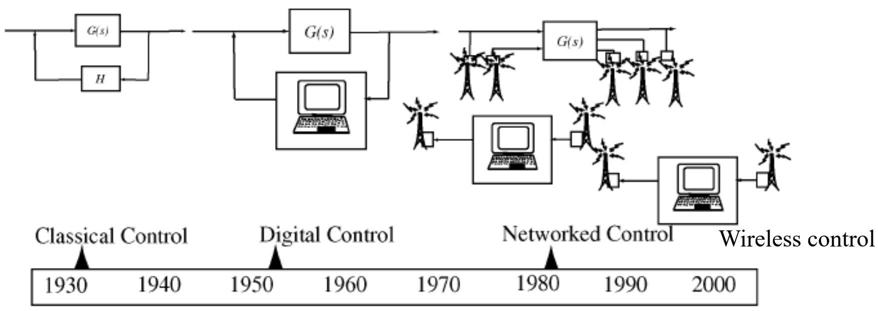

1

# A brief history of control

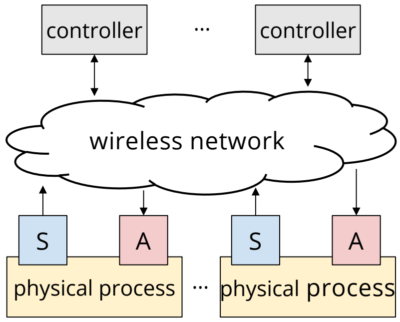



**From dedicated** communication links and networks for control systems
**To open and ubiquitous** wireless networks for control applications

Adopted from [Baillieul & Antsaklis, 2007]

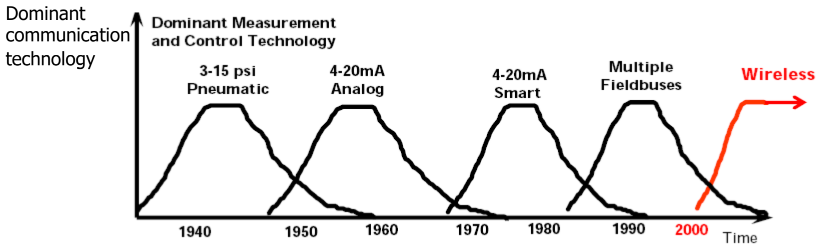
3

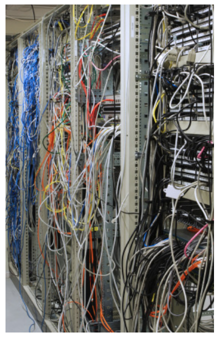
# From Pneumatic to Wireless




Wireless networked control systems benefit from

- Reduced cabling cost by $300–$6000/m
- Lower installation, operation, and maintenance costs
- Increased sensing & control capabilities and flexibility
- Possibility to locate controllers anywhere in the network



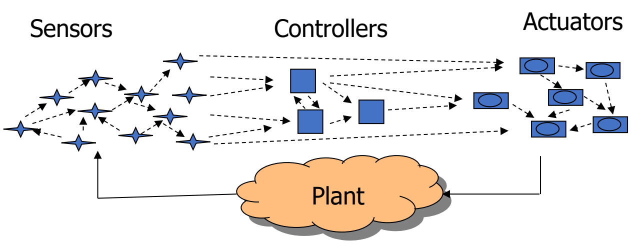



Samad et al., 2007; ISA

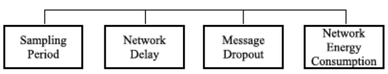
4

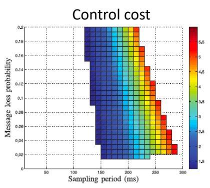
# Wireless networked control

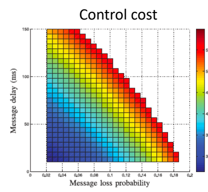
How to systematically share common network resources while maintaining guaranteed closed-loop performance?




Communication-control interactive variables




Park et al., IEEE Communications Surveys & Tutorials, 2018.

5

# Outline

- Introduction
- Theory
- Applications
- Conclusions

6

6

# Outline

- Introduction
- Theory
    - Optimal communication and control co-design
- Applications
    - Truck platooning
    - Pulp and paper processes
    - Shared-autonomy systems
- Conclusions

7

7

# Joint Design of Plant and Network Controls

Plant model:

$$\mathcal{P}: x_{k+1} = Ax_k + Bu_k + w_k$$
$$x_0 \sim \mathcal{N}(0, \Sigma_0) \; w_k \sim \mathcal{N}(0, W)$$

Network model:

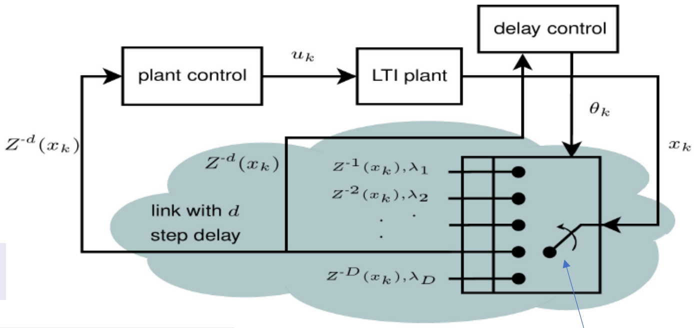
delay variable: $d \in \{1, \ldots, D\}$
$Z^{-d}(x_k) \to x_k$ delivered at $k+d$

$$\theta_k^i = \begin{cases} 1, & \text{link with } i \text{ step delay is selected at time } k \\ 0, & \text{link with } i \text{ step delay is not selected at time } k \end{cases}$$

Associated communication price $\rightarrow$ $\lambda_d$ for $d$-step delay

$$\lambda_1 > \lambda_2 > \ldots > \lambda_D, \quad \lambda_d \in \mathbb{R}_{\geq 0}$$

One link to be selected at each time $\rightarrow \sum_{i=1}^{D} \theta_k^i = 1, \; \forall \, k$




Network resource control algorithm decides on how urgently sensor data should be delivered to the controller

Maity et al., 2018





# Information Structure and Optimal Control

Information available at delay control:

$$\mathcal{I}_k \triangleq \{\mathcal{Y}_0, \ldots, \mathcal{Y}_{k-1}, u_0, \ldots, u_{k-1}, \cup_{t=1}^{k-1}\{\theta_t\}\}$$

$$\mathcal{Y}_k = \{\theta_{k-1}^1 x_{k-1}, \theta_{k-2}^2 x_{k-2}, \ldots, \theta_{k-D}^D x_{k-D}\}$$

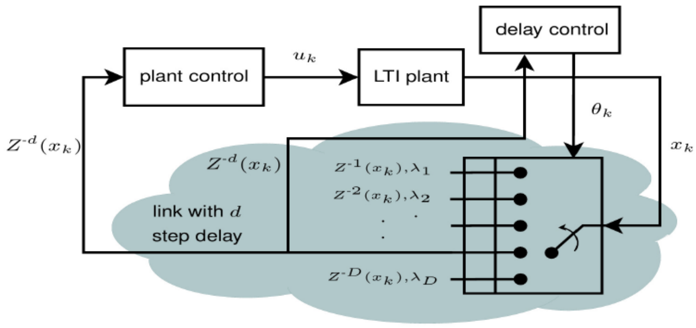
Information available at plant control:

$$\bar{\mathcal{I}}_k \triangleq \{\mathcal{I}_k, \mathcal{Y}_k, \theta_k\}$$

Joint optimal control cost function:

$$J(u,\theta) = \mathsf{E}\left[\underbrace{\sum_{t=0}^{T-1}\left[x_t^\top Q_1 x_t + u_t^\top R u_t\right] + x_T^\top Q_2 x_T}_{\text{control cost}} + \underbrace{\sum_{t=0}^{T-1} \theta_t^\top \Lambda}_{\text{delay cost}}\right]$$

where $\Lambda \triangleq [\lambda_1, \ldots, \lambda_D]^\top$, $Q_1 \succeq 0$, $Q_2 \succeq 0$, and $R \succ 0$.




Non-classical control problem because of the information structure, cf. [Witsenhausen, 1971].

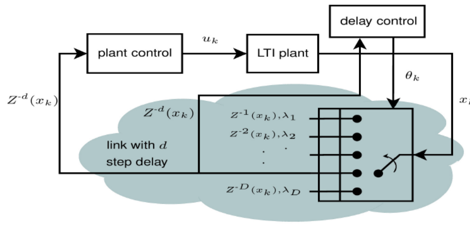
Maity et al., 2018

# Information Structure and Optimal Control

Find optimal plant control and network delay control:

$$(u^*, \theta^*) = \arg\min_{u,\theta} J(u,\theta)$$

$$J(u,\theta) = \mathsf{E}\left[\underbrace{\sum_{t=0}^{T-1}\left[x_t^\top Q_1 x_t + u_t^\top R u_t\right] + x_T^\top Q_2 x_T}_{\text{control cost}} + \underbrace{\sum_{t=0}^{T-1}\theta_t^\top \Lambda}_{\text{delay cost}}\right]$$




- What is the structure of the optimal solution?
- Is the optimal plant controller estimator based?
- How find the optimal delay controller?

Maity et al., 2018

10

10

# Optimal Plant Control and Separation Principle

**Theorem**

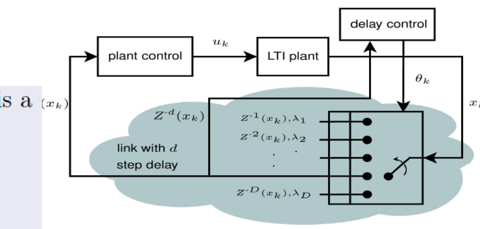
Given $\bar{\mathcal{I}}_k$, the optimal control policy $u_k^* = g_k^*(\bar{\mathcal{I}}_k)$, $k \in \{0, \dots, T-1\}$ is a linear feedback of the form

$$u_k^* = -(R + B^\top P_{k+1} B)^{-1} B^\top P_{k+1} A \mathsf{E}[x_k | \bar{\mathcal{I}}_k]$$

$P_k$ satisfies the RE

$$P_k = Q_1 + A^\top \left(P_{k+1} - P_{k+1} B \left(R + B^\top P_{k+1} B\right)^{-1} B^\top P_{k+1}\right) A$$

$$P_T = Q_2$$




$$(u^*, \theta^*) = \arg\min_{u,\theta} J(u,\theta)$$

- Optimal plant controller is based on estimator
- Optimal plant controller does not depend on the delay control

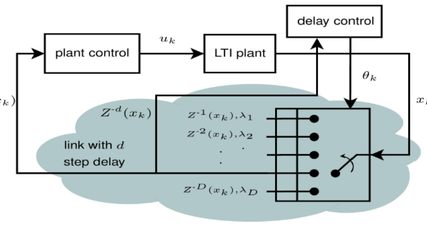
$$J(u,\theta) = \mathsf{E}\left[\underbrace{\sum_{t=0}^{T-1}\left[x_t^\top Q_1 x_t + u_t^\top R u_t\right] + x_T^\top Q_2 x_T}_{\text{control cost}} + \underbrace{\sum_{t=0}^{T-1}\theta_t^\top \Lambda}_{\text{delay cost}}\right]$$

Maity et al., 2018

11

11

# Optimal Plant Control and Separation Principle




Theorem

Given $\bar{\mathcal{I}}_k$, the optimal control policy $u_k^* = g_k^*(\bar{\mathcal{I}}_k)$, $k \in \{0, \ldots, T-1\}$ is a linear feedback of the form

$$u_k^* = -(R + B^\mathsf{T} P_{k+1} B)^{-1} B^\mathsf{T} P_{k+1} A \mathsf{E}[x_k | \bar{\mathcal{I}}_k]$$

$$\hat{x}_k = \mathsf{E}[x_k | \bar{\mathcal{I}}_k] = \sum_{i=1}^{\min\{D,\ k+1\}} b_{i,k} \mathsf{E}[x_k | x_{k-i}, U^{k-1}]$$

$$b_{i,k} = \prod_{d=1}^{i-1} \prod_{j=1}^{d} \left(1 - \theta_{k-d}^j\right) (\vee_{l=1}^{D} \theta_{k-i}^l)$$

$$\forall i \in \{1, \cdots, D\},\ b_{i,k} \in \{0, 1\}\ ,\ \sum_{i=1}^{\min\{D,k+1\}} b_{i,k} = 1$$

- Optimal plant controller is based on estimator (separation principle holds)
- Optimal plant controller does not depend on the delay controller
- But the estimator is a nonlinear function of the delay control

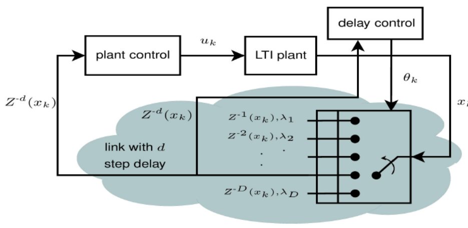
Maity et al., 2018





# Optimal Network Delay Control

Optimal delay control can be **computed offline** by solving the mixed-integer nonlinear program




$$\min_{\theta_{[0,T-1]}} \sum_{k=0}^{T-1} \left[\theta_k^\mathsf{T} \Lambda + \gamma_k^\mathsf{T} r_k\right]$$

$$\text{subject to} \quad (\gamma_k)_i = \sum_{j=i}^{D} b_{j,k}, \quad \sum_{i=1}^{D} \theta_k^i = 1$$

$$b_{i,k} = \prod_{d=1}^{i-1} \prod_{j=1}^{d} (1 - \theta_{k-d}^j)(\vee_{l=1}^{i} \theta_{k-i}^l)$$

$$\sum_{i=1}^{\tau_k} b_{i,k} = 1, \quad \sum_{i=\tau_k+1}^{D} b_{i,k} = 0$$

$$\gamma_t \triangleq [c_{1,t}, c_{2,t}, \cdots, c_{D,t}]^\mathsf{T},\ c_{i,k} = \sum_{j=i}^{\tau_k} b_{j,k},\ \tau_k = \min\{D, k+1\}$$

$$r_t \triangleq [tr(\tilde{P}_t W), \cdots, tr(\tilde{P}_t A^{D-1^\mathsf{T}} W A^{D-1})]^\mathsf{T},\ \tilde{P}_t = Q_1 + A^\mathsf{T} P_{t+1} A - P_t$$

- Relaxed mixed-integer **linear** program easier to solve
- Solution to relaxed problem is a solution to the original problem

Maity et al., 2018

# Example

Plant model:

$$x_{k+1} = \begin{bmatrix} 1.01 & 0 \\ 0 & 1 \end{bmatrix} x_k + \begin{bmatrix} 0.1 & 0 \\ 0 & 0.15 \end{bmatrix} u_k + \sqrt{1.5} w_k, \quad w_k \sim \mathcal{N}(0, \mathbb{I}_2)$$

Network model:

delay variable: $d \in \{1, \ldots, D\}$
$Z^{-d}(x_k) \to x_k$ delivered at $k+d$

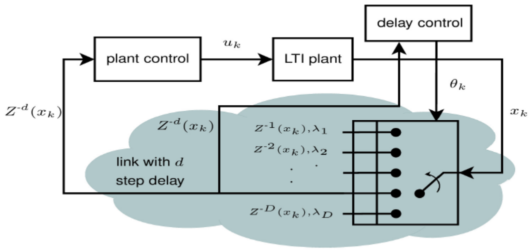
$$\theta_k^i = \begin{cases} 1, & \text{link with } i \text{ step delay is selected at time } k \\ 0, & \text{link with } i \text{ step delay is not selected at time } k \end{cases}$$

Associated communication price $\rightarrow$ $\lambda_d$ for $d$-step delay

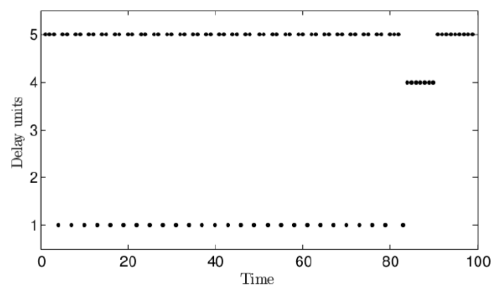
$$\lambda_1 > \lambda_2 > \ldots > \lambda_D, \quad \lambda_d \in \mathbb{R}_{\geq 0}$$

5 delay links with prices $[20, 13, 8, 2, 1]$

- Link with lower delay has higher cost
- Optimal solution is a trade off between control performance and usage of network resources




Optimal link utilization




Maity et al., 2018

14

14

# Example

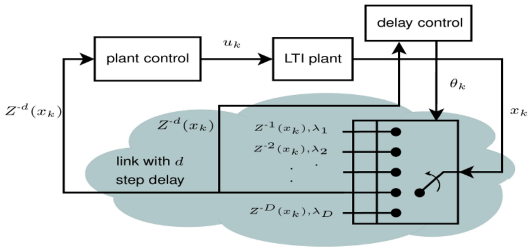
$$\theta_k^i = \begin{cases} 1, & \text{link with } i \text{ step delay is selected at time } k \\ 0, & \text{link with } i \text{ step delay is not selected at time } k \end{cases}$$

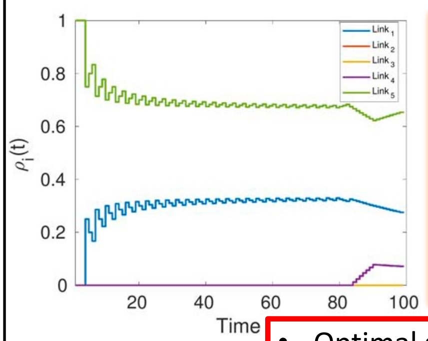
Associated communication price $\rightarrow$ $\lambda_d$ for $d$-step delay

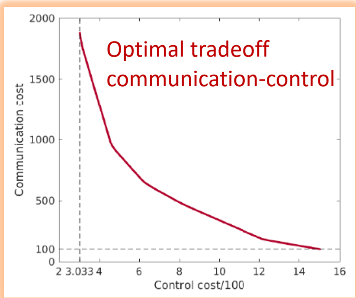
$$\lambda_1 > \lambda_2 > \ldots > \lambda_D, \quad \lambda_d \in \mathbb{R}_{\geq 0}$$

5 delay links with prices $[20, 13, 8, 2, 1]$

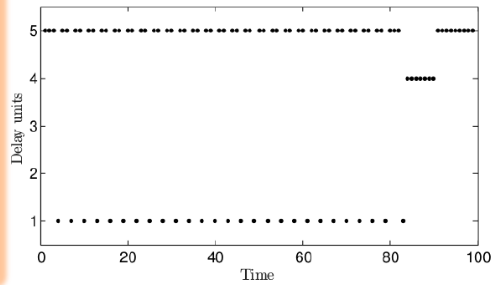
Average link utilization $\rho_i(t) \triangleq \dfrac{\#\text{ usage of link } i \text{ until time } t}{t}$




Optimal link utilization



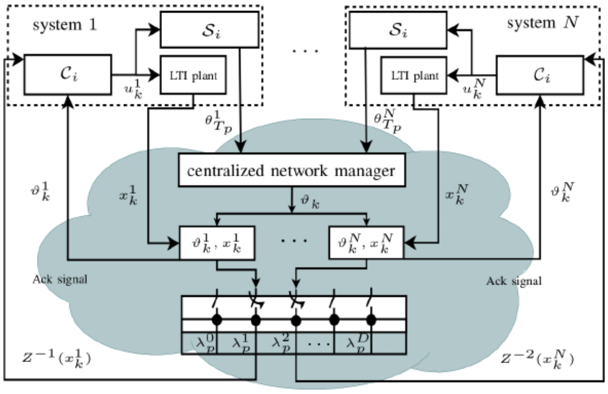

- Optimal solution uses mainly **cheap** and **costly** links
- >60% of the time the system is in open loop (delayed)

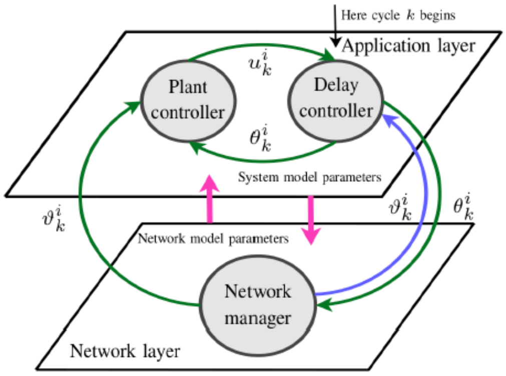
Maity et al., 2018

15

15

# Extension to Multiple Control Loops

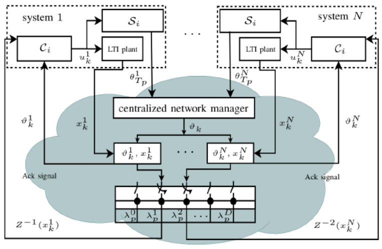



16

16

# Example with N=20 Control Loops



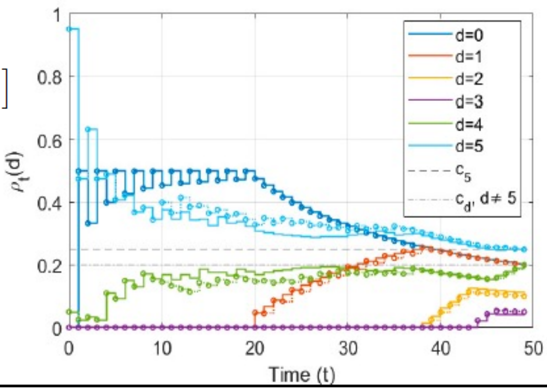

20 plants: $x^i_{k+1} = \begin{bmatrix}1.01 & 0.2\\ 0.2 & 1\end{bmatrix} x^i_k + \begin{bmatrix}0.1 & 0\\ 0 & 0.15\end{bmatrix} u^i_k + w^i_k$

Network: 6 network services: $\Lambda_{\max} = [31, 19, 12, 9, \frac{11}{2}, \frac{5}{2}]$

$d \in \{0, 1, \dots, 5\}$

Average link utilization

$$\rho_t(d) = \frac{1}{N(t+1)}\left[\sum_{k=0}^{t} \sum_{i=1}^{N} \vartheta^i_k(d)\right]$$




- Automatic and optimal allocation of network resources to multiple control loops
- Suitable to integrate with network slices in 5G cellular networks

17

# Outline

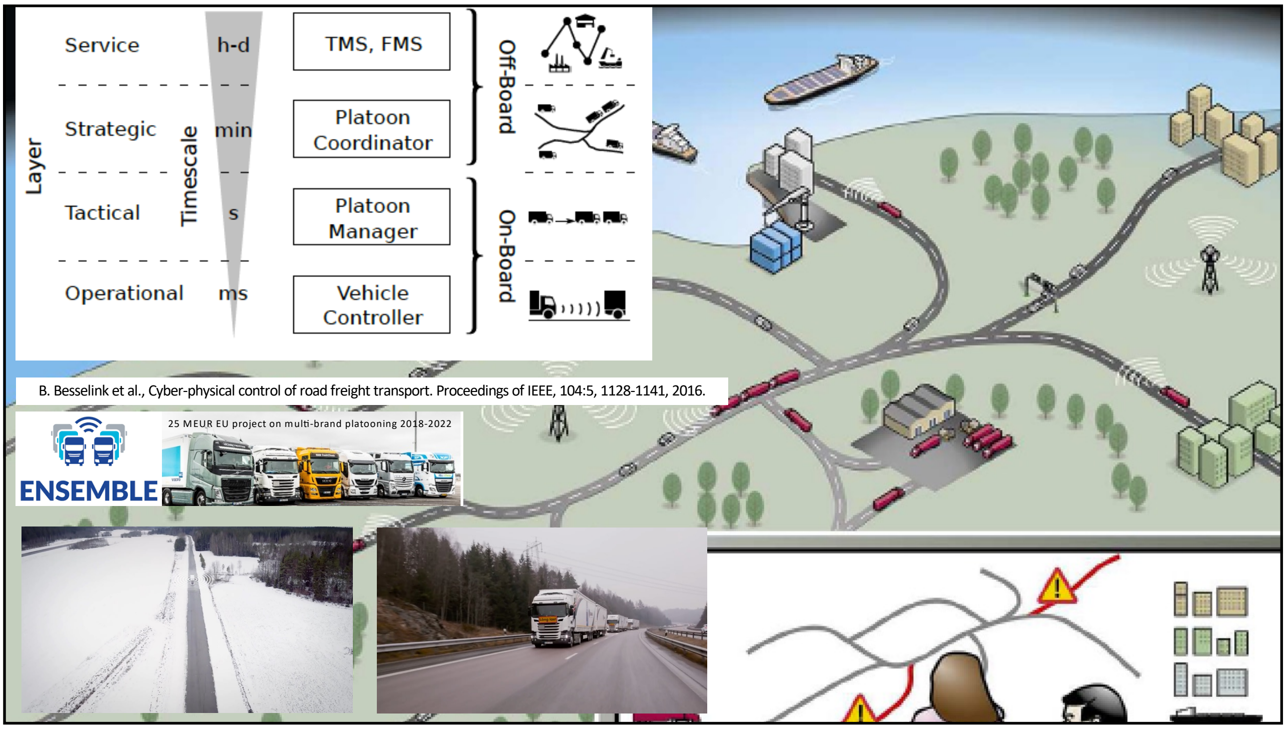
- Introduction
- Theory
  - Optimal communication and control co-design
- Applications
  - Truck platooning
  - Pulp and paper processes
  - Shared-autonomy systems
- Conclusions

19

19



20




21

# Control of Vehicle Platoons

IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. AC-11, NO. 3, JULY, 1966

On the Optimal Error Regulation of a String of Moving Vehicles

W. S. LEVINE, STUDENT MEMBER, IEEE, AND M. ATHANS, MEMBER, IEEE

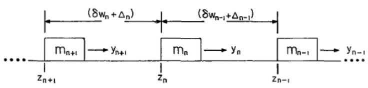
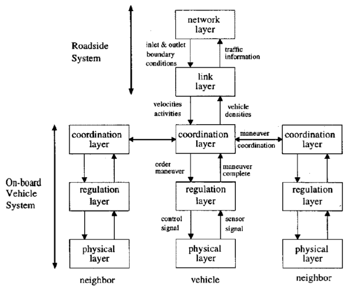



Fig. 1. Vehicles moving in a string.

PATH platoon demo San Diego 1997

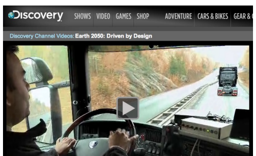



IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 38, NO. 2, FEBRUARY 1993

Smart Cars on Smart Roads: Problems of Control

Pravin Varaiya, *Fellow, IEEE*

Scania

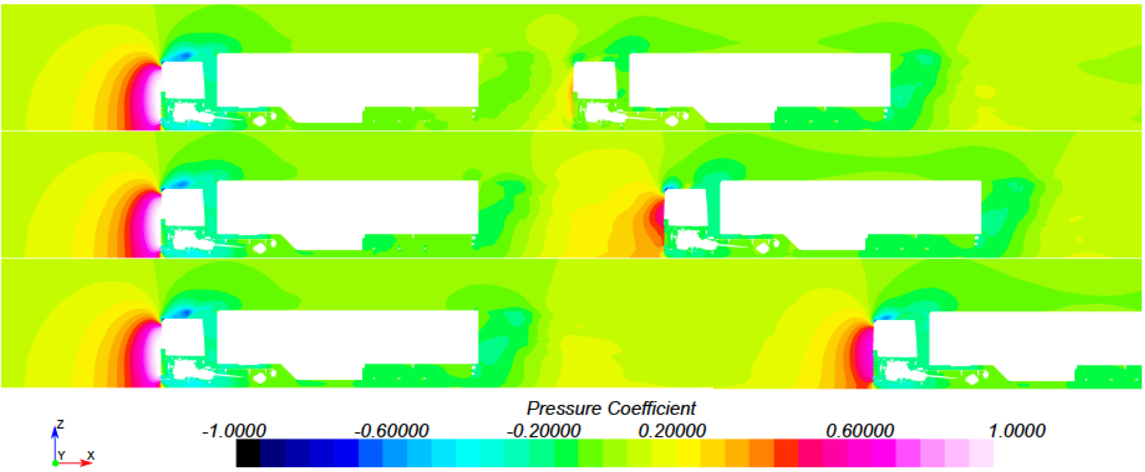



Swedish success stories

Volvo

22

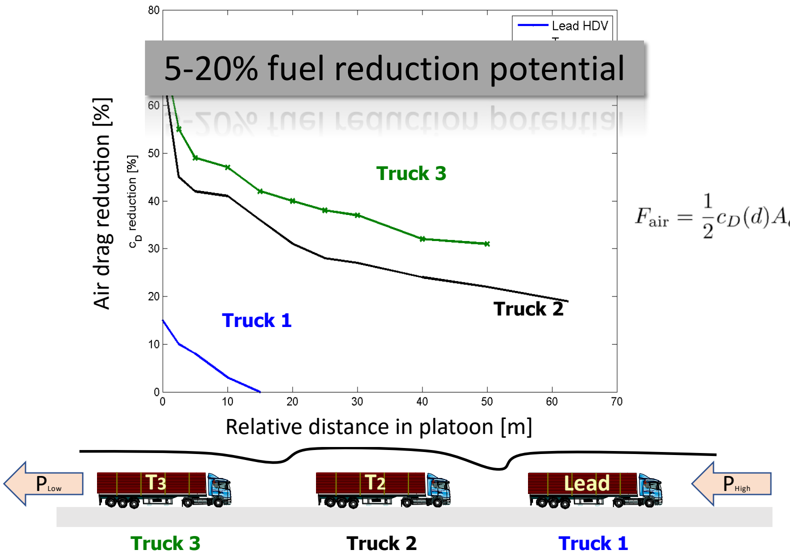
# The Physics




Norrby (2014), Liang (2016)

23

# Air Drag Reduction in Truck Platooning




$$F_{\text{air}} = \frac{1}{2} c_D(d) A_a \rho_a v^2$$

Wolf-Heinrich & Ahmed (1998), Bonnet & Fritz (2000), Scania CV AB (2011)

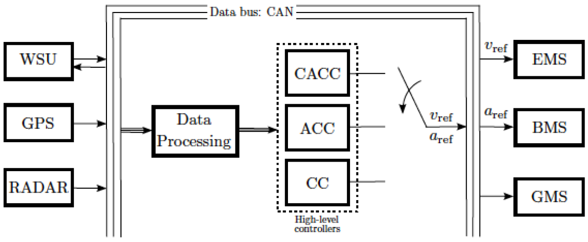
24

# Vehicle System Architecture

Data from other vehicles

Own position and velocity

Pos from vehicle ahead



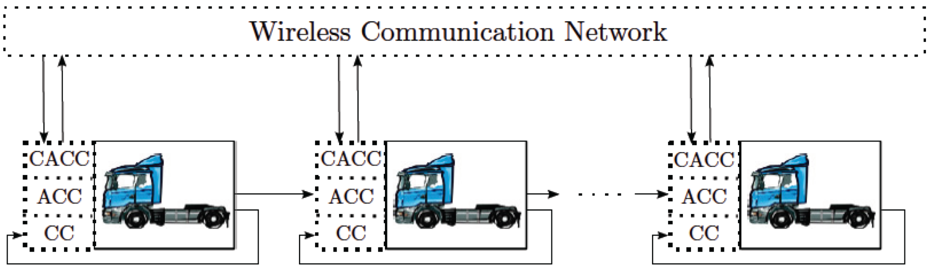

CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

EMS – Engine management system
BMS – Brake management system
GMS – Gear management system

Alam et al., 2014

25

# Platoon System Architecture



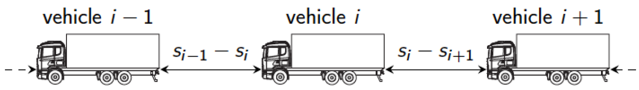

CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

No need for new hardware

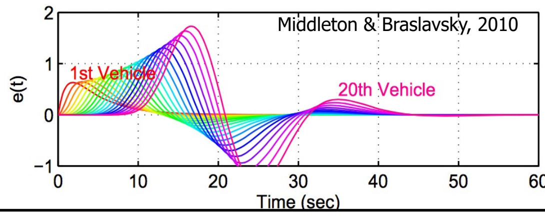
Alam et al., 2014

26

# How to Control Inter-vehicular Spacings?

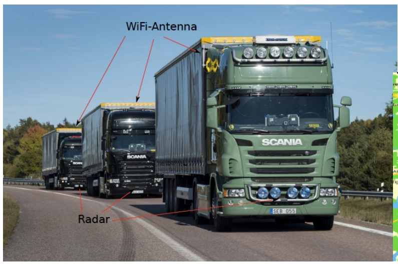


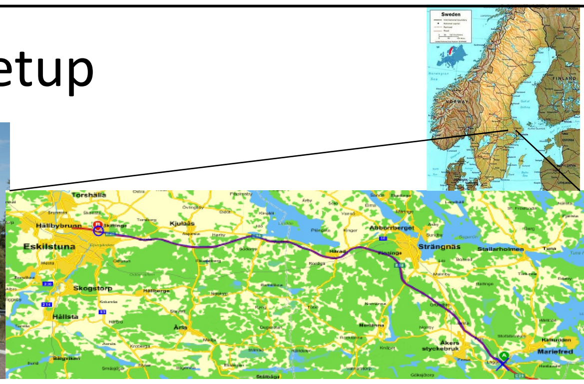

- Limited sensing and inter-vehicle communication suggests **distributed** control strategy
- Important to attenuate disturbances: **string stability**
- Extensively studied problem in ideal environments
  - E.g., Levine & Athans (1966), Peppard (1974), Ioannou & Chien (1993), Swaroop et al. (1994), Stankovic et al. (2000), Seiler et al. (2004), Naus et al. (2010),…

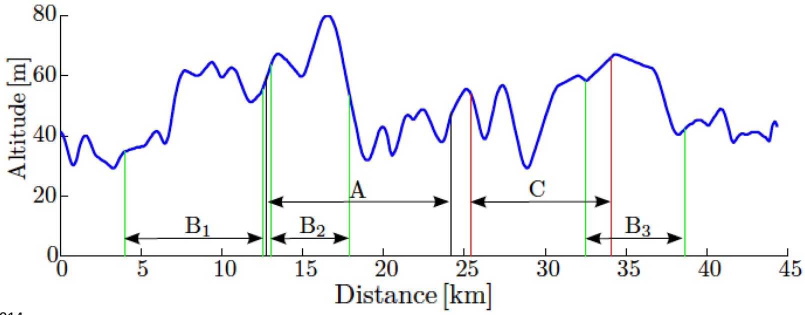



27

# Experimental Setup



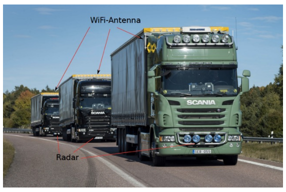



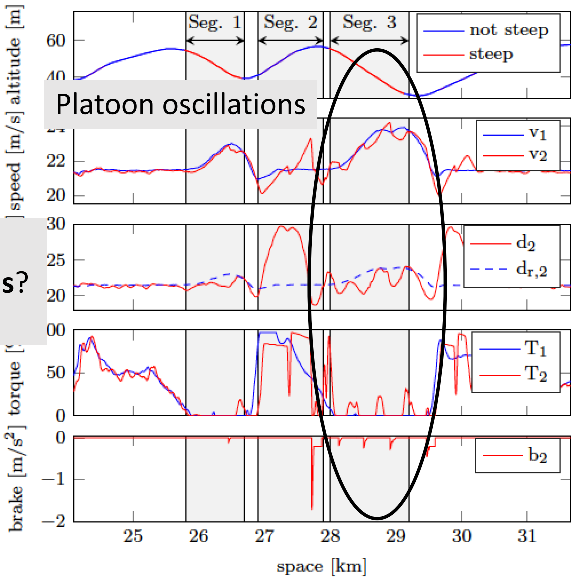




Alam, 2014

28

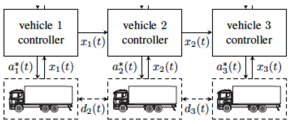
# Experimental Results




**Challenge**

How to handle **topography variations**?
Which **spacing policy** to choose?

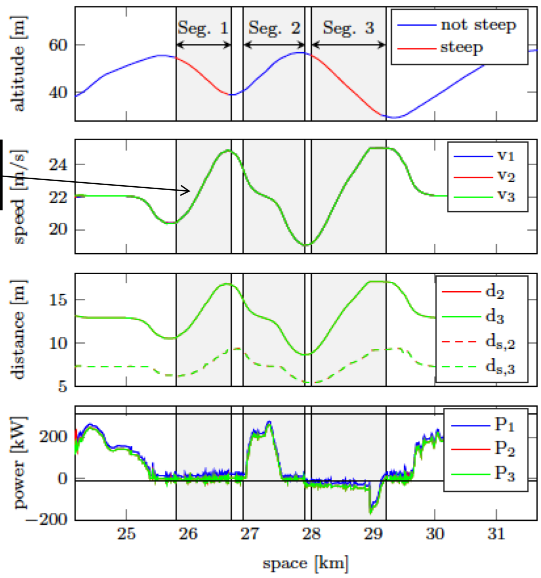


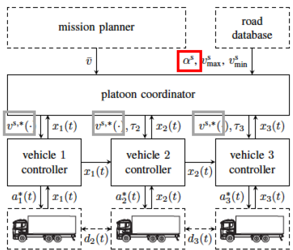

Alam, 2014

29

# Simulations **with** Platoon Coordinator and Look-ahead Road Grade Information


Successful tracking of common platoon velocity reference

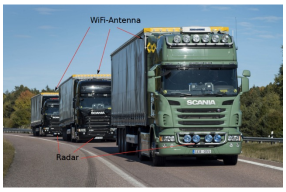


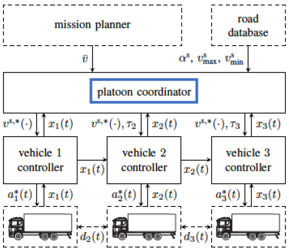

Turri et al., 2015

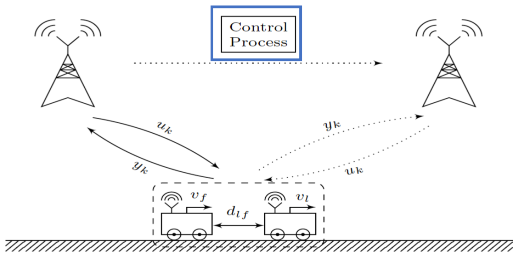
30

# Cellular Implementation of Platoon Coordinator




- Platoon coordinator generates common velocity reference: $v_i(t) \to v_{\text{ref}}(s_i(t))$,
- Can be computed in the cellular system (5G, 6G)
- New handover scheme for moving control computations between base stations

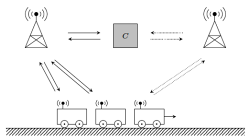


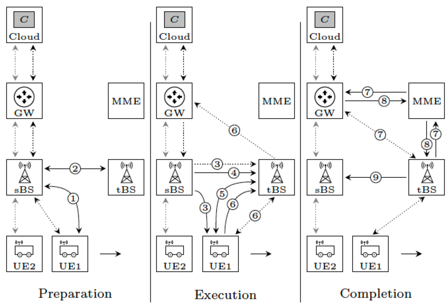

van Dooren et al., 2017

31

# Controller Code Handover Supporting Vehicle Platooning



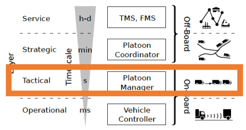

- Proposed new handover schemes
- Support real-time control from edge cloud



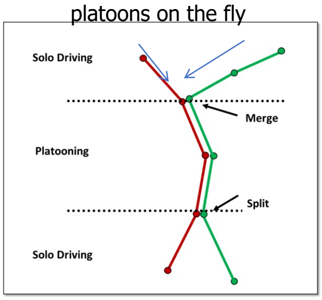

van Dooren et al., 2017, 2018

32

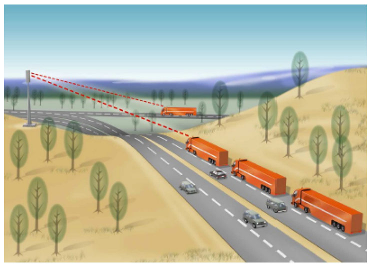
# Platoon Formation



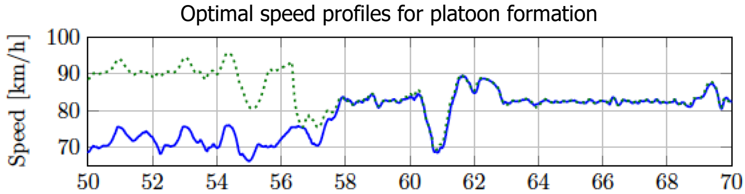

Merge and split vehicle platoons on the fly




Predictions on whether it is beneficial for a vehicle to catch up another vehicle



Optimal speed profiles for platoon formation

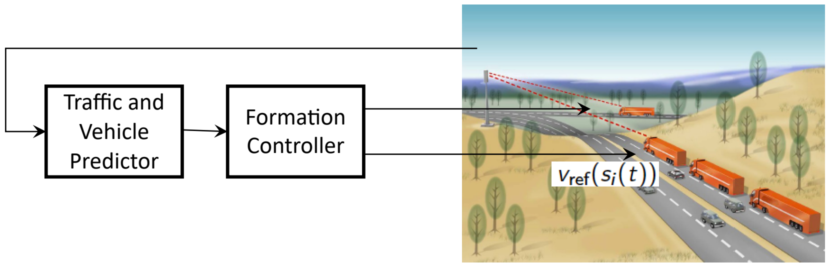



Liang et al., 2016

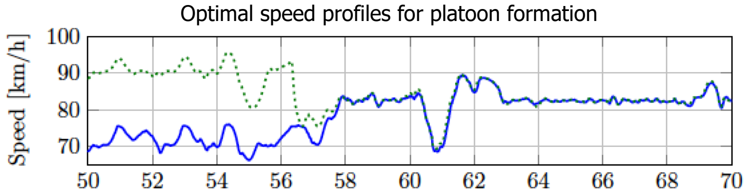
33

# Platoon Formation

Feedback control of merging point based on real-time vehicle state and traffic information



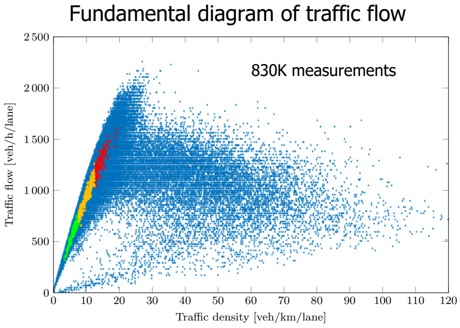

Optimal speed profiles for platoon formation




Liang et al., 2016; Cicic et al., 2017

34

# Platoon Formation Experiments



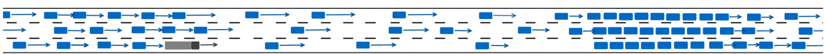

- 600 test runs on E4 in Nov 2015
- Traffic measurements from road units together with onboard sensors


Liang et al., 2016

35

# Can controlled truck platoons be used to improve traffic conditions?

- Trucks act as bottlenecks moving in car traffic
- Regulate cars flowing into congested area



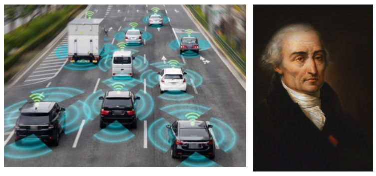
Lin et al., 2018; Cicic and J, 2018

Cf., [Lebacque et al. 1998; Delle Monache & Goatin 2014]

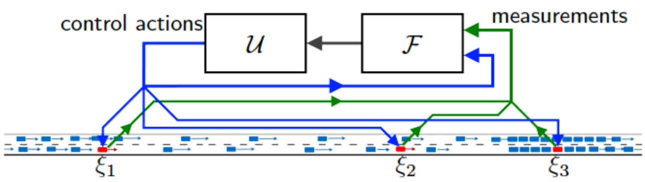
36

# From Eulerian to Lagrangian traffic control

**Leonhard Euler (1707-1783)**
Stationary observer of the flow
Traffic control based on fixed infrastructure
High deployment costs and limited flexibility

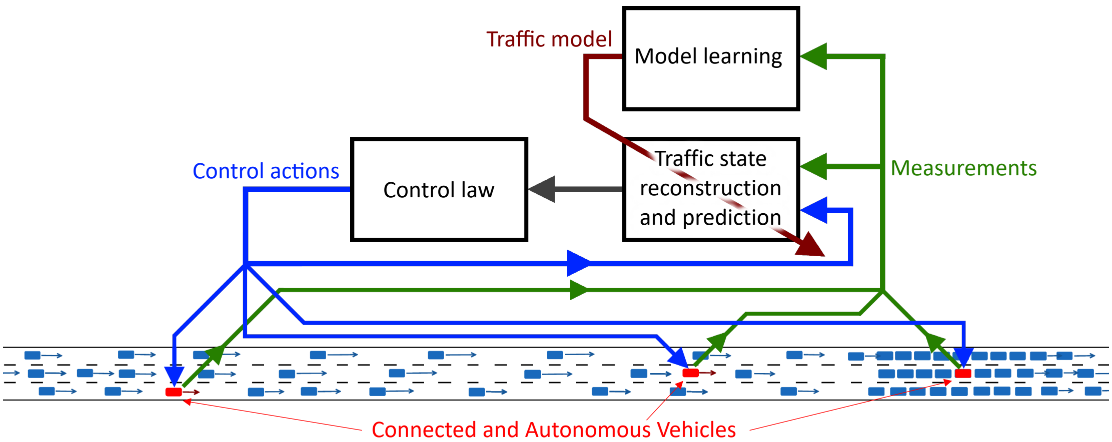


**Joseph-Louis Lagrange (1736-1813)**
Observers moves with the flow
Traffic control based on mobile sensors and actuators
Need for a new system theoretic foundation




37

# Lagrangian traffic control system




$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q(\rho(x,t),x,t)}{\partial x} = 0$$

[Čičić., 2021]

38

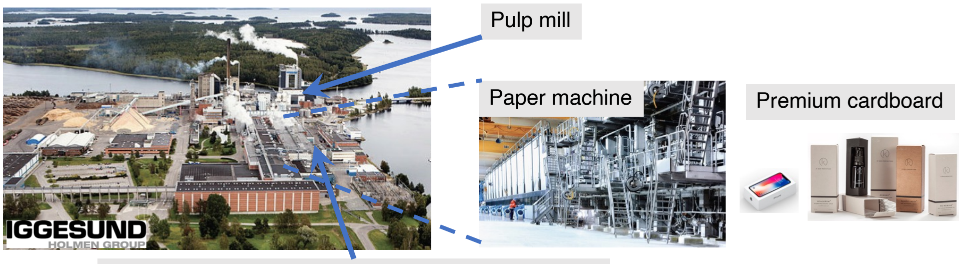
# Outline

- Introduction
- Theory
  - Optimal communication and control co-design
- Applications
  - Truck platooning
  - Pulp and paper processes
  - Shared-autonomy systems
- Conclusions

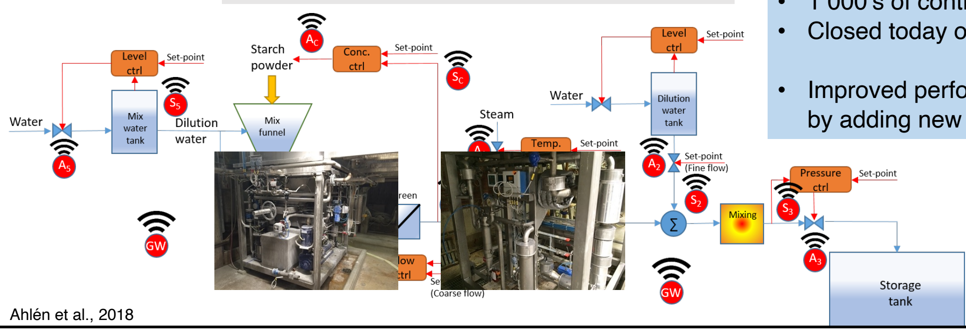
39

39

# Wireless Control of Pulp and Paper Mill




Starch cooker process producing cardboard coating

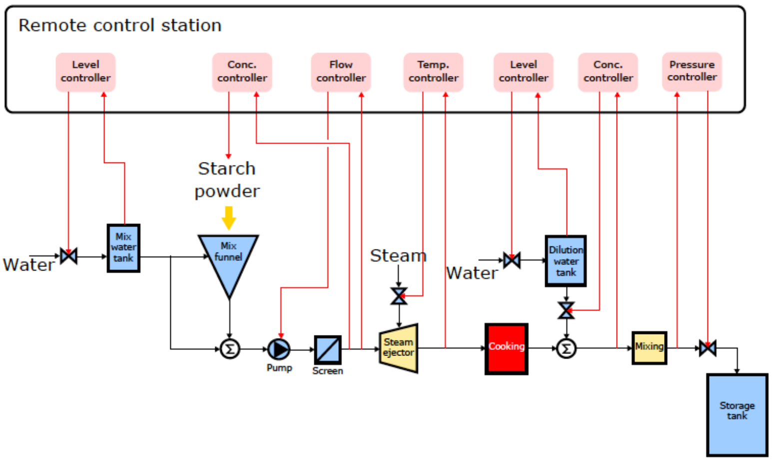



- 1 000’s of control loops and sensors
- Closed today over fixed wired network
- Improved performance and flexibility by adding new wireless sensors

Ahlén et al., 2018

40

# Wireless Control of Pulp and Paper Mill

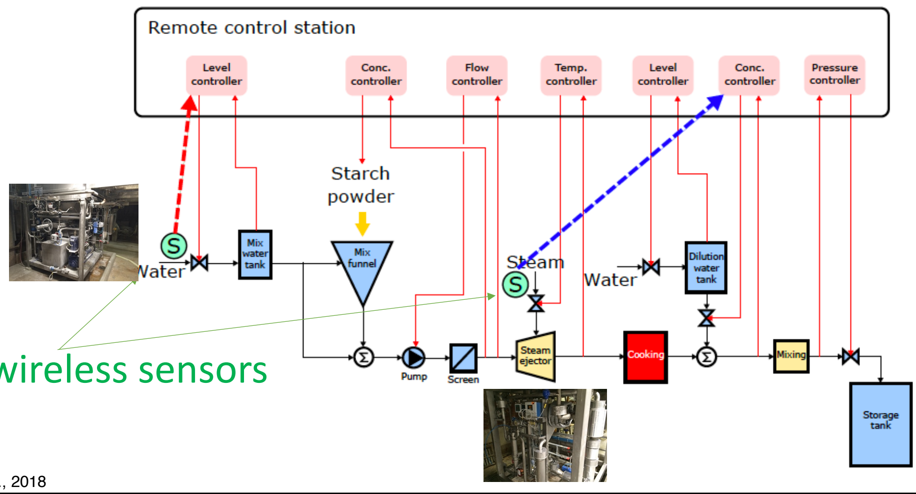



Ahlén et al., 2018

41

# Wireless Control of Pulp and Paper Mill

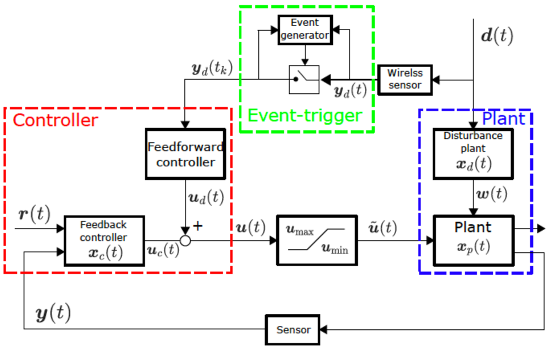
- Improve the response to the water flow variation by **cascade control**
- Attenuate the effect of steam flow variation by **feedforward control**

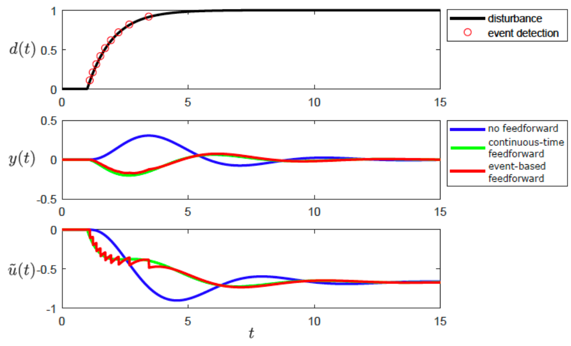



Ahlén et al., 2018

42

# Event-based Feedforward Control




Only 9 samplings are needed for good feedforward control

Iwaki et al., 2018

43

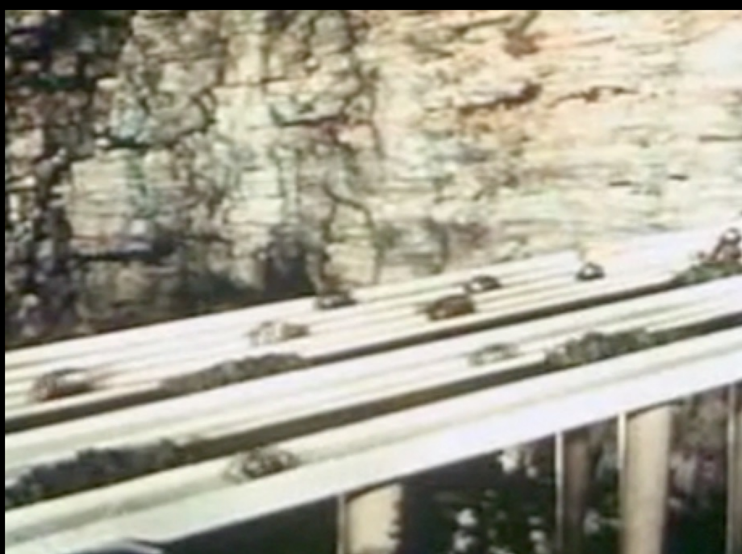
43

## General Motors vision 83 years ago

44

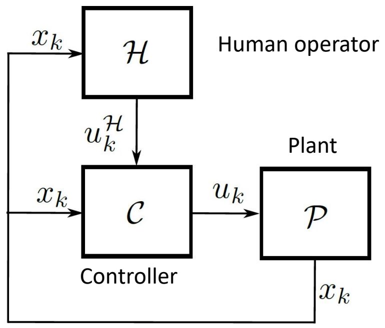
45

Cyber = “Automatic radio control”
Physical = “Curved sides”



46

## Shared-Autonomy Systems

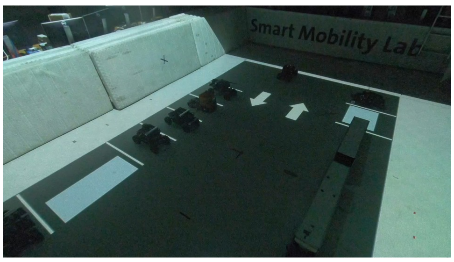



Shared-autonomy systems are systems that can mix human and automated decisions in a systematic way.

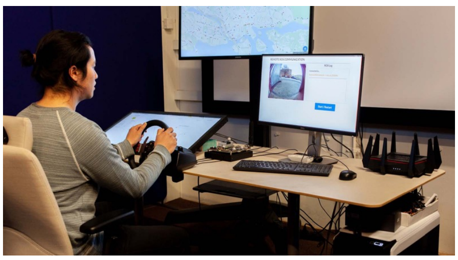
Teleoperation of trucks by Einride

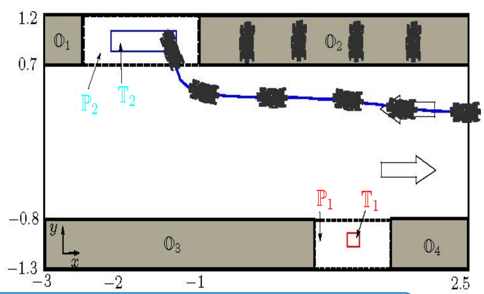
47

47




Teleoperation of trucks by Einride






LTL-specified parking tasks

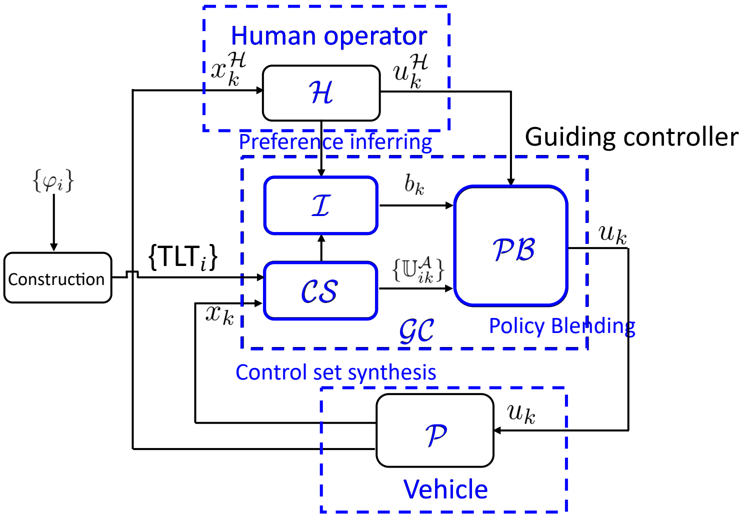
$\varphi_1 = ([\text{Parking lot}] \wedge \neg\mathbb{O}_1 \wedge \neg\mathbb{O}_2 \wedge \neg\mathbb{O}_3 \wedge \neg\mathbb{O}_3)\mathsf{U}\mathbb{P}_1\mathsf{U}\Box\mathbb{T}_1$

$\varphi_2 = ([\text{Parking lot}] \wedge \neg\mathbb{O}_1 \wedge \neg\mathbb{O}_2 \wedge \neg\mathbb{O}_3 \wedge \neg\mathbb{O}_3)\mathsf{U}\mathbb{P}_2\mathsf{U}\Box\mathbb{T}_2$

48

48

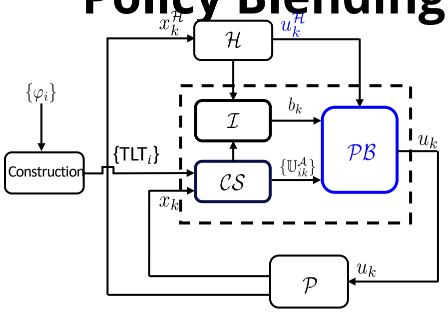
# Guiding Controller

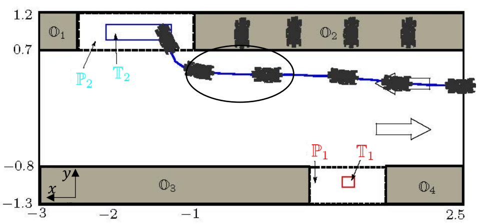



18



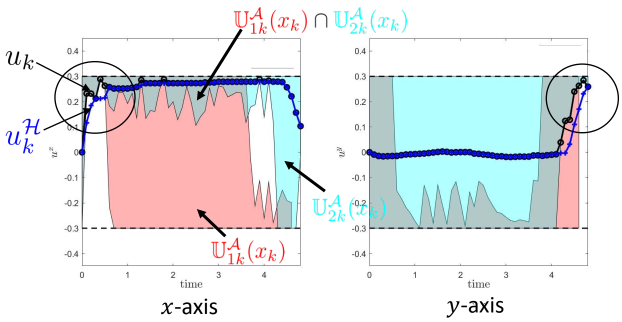
# Policy Blending



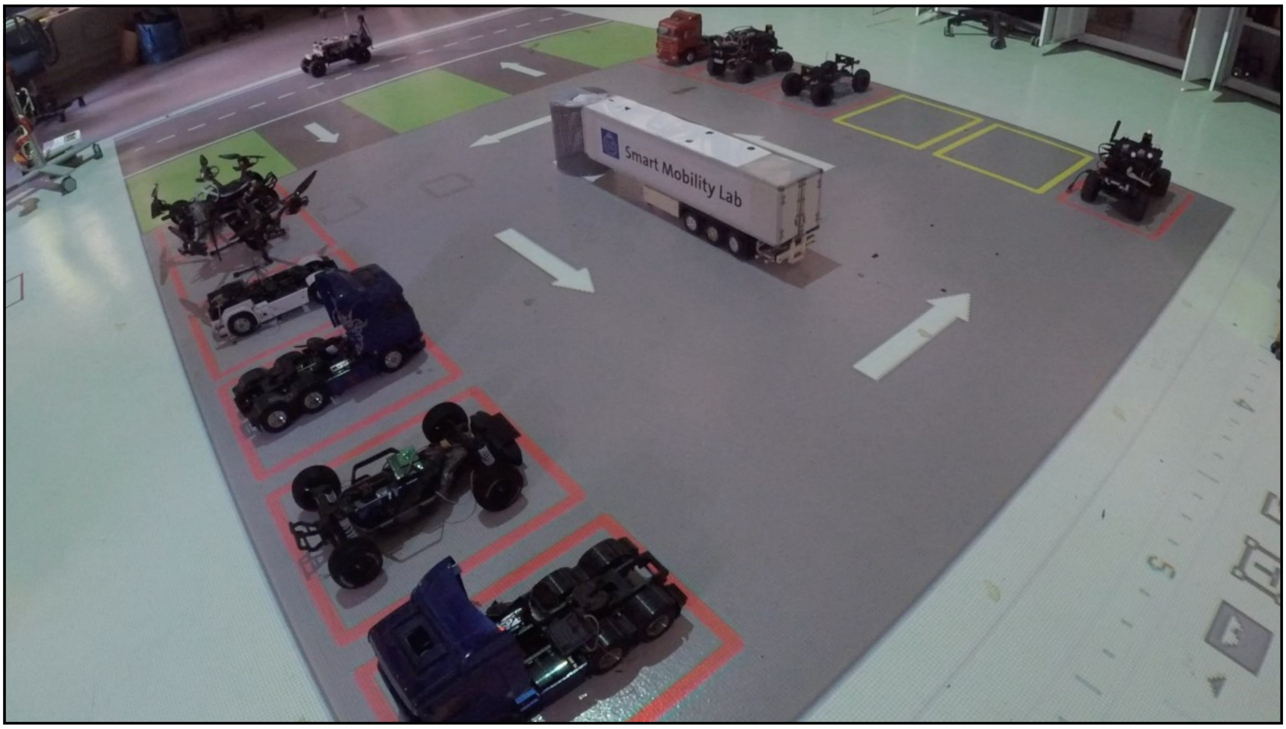

The control command depends on the control set and belief:

$$u_k = \begin{cases} u_k^{\mathcal{H}}, & \text{if } \exists i \text{ s.t. } u_k^{\mathcal{H}} \in \mathbb{U}_{ik}^{\mathcal{A}}, \\ \arg \min\limits_{u \in \mathbb{U}_{ik}^{\mathcal{A}}, i=1,\ldots,|\mathcal{E}|} \frac{\|u-u_k^{\mathcal{H}}\|}{b_k(i)}, & \text{otherwise.} \end{cases}$$




- ❑ Human decisions are corrected in the beginning
- ❑ And also at the end

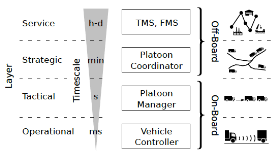
55

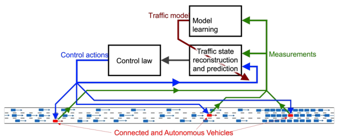



56

# Conclusions

- **Wireless** networking, sensing, and actuation **enable** a multitude of new large-scale control applications
- Need to guarantee stability, robustness, and safety by systematic **control and communication co-design**
- Novel architectures, design principles and algorithms together with **experimental demonstrations**
- **Extensions** to mixed data- and model-based approaches




people.kth.se/~kallej

57

P. Park, S. Coleri Ergen, C. Fischione, C. Lu, and K. H. Johansson, Wireless network design for control systems: a survey. IEEE Communications Surveys & Tutorials, 20:2, 978-1013, 2018.

57

# Some surveys on networked control


- Z. Meng, T. Yang, and K. H. Johansson, Modelling, Analysis, and Control of Networked Dynamical Systems, Birkhäuser, 2021
- P. Park, S. Coleri Ergen, C. Fischione, C. Lu, and K. H. Johansson, Wireless network design for control systems: a survey. IEEE Communications Surveys & Tutorials, 20:2, 978-1013, 2018.
- A. Seuret, L. Hetel, J. Daafouz, and K. H. Johansson (Eds.), Delays and Networked Control Systems, Springer-Verlag, 2016.
- W.P.M.H. Heemels, K. H. Johansson, and P. Tabuada, An introduction to event-triggered and self-triggered control, IEEE Conference on Decision and Control, Maui, HI, USA, 2012. Invited tutorial paper.
- K. H. Johansson, G. J. Pappas, P. Tabuada, C. J. Tomlin, Guest Editorial Special Issue on Control of Cyber-Physical Systems. IEEE Transactions on Automatic Control, 59:12, 3120-3121, 2014.
- J. Chen, K. H. Johansson, S. Olariu, I. Ch. Paschalidis, and I. Stojmenovic, Guest Editorial Special Issue on Wireless Sensor and Actuator Networks. IEEE Transactions on Automatic Control, 56:10, 2244-2246, 2011.
- A. Zolich, D. Palma, K. Kansanen, K. Fjortoft, J. Sousa, K. H. Johansson, Y. Jiang, H. Dong, and T. A. Johansen, Survey on communication and networks for autonomous marine systems. Journal of Intelligent and Robotic Systems, 95:3-4, 789–813, 2019.
- T. Yang, X. Yi, J. Wu, Y. Yuan, D. Wu, Z. Meng, Y. Hong, H. Wang, Z. Lin, and K. H. Johansson, A survey of distributed optimization. Annual Reviews in Control, 47, 278-305, 2019.
- H. Sandberg, S. Amin, and K. H. Johansson, Guest Editorial Special Issue on Cyberphysical Security in Networked Control Systems. IEEE Control Systems Magazine, 35:1, 20-23, 2015.