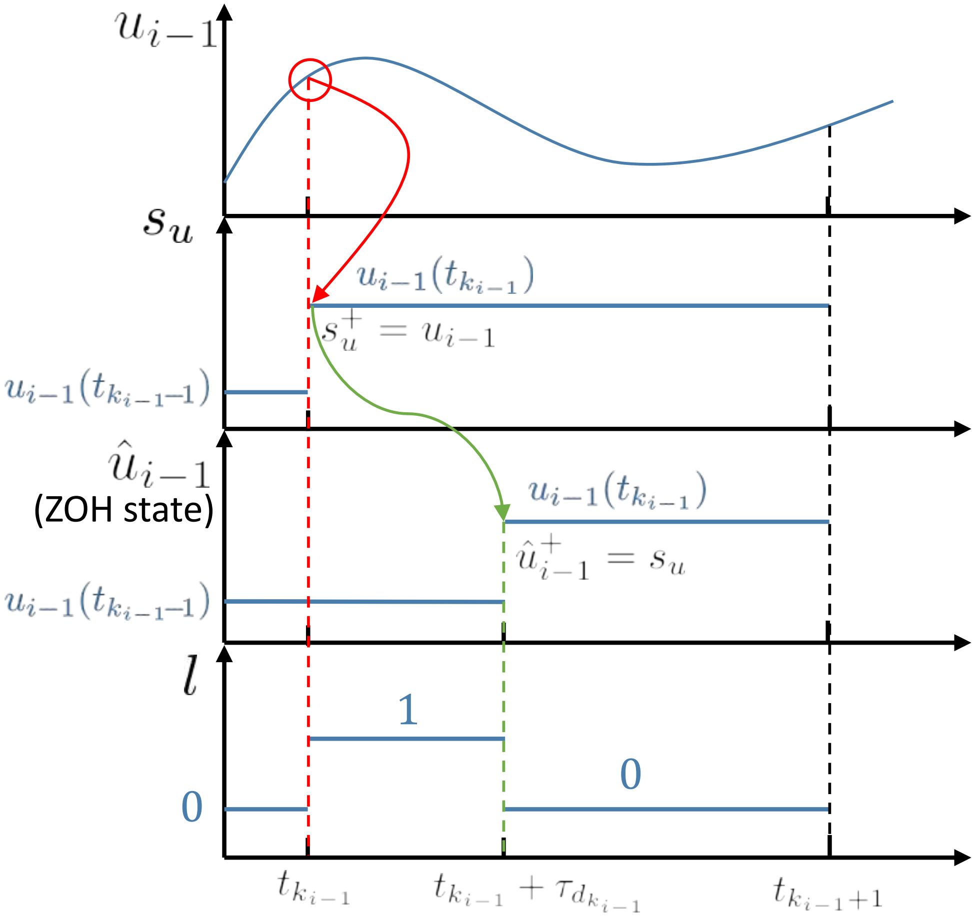
Each vehicle can be represented as linear system with jumps

$$\mathcal{V}_i \begin{cases} \begin{cases} \dot{e}_i(t) = \underbrace{\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\frac{k_p}{\tau_d} & -\frac{k_d}{\tau_d} & -\frac{1}{\tau_d} \end{bmatrix}}_{A_e} e_i(t) + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\tau_d} \end{bmatrix} u_{i-1}(t) + \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{\tau_d} \end{bmatrix} \hat{u}_{i-1}(t) \\ \boxed{\dot{u}_{i-1}(t) = -\frac{1}{h} u_{i-1}(t) + \frac{1}{h} \omega_{i-1}(t)} \\ \dot{\hat{u}}_{i-1}(t) = 0 \end{cases} & \forall t \neq t_{k_{i-1}} \vee t_{k_{i-1}} \in \bigcup_{n \in \mathbb{N}} H_n \\ \begin{cases} e_i(t^+) = e_i(t) \\ u_{i-1}(t^+) = u_{i-1}(t) \\ \hat{u}_{i-1}(t^+) = u_{i-1}(t) \end{cases} & \forall t = t_{k_{i-1}} \wedge t_{k_{i-1}} \notin \bigcup_{n \in \mathbb{N}} H_n \\ \omega_i(t) = k_p e_i(t) + k_d \dot{e}_i(t) + u_{i-1}(t) \end{cases}$$

$$\omega_{i-1}(t) = k_p e_{i-1}(t) + k_d \dot{e}_{i-1}(t) + u_{i-2}(t)$$

Hybrid Model of CACC





Modelling Characteristics:

- Platooning as cascade of dynamical systems
- We follow the Hybrid Systems framework proposed by R. Goebel, R. Sanfelice, A. Teel[1]
- State space of the model enlarged with the auxiliary variables subject to reset:
  - $\hat{u}_{i-1}$, s_u, l
  - τ_{i-1} for time-based network trigger

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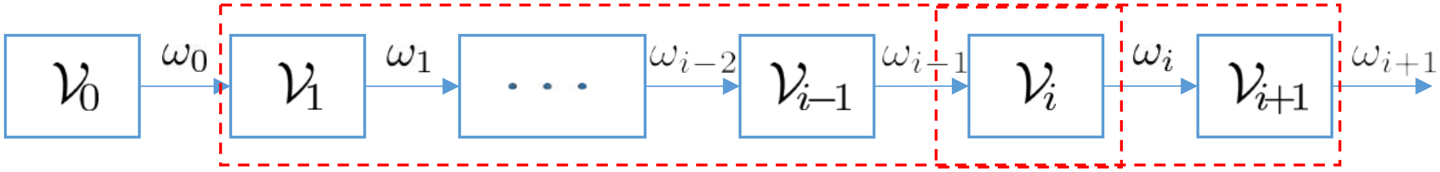
[1] R. Goebel, R. G. Sanfelice, and A. R. Teel. Hybrid Dynamical Systems: Modeling, Stability, and Robustness. Princeton University Press, 2012.

Control Requirements

String stability



$\frac{\|\omega_0\|_{\mathcal{L}_2}}{\|\omega_{i-1}\|_{\mathcal{L}_2}} \leq 1$ ⇒ $\mathcal{L}_2$ stability of $\mathcal{V}_i$ $\frac{\|\omega_i\|_{\mathcal{L}_2}}{\|\omega_{i-1}\|_{\mathcal{L}_2}} \leq 1$

Definition. The vehicle platooning is said to be string stable if the systems $\mathcal{V}_i$ in the platoon are $\mathcal{L}_2$-stable from the input $\omega_{i-1} \in \mathcal{L}_2$ to the output $\omega_i \in \mathcal{L}_2$ with an $\mathcal{L}_2$-gain less than or equal to one.

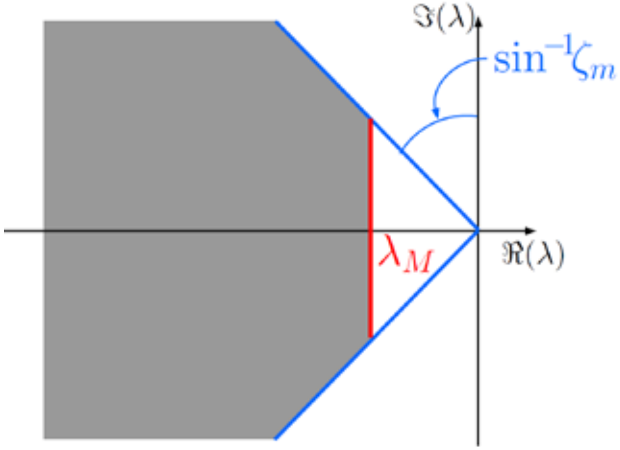
Individual vehicle stability ($\lim_{t\to\infty} e_i(t) = 0$)

“Networked-free” error dynamics with performance requirements

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

$$\lambda_M < 0,\ \zeta_m \in (0, 1]$$

$$A_e = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\frac{k_p}{\tau_d} & -\frac{k_d}{\tau_d} & -\frac{1}{\tau_d} \end{bmatrix} \in \mathbb{P}(\lambda_M, \zeta_m)$$



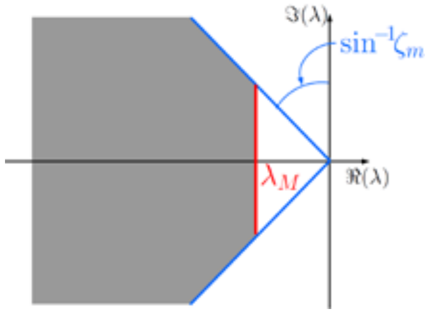
Control Problem

Problem. Given the platooning parameters h and τ_d, and the performance requirements $\mathbb{P}$, design gains k_p and k_d for the hybrid controller such that the vehicle platooning satisfies the following properties with the largest achievable value of T_{mati} and T_{mad}:

(P1) Individual vehicle stability with performance $\mathbb{P}$, i.e., $A_e \in \mathbb{P}$.

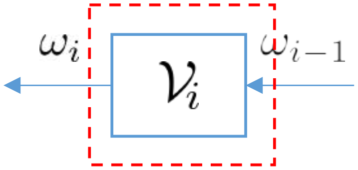
(P2) String stability.

Performance



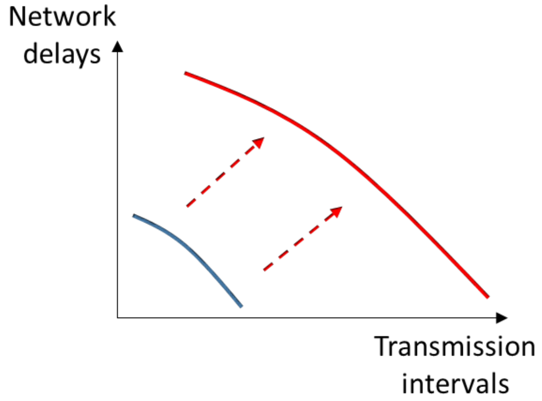
$A_e \in \mathbb{P}(\lambda_M, \zeta_m)$

String Stability

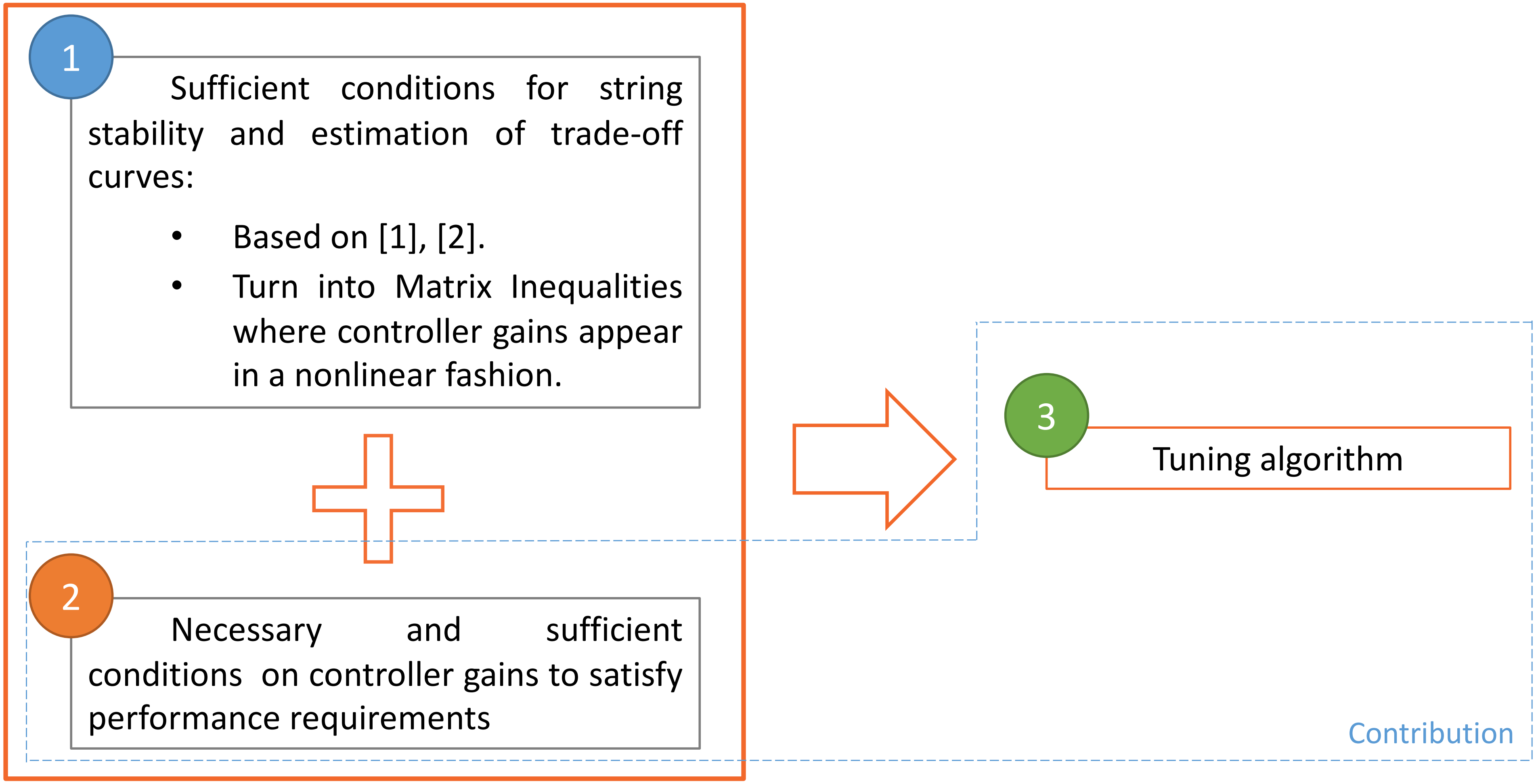


$$\frac{\|\omega_i\|_{\mathcal{L}_2}}{\|\omega_{i-1}\|_{\mathcal{L}_2}} \leq 1$$

Resiliency



Design Approach



1

Sufficient conditions for string stability and estimation of trade-off curves:

- Based on [1], [2].
- Turn into Matrix Inequalities where controller gains appear in a nonlinear fashion.

2

Necessary and sufficient conditions on controller gains to satisfy performance requirements

3

Tuning algorithm

Contribution

[1] W. M. H. Heemels, A. R. Teel, N. Van de Wouw, and D. Nesic, "Networked control systems with communication constraints: Tradeoffs between transmission intervals, delays and performance," IEEE Transactions on Automatic Control, vol. 55, no. 8, pp. 1781–1796, 2010.

[2] V. S. Dolk, J. Ploeg, and W. M. H. Heemels, "Event-triggered control for string-stable vehicle platooning," IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 12, pp. 3486–3500, 2017.

Controller Design: S.C. for String Stability

1

Assumption 1. There exist constants γ, $\epsilon \in \mathbb{R}_{\geq 0}$, $\mu \in \mathbb{R}_{>0}$ and $P = P^\top > 0$ such that

$$\begin{bmatrix} \mathrm{He}(PA_{11}) + A_{21}^\top A_{21} + \mu C^\top C & PA_{12} + \mu C^\top D & A_{21}^\top A_{23} + PA_{13} \\ \bullet & \mu D^\top D - \gamma^2 & 0 \\ \bullet & \bullet & A_{23}^T A_{23} - \mu(1+\epsilon) \end{bmatrix} < 0$$

Nonlinear in controller gains

$\mathcal{L}_2$ gain from network imperfection to error dynamics

$$\boxed{\gamma \downarrow \Rightarrow T_{mati} \uparrow, T_{mad} \uparrow}$$

Assumption 2. There exists a pair (T_{mati}, T_{mad}) such that

For the computation of trade-off curves

$$\gamma_1\phi_1(\tau_{i-1}) \geq \gamma_0\phi_0(\tau_{i-1}), \quad \forall \tau_{i-1} \in [0, T_{mad}]$$
$$\gamma_0\phi_0(\tau_{i-1}) \geq \lambda^2\gamma_1\phi_1(0), \quad \forall \tau_{i-1} \in [0, T_{mati}]$$

with $T_{mati} \geq T_{mad} \geq 0$, $\lambda \in (0,1)$, constants $\gamma_0 := \gamma$ and $\gamma_1 := \frac{\gamma}{\lambda}$, and where $\phi_{l_{i-1}} : \mathbb{R}_{\geq 0} \mapsto \mathbb{R}, l_{i-1} \in \{0,1\}$ is the unique maximal solution to

$$\dot{\phi}_{l_{i-1}} = -\gamma_{l_{i-1}}(\phi_{l_{i-1}}^2 + 1)$$

with initial conditions $\phi_1(0) \geq \phi_0(0) \geq \lambda^2\phi_1(0)$, $\phi_0(T_{mati}) \geq 0$.

Theorem. Let Assumption 1 with $\epsilon = 0$ and Assumption 2 hold. Then, hybrid system $\mathcal{V}_i$ is $\mathcal{L}_2$-stable from the input ω_{i-1} to the output ω_i with an $\mathcal{L}_2$-gain less than or equal to one.

Based on:

[1] W. M. H. Heemels, A. R. Teel, N. Van de Wouw, and D. Nesic, “Networked control systems with communication constraints: Tradeoffs between transmission intervals, delays and performance,” IEEE Transactions on Automatic Control, vol. 55, no. 8, pp. 1781–1796, 2010.

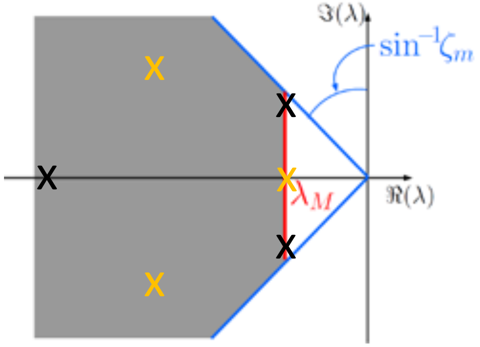
[2] V. S. Dolk, J. Ploeg, and W. M. H. Heemels, “Event-triggered control for string-stable vehicle platooning,” IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 12, pp. 3486–3500, 2017.

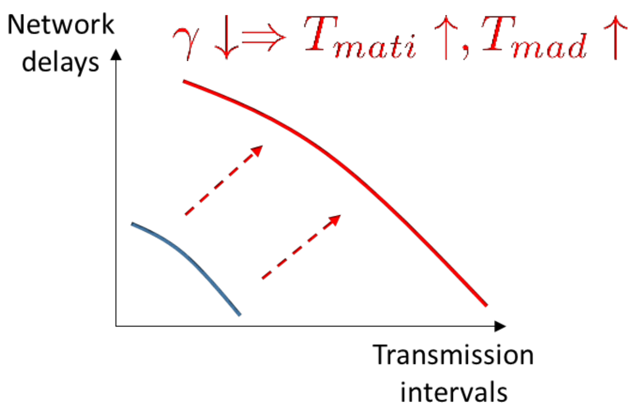
Computationally Efficient Design Algorithm

Suff. Cond. for string stability and estimation of trade-off curves are based on the solution of the matrix inequality :

$$\begin{bmatrix} \mathrm{He}(PA_{11}) + A_{21}^\top A_{21} + \mu C^\top C & PA_{12} + \mu C^\top D & A_{21}^\top A_{23} + PA_{13} \\ \bullet & \mu D^\top D - \gamma^2 & 0 \\ \bullet & \bullet & A_{23}^T A_{23} - \mu(1+\epsilon) \end{bmatrix} < 0$$

Nonlinear in controller parameters.
Proposed solution:





$\gamma \downarrow \Rightarrow T_{mati} \uparrow, T_{mad} \uparrow$

Condition (C1). The real eigenvalue is equal to λ_M.

$k_d = f_{C1}(k_p)$
$k_p \in [\underline{k}_{pC1}, \bar{k}_{pC1}]$

Condition (C2). Single couple of complex eigenvalues with real part equal to λ_M.

$k_d = f_{C2}(k_p)$
$k_p \in (\underline{k}_{pC2}, \bar{k}_{pC2}]$

Controller Design: N.S.C. for Individual Vehicle Stability

2

Proposition 1 (N.S.C. for C1). Let $k_p, k_d \in \mathbb{R}$, $\lambda_M \in \mathbb{R}_{<0}$, and $\zeta_m \in \mathbb{R}_{>0}$. Then, C1 is satisfied if and only if the following conditions hold:

$$k_d = f_{C1}(k_p) := -\frac{1}{\lambda_M}k_p - \lambda_M^2\tau_d - \lambda_M$$

$$k_p \leq \frac{|\lambda_M|(\lambda_M\tau_d + 1)^2}{4\tau_d\zeta_m^2} := \bar{k}_{pC1}$$

$$k_p \geq 2\tau_d\lambda_M^3 + \lambda_M^2 := \underline{k}_{pC1}$$

$$\lambda_M > -\frac{1}{3\tau_d}$$

Proposition 2 (N.S.C. for C2). Let $k_p, k_d \in \mathbb{R}$, $\lambda_M \in \mathbb{R}_{<0}$, and $\zeta_m \in (0, 1)$. Then, C2 holds if and only if the following conditions hold:

$$k_d = f_{C2}(k_p) := -\frac{8\lambda_M^3\tau_d^2 + 8\lambda_M^2\tau_d + 2\lambda_M - \tau_d k_p}{2\lambda_M\tau_d + 1}$$

$$k_p \leq \frac{2\tau_d\lambda_M^3 + \lambda_M^2}{\zeta_m^2} := \bar{k}_{pC2}$$

$$k_p > 2\tau_d\lambda_M^3 + \lambda_M^2 := \underline{k}_{pC2}$$

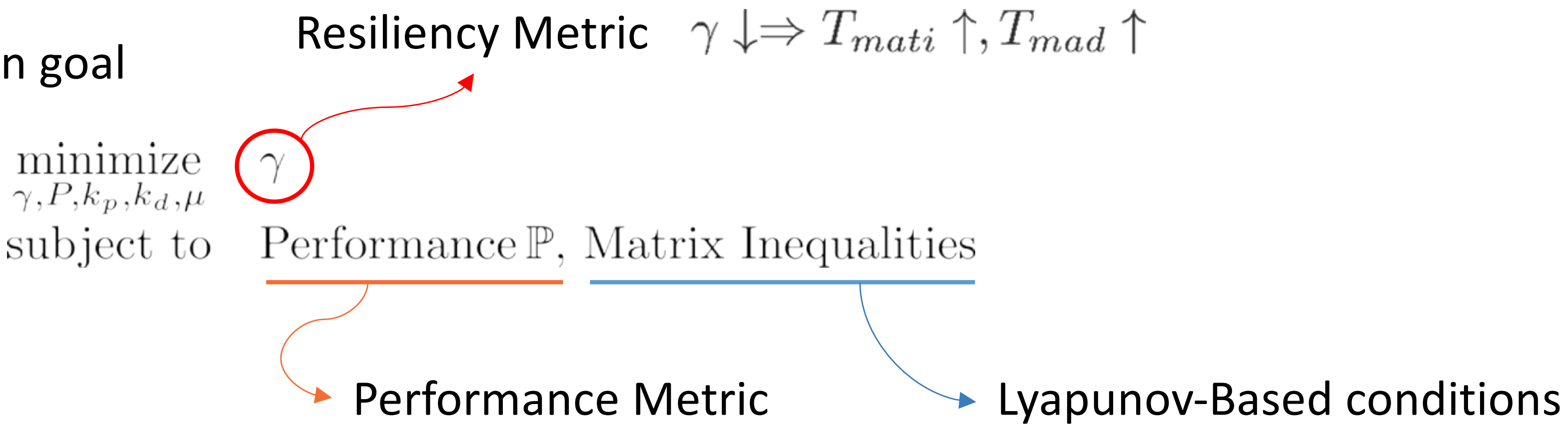
$$\lambda_M > -\frac{1}{3\tau_d}$$

Number of control variables is reduced

Performances are constrained by powertrain time constant

Controller Design: Tuning Algorithm

③ Design goal



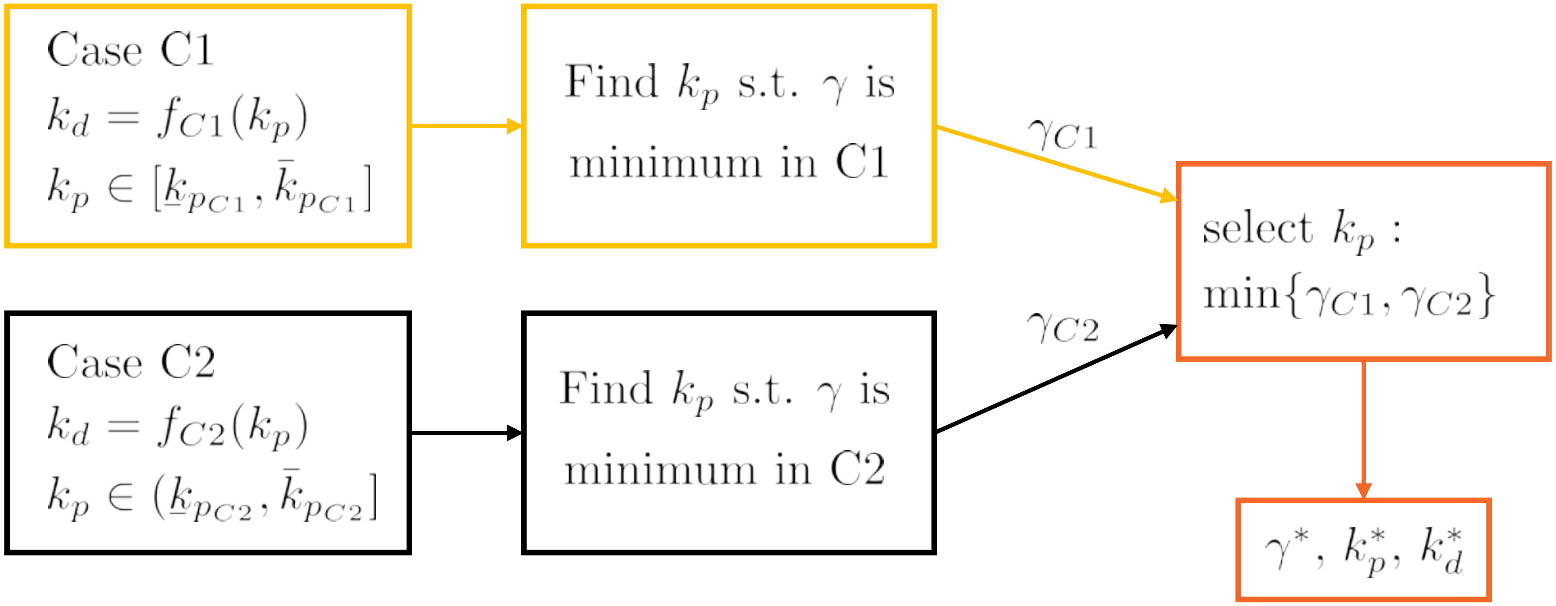
Resiliency Metric $\gamma \downarrow \Rightarrow T_{mati} \uparrow, T_{mad} \uparrow$

$$\underset{\gamma,P,k_p,k_d,\mu}{\text{minimize}} \quad \gamma$$
$$\text{subject to} \quad \underline{\text{Performance}\,\mathbb{P}}, \ \underline{\text{Matrix Inequalities}}$$

Performance Metric

Lyapunov-Based conditions

Design Algorithm



Case C1
$k_d = f_{C1}(k_p)$
$k_p \in [\underline{k}_{pC1}, \bar{k}_{pC1}]$

Find k_p s.t. γ is minimum in C1

γ_{C1}

Case C2
$k_d = f_{C2}(k_p)$
$k_p \in (\underline{k}_{pC2}, \bar{k}_{pC2}]$

Find k_p s.t. γ is minimum in C2

γ_{C2}

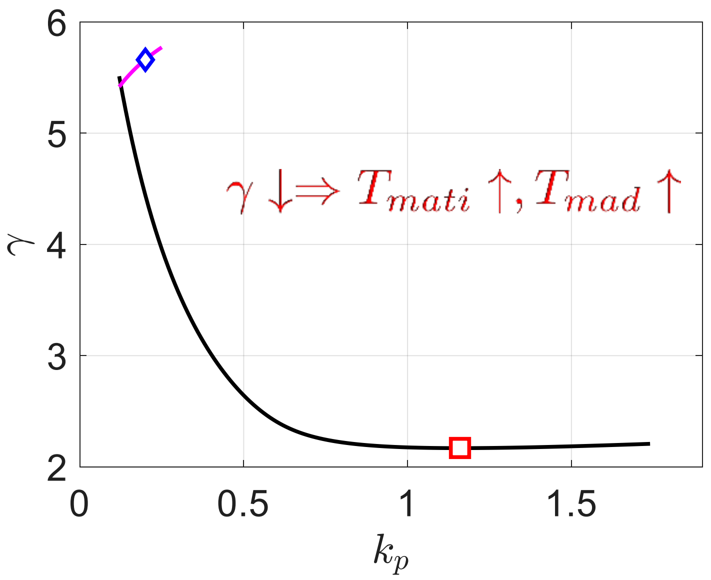
select k_p : $\min\{\gamma_{C1}, \gamma_{C2}\}$

$\gamma^*, \ k_p^*, \ k_d^*$

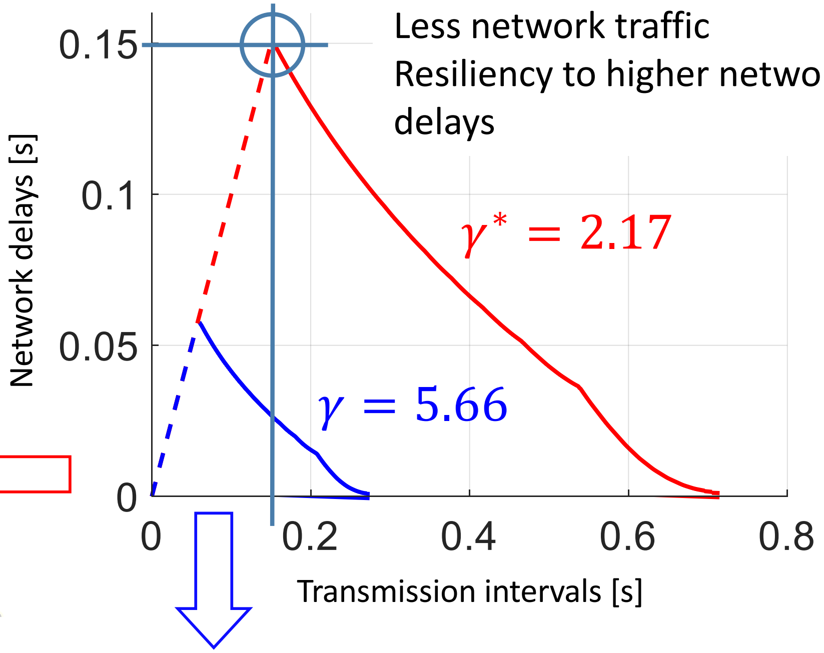
Numerical Results

◇ Tuning as in Ploeg at al.

□ Our approach



$\gamma \downarrow \Rightarrow T_{mati} \uparrow, T_{mad} \uparrow$

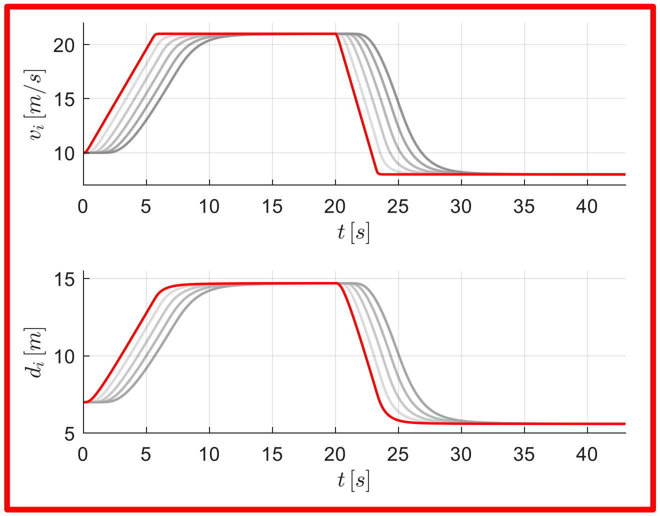


Less network traffic

Resiliency to higher network delays

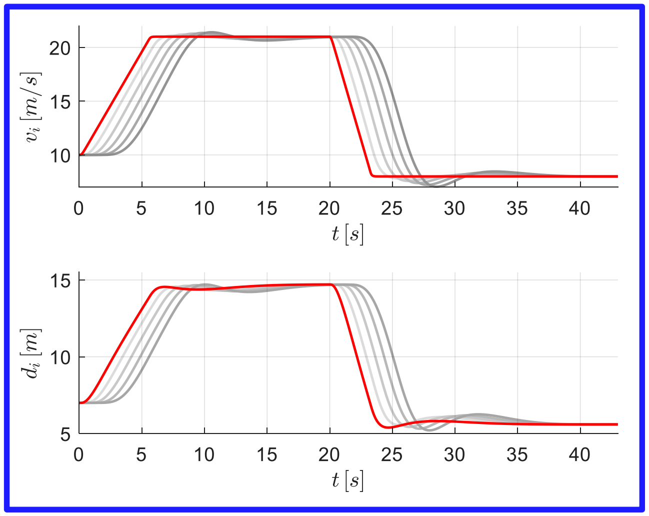
Our approach

Network-resilient tuning



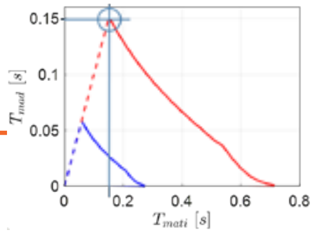
Tuning as in Ploeg et al.

Non network-resilient tuning



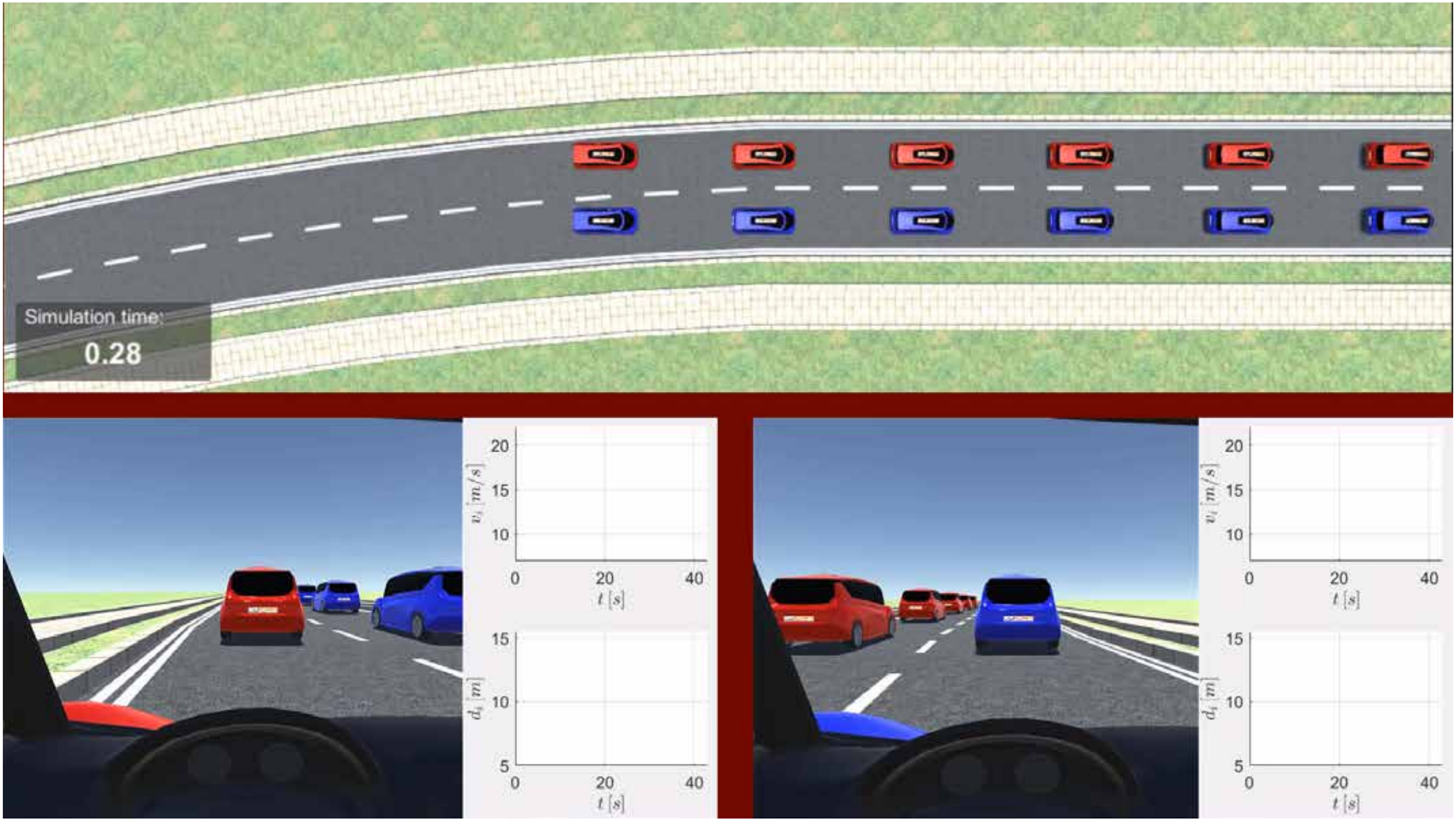
J. Ploeg, B. TM. Scheepers, E. Van Nunen, N. Van de Wouw, and H. Nijmeijer. Design and experimental evaluation of cooperative adaptive cruise control. In Proceedings of the 14th IEEE International Conference on Intelligent Transportation Systems, pages 260–265, 2011.

Numerical Results



Left lane, in red, network-resilient tuning

Right lane, in blue, non network-resilient tuning



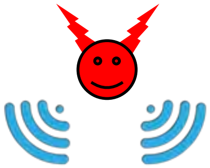
Inside last vehicle in the left lane
network-resilient tuning

Inside last vehicle in the right lane
non network-resilient tuning

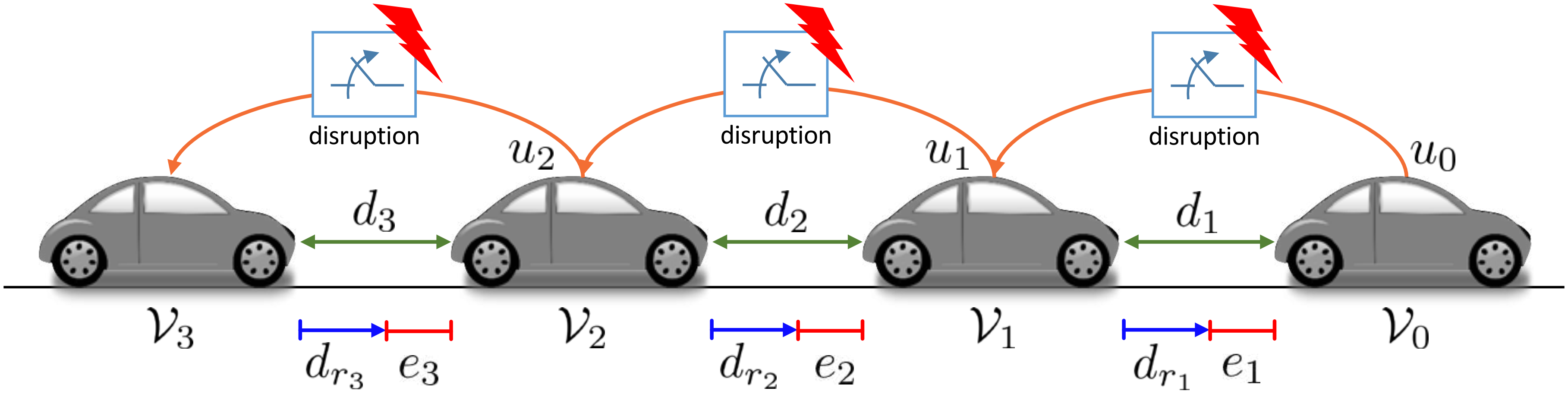
Resilient CACC Under Denial-of-Service Attacks

Vehicle Platooning under Denial-of-Service (DoS) Attack

Radio jamming with unknown strategy[1]



Energy[2] and geography constrained[1]



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

CACC Pros:

Closer inter-vehicle distance:

- Traffic throughput
- Fuel economy

CACC Cons:

String Stability influenced by:

- Network unreliability
- Cyber Attacks

---

[1] M. Amoozadeh, A. Raghuramu, C.-N. Chuah, D. Ghosal, H. M. Zhang, J. Rowe, and K. Levitt. Security vulnerabilities of connected vehicle streams and their impact on cooperative driving. IEEE Communications Magazine, 53(6):126–132, 2015.

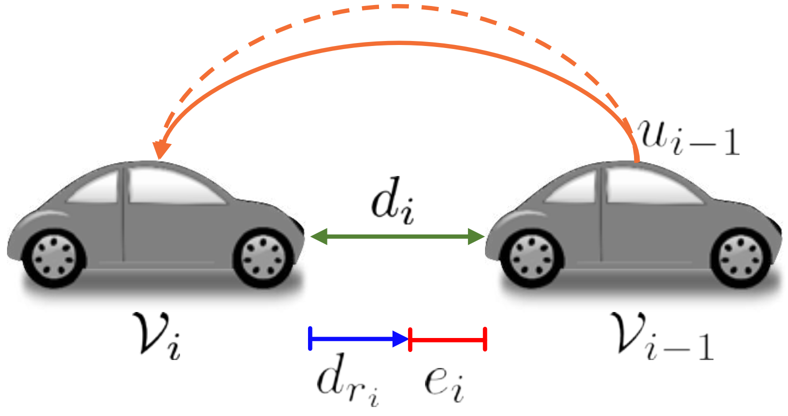
[2] V. S. Dolk, P. Tesi, C. De Persis, and W.P.M.H. Heemels. Event-triggered control systems under denial-of-service attacks. IEEE Transactions on Control of Network Systems, 4(1):93–105, 2017.

Secure and Safe Control Strategies for Vehicle Platooning

Adaptive Cruise Control (ACC)
no communication

Estimation-based CACC[1]
action is estimated by on-board sensors

Switching Strategy CACC/ACC[2]
control strategy ACC and CACC switched over time based on communication status



Inter-vehicle time gaps without CACC
are larger than
inter-vehicle time gaps with CACC

→

Trade off between safety and performance is needed

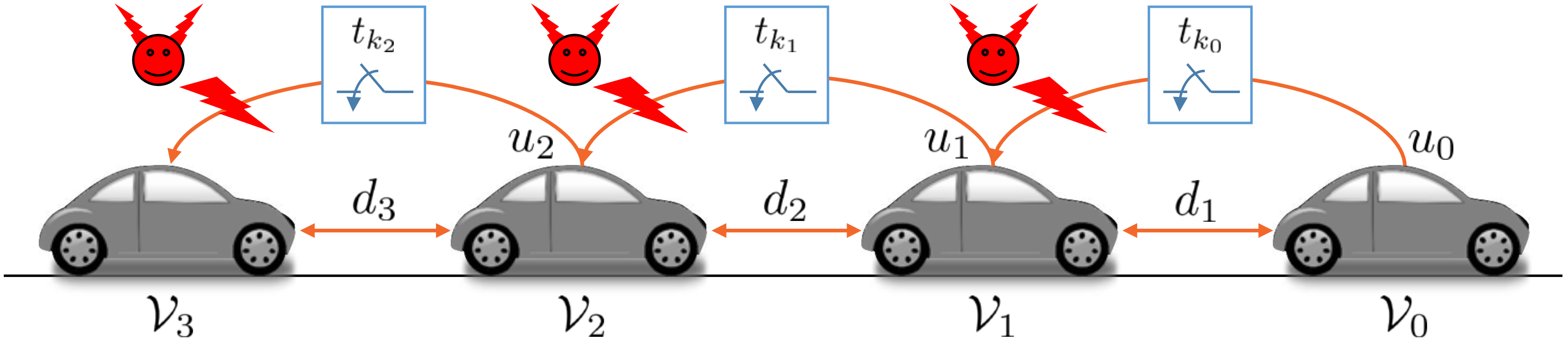
Research questions:

1. What network unreliability and DoS attacks can we tolerate without the need to fall back to safe strategies?
2. How to design a CACC that maximize the resilience to network unreliability and DoS attack?

[1] J. Ploeg, E. Semsar-Kazerooni, G. Lijster, N. van de Wouw, and H. Nijmeijer. Graceful degradation of cooperative adaptive cruise control. IEEE Transactions on Intelligent Transportation Systems, 2014

[2] Y. A. Harfouch, S. Yuan, and S. Baldi. An adaptive switched control approach to heterogeneous platooning with intervehicle communication losses. IEEE Transactions on Control of Network Systems, 2017.

Vehicle Platooning with DoS attacks



Controller Dynamics:

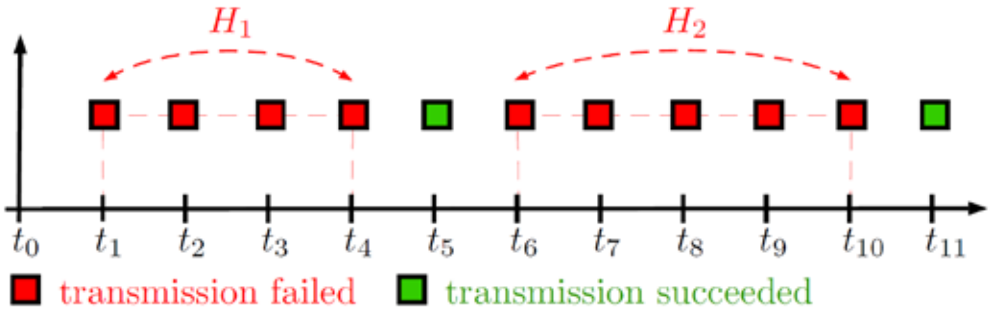
Available in sporadic fashion: data shared with period T_s

$$\dot{u}_i = -\frac{1}{h}u_i + \frac{1}{h}\left(\underbrace{k_p e_i + k_d \dot{e}_i}_{\text{on-board sensors}} + \underbrace{u_{i-1}}_{\text{V2V}}\right)$$

Δ is the resiliency metric

DoS attacks as a sequence of intervals $\{H_n\}_{n\in\mathbb{N}}$ of limited length bounded by $\Delta \in \mathbb{N}_0$

$\Delta \in \mathbb{N}_0$ is the maximum allowable number of successive packet dropouts (MANSD)



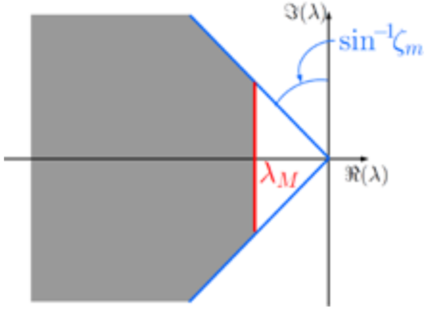
Control Problem

Problem. Given the platooning parameters h and τ_d, and the performance requirements $\mathbb{P}$, design gains k_p and k_d for the hybrid controller such that the vehicle platooning satisfies the following properties with the largest achievable value of Δ:

(P1) Individual vehicle stability with performance $\mathbb{P}$, i.e., $A_e \in \mathbb{P}$.

(P2) String stability.

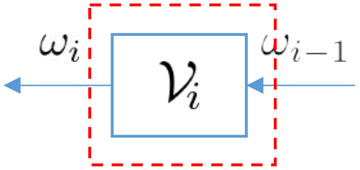
Performance



$A_e \in \mathbb{P}(\lambda_M, \zeta_m)$

+

String Stability



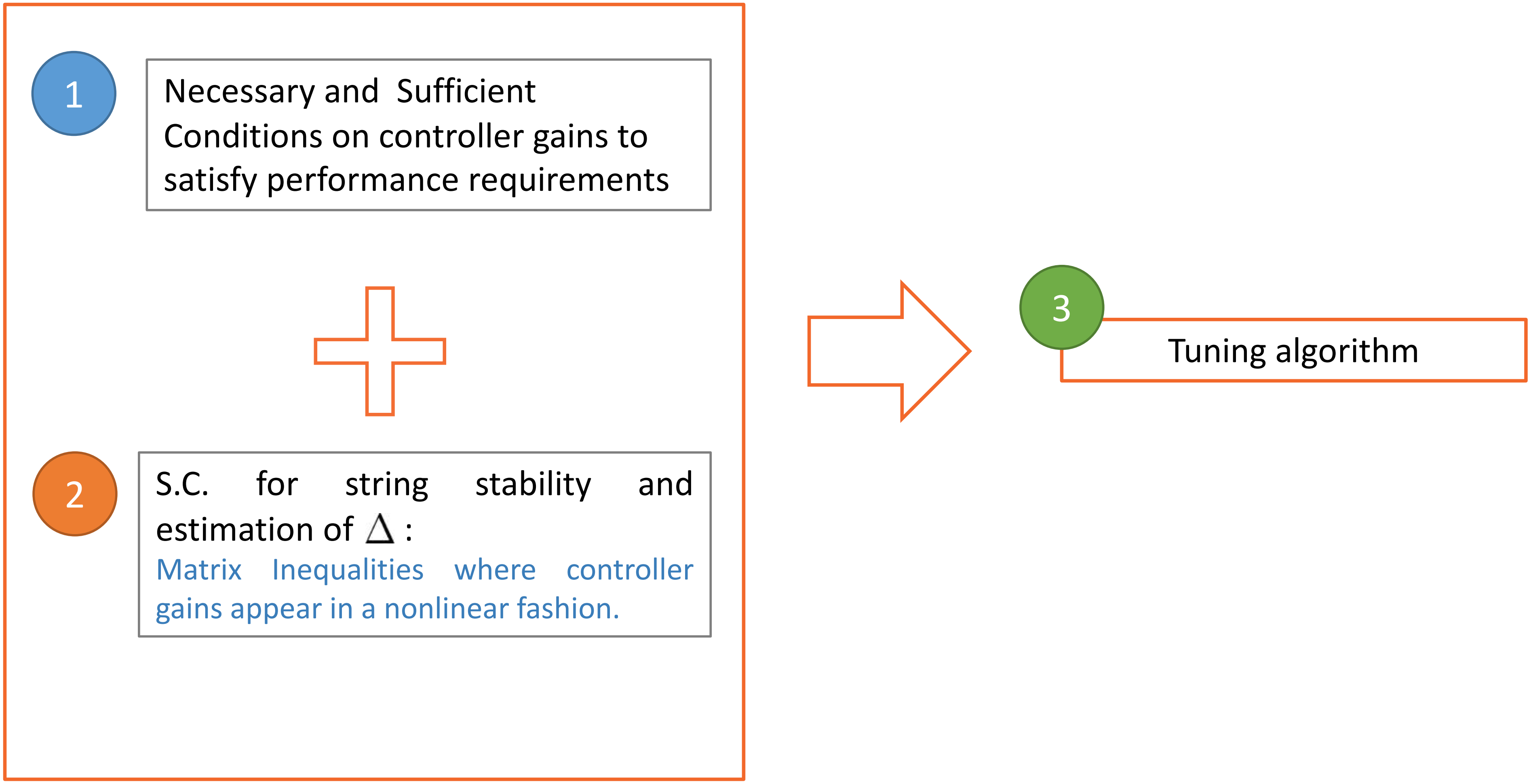
$$\frac{\|\omega_i\|_{\mathcal{L}_2}}{\|\omega_{i-1}\|_{\mathcal{L}_2}} \leq 1$$

+

Resiliency

$$\max \Delta$$

Design Approach



1

Necessary and Sufficient Conditions on controller gains to satisfy performance requirements

2

S.C. for string stability and estimation of Δ :

Matrix Inequalities where controller gains appear in a nonlinear fashion.

3

Tuning algorithm

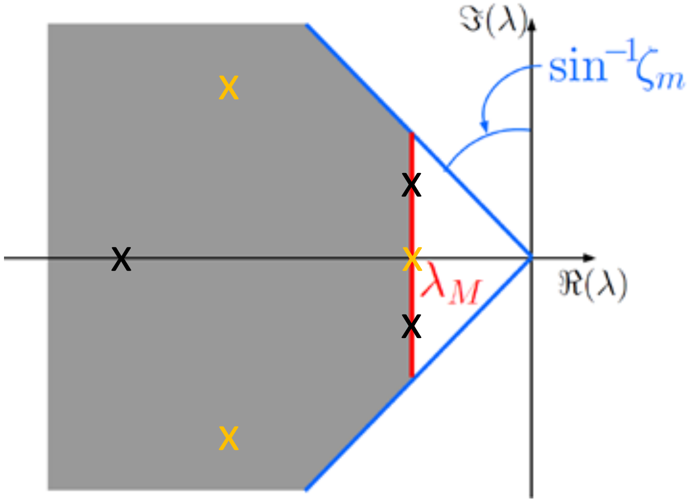
Controller Design: Individual Vehicle Stability

1

To satisfy performance

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

$$A_e = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\frac{k_p}{\tau_d} & -\frac{k_d}{\tau_d} & -\frac{1}{\tau_d} \end{bmatrix} \in \mathbb{P}(\lambda_M, \zeta_m)$$



Condition (C1). The real eigenvalue is equal to λ_M and, the other two eigenvalues have real part less than or equal to λ_M with damping ratio greater than ζ_m.

Condition (C2). The spectrum of A_e is characterized by a single couple of complex eigenvalues with real part equal to λ_M and damping ratio greater than ζ_m, and the other real eigenvalue is less than λ_M.

Controller Design: String Stability – Challenges in Matrix Inequalities

2

Lemma. Let $P_1 \in \mathcal{S}_+^4$, p_2, δ, τ_d, h, and T_s be given positive real number, $\Delta \in \mathbb{N}_0$, and k_p, and k_d be given real numbers. For each $\tau_{i-1} \in [0, (\Delta+1)T_s]$, define $\mathcal{M} : \tau_{i-1} \mapsto \mathcal{M}(\tau_{i-1})$. Then, $\mathrm{rge}\mathcal{M} = \mathrm{Co}\{\mathcal{M}(0), \mathcal{M}((\Delta+1)T_s)\}$. Therefore, $\mathcal{M}(\tau_{i-1}) < 0$, $\forall \tau_{i-1} \in [0, (\Delta+1)T_s]$ holds if and only if

$$\mathcal{M}(0) < 0, \quad \mathcal{M}((\Delta+1)T_s) < 0$$

$$\mathcal{M}(\tau_{i-1}) = \begin{pmatrix} \mathrm{He}(P_1 A_{xx}) + C_\omega^\top C_\omega & P_1 A_{x\eta} + C_\omega^\top + e^{-\delta\tau_{i-1}} p_2 A_{\eta x}^\top & P_1 A_{x\omega} \\ \bullet & -\delta p_2 e^{-\delta\tau_{i-1}} + 1 & -e^{-\delta\tau_{i-1}} p_2 / h \\ \bullet & \bullet & -1 \end{pmatrix} < 0, \ \forall \tau_{i-1} \in [0, (\Delta+1)T_s]$$

k_p, k_d, δ fixed.

k_d univocally determined by the choice of k_p via Conditions 1 and 2

k_p gridding on an interval known a priori.

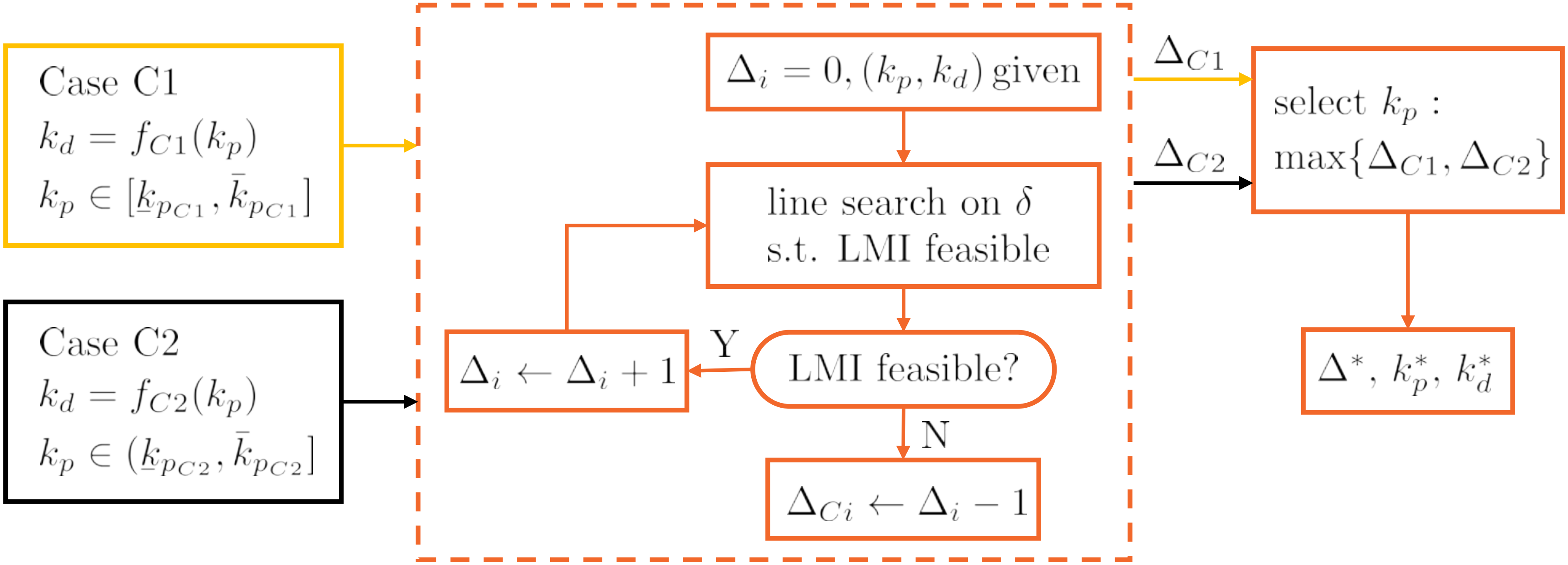
Controller Design: Tuning Algorithm

3

Design goal

$$\begin{aligned} \underset{P_1, p_2, \delta, k_p, k_d}{\text{maximize}} \quad & \Delta \\ \text{subject to} \quad & A_e \in \mathbb{P},\ \mathcal{M}(0) < 0,\ \mathcal{M}((\Delta+1)T_s) < 0 \end{aligned}$$

Design Algorithm



Case C1
$k_d = f_{C1}(k_p)$
$k_p \in [\underline{k}_{pC1}, \bar{k}_{pC1}]$

Case C2
$k_d = f_{C2}(k_p)$
$k_p \in (\underline{k}_{pC2}, \bar{k}_{pC2}]$

$\Delta_i = 0, (k_p, k_d)$ given

line search on δ
s.t. LMI feasible

LMI feasible?

Y

$\Delta_i \leftarrow \Delta_i + 1$

N

$\Delta_{Ci} \leftarrow \Delta_i - 1$

Δ_{C1}

Δ_{C2}

select k_p :
$\max\{\Delta_{C1}, \Delta_{C2}\}$

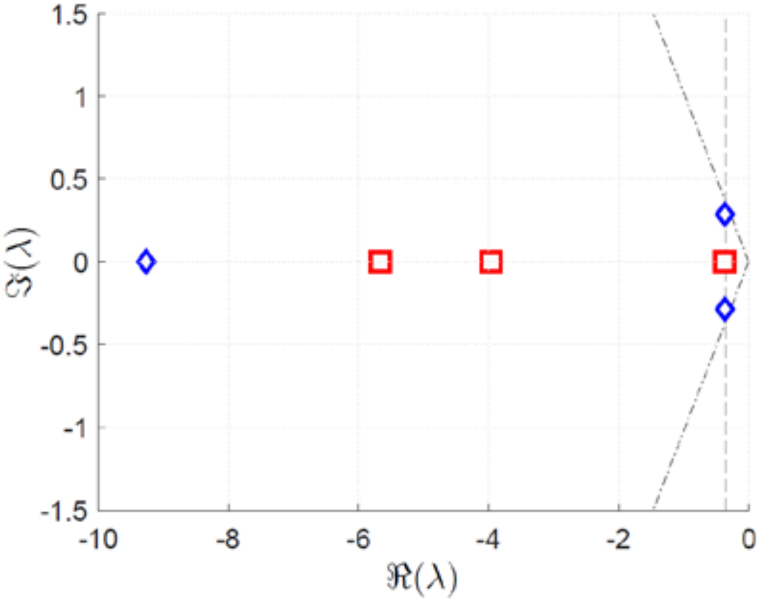
$\Delta^*,\ k_p^*,\ k_d^*$

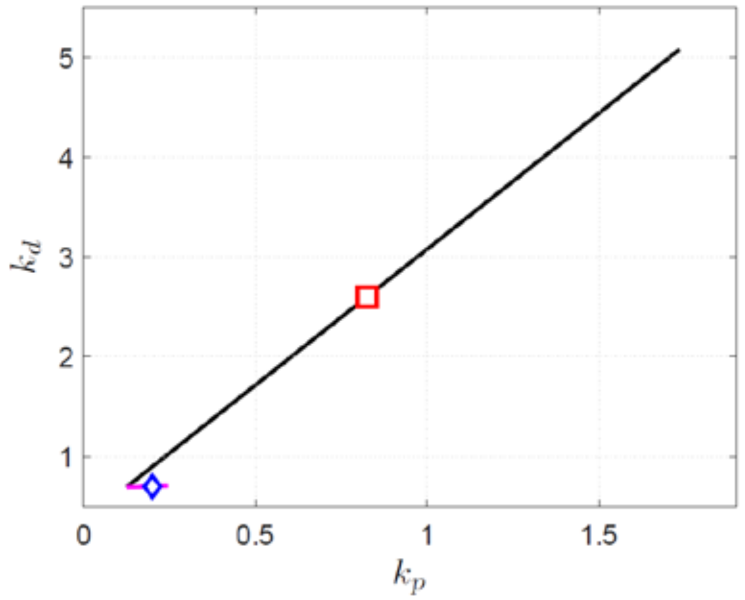
Numerical Results

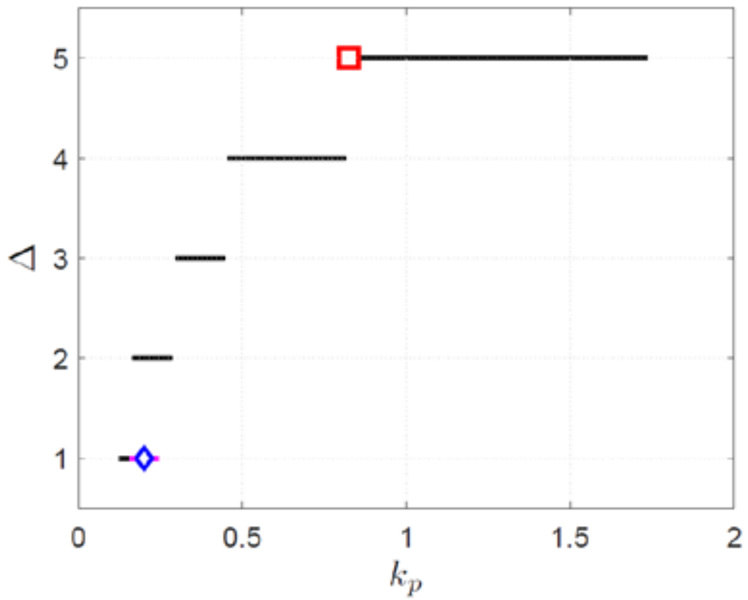
◇ Tuning as in [Ploeg et al CITS ‘11][1]

[1] J. Ploeg et al, “Design and experimental evaluation of cooperative adaptive cruise control,” in IEEE ITSC,2011.

□ Tuning as our approach





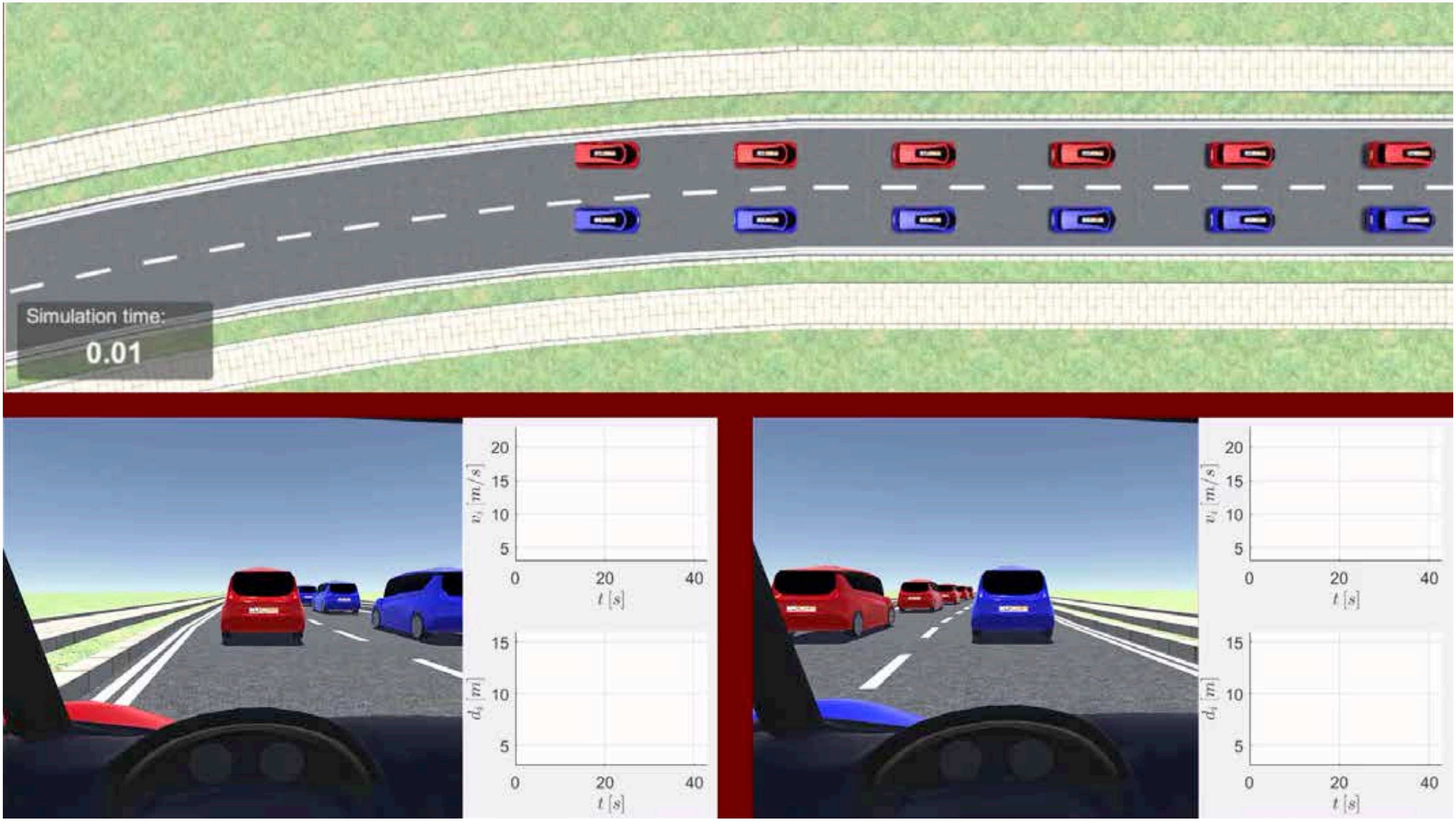


Available at:
R. Merco, F. Ferrante, P. Pisu, “DoS-Resilient Hybrid Controller for String-Stable Connected Vehicles”, IEEE Intelligent Vehicles Symposium (IV), 2019.

Numerical Results – DoS

Left lane, in red, network-resilient tuning

Right lane, in blue, non network-resilient tuning



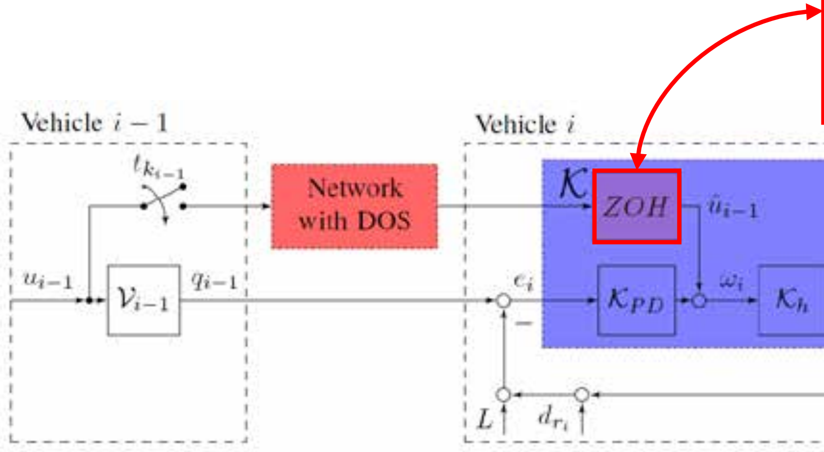
Inside last vehicle in the left lane
network-resilient tuning

Inside last vehicle in the right lane
non network-resilient tuning

CACC with intersample dynamics

Zero-Order Hold

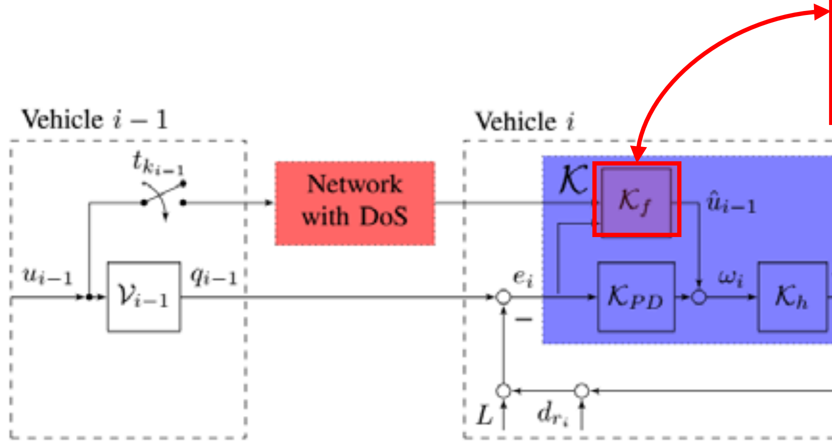
$$\begin{cases} \dot{\hat{u}}_{i-1}(t) = 0 & \forall t \neq t_{k_{i-1}} \;\vee\; \text{NoDoS} \\ \hat{u}_{i-1}(t^{+}) = u_{i-1}(t_{k_{i-1}}) & \forall t = t_{k_{i-1}} \;\wedge\; \text{DoS} \end{cases}$$



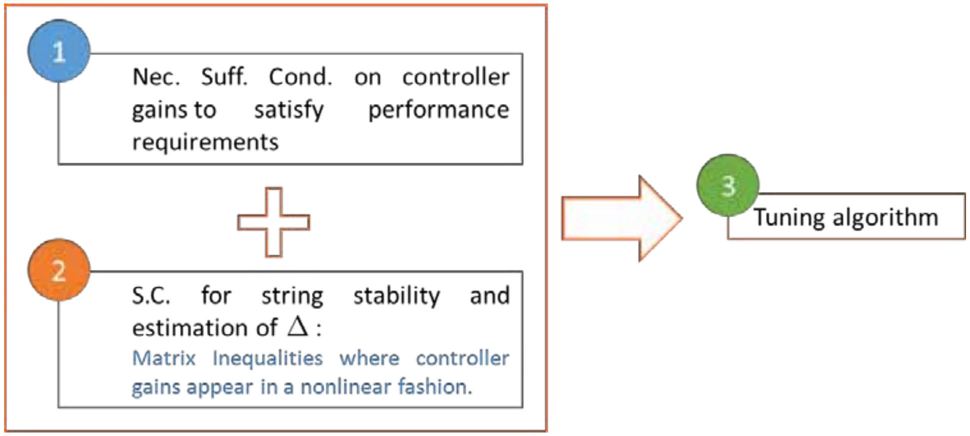
Can we enhance the ZOH by using continuous-time measurements in between communication updates?

Intersample Dynamics

$$\begin{cases} \dot{\hat{u}}_{i-1}(t) = \gamma_p e_i + \gamma_d \dot{e}_i & \forall t \neq t_{k_{i-1}} \;\vee\; \text{NoDoS} \\ \hat{u}_{i-1}(t^{+}) = u_{i-1}(t_{k_{i-1}}) & \forall t = t_{k_{i-1}} \;\wedge\; \text{DoS} \end{cases}$$



Design Approach Overview – CACC with Intersample Dynamics



Same design approach.

LMI conditions become design tool for intersample dynamics.

2

$$\mathcal{M}(\tau_{i-1}) = \begin{pmatrix} \mathrm{He}(P_1 A_{xx}) + C_\omega^\top C_\omega & A_{x\eta} + C_\omega^\top + e^{-\delta\tau_{i-1}} \begin{bmatrix} \gamma_p p_2 & \gamma_d p_2 & 0 & p_2/h \end{bmatrix}^\top & P_1 A_{x\omega} \\ \bullet & -\delta p_2 e^{-\delta\tau_{i-1}} + 1 & -p_2 e^{-\delta\tau_{i-1}}/h \\ \bullet & \bullet & -(1+\epsilon) \end{pmatrix}$$

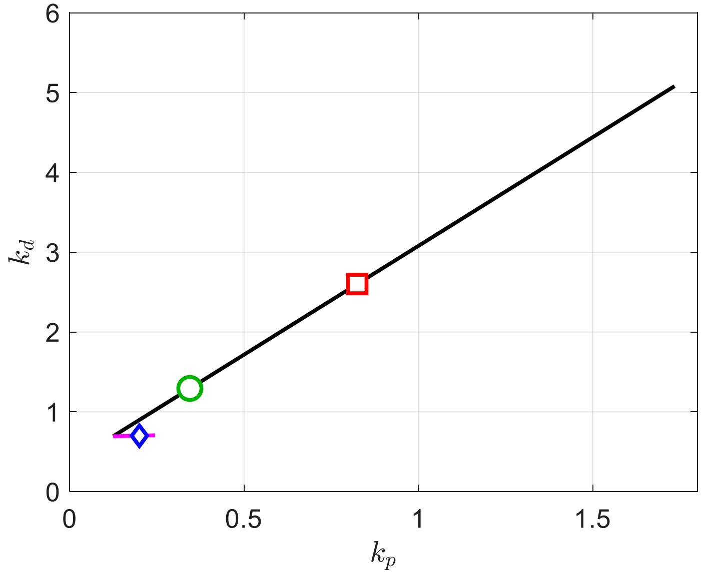
Change of variables

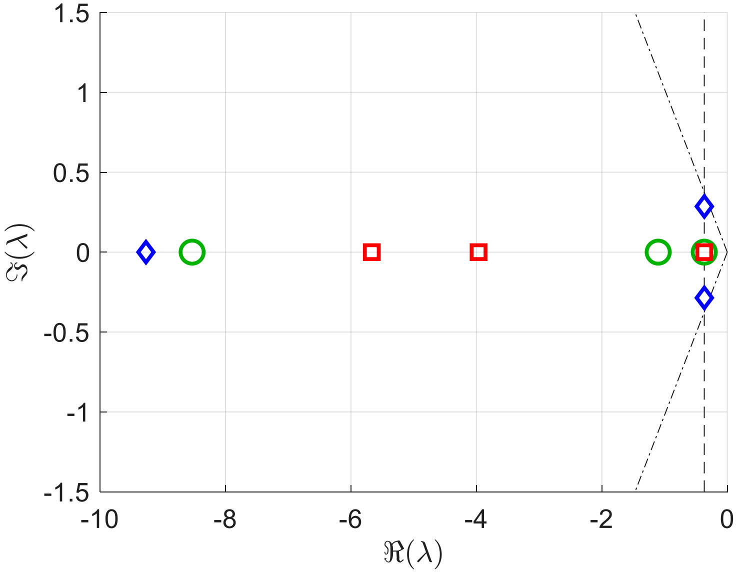
$$\gamma_p = \psi_p / p_2$$
$$\gamma_d = \psi_d / p_2$$

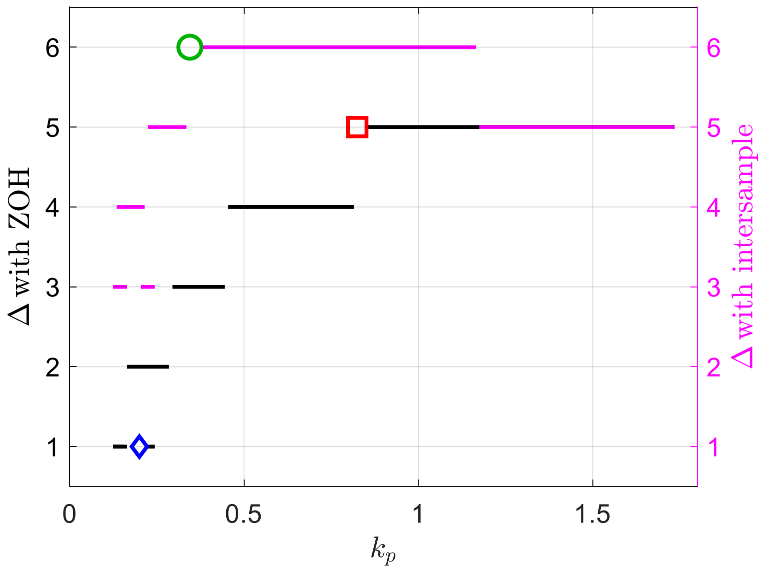
$$\widehat{\mathcal{M}}(\tau_{i-1}) = \begin{pmatrix} \mathrm{He}(P_1 A_{xx}) + C_\omega^\top C_\omega & A_{x\eta} + C_\omega^\top + e^{-\delta\tau_{i-1}} \begin{bmatrix} \psi_p & \psi_d & 0 & p_2/h \end{bmatrix}^\top & P_1 A_{x\omega} \\ \bullet & -\delta p_2 e^{-\delta\tau_{i-1}} + 1 & -p_2 e^{-\delta\tau_{i-1}}/h \\ \bullet & \bullet & -(1+\epsilon) \end{pmatrix}$$

Numerical Results

- ◇ Tuning as in [Ploeg et al CITS '11] (with ZOH)
- □ Tuning as our approach with ZOH
- ○ Tuning as our approach with Intersample







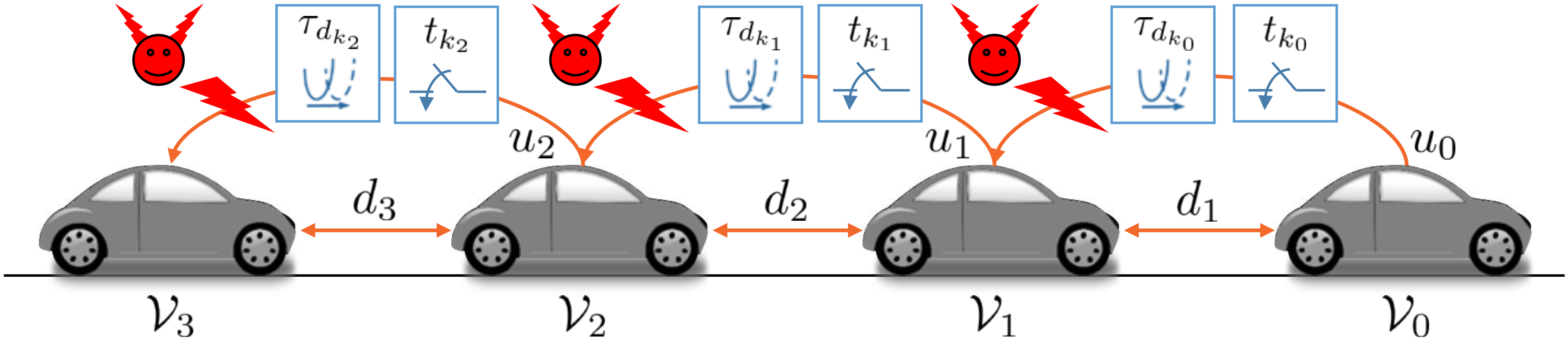
Numerical Results – evaluation for different time gaps

	Δ		k_p		k_d		$-\gamma_p$		γ_d	
h [s]	ZOH	INT	ZOH	INT	ZOH	INT	ZOH	INT	ZOH	INT
0.3	0	1	0.62	0.5	2.05	1.73	0	1.87	0	11.3
0.4	1	2	0.5	0.41	1.73	1.48	0	0.85	0	6.57
0.5	2	3	0.5	0.33	1.73	1.27	0	0.45	0	4.33
0.6	4	5	1.05	0.44	3.23	1.56	0	0.29	0	2.53
0.7	5	6	0.82	0.34	2.6	1.29	0	0.19	0	1.95
0.8	6	7	0.69	0.27	2.25	1.1	0	0.13	0	1.56
0.9	7	8	0.59	0.22	1.97	0.97	0	0.09	0	1.28
1	8	10	0.52	0.26	1.78	1.07	0	0.07	0	0.94
1.1	9	11	0.46	0.21	1.62	0.94	0	0.06	0	0.8
1.2	10	12	0.41	0.17	1.48	0.83	0	0.04	0	0.7

Remarks:

- Increasing time gaps, resilience increases.
- CACC with intersample always guarantee higher resilience.
- Resilience gained by increasing derivative action.

Adding Network Delays to the Resiliency Metric



Assumption:

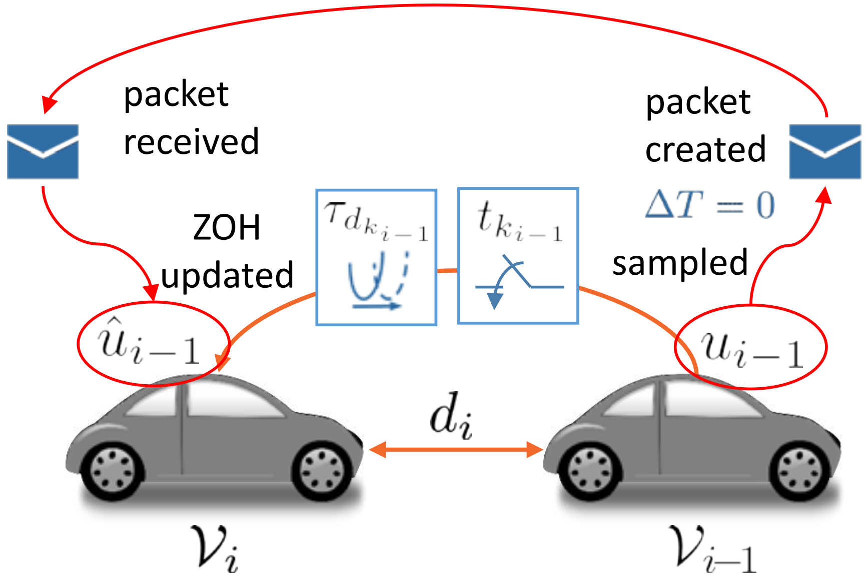
communication period

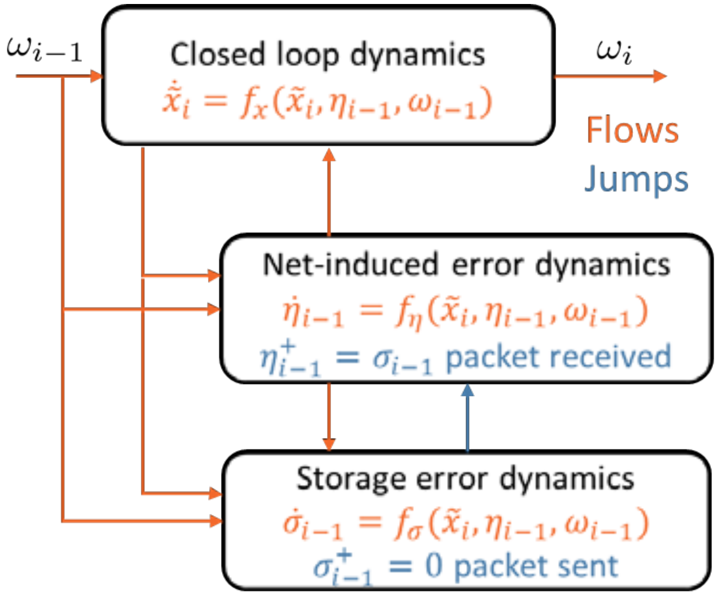
$$0 \leq \tau_{d_{k_i}} \leq T_{mad} \leq T_s$$

maximum allowable delay

- Packet disorder phenomena – forced dropouts for outdated information
- Packet dropouts and network delays captured in a simple and unified model
- Vehicle networks: communication frequency 10 to 20 Hz

Modeling Network Delays





Closed loop dynamics

$\dot{\tilde{x}}_i = f_x(\tilde{x}_i, \eta_{i-1}, \omega_{i-1})$

Net-induced error dynamics

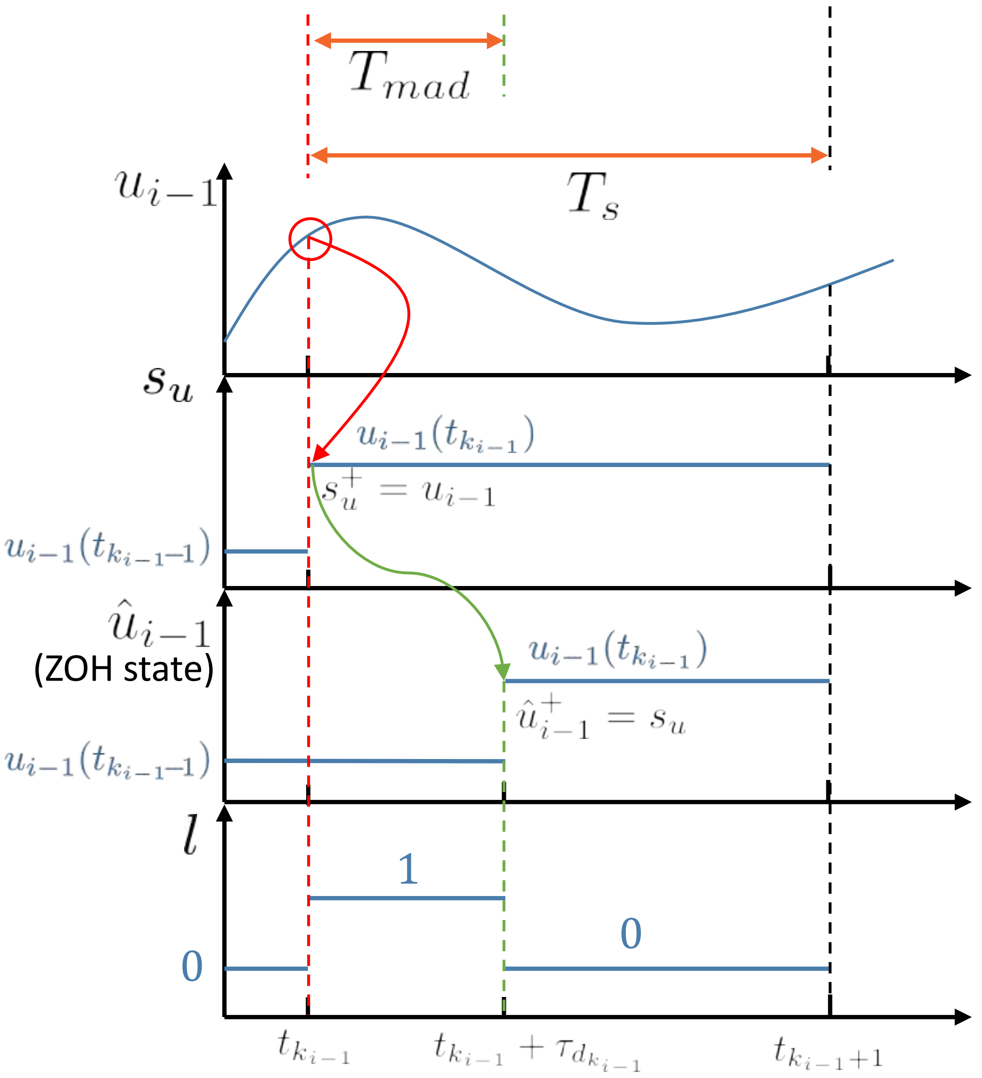
$\dot{\eta}_{i-1} = f_\eta(\tilde{x}_i, \eta_{i-1}, \omega_{i-1})$

$\eta^+_{i-1} = \sigma_{i-1}$ packet received

Storage error dynamics

$\dot{\sigma}_{i-1} = f_\sigma(\tilde{x}_i, \eta_{i-1}, \omega_{i-1})$

$\sigma^+_{i-1} = 0$ packet sent



General results for NCS available at:
R. Merco, F. Ferrante, P. Pisu, “On DoS Resiliency Analysis of Networked Control Systems: Trade-off between Jamming Actions and Network Delays”, IEEE Control Systems Letters, 2019

Stability Analysis

Sketch of the proof: based on Lyapunov theory for Hybrid Systems

$$V(x_i) = \underbrace{\tilde{x}_i^\top P_1 \tilde{x}_i}_{V_1(\tilde{x}_i)} + \underbrace{p_{2,l}\eta_{i-1}^2 e^{-\delta\tau_{i-1}}}_{V_2(\eta_{i-1},\tau_{i-1},l_{i-1})} + \underbrace{p_{3,l}\sigma_{i-1}^2 e^{-\delta\tau_{i-1}}}_{V_3(\sigma_{i-1},\tau_{i-1},l_{i-1})}$$

Decreases at jumps

$$p_{2,1} - e^{-\delta_2(1+\Delta)T_s} p_{2,0} \leq 0$$

$$p_{2,0} + p_{3,0} - p_{3,1} \leq 0$$

Decreases while flows

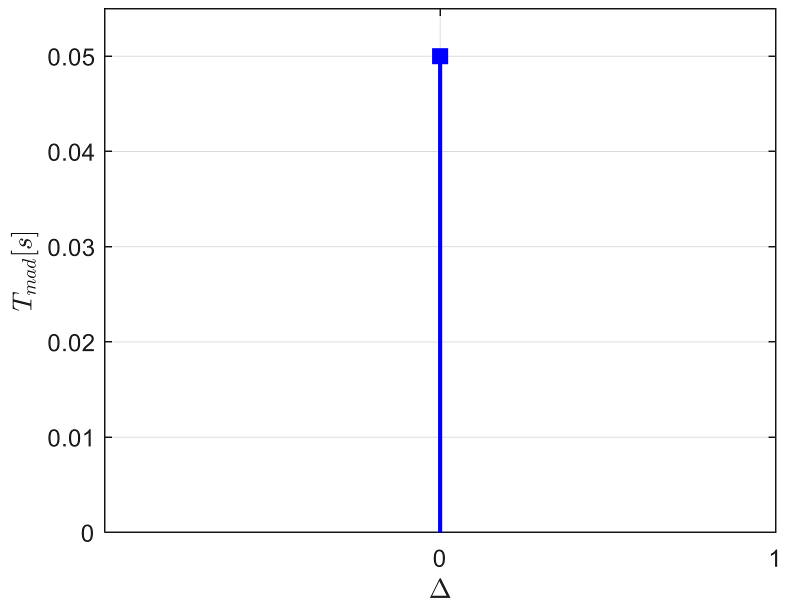
$$\mathcal{M}(\tau_{i-1}, l_{i-1}) < 0,$$
$$\forall \tau_{i-1} \in [0, (\Delta+1)T_s], l_{i-1} \in \{0,1\}$$

$$\mathcal{M}(\tau_{i-1}, l_{i-1}) =$$
$$\begin{pmatrix} \mathrm{He}(P_1 A_{xx}) + C_\omega^\top C_\omega & P_1 A_{x\eta} + C_\omega^\top + e^{-\delta\tau_{i-1}} p_{2,l_{i-1}} A_{\eta x}^\top & e^{-\delta\tau_{i-1}} p_{3,l_{i-1}} A_{\eta x}^\top & P_1 A_{x\omega} \\ \bullet & -\delta p_{2,l_{i-1}} e^{-\delta\tau_{i-1}} + 1 & 0 & -e^{-\delta\tau_{i-1}} p_{2,l_{i-1}}/h \\ \bullet & \bullet & -\delta e^{-\delta\tau_{i-1}} p_{3,l_{i-1}} & -e^{-\delta\tau_{i-1}} p_{3,l_{i-1}}/h \\ \bullet & \bullet & \bullet & -\theta^2 \end{pmatrix}$$

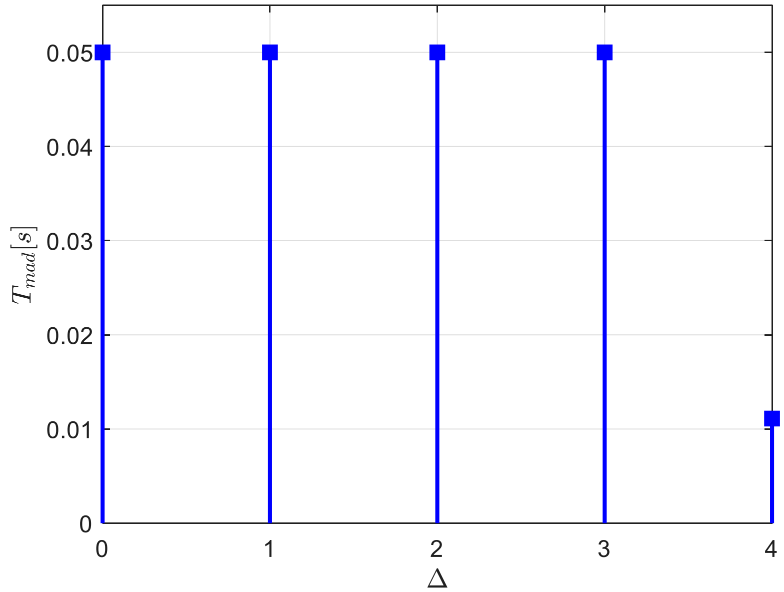
$\mathcal{L}_2$-stability

General results for NCS available at:
R. Merco, F. Ferrante, P. Pisu, "On DoS Resiliency Analysis of Networked Control Systems: Trade-off between Jamming Actions and Network Delays", IEEE Control Systems Letters, 2019

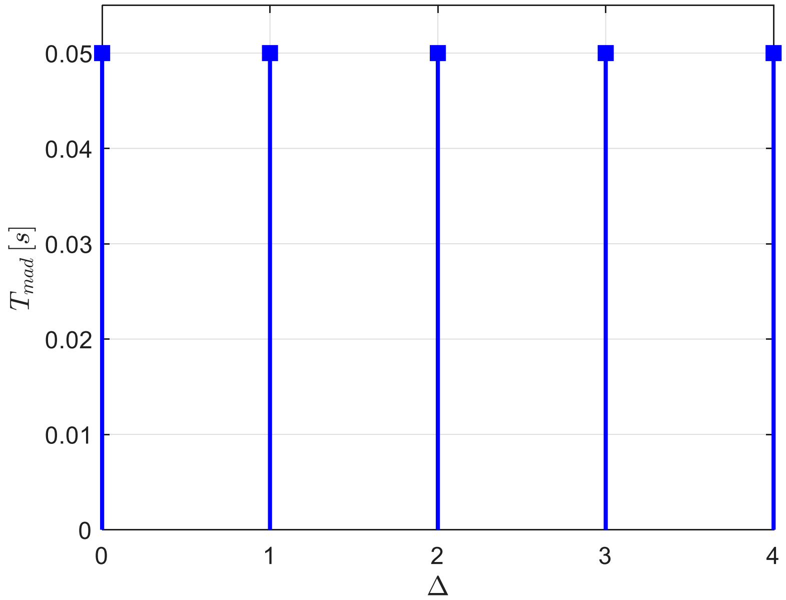
Numerical Results



Tuning as [Ploeg et al CITS '11]

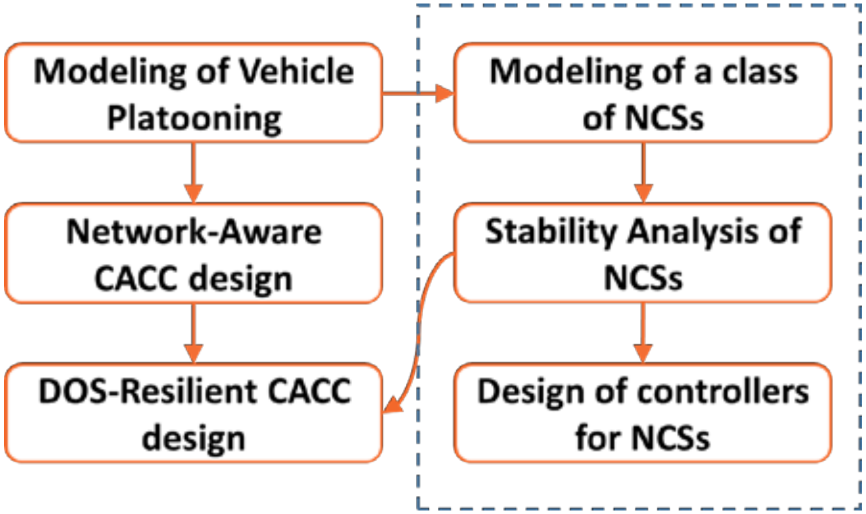


Tuning as our approach with ZOH



Tuning as our approach with Intersample

From Vehicle Platooning to a Class of Networked Control Systems



Modeling of Vehicle Platooning

Network-Aware CACC design

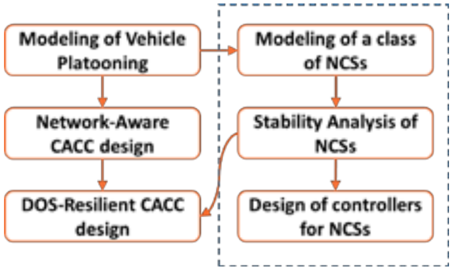
DOS-Resilient CACC design

Modeling of a class of NCSs

Stability Analysis of NCSs

Design of controllers for NCSs

From Vehicle Platooning to a Class of Networked Control Systems



Modeling of Vehicle Platooning

Network-Aware CACC design

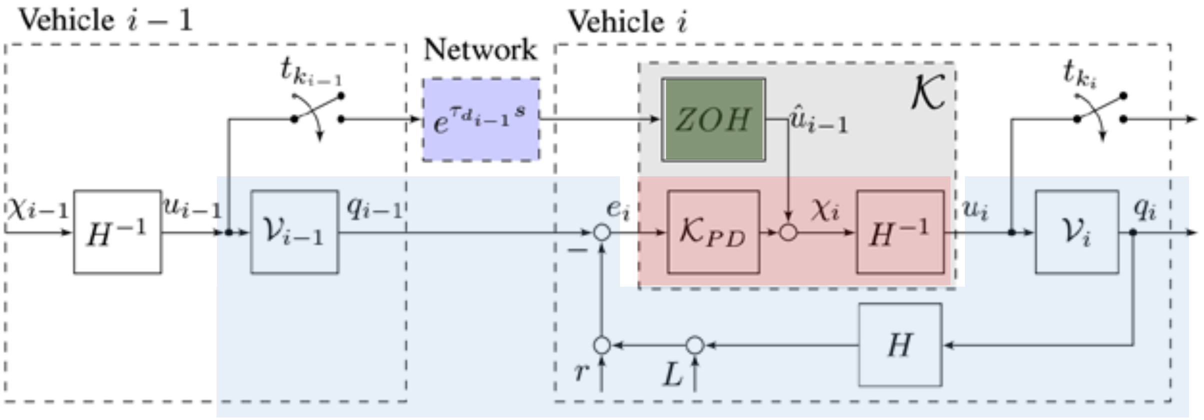
DOS-Resilient CACC design

Modeling of a class of NCSs

Stability Analysis of NCSs

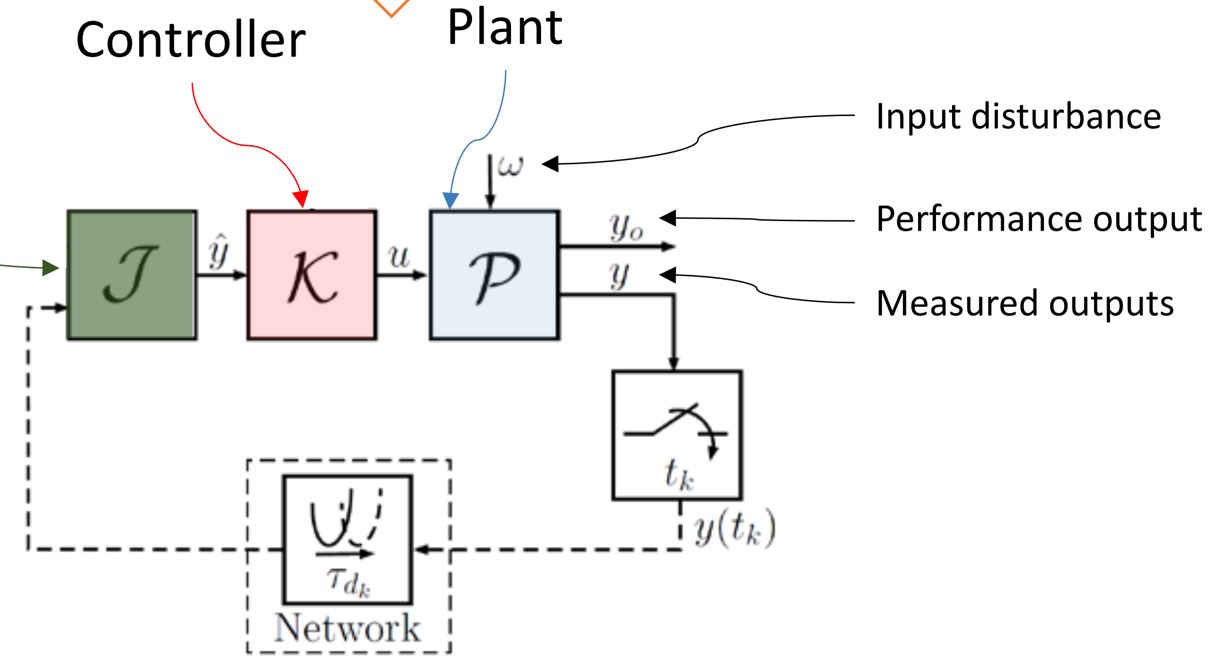
Design of controllers for NCSs

Vehicle Platooning model



Generic Networked Control System

Holding Device



Controller

Plant

Input disturbance

Performance output

Measured outputs

Applications based on remote networked sensors:

- Drones
- Smart Grids
- Process control
- …

Research Gaps

Majority of existing design approaches:

1. Does not consider dynamic output feedback controllers

$$\mathcal{K}\begin{cases}\dot{x}_c = A_c x_c + B_c \hat{y} \\ u = C_c x_c + D_c \hat{y}\end{cases}$$

More suitable to account for performance → For example: $\mathcal{H}_\infty$ robust controllers

2. Are not suitable for the evaluation of trade-off curves as shown earlier

   When NCS are not modeled as hybrid systems, network delays and packet dropping are commonly not considered together

3. Use Zero-Order Hold (ZOH) as holding device

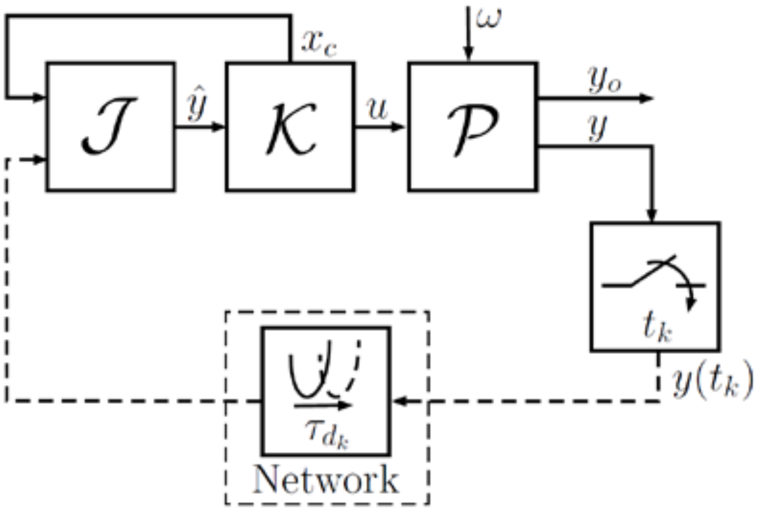
$$ZOH\begin{cases}\dot{\hat{y}}(t) = 0 & \forall t \neq t_k + \tau_{d_k} \\ \hat{y}(t^+) = y(t_k) & \forall t = t_k + \tau_{d_k}\end{cases}$$

Suitable for small transmission intervals, but potentially not for long period without network updates

4. Does not explicitly account for network unreliability metrics in the stability analysis

   Network resilience does not appear directly in design conditions

Problem Statements



$$\mathcal{P}\begin{cases}\dot{x}_p = A_p x_p + B_p u + W\omega \\ y = C_p x_p \\ y_o = C_o x_p\end{cases}$$

$$\mathcal{K}\begin{cases}\dot{x}_c = A_c x_c + B_c \hat{y} \\ u = C_c x_c + D_c \hat{y}\end{cases}$$

$$\mathcal{J}\begin{cases}\dot{\hat{y}}(t) = H\hat{y}(t) + E x_c(t) & \forall t \neq t_k + \tau_{d_k} \\ \hat{y}(t^+) = y(t_k) & \forall t = t_k + \tau_{d_k}\end{cases}$$

To address research gaps we solve:

Problem #1 (Compute Trade-off Curves):
Assume controller and holding device given. Find trade-off curves between transmission intervals and network delays such that the NCS is input-output stable.

Problem #2 (Controller Design):
Design controller and holding device such that the NCS is input-output stable with the largest transmission intervals.

Challenges

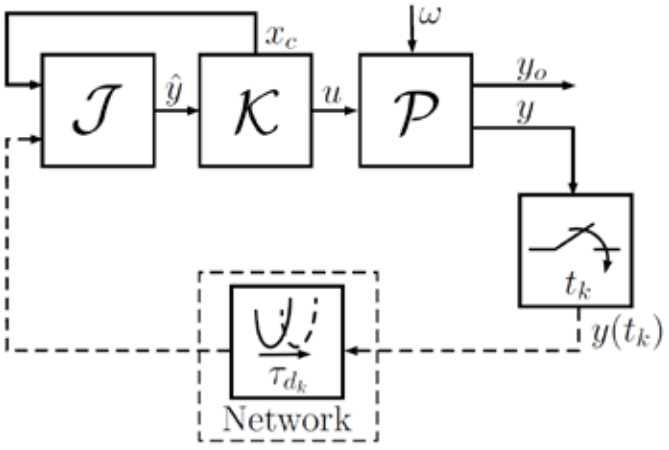
Challenges for Problem #1 (Compute Tradeoff Curves) and Problem #2 (Controller Design):

1. Choice of clock-dependent Lyapunov function (related to Problem #1 and #2)
   - Lyapunov function for Hybrid Dynamical Systems must be properly designed:
     - Decreases during flows
     - Decreases as jumps
     - Conservatism of the trade-off curves

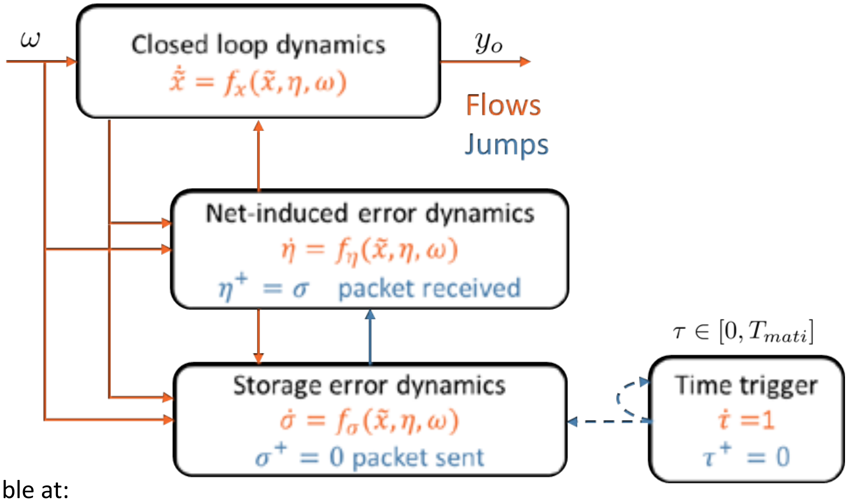
2. Linearization of matrix inequalities
   - Linearization of stability conditions (related to Problem #1 and #2)
   - Controller parameters linearization (related to Problem #2)

Problem #1: Compute Trade-off Curves

Networked Control System



Hybrid dynamical system for stability analysis


ω

Closed loop dynamics
$\dot{\tilde{x}} = f_x(\tilde{x},\eta,\omega)$

y_o

Flows
Jumps

Net-induced error dynamics
$\dot{\eta} = f_\eta(\tilde{x},\eta,\omega)$
$\eta^+ = \sigma$ packet received

$\tau \in [0, T_{mati}]$

Storage error dynamics
$\dot{\sigma} = f_\sigma(\tilde{x},\eta,\omega)$
$\sigma^+ = 0$ packet sent

Time trigger
$\dot{\tau} = 1$
$\tau^+ = 0$

Challenge:

Find the Clock-Dependent Lyapunov function

$$V(x) = \underbrace{\tilde{x}^\top P_1 \tilde{x}}_{V_1(\tilde{x})} + \underbrace{e^{-\delta\tau}\eta^\top P_{2,l}\eta}_{V_2(\eta,\tau,l)} + \underbrace{e^{-\delta\tau}\sigma^\top P_{3,l}\sigma}_{V_3(\sigma,\tau,l)}$$

Decreases at jumps

$$P_{2,1} - e^{-\delta(T_{mati})} P_{2,0} \leq 0$$
$$P_{2,0} + P_{3,0} - P_{3,1} \leq 0$$

Decreases during flows

$$\mathcal{M}(\tau, l) < 0,$$
$$\forall \tau \in [0, T_{mati}], l \in \{0, 1\}$$

Available at:
R. Merco, F. Ferrante, P. Pisu, “On DoS Resiliency Analysis of Networked Control Systems: Trade-off between Jamming Actions and Network Delays”, IEEE Control Systems Letters, 2019

Problem #1: Compute Trade-off Curves

Clock-Dependent Lyapunov function

$$V(x) = \underbrace{\tilde{x}^\top P_1 \tilde{x}}_{V_1(\tilde{x})} + \underbrace{e^{-\delta\tau} \eta^\top P_{2,l} \eta}_{V_2(\eta,\tau,l)} + \underbrace{e^{-\delta\tau} \sigma^\top P_{3,l} \sigma}_{V_3(\sigma,\tau,l)}$$

Decreases at jumps

$$P_{2,1} - e^{-\delta(T_{mati})} P_{2,0} \leq 0$$
$$P_{2,0} + P_{3,0} - P_{3,1} \leq 0$$

Decreases during flows

$$\mathcal{M}(\tau, l) < 0,$$
$$\forall \tau \in [0, T_{mati}], l \in \{0, 1\}$$

Challenges:

- Variables appear in a nonlinear fashion
- Infinite conditions to be satisfies

Proposed solutions:

- Line search on δ
- Employ convexity of $\mathcal{M}(\tau, l)$

⇩

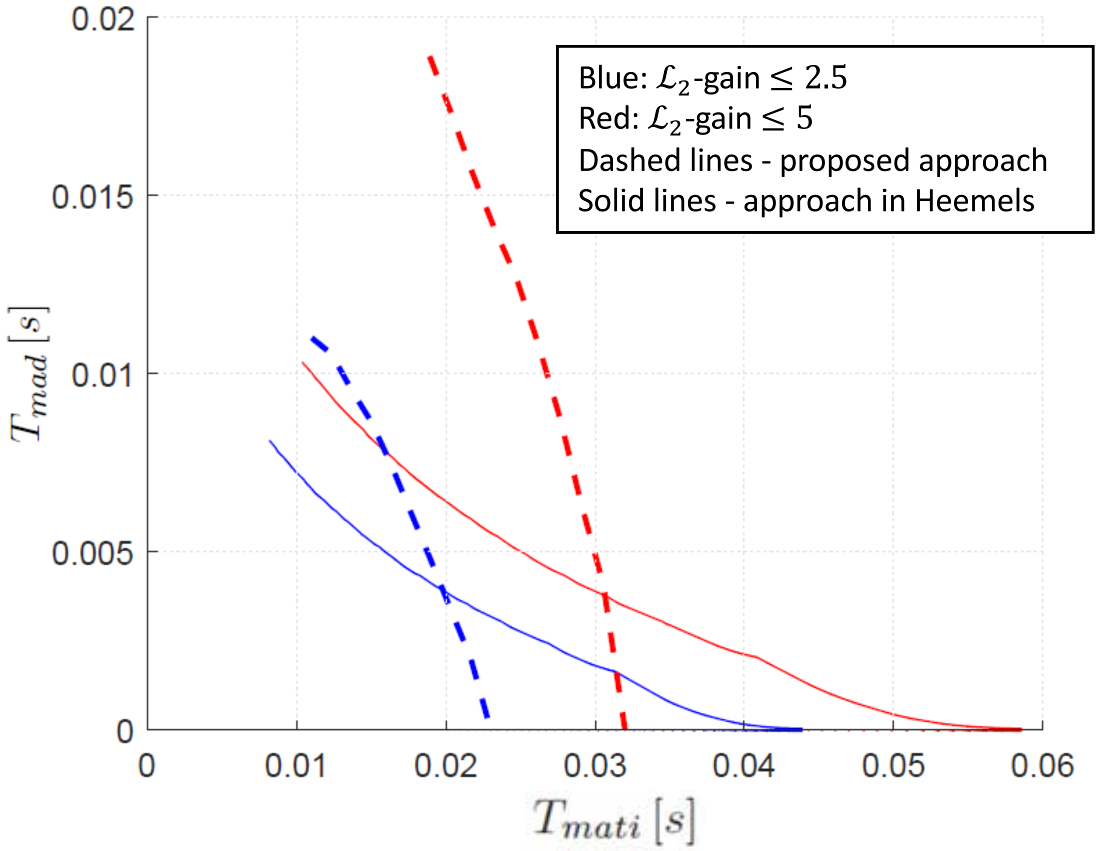
$$\mathcal{M}(0,1) < 0,\ \mathcal{M}(T_{mad}, 1) < 0,$$
$$\mathcal{M}(T_{mad}, 0) < 0,\ \mathcal{M}(T_{mati}, 0) < 0$$

Stability conditions expose trade-off curves parameters:

- Stability at a network operating point can be directly checked
- Trade-off curves can be obtained by an iterative algorithm by changing T_{mad}, T_{mati}

Problem #1: Compute Trade-off Curves – Example

Batch reactor: output feedback control system
$\mathcal{L}_2$ stability



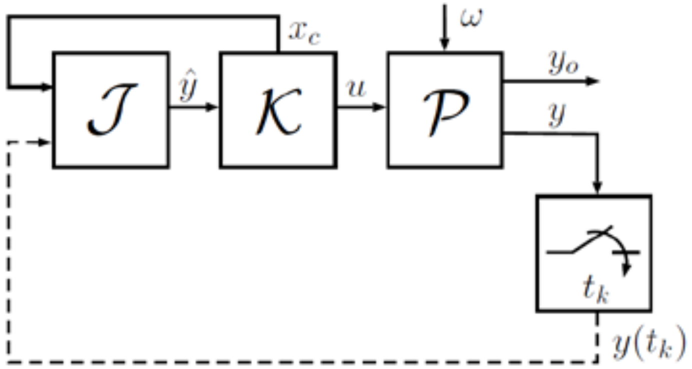
For this control system:

- Approach in Heemels et al. is less conservative for transmission intervals
- Proposed approach is less conservative for network delays
- Proposed approach accounts for intersample dynamics

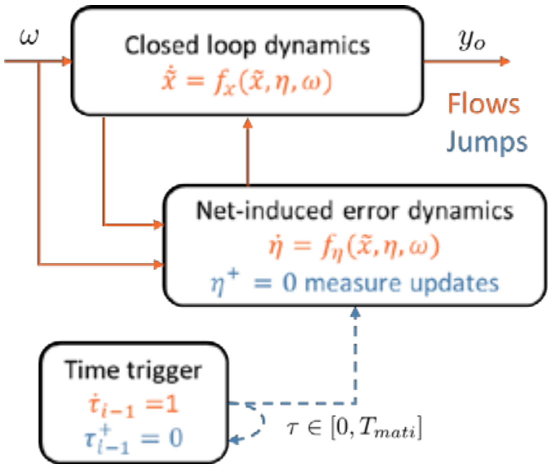
W.P.M.H. Heemels, A. R. Teel, N. Van de Wouw, and D. Neˇsi´c. Networked control systems with communication constraints: Tradeoffs between transmission intervals, delays and performance. IEEE Transactions on Automatic Control, 55(8):1781–1796, 2010.

Problem #2: Dynamic Output Feedback Controller Design

Networked Control System



Hybrid dynamical system for stability analysis



Approach in Scherer et al. introduced for $\mathcal{H}_\infty$ control design, does not work in this case.

Challenge:

Find the Clock-Dependent Lyapunov function such that stability conditions turn into linear matrix inequality.

Parameters of controller and holding device can be computed by employing semidefinite programming tools.

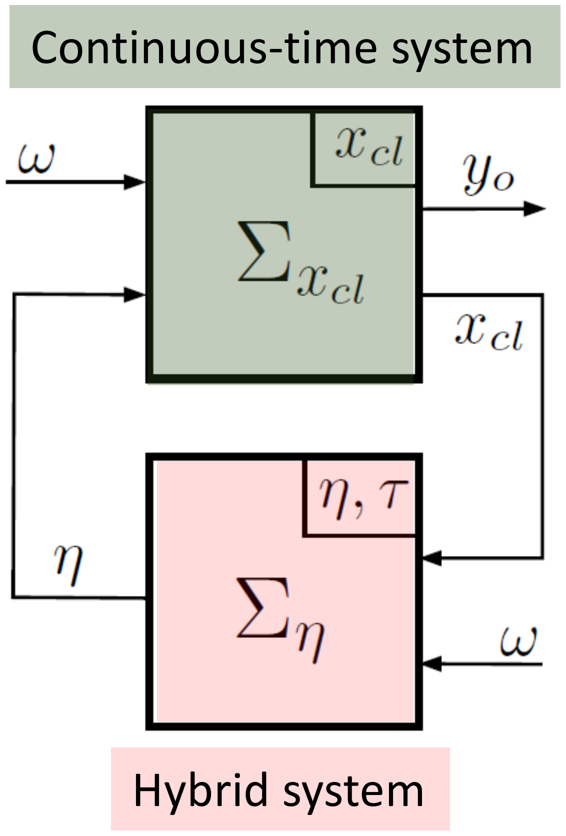
$$\mathcal{H}\left\{\begin{array}{l} \left.\begin{array}{l} \dot{x}_p = (A_p+B_pD_cC_p)x_p + B_pC_cx_c - B_pD_c\eta \\ \dot{x}_c = A_cx_c+B_cC_px_p - B_c\eta \\ \dot{\eta} = (C_pA_p - HC_p)x_p + Ex_c + H\eta \\ \dot{\tau} = -1 \qquad \eta := y - \hat{y} \end{array}\right\} (x_p, x_c, \eta, \tau) \in \mathcal{C} \\ \left.\begin{array}{l} x_p^+ = x_p \\ x_c^+ = x_c \\ \eta^+ = 0 \\ \tau^+ \in [T_1, T_2] \end{array}\right\} (x_p, x_c, \eta, \tau) \in \mathcal{D} \end{array}\right.$$

C. Scherer, P. Gahinet, and M. Chilali. Multiobjective output-feedback control via LMI optimization. IEEE Transactions on Automatic Control, 42(7):896–911, 1997.

Problem #2: Dynamic Output Feedback Controller Design

Proposed solutions:

Approach reminiscent of an “input-to-state stability small gain” philosophy.



$$\Sigma_{x_{cl}}: \begin{bmatrix} \dot{x}_p \\ \dot{x}_c \end{bmatrix} = \mathbb{A} \underbrace{\begin{bmatrix} x_p \\ x_c \end{bmatrix}}_{x_{cl}} + \mathbb{B}\eta$$

$$\Sigma_\eta: \begin{cases} \begin{bmatrix} \dot{\eta} \\ \dot{\tau} \end{bmatrix} = \begin{bmatrix} H\eta + \mathbb{J}\bar{x} \\ -1 \end{bmatrix} & \tau \in [0, T_2] \\ \begin{bmatrix} \eta^+ \\ \tau^+ \end{bmatrix} \in \begin{bmatrix} 0 \\ [T_1, T_2] \end{bmatrix} & \tau = 0 \end{cases}$$

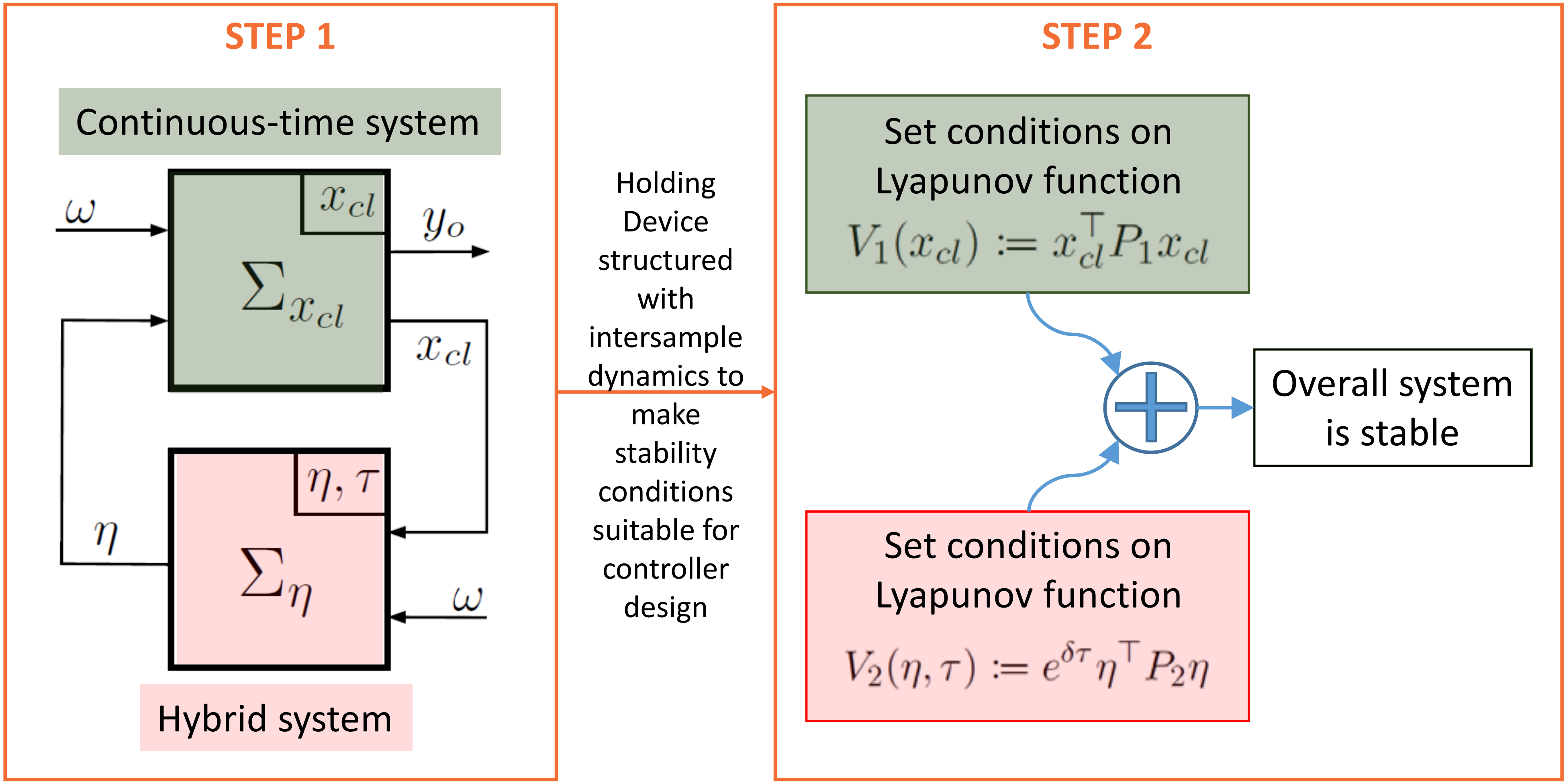
$$\mathbb{A} := \left[\begin{array}{c|c} A_p + B_p D_c C_p & B_p C_c \\ \hline B_c C_p & A_c \end{array} \right], \quad \mathbb{B} := -\left[\begin{array}{c} B_p D_c \\ \hline B_c \end{array} \right]$$

$$\mathbb{J} := \left[\begin{array}{c|c} C_p A_p - H C_p & -E \end{array} \right]$$

Problem #2: Dynamic Output Feedback Controller Design

Proposed solutions:

Approach reminiscent of an “input-to-state stability small gain” philosophy.



STEP 1

Continuous-time system

Hybrid system

Holding Device structured with intersample dynamics to make stability conditions suitable for controller design

STEP 2

Set conditions on Lyapunov function

$$V_1(x_{cl}) := x_{cl}^\top P_1 x_{cl}$$

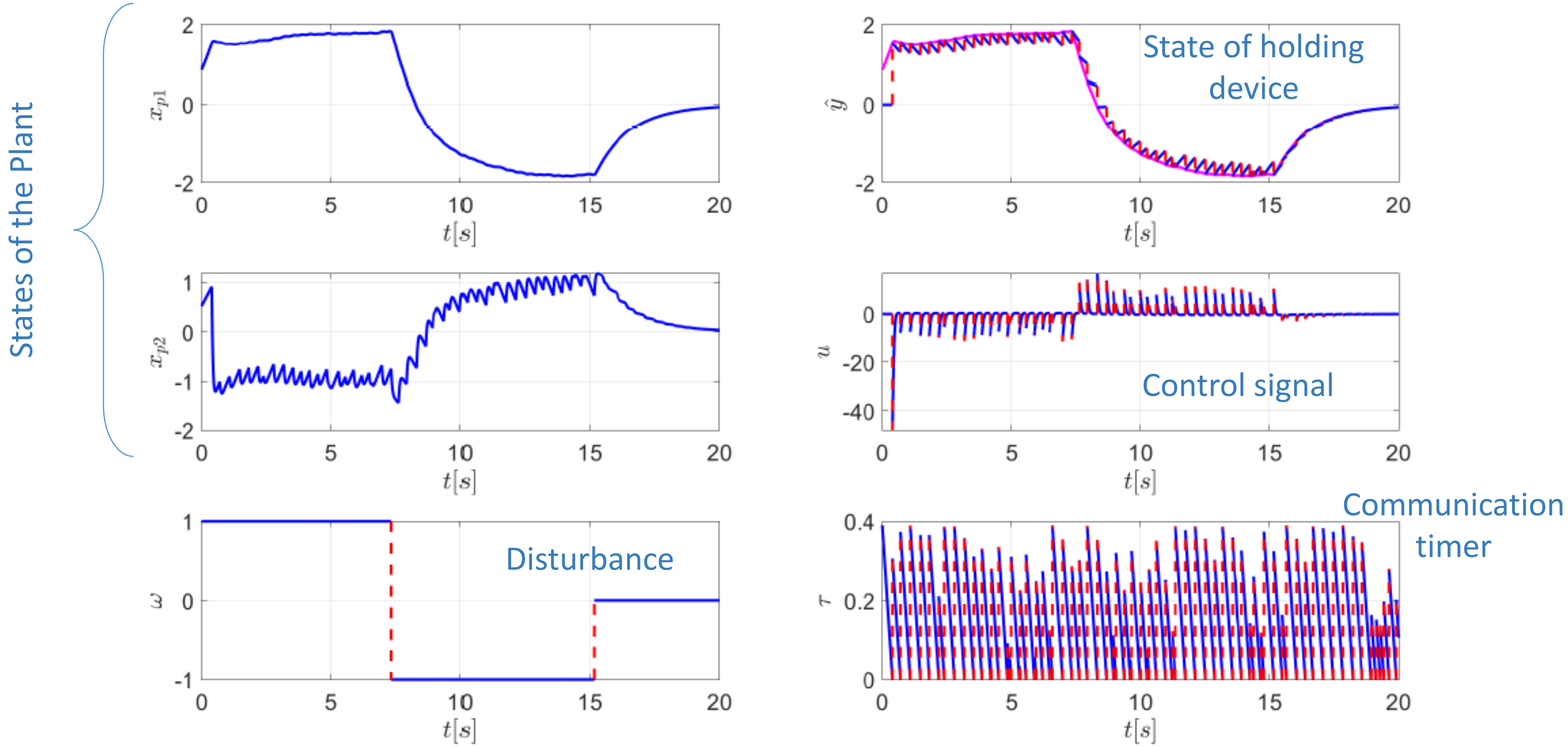
Set conditions on Lyapunov function

$$V_2(\eta, \tau) := e^{\delta\tau} \eta^\top P_2 \eta$$

Overall system is stable

Problem #2: Dynamic Output Feedback Controller Design – Example

$\mathcal{L}_2$ stability of a double integrator with $\mathcal{L}_2$ gain less than or equal to 5.
A value of $T_{mati} = 0.39\,s$ is obtained by design.



States of the Plant

State of holding device

Control signal

Disturbance

Communication timer

R. Merco, F. Ferrante, R. Sanfelice, P. Pisu, “LMI-Based Output Feedback Control Design in the Presence of Sporadic Measurements”, American Control Conference (ACC), 2020.

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Prof. Ricardo Sanfelice, University of California, Santa Cruz, CA

THANK YOU FOR YOUR ATTENTION!

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