Schwerpunktprogramm der
Deutschen Forschungsgemeinschaft

Regelungstheorie digital vernetzter dynamischer Systeme

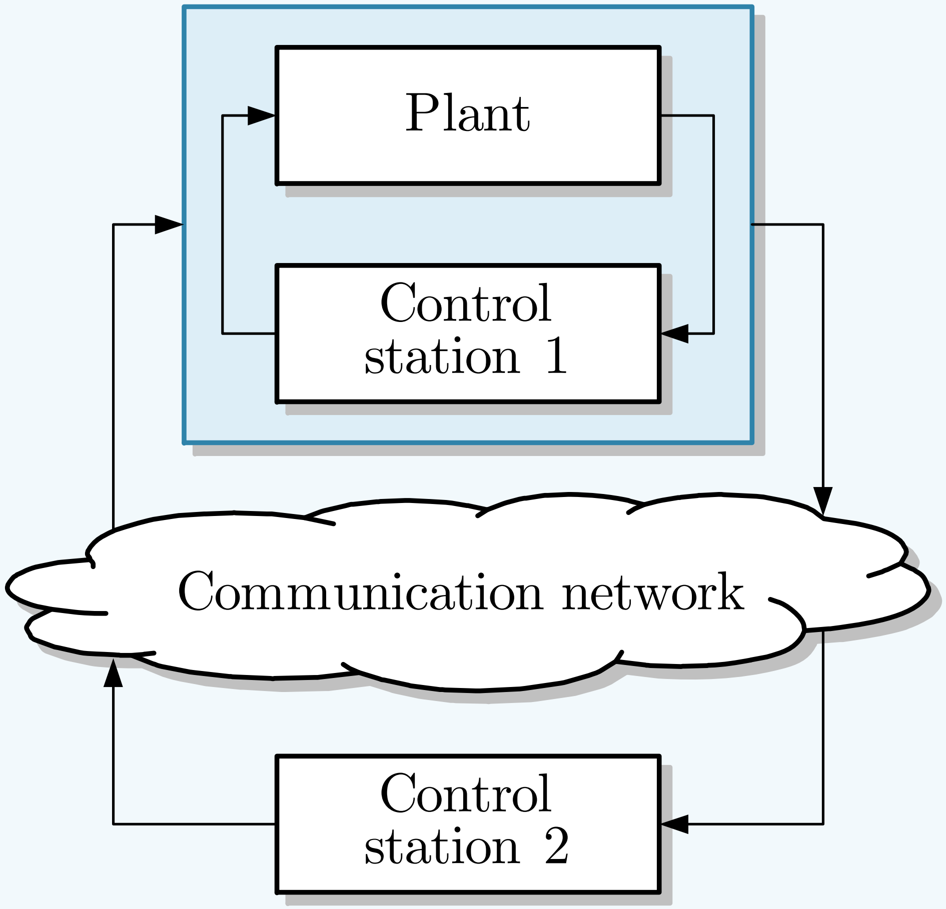
Control theory of digitally networked dynamical systems

Jan Lunze

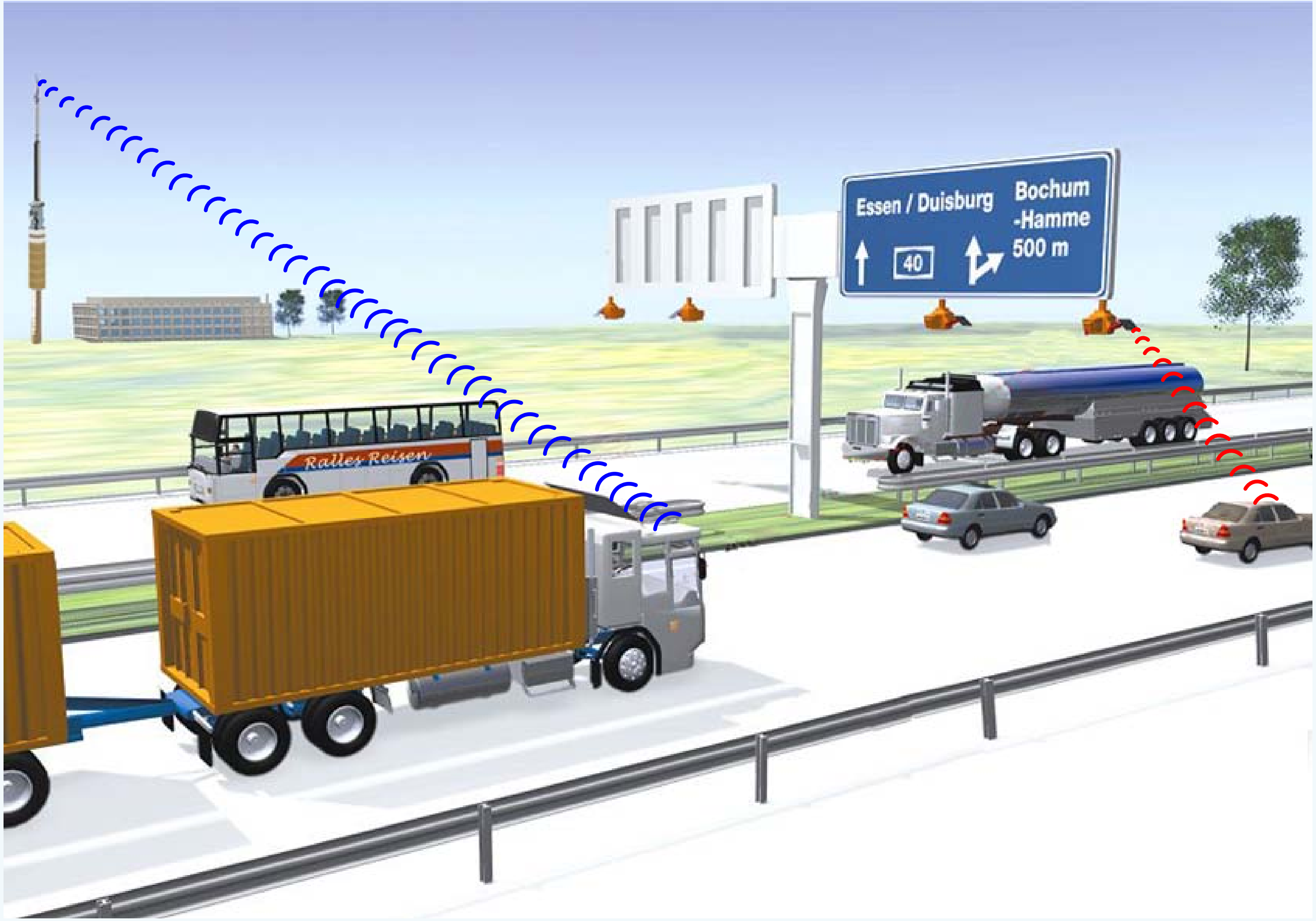
Overview

- Control over communication networks
- Fundamental problems
  - Modelling, analysis and design of asynchronous control systems
  - Performance of networked control systems
  - Development of innovative control concepts
- Outlook

Control over communication networks

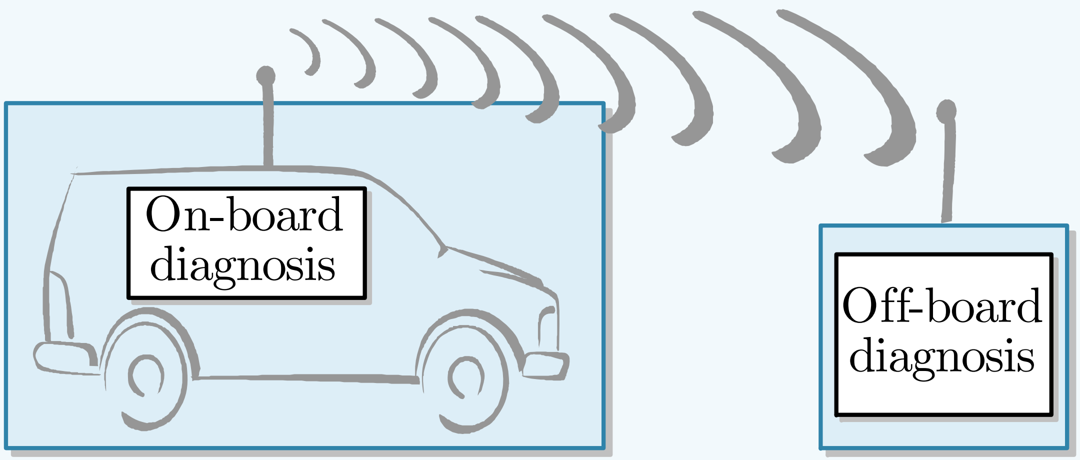


Example: Traffic control with floating-car data



Further examples

- Telerobotics
- Self-organising vehicle control
- Remote process control and supervision



Properties of communication networks

The communication network is open, heterogeneous:

- **Nondeterministic behaviour** due to changing network size and communication traffic
  - Quality of service (QoS): bandwidth, time-to-connect, transmission delay, data loss
- **Flexible communication structure**
  - In wireless communication: Access to the network is not locally fixed
  - In ad-hoc networks: Network structure depends upon the movement of the nodes

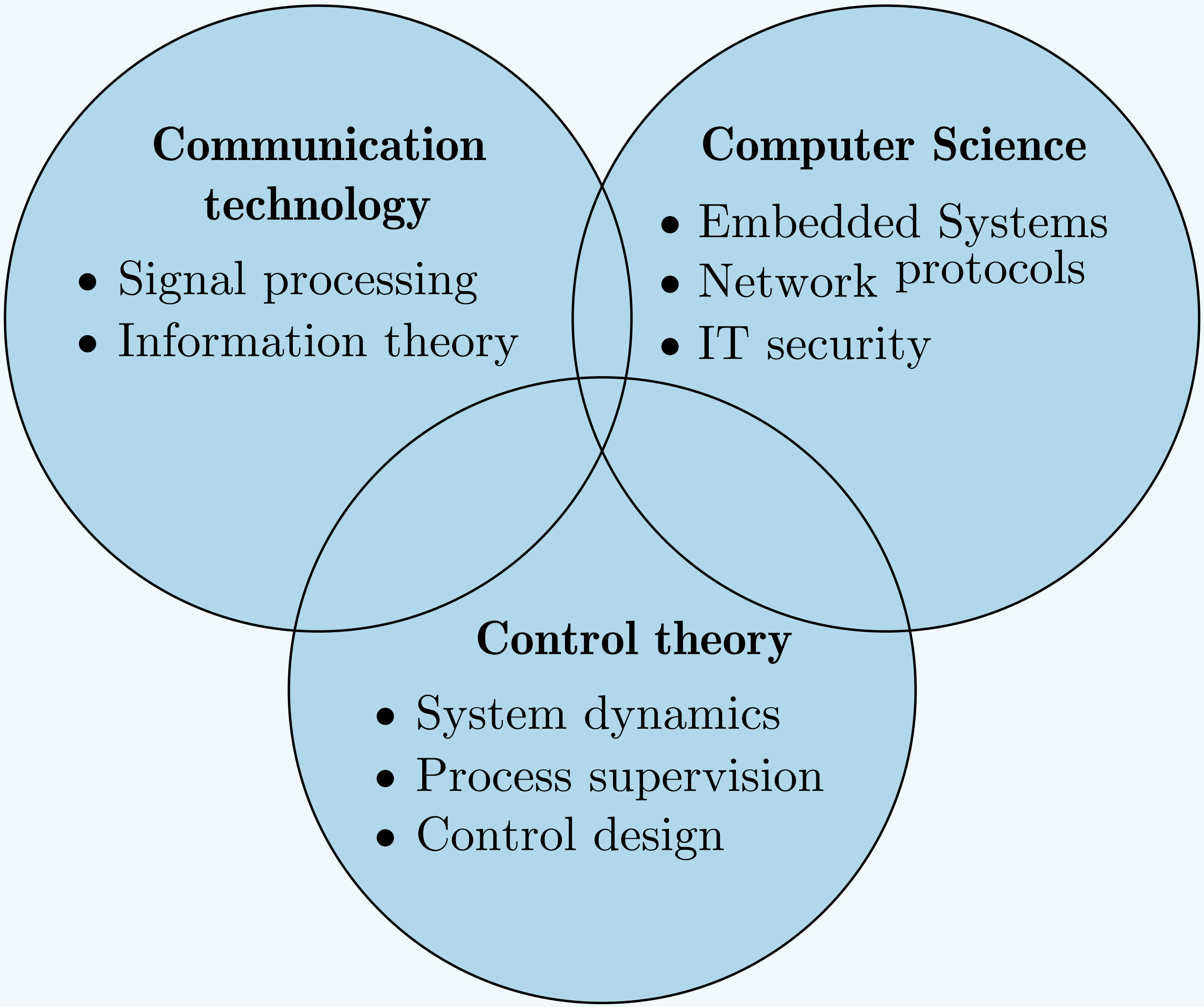
The real-time behaviour of the closed-loop system is severely influenced by the communication network

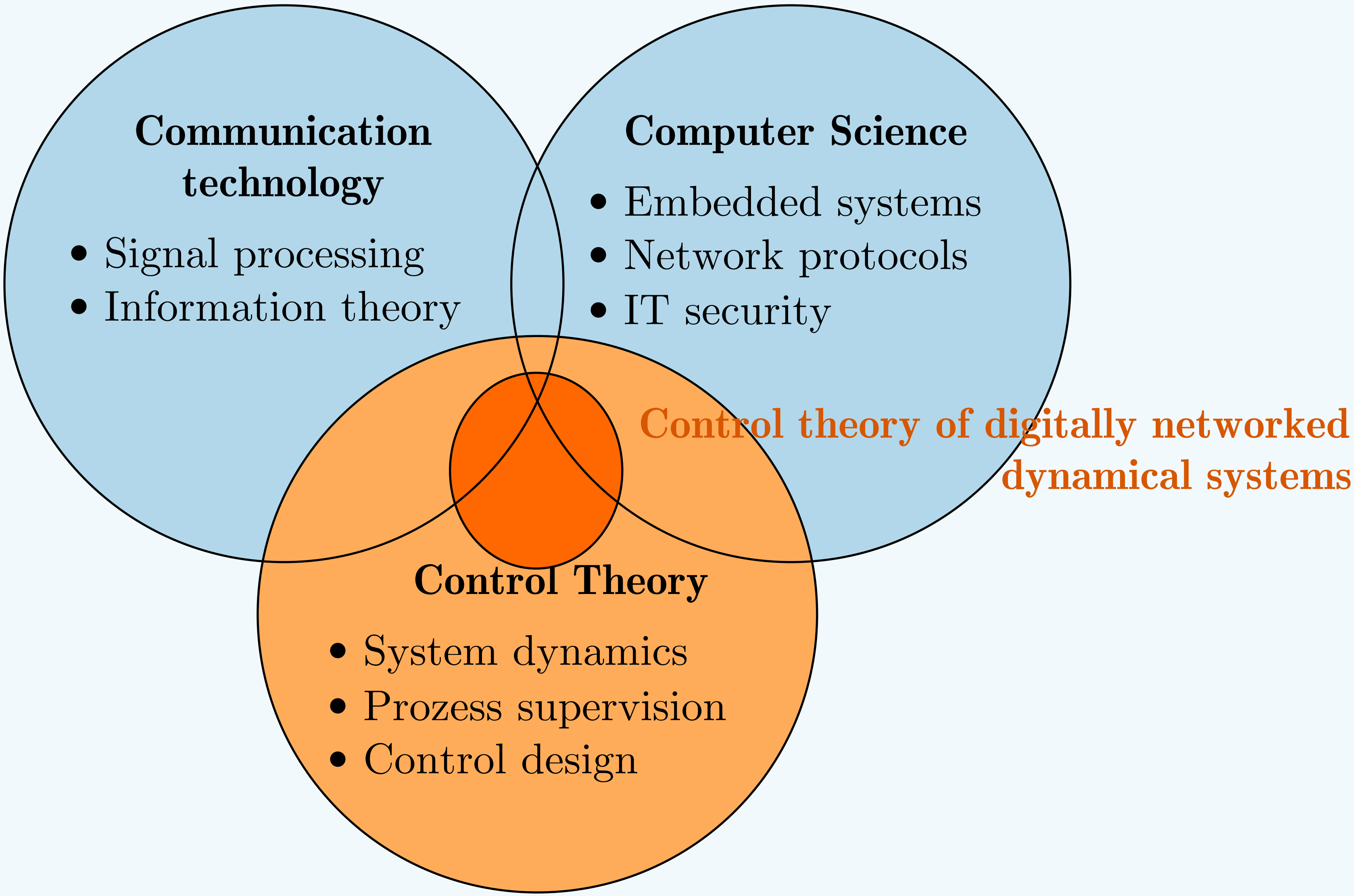
QoS → *QoP*

Quality of service

Quality of performance

- Stability
- Disturbance attenuation
- Set-point following
- Fault tolerance


Communication technology
• Signal processing
• Information theory
Computer Science
• Embedded Systems
• Network protocols
• IT security
Control theory
• System dynamics
• Process supervision
• Control design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Control theory of digitally networked dynamical systems
Control Theory
• System dynamics
• Prozess supervision
• Control design

Fundamental problems

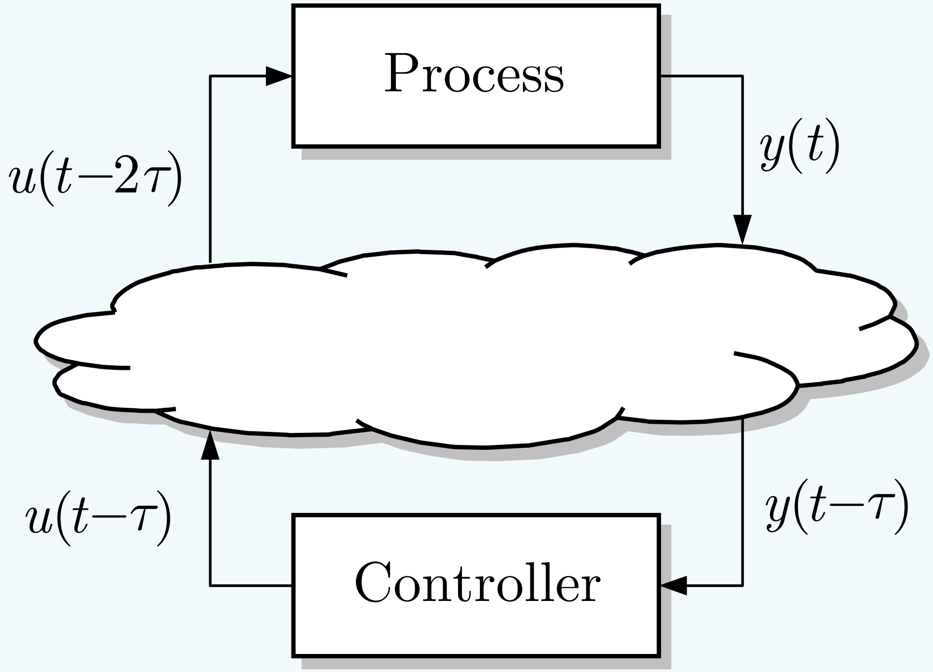
Fundamental problems

Physical entities are controlled and supervised over a communication network

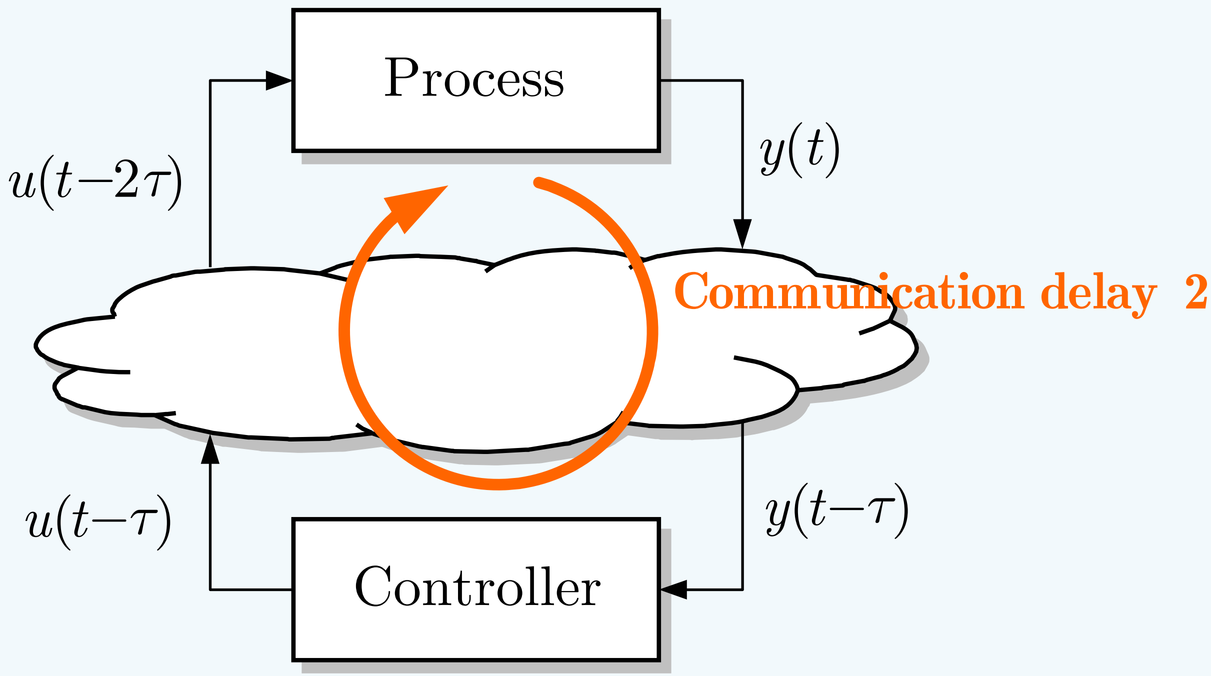
- Modelling, analysis and design of asynchronous control systems
- Performance of networked control systems
- Development of innovative control concepts

Modelling, analysis and design of asynchronous control systems

Networked Control Systems

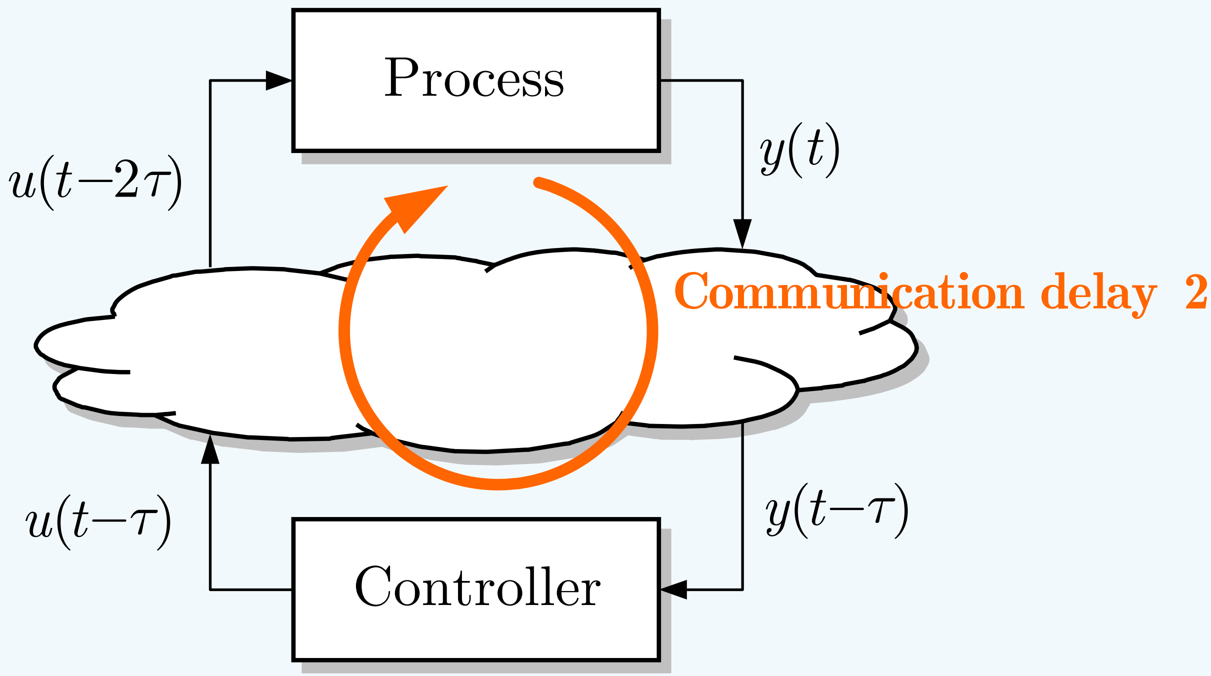


Networked Control Systems



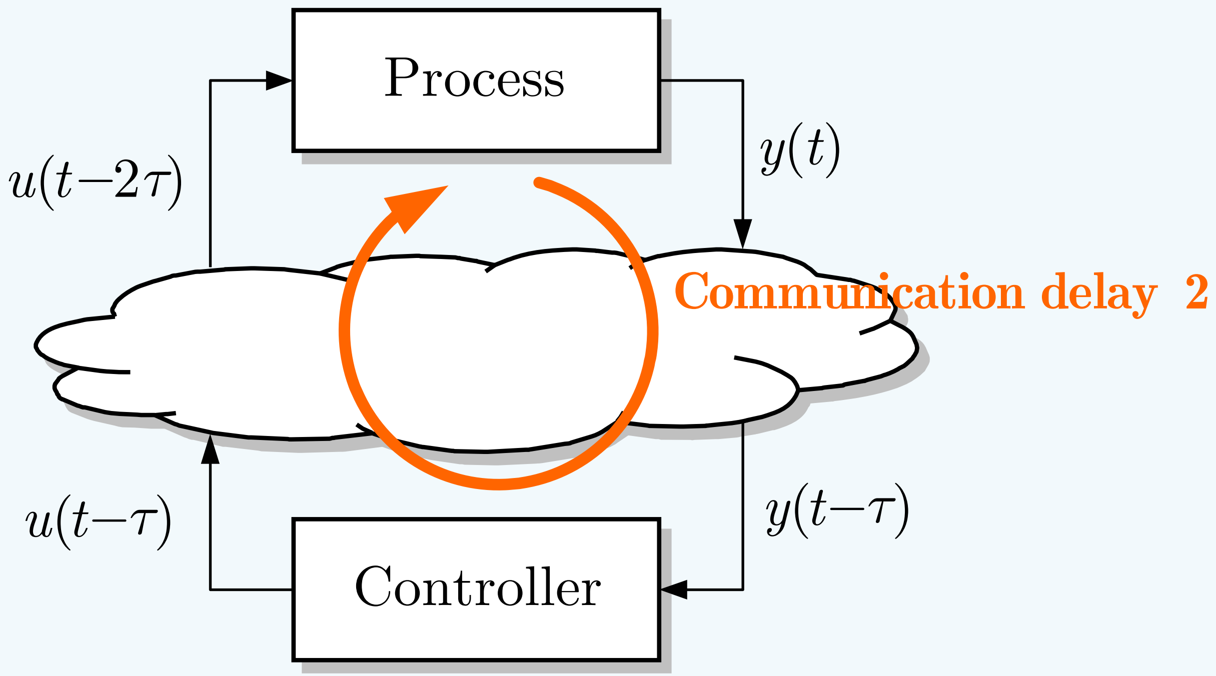
Basic assumptions of digital control are invalid

Networked Control Systems



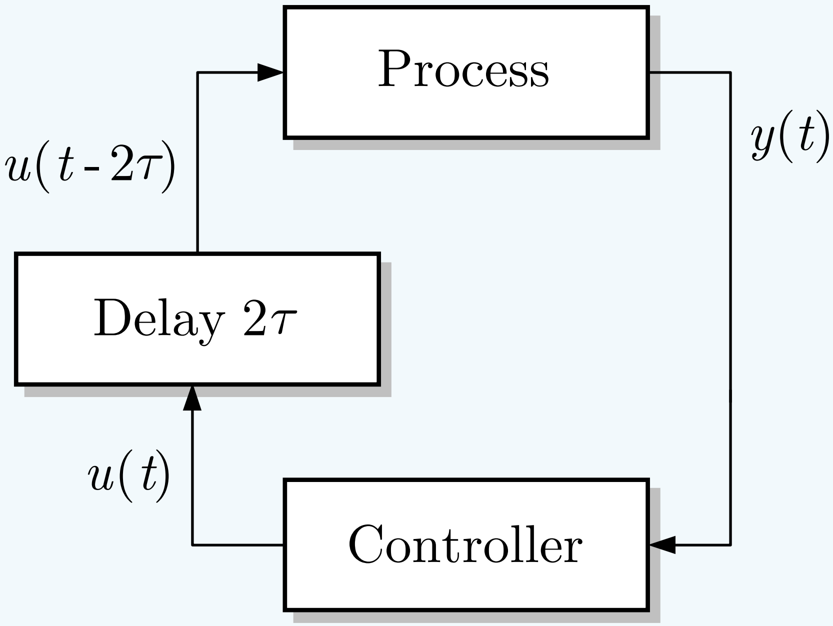
Aim:
Tolerance of the closed-loop system performance against time delay and package loss

Networked Control Systems



Litz/Gabriel/Groß/Gabel :
Networked Control Systems (NCS) – Stand und Ausblick,
Automatisierungstechnik **58** (2008), H. 1, S. 4-19

Networked Control Systems



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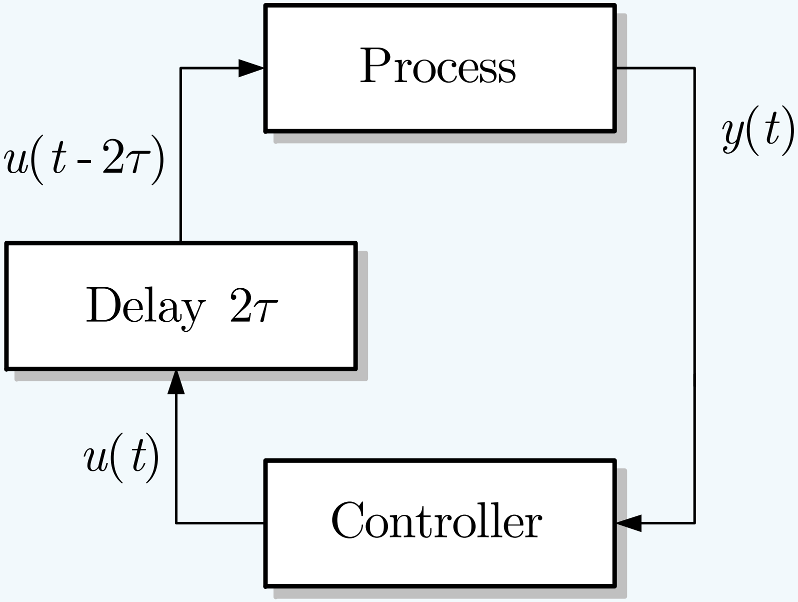
Automatisierungstechnik **58** (2008), H. 1, S. 4-19

Networked Control Systems

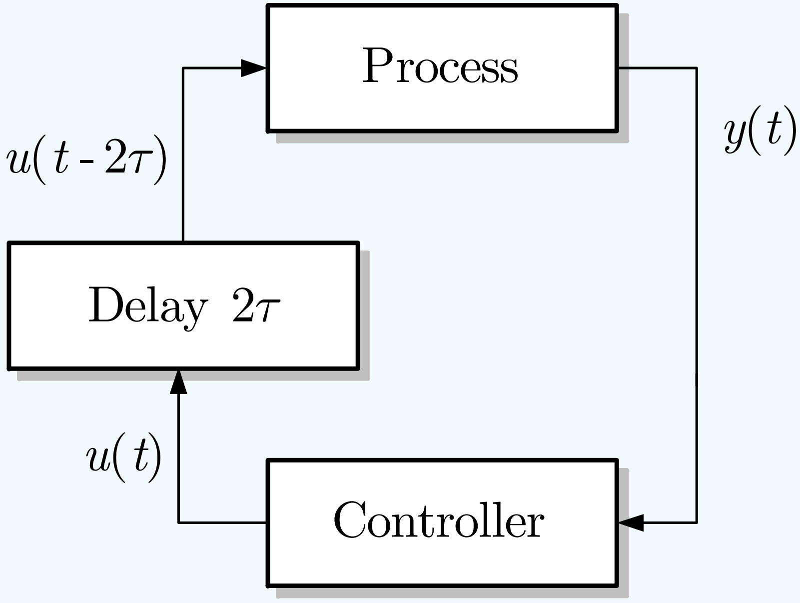


$$\begin{aligned} \dot{\boldsymbol{x}}(t) &= \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t) \\ \boldsymbol{y}(t) &= \boldsymbol{C}\boldsymbol{x}(t) \end{aligned}$$

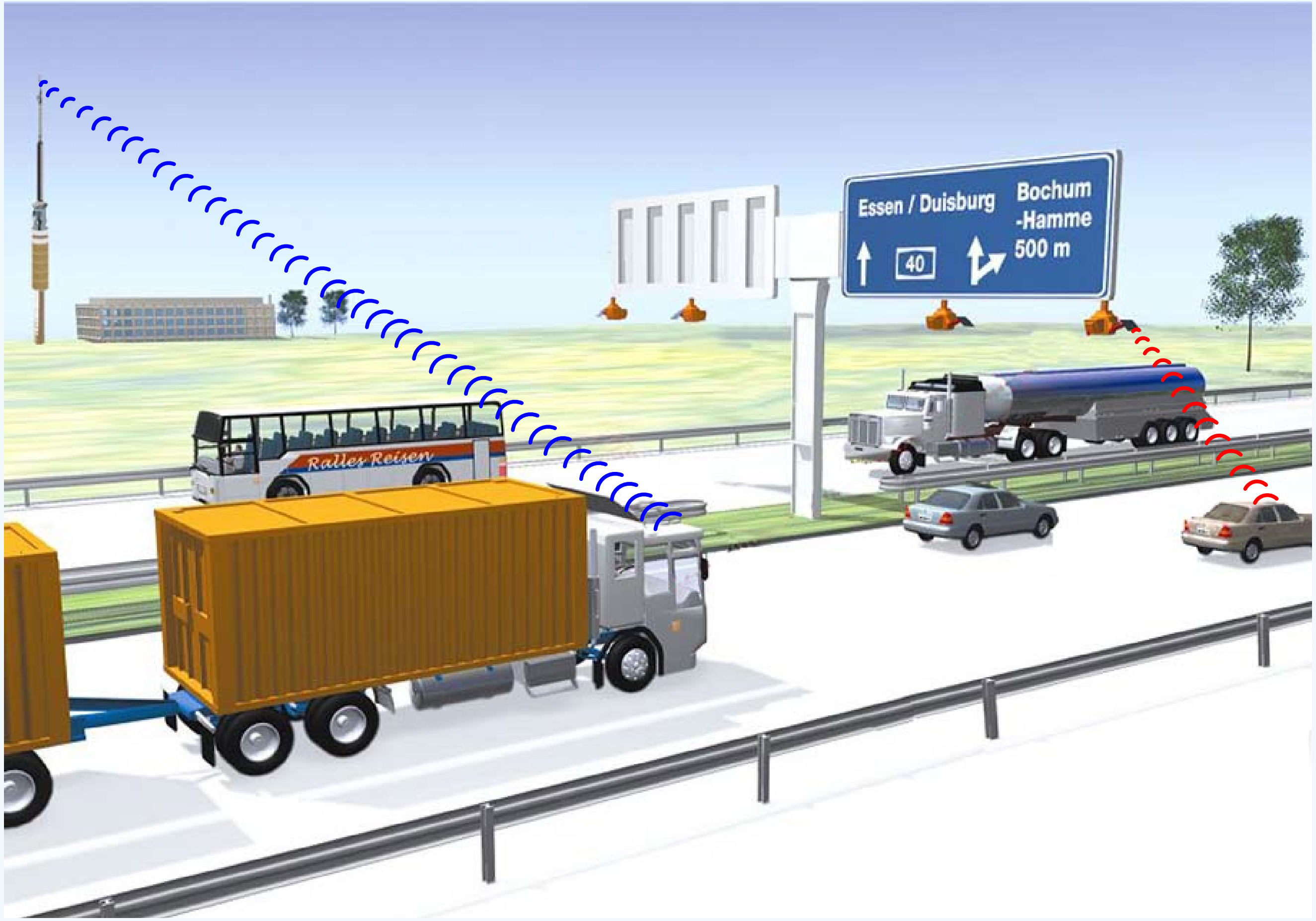
$$\downarrow$$

$$\begin{aligned} \boldsymbol{x}(k+1) &= \boldsymbol{A}(T)\boldsymbol{x}(k) + \boldsymbol{B}(T)\boldsymbol{u}(k) \\ \boldsymbol{y}(k) &= \boldsymbol{C}\boldsymbol{x}(k) \end{aligned}$$

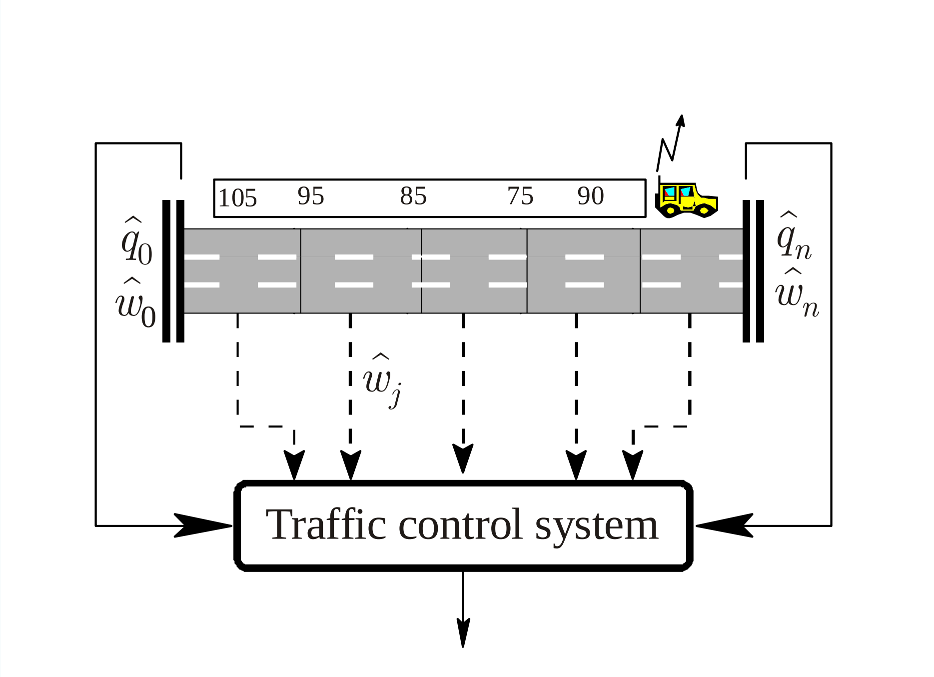
Networked Control Systems



Example:
Traffic control with floating-car data



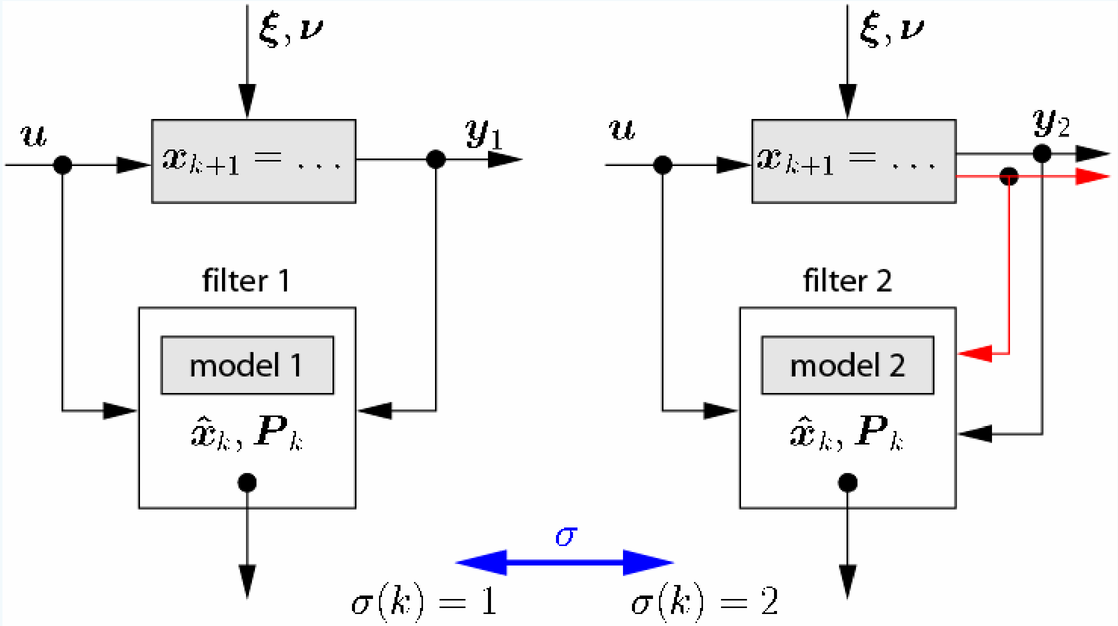
Example:
Traffic control with floating-car data



$$\boldsymbol{x}_{k+1} = \boldsymbol{A}\boldsymbol{x}_k + \boldsymbol{B}\boldsymbol{u}_k$$

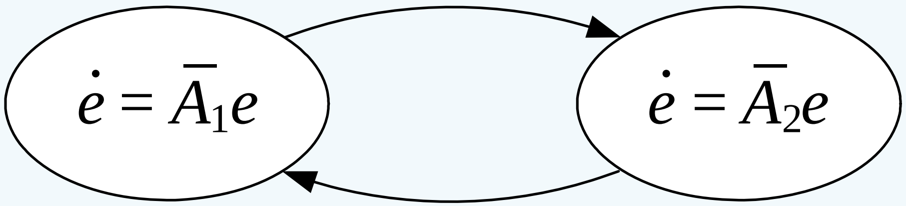
$$\boldsymbol{y}_k = \boldsymbol{C}_{\sigma(k)}\,\boldsymbol{x}_k$$

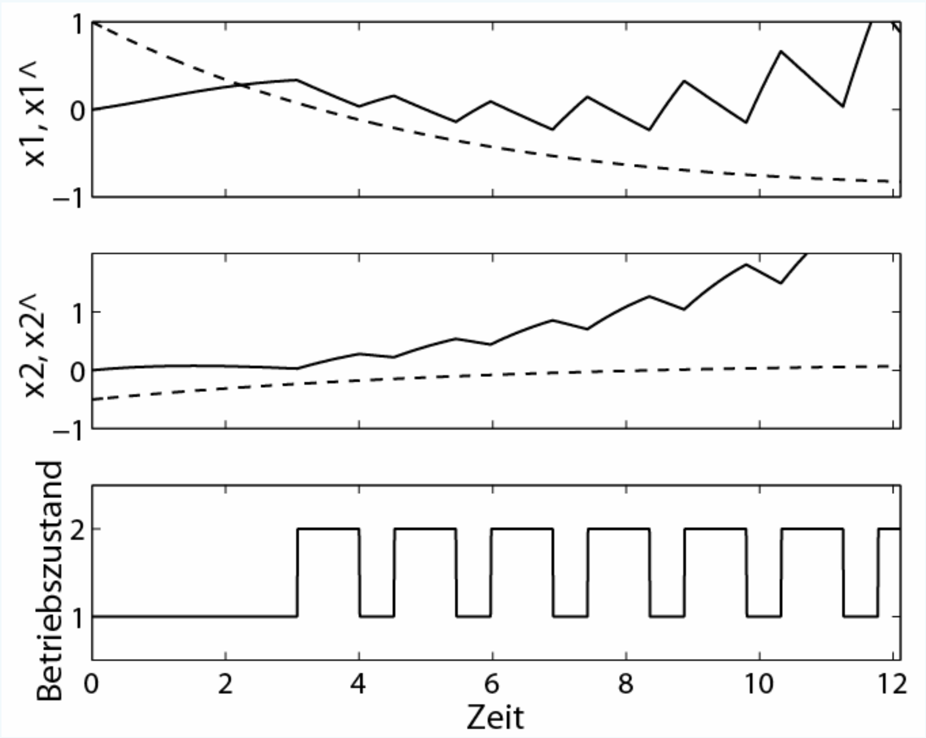
Switching observer



Does the switching observer converge?

Two stable observers…

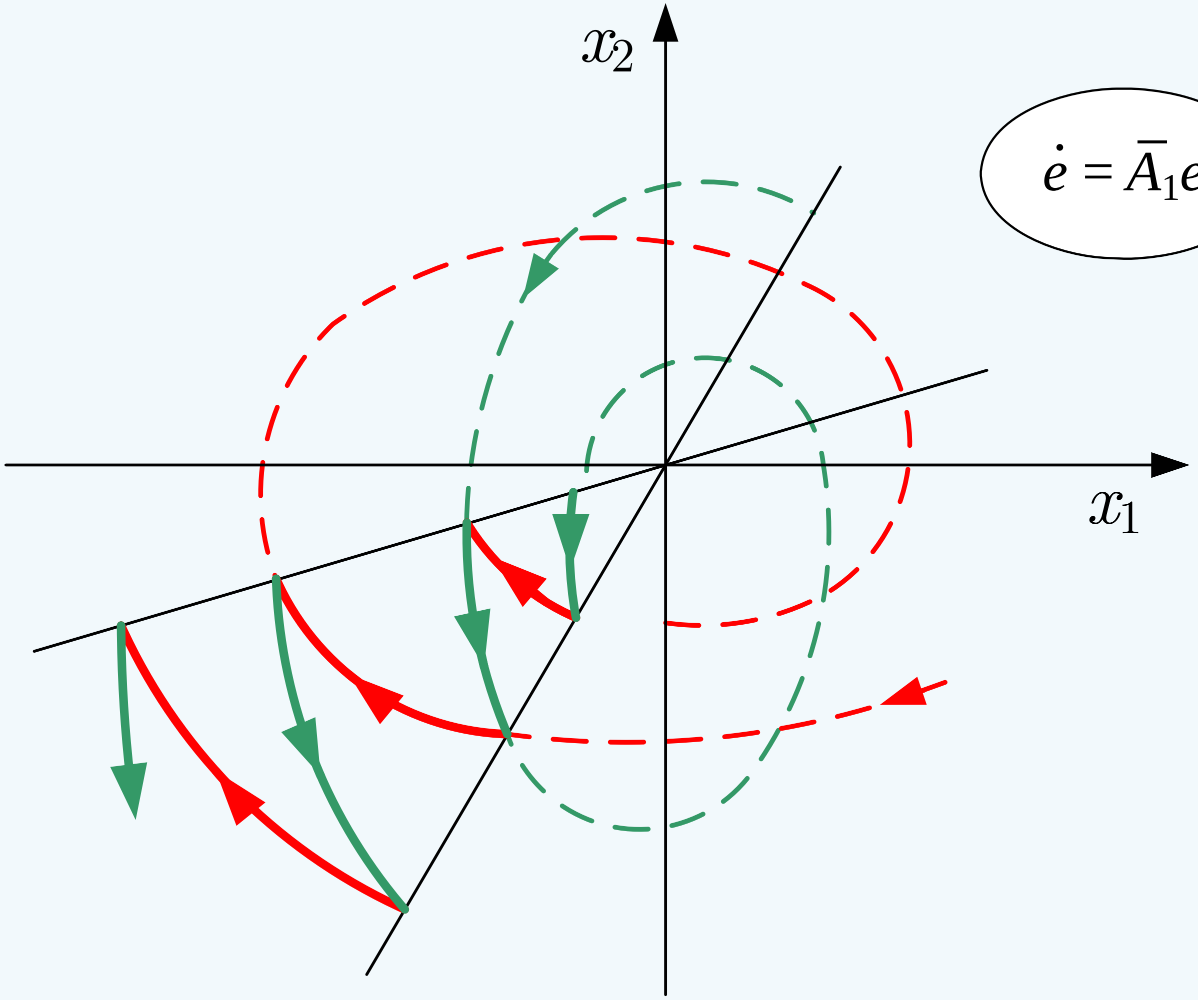


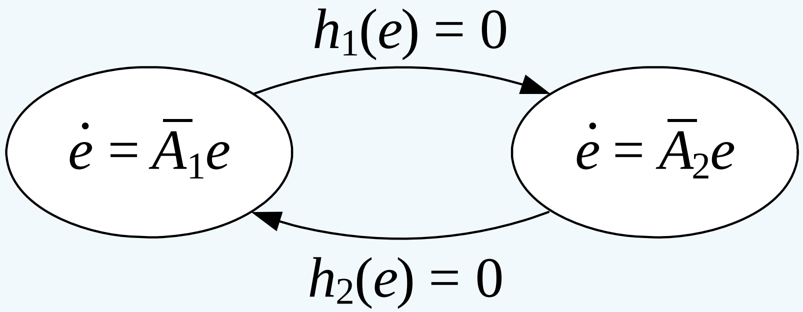


… may result in an unstable switching observer

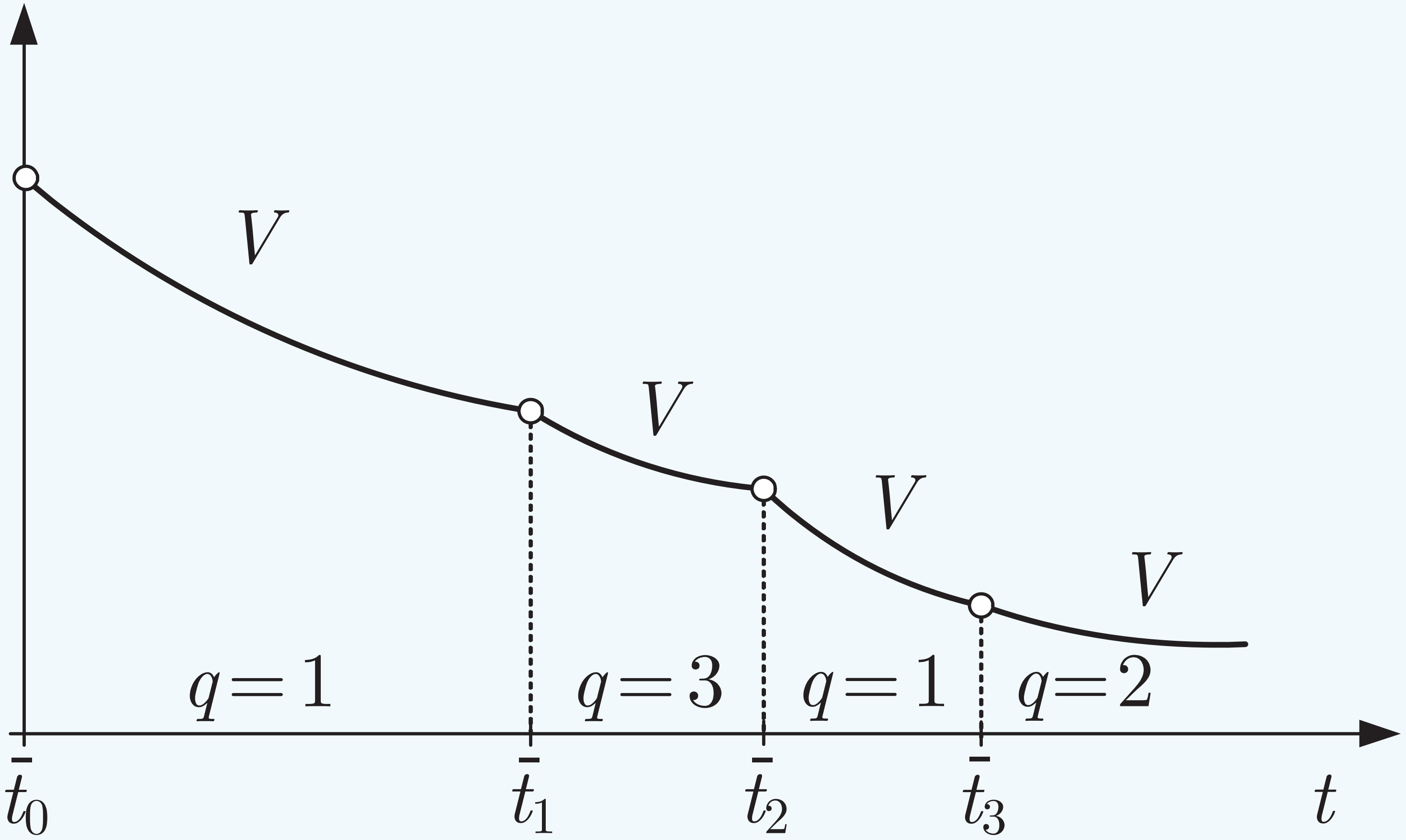
Lunze: Ein Beispiel für den Entwurf schaltender Beobachter, *Automatisierungstechnik* **48** (2000)

Analysis of the example:

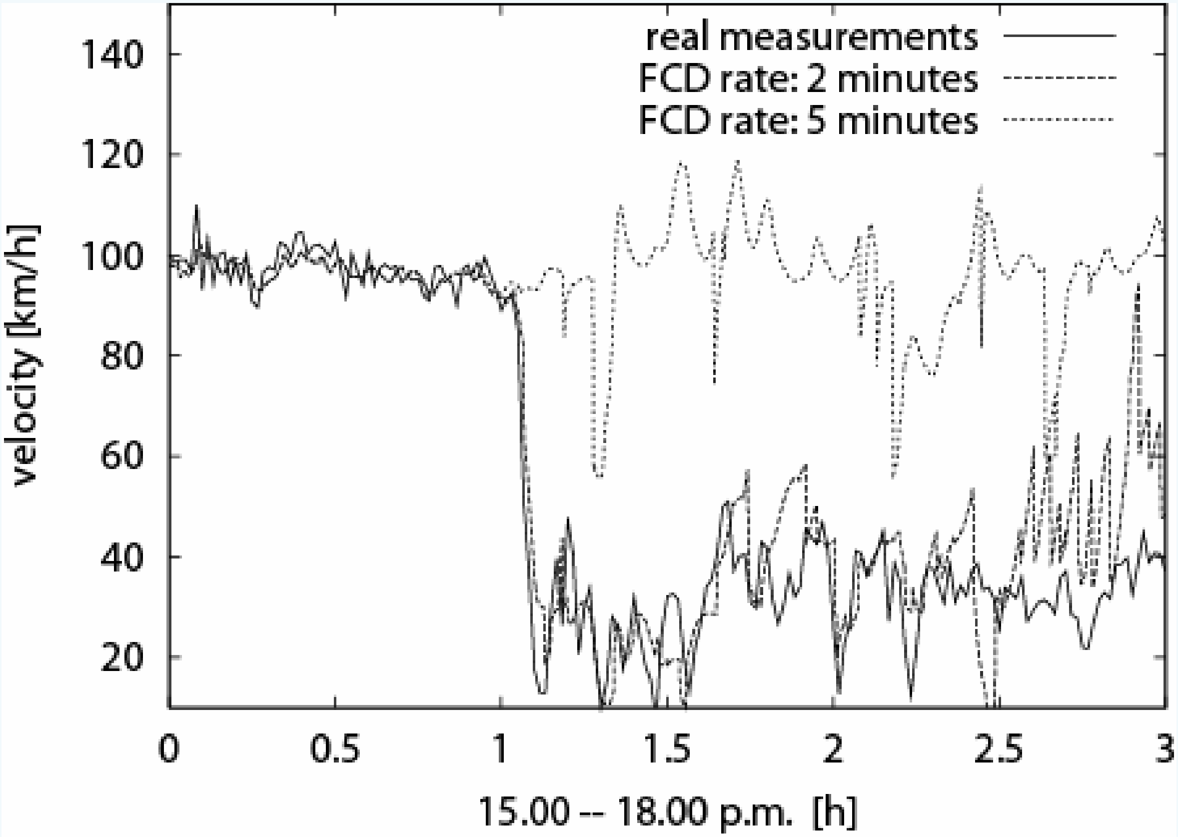




Stability of the switching observer: Use a common Lyapunov function



Estimation results obtained with a switching Kalman filter



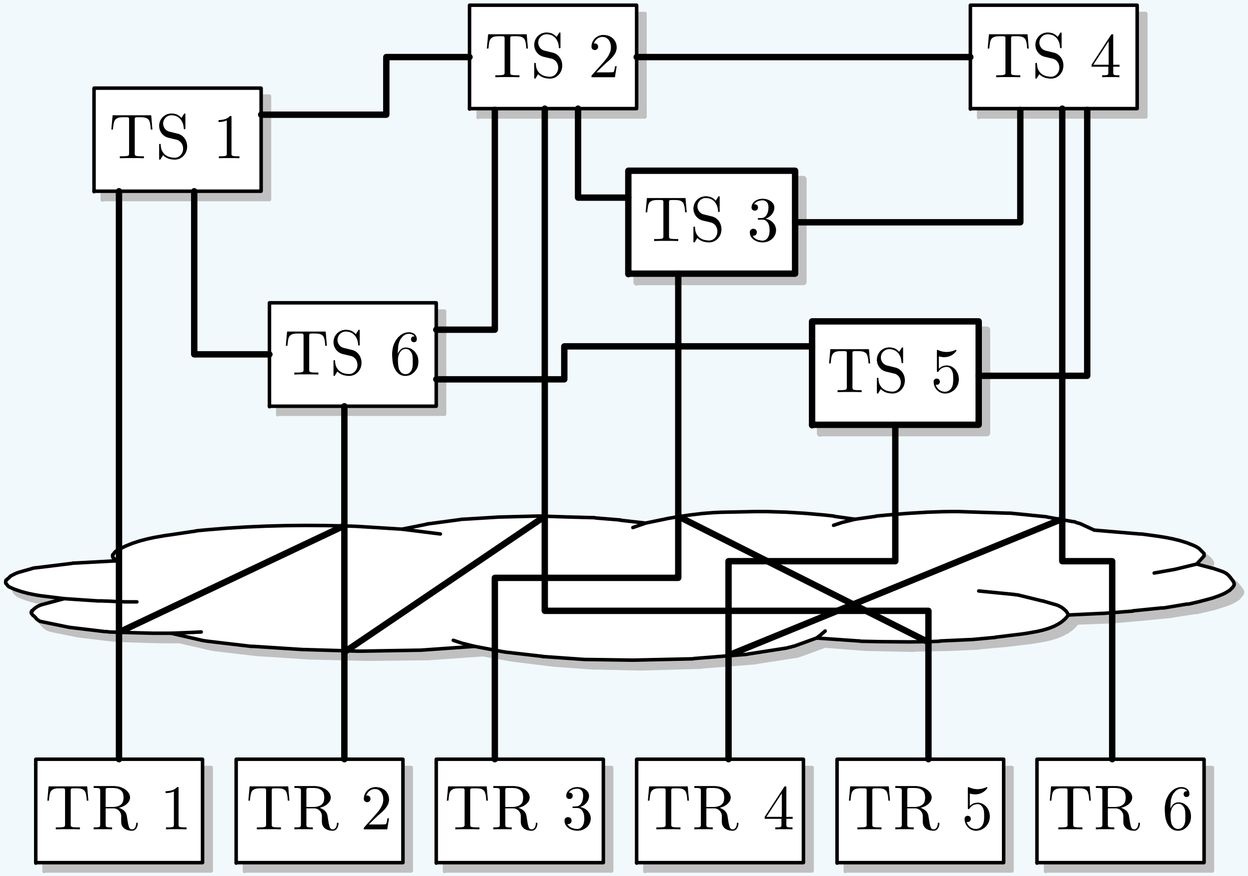
Böker/Lunze: Stability and performance of switched Kalman filters, *International Journal of Control*

SPP-Projekte: Modellierung, Analyse und Entwurf asynchron arbeitender Regelungssysteme

- Entwicklung asynchroner prädiktiver Regelungsverfahren für digital vernetzte Systeme (*Allgöwer*, *Grüne*, *Findeisen*)
- Stabilität und Regelungsentwurf in digital vernetzten dynamischen Systemen mit nichtdeterministischem Datenverlust und Totzeit (*Hirche*)
- Dynamische Stabilitätsraten für Networked Control Systems (*Siegmund*)
- Stabilität und Stabilisierung großer digitaler Netzwerke (*Wirth*)
- Beobachtung und Regelung heterogener dynamischer Systeme (*Helmke*, *Schilling*)
- Zustandsbeobachtung auf bewegtem Horizont bei variablen Totzeiten, Paketverlusten und Paketüberholvergängen (*Lohmann*)

Performance of networked control systems

Control of networked systems



Physical couplings

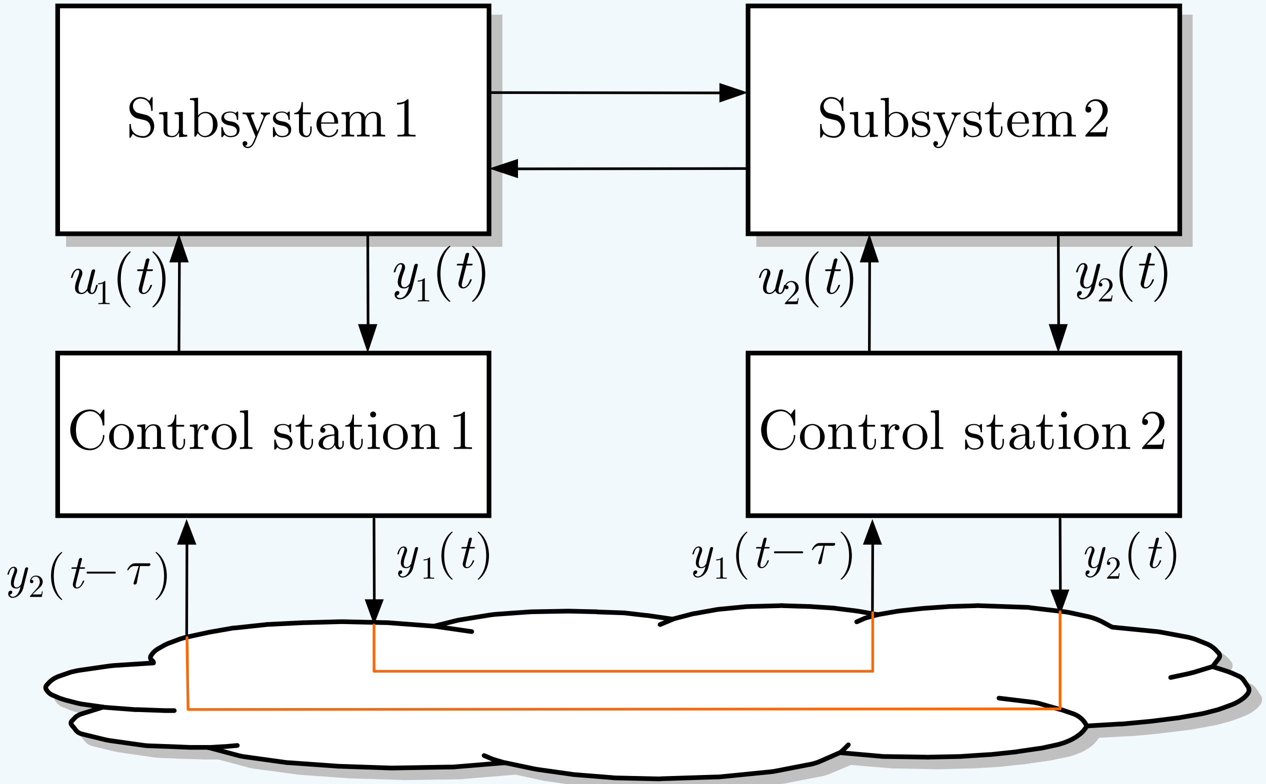
Couplings of communication links

Control

Control of networked systems

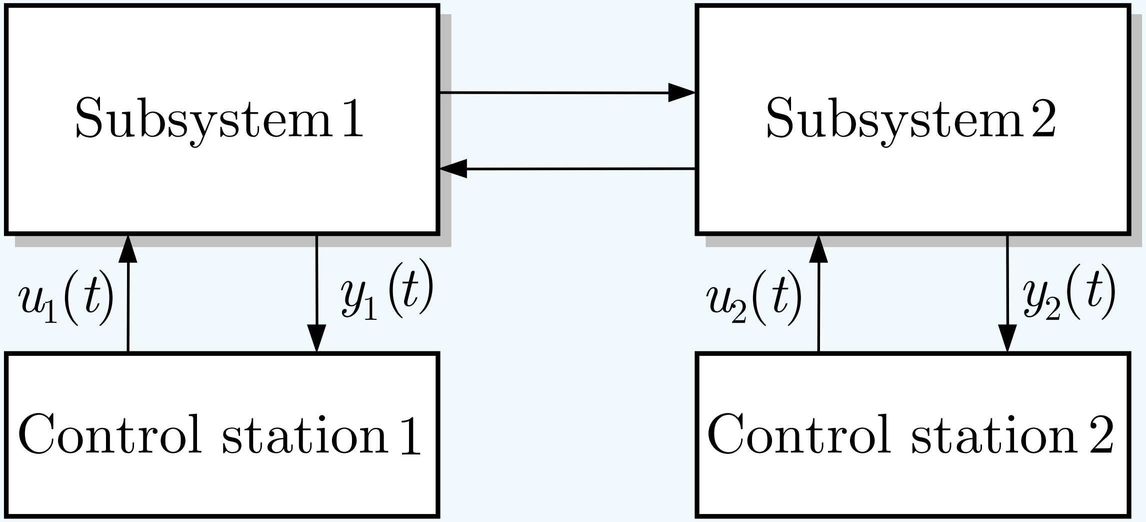
- Which information links are necessary/reasonable?
- Which new functions can be implemented by networking?
  - Improvement of performance
  - Robustness
  - Fault tolerance

Distributed control



$u_1(t) = k_1(y_1(t), y_2(t-\tau))$ $\quad$ $u_2(t) = k_2(y_2(t), y_1(t-\tau))$

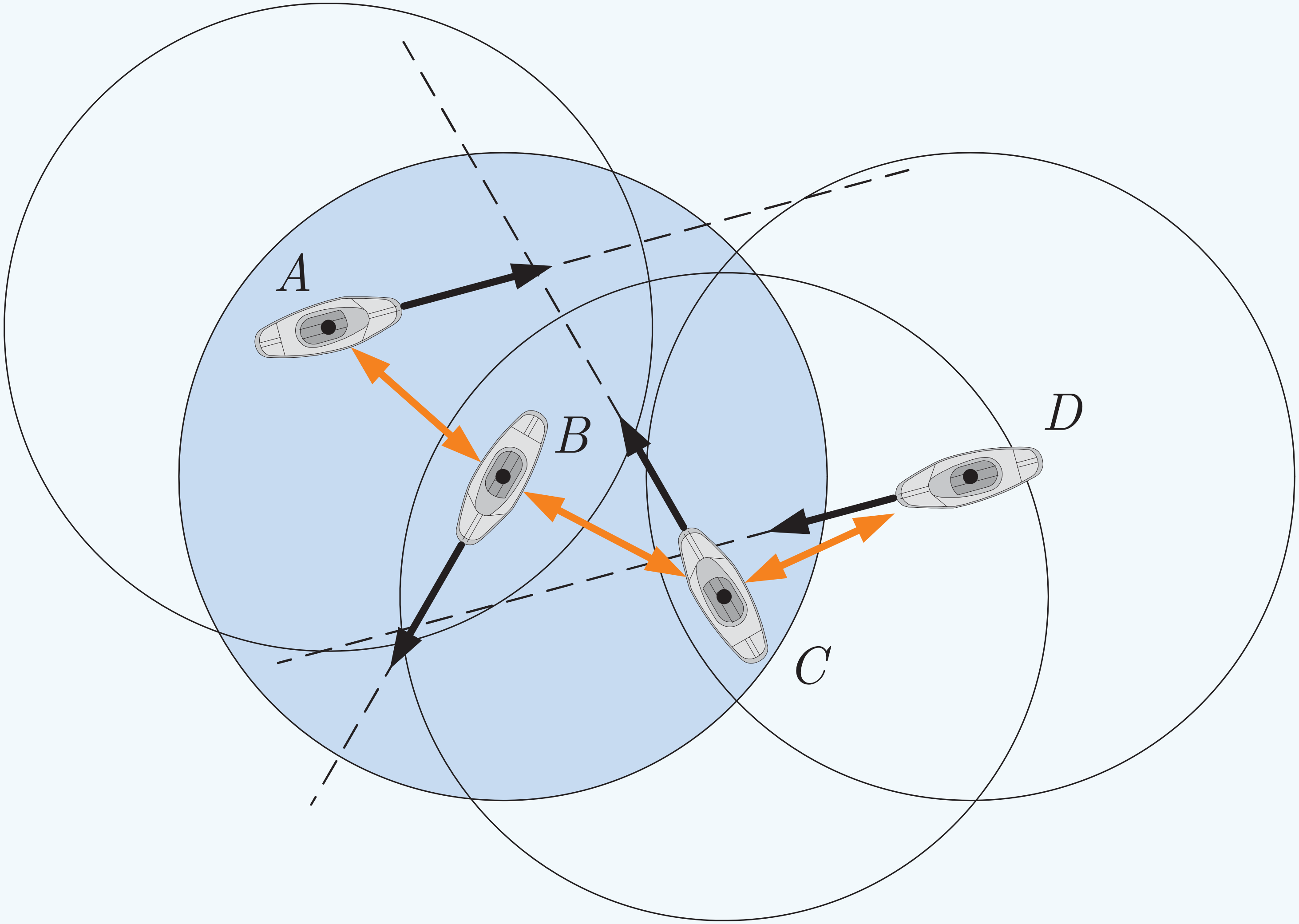
Distributed control



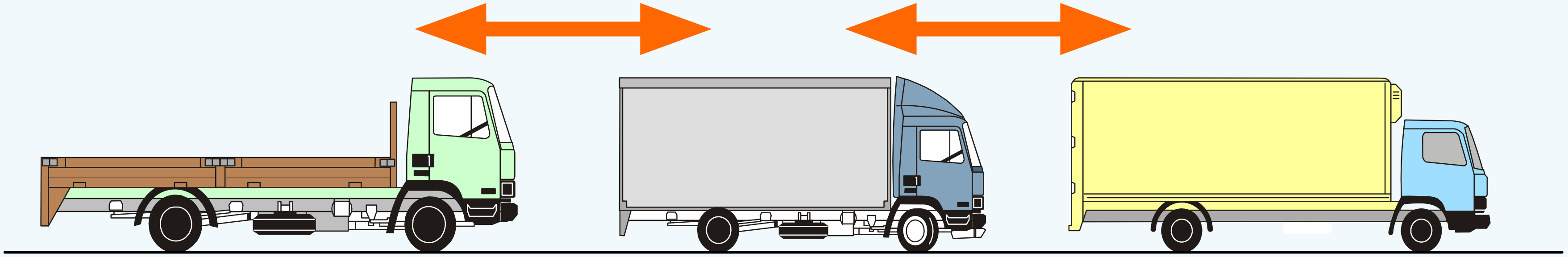
In case of data loss: decentralised control

$u_1(t) = k_1(y_1(t), \cdot)$ $\qquad$ $u_2(t) = k_2(y_2(t), \cdot)$

Example: Supervision of the ship traffic

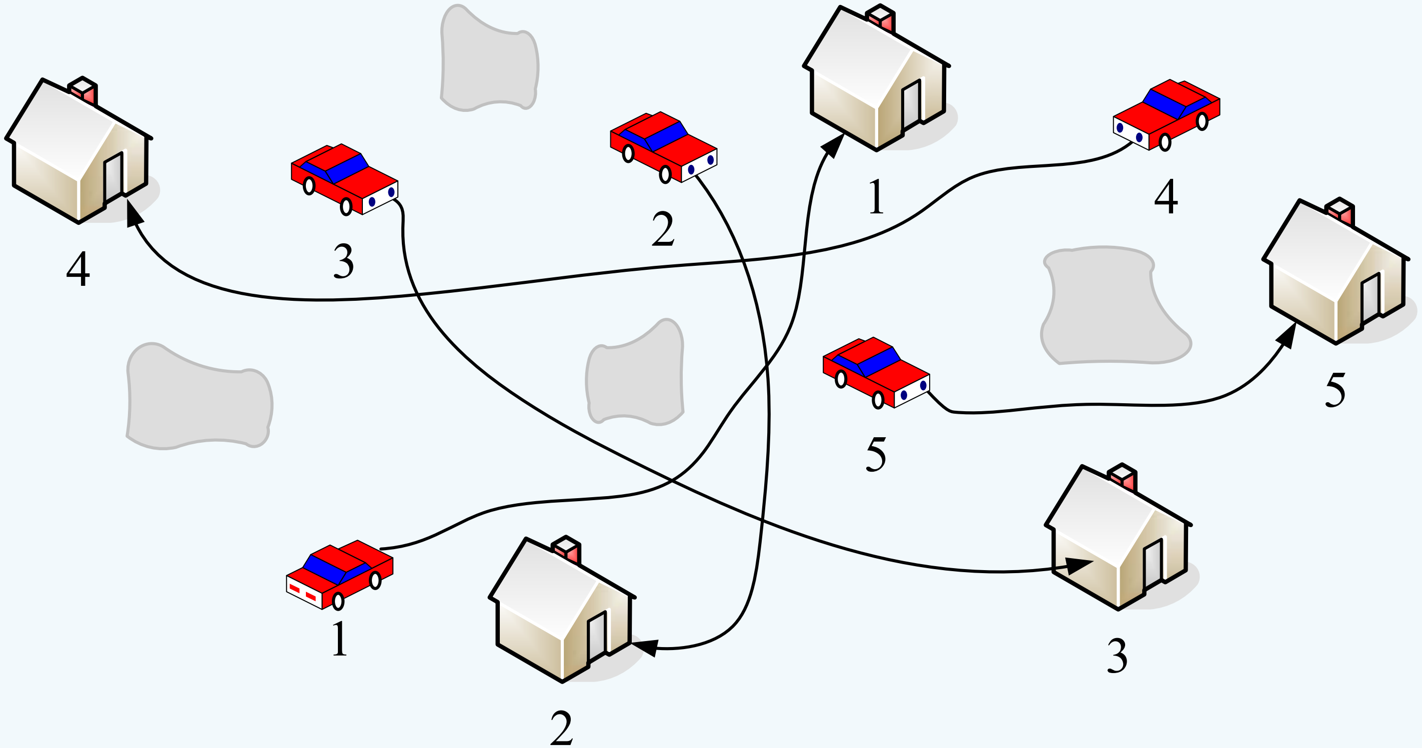


Example: Platooning on highways

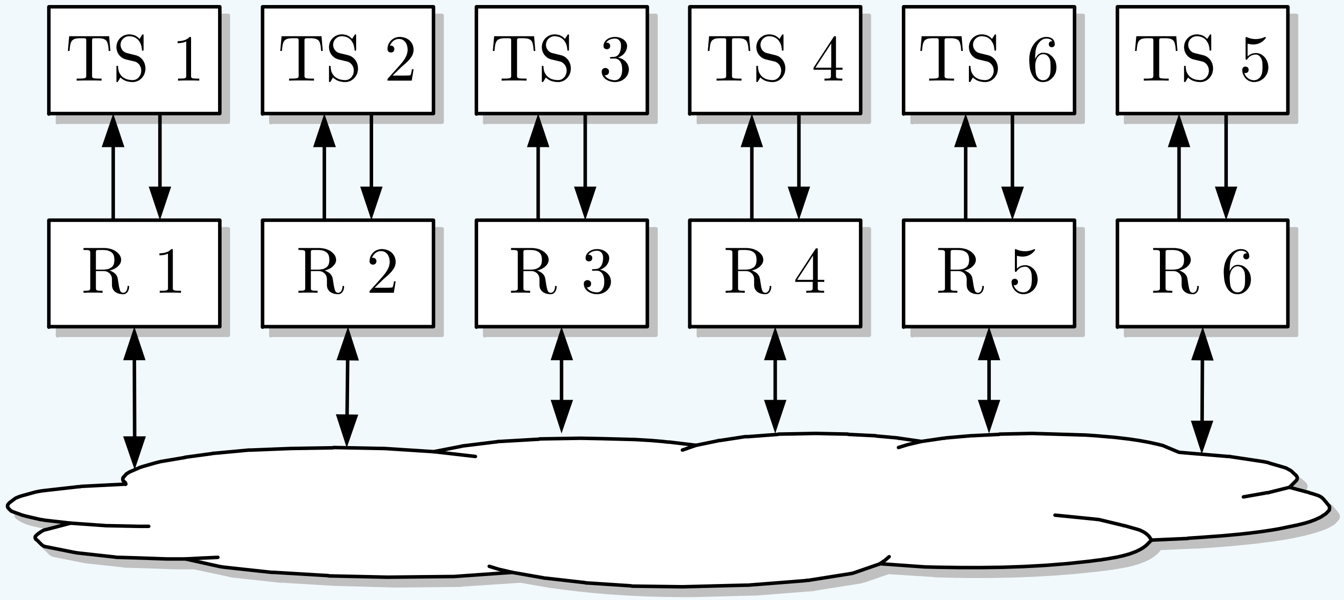


Distance and velocity control subject to changing structure

Example: Autonomous agents



Example: Autonomous agents



Consensus problem:

The agents should find a common „average state“

SPP-Projekte: Verhalten vernetzter Regelungssysteme

- Entwurf von dezentralen, digital vernetzten Regelungen mit garantierter Stabilität und Regelgüte für gekoppelte Systeme (*Allgöwer*)
- Regelung von Fahrzeugkolonnen mit topologisch veränderlichem Kommunikationsnetzwerk auf der Basis von Energiemethoden (*Abel*, *Kowalewski*)
- Autonomie und Kooperation in digital vernetzten Regelungssystemen (*Lunze*)
- Informationsmaße und Invarianz für vernetzte Kontrollsysteme (*Colonius*)

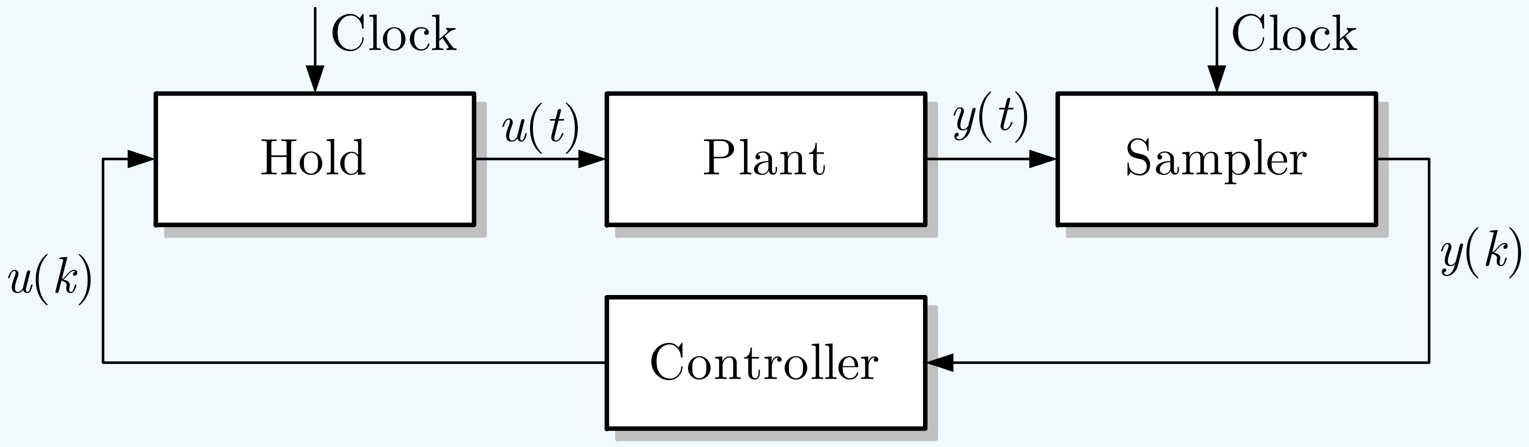
Development of innovative control concepts

New control structures

- Extension of the function of the control components (Event-based control)
- Distribution of the functions among the components in dependence upon the load
- Improvement of the fault tolerance by using additional sensors and actuators
(Control reconfiguration)

Event-based control

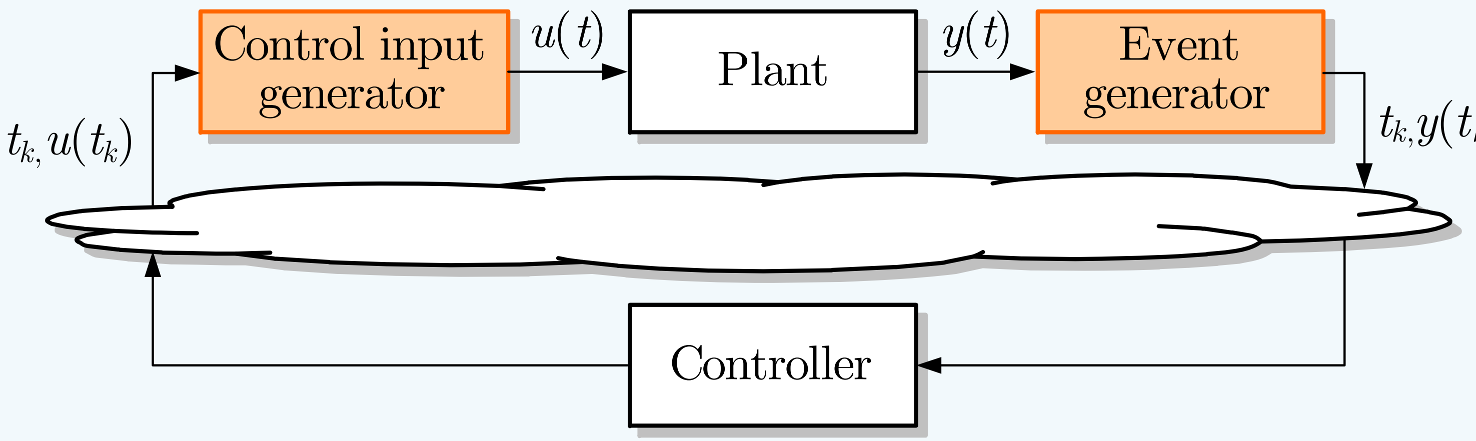
Sampled-data control loop



Time-triggered

+ Deterministic behaviour
+ Theory of sampled-data control for modelling and design
– No adaptation of the communication
– No flexibility of the communication

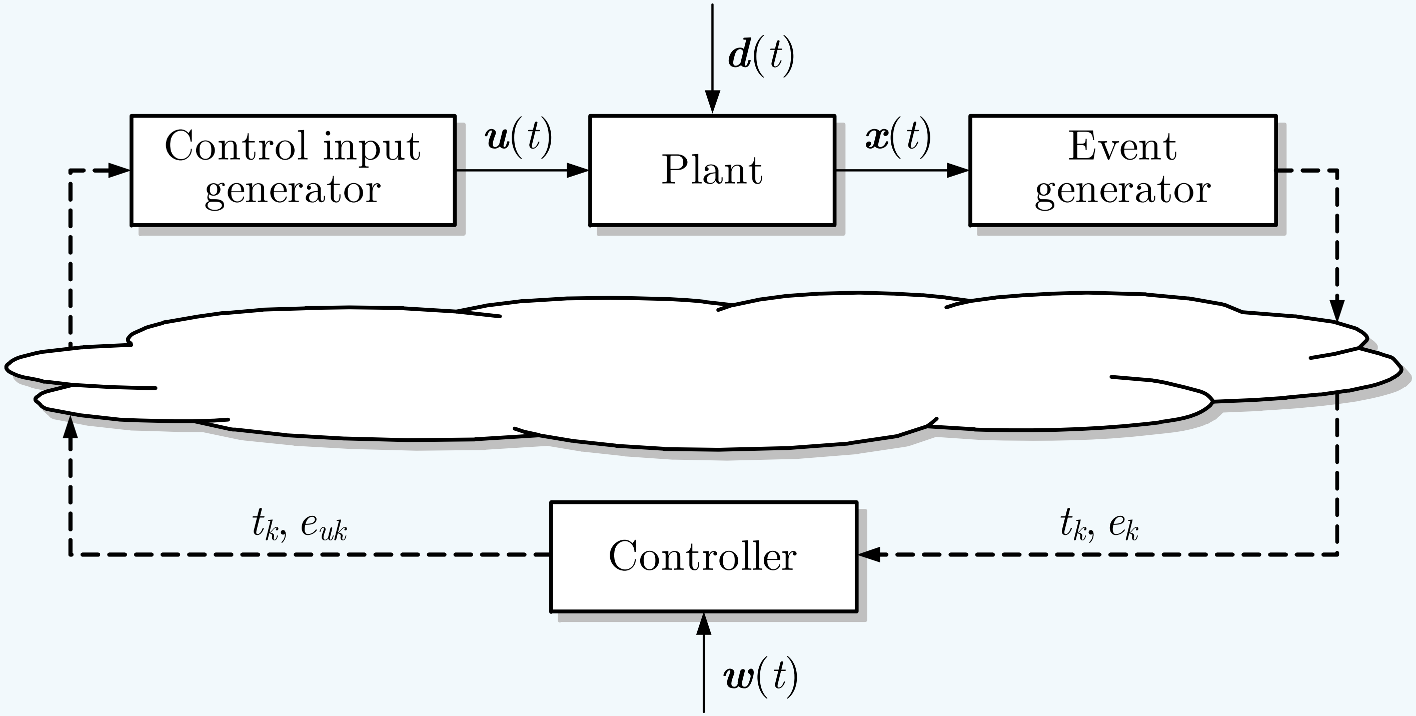
Event-based control



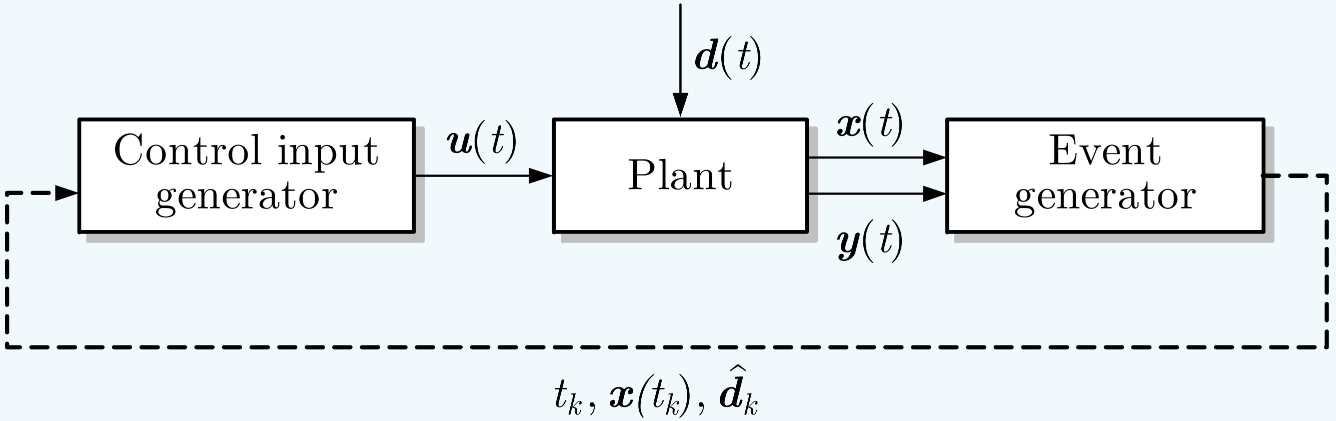
Event-triggered

+ Adaptation of the information communication to the loop performance
+ Higher-order modelling (Parameters depend upon the „sampling time")
- No theory available

Event-based control



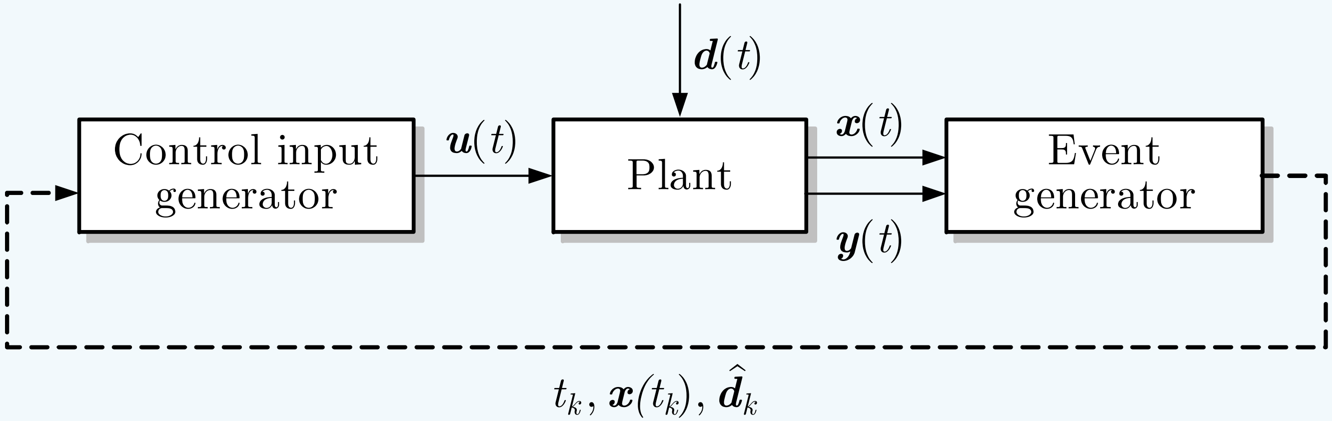
Event-based control



In which situation do we need a feedback loop?

- for stabilising the plant,
- for disturbance attenuation,
- for robustness against model uncertainties.

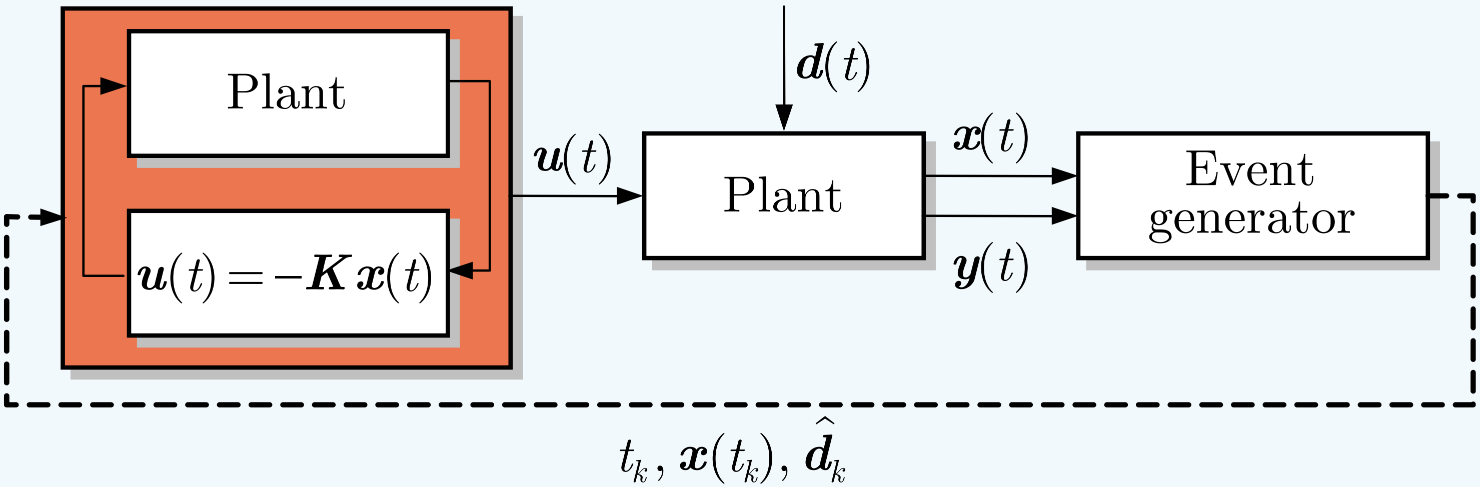
Event-based control



In which situation do we need a feedback loop?

- … for disturbance attenuation

Event-based state feedback

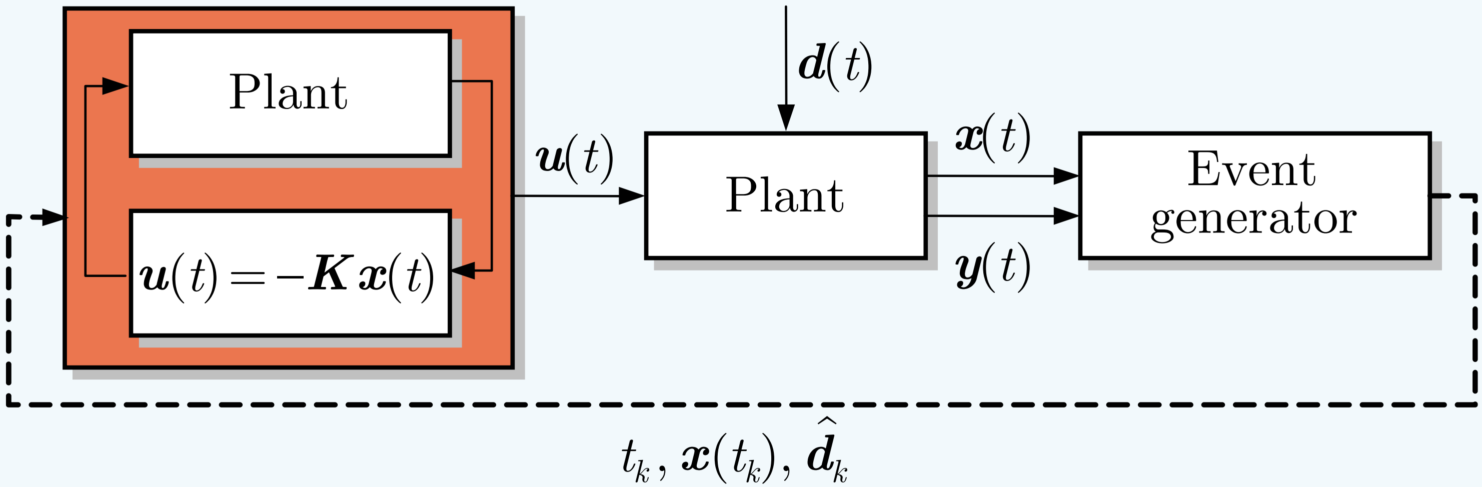


Control input generator: generates the same input as a continuous state-feedback controller

$$\boldsymbol{u}(t) = -\boldsymbol{K}\mathrm{e}^{\bar{\boldsymbol{A}}(t-t_k)}\boldsymbol{x}(t_k) + \int_{t_k}^{t} -\boldsymbol{K}\mathrm{e}^{\bar{\boldsymbol{A}}(t-\tau)}\boldsymbol{E}\boldsymbol{d}(\tau)\,\mathrm{d}\tau, \qquad t \geq t_k$$

unknown

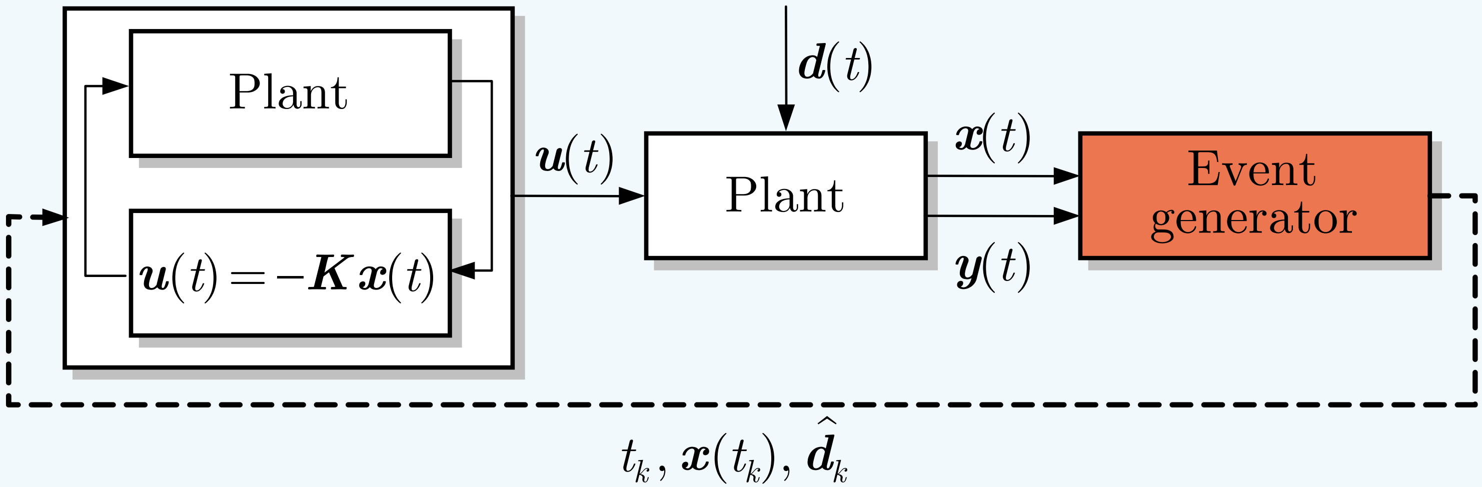
Event-based state feedback



$$\boldsymbol{u}(t) = -\boldsymbol{K}\mathrm{e}^{\bar{\boldsymbol{A}}(t-t_k)}\boldsymbol{x}(t_k) - \boldsymbol{K}\bar{\boldsymbol{A}}^{-1}\left(\mathrm{e}^{\bar{\boldsymbol{A}}(t-t_k)} - \boldsymbol{I}\right)\boldsymbol{E}\hat{\boldsymbol{d}}_k, \qquad t \geq t_k$$

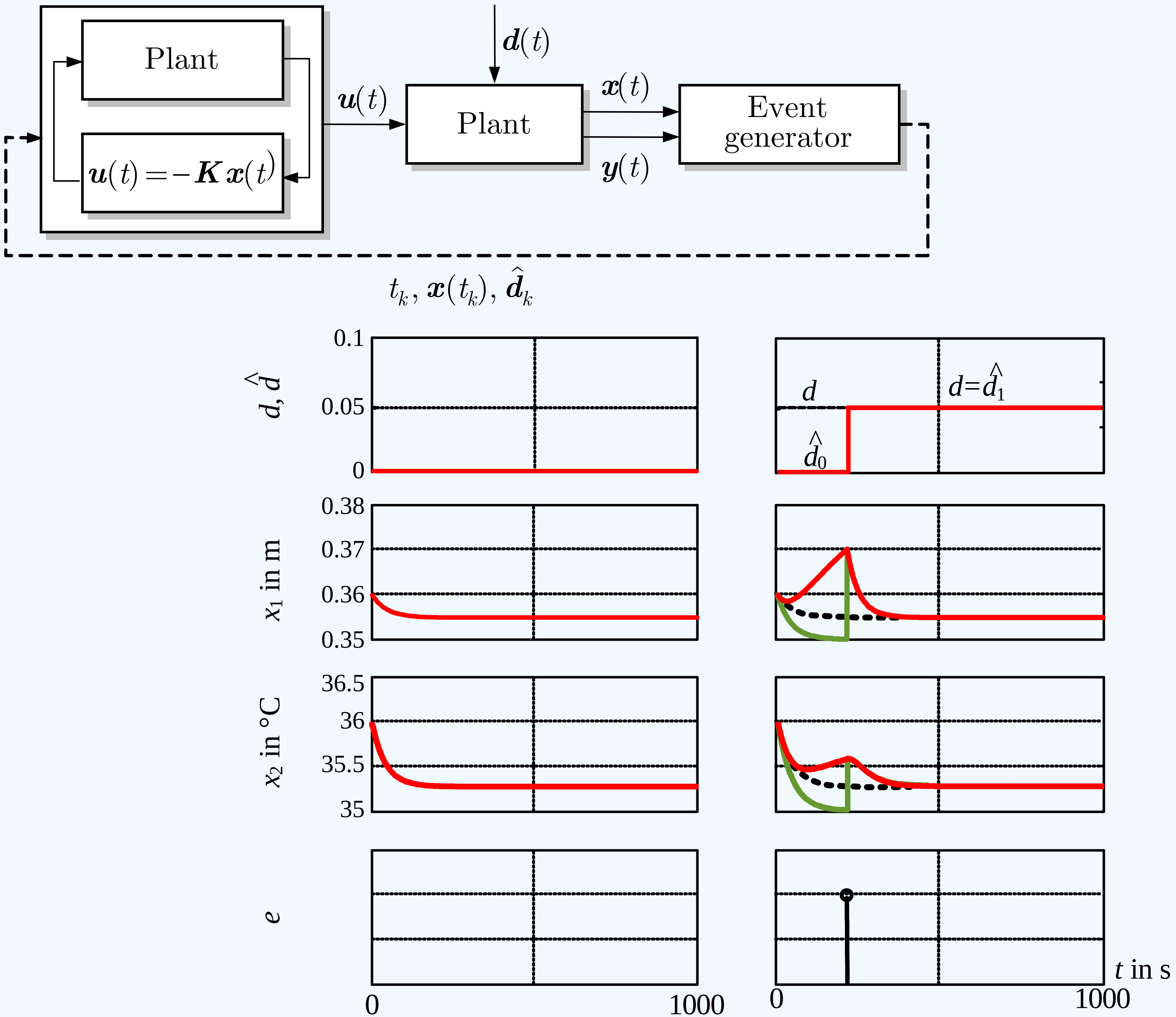
Estimate of disturbance

Event-based state feedback

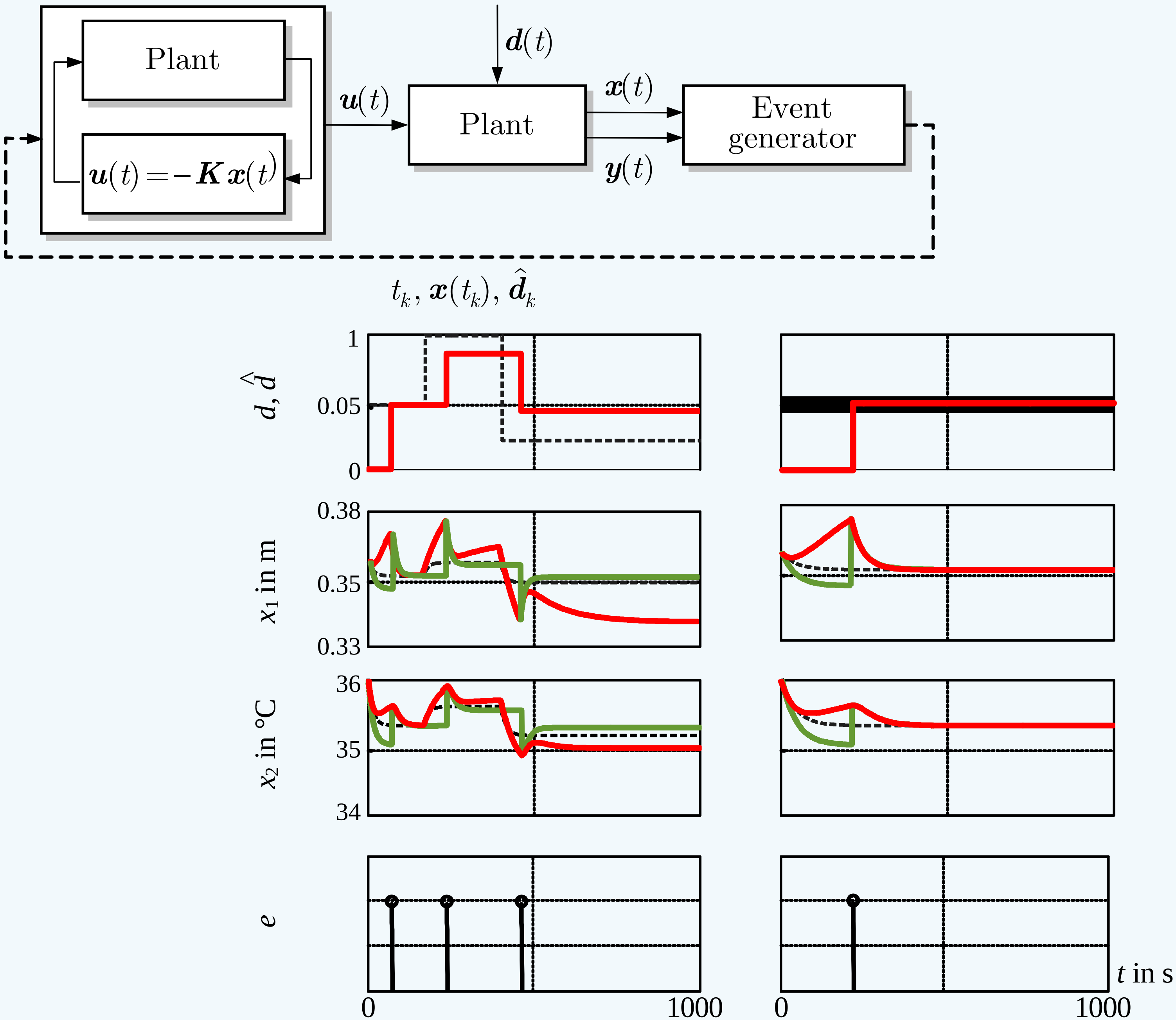


Event generator: initiates an information exchange, if the difference between the event-based and the state-feedback loops are too large:

$$\|\boldsymbol{x}(t_{k+1}) - \boldsymbol{x}_{\mathrm{s}}(t_{k+1})\| = \bar{e}$$



Plant
u(t) = −K x(t)
u(t)
d(t)
Plant
x(t)
y(t)
Event generator
t_k, x(t_k), d̂_k
d, d̂
0.1
0.05
0
d
d = d̂_1
d̂_0
x_1 in m
0.38
0.37
0.36
0.35
x_2 in °C
36.5
36
35.5
35
e
t in s
0
1000
0
1000



Plant
$u(t) = -K\,x(t)$
$u(t)$
$d(t)$
Plant
$x(t)$
$y(t)$
Event generator
$t_k,\ x(t_k),\ \hat{d}_k$
$d, \hat{d}$
1
0.05
0
x_1 in m
0.38
0.35
0.33
x_2 in °C
36
35
34
e
t in s
0
1000
0
1000

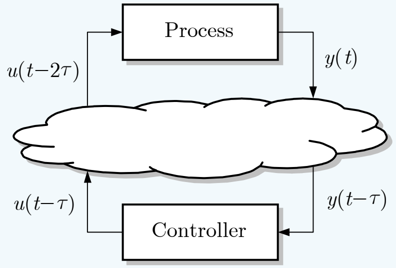
SPP-Projekte: Entwicklung innovativer Regelungskonzepte und deren Entwurfsmethoden

- Analyse und Entwurf ereignisbasierter Regelungen mit quantisierten Signalräumen (*Grüne*, *Junge*, *Lunze*)
- Prädiktive Regelung hybrid modellierter digital vernetzter Systeme (*Stursberg*)
- Modellgestütztes CCC-Cross-Design für funkbasierte Regelungssysteme (*Gotzhein*, *Litz*)

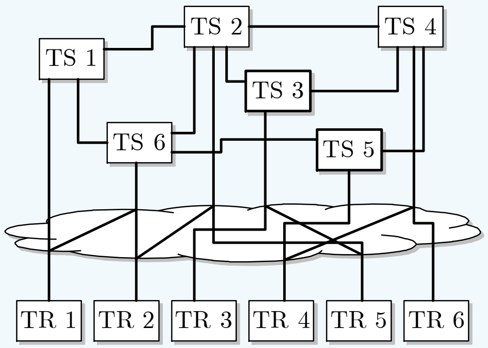
Outlook

Fundamental problems

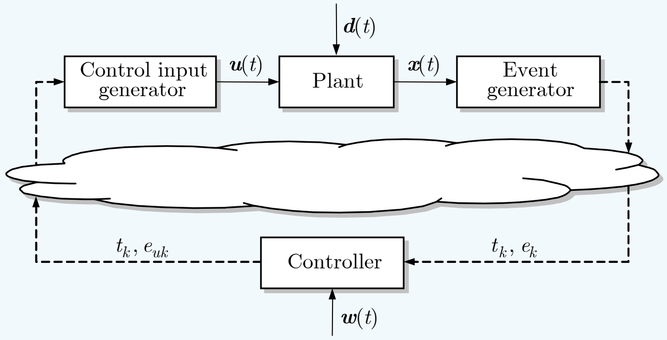
- Modelling, analysis and design of asynchronous control systems



- Performance of networked control systems



- Development of innovative control concepts



Doktorandenschule
06. - 10. Oktober 2008, Willingen

K. H. Johansson (KTH Stockholm): **Control under communication constraints**

C. De Persis (Universität Rom): **Encoding and control of networked systems**

S. Zampieri (Universität Padua): **Introduction to average consensus algorithms and it applications**

N. Wehn (TU Kaiserslautern): **Hardware-Software Codesign**

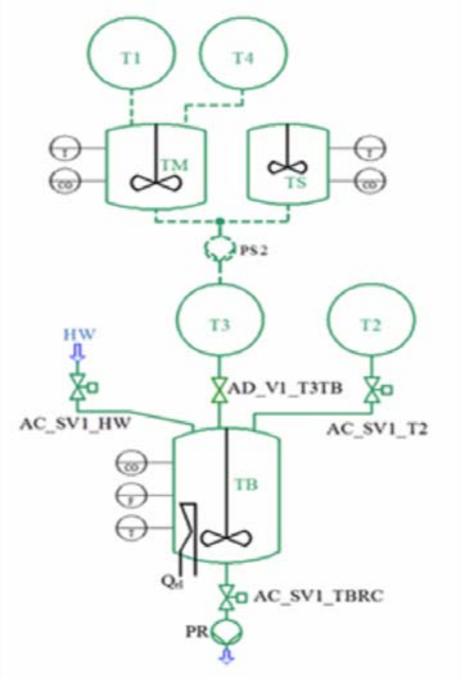
A. Rantzer (Lund University): **Distributed control of networked dynamical systems**

U. D. Hanebeck (Universität Karlsruhe): **Informationsverarbeitung in Sensor-Aktor-Netzwerken**

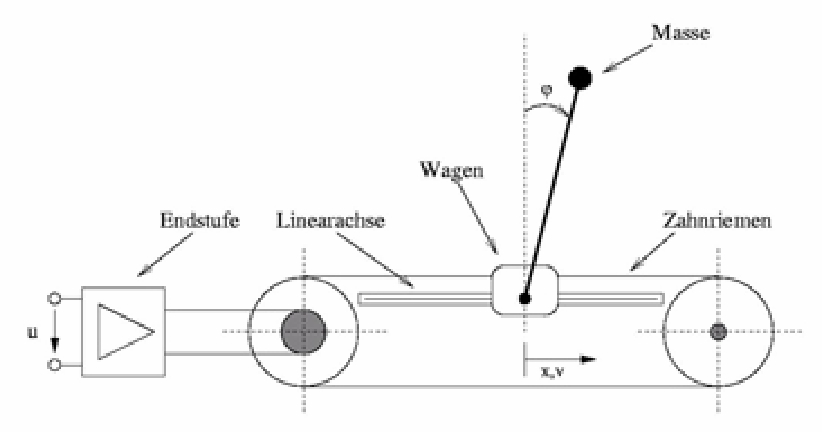
G. Frey (TU Kaiserslautern): **Zeitverhalten vernetzter Automatisierungssysteme**

Benchmark problems

Füllstands- und Leitfähigkeitsregelung an der verfahrenstechnischen Pilotanlage VERA



Stabilisierung eines inversen Pendels über ein Funknetzwerk



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