Chair of Communication Networks
Department of Electrical and Computer Engineering
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# Communications and Control
# An introduction to Cyber Physical Networking

12th ITG SCC, Rostock, Germany

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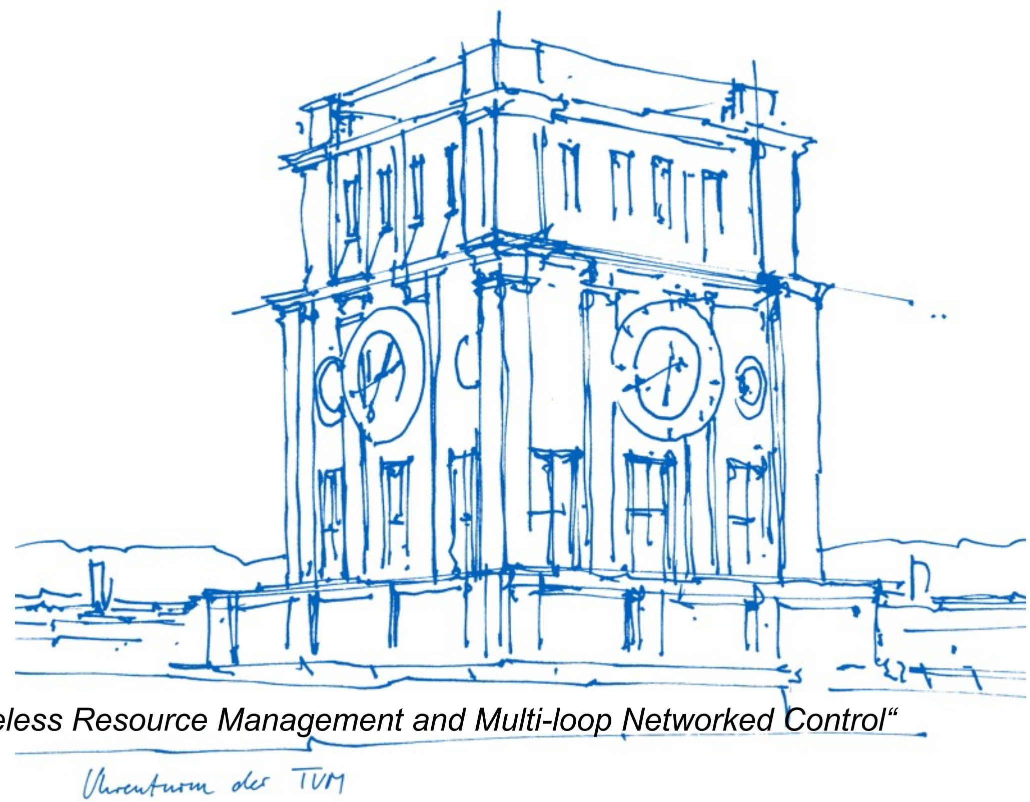



*DFG SPP 1914 project „Optimal Co-Design of Wireless Resource Management and Multi-loop Networked Control“*



This work is supported by the DFG Priority Programme 1914 Cyber-Physical Networking grant number KE1863/5-1

# Motivation: 5G Vision

*enhanced Mobile BroadBand*

**eMBB**

*Ultra Reliable Low Latency Communication*

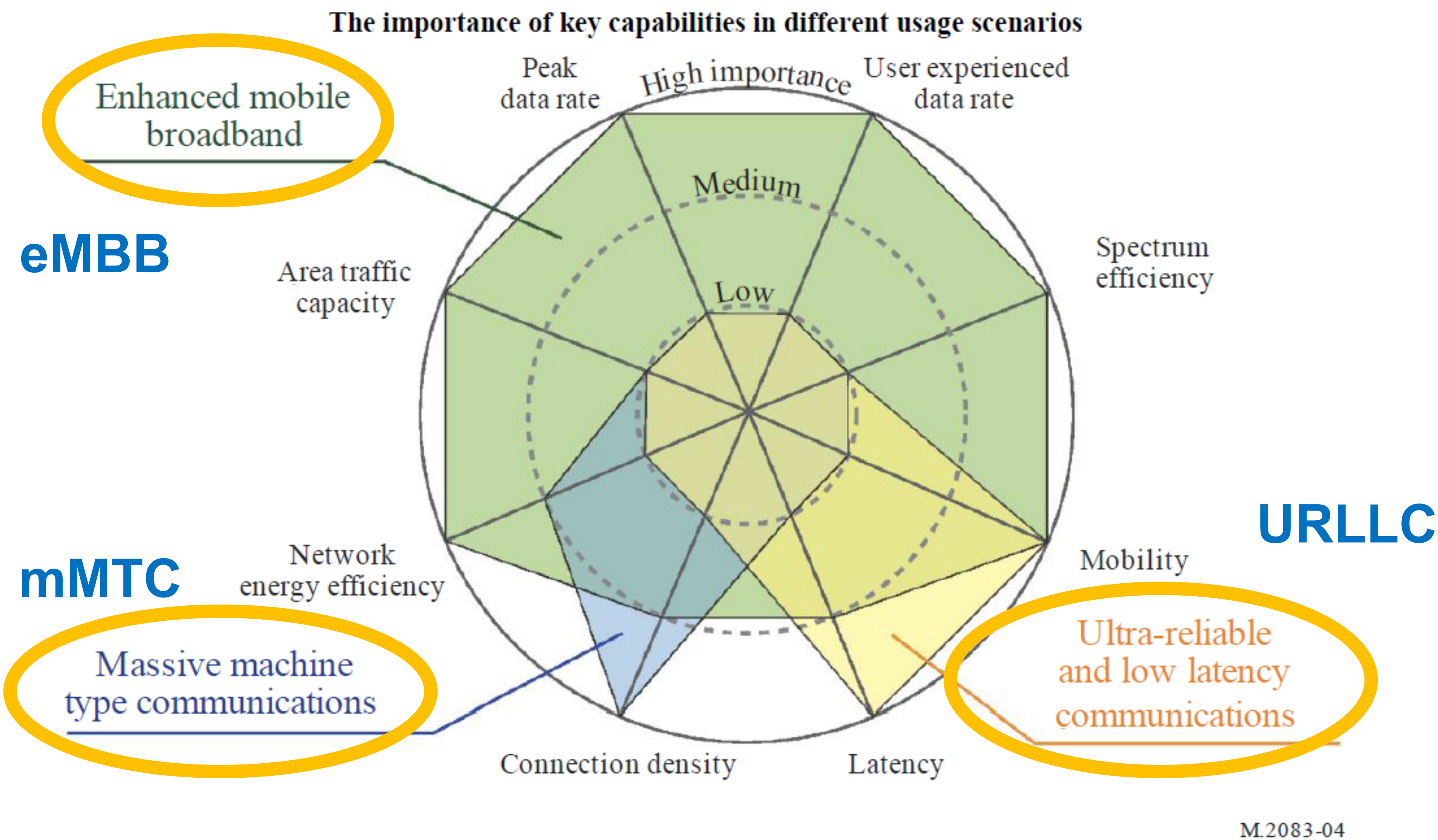
**URLLC**

**mMTC**

*massive Machine-Type Communication*

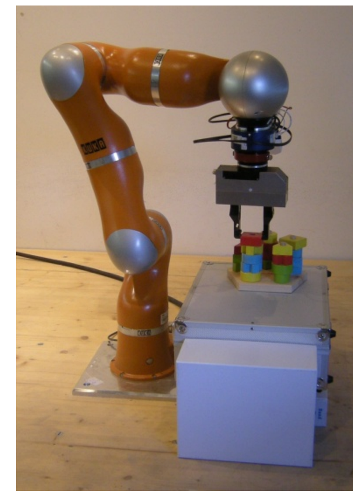
Source: 3gpp.org

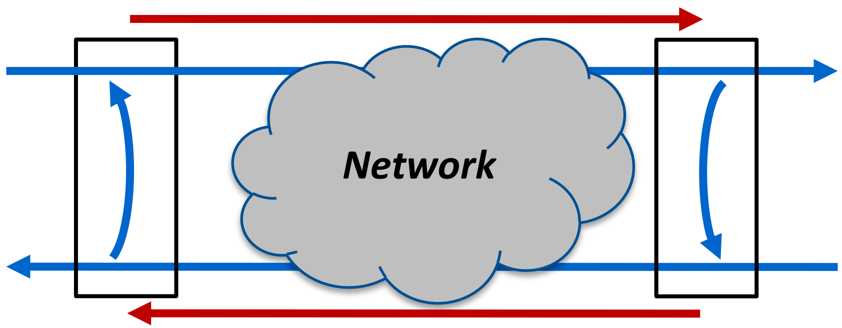
# Motivation: 5G Vision




Source:
ITU-R (2015): Recommendation ITU-R M.2083-0 IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond (09/2015)

# It is mostly machines that communicate over networks

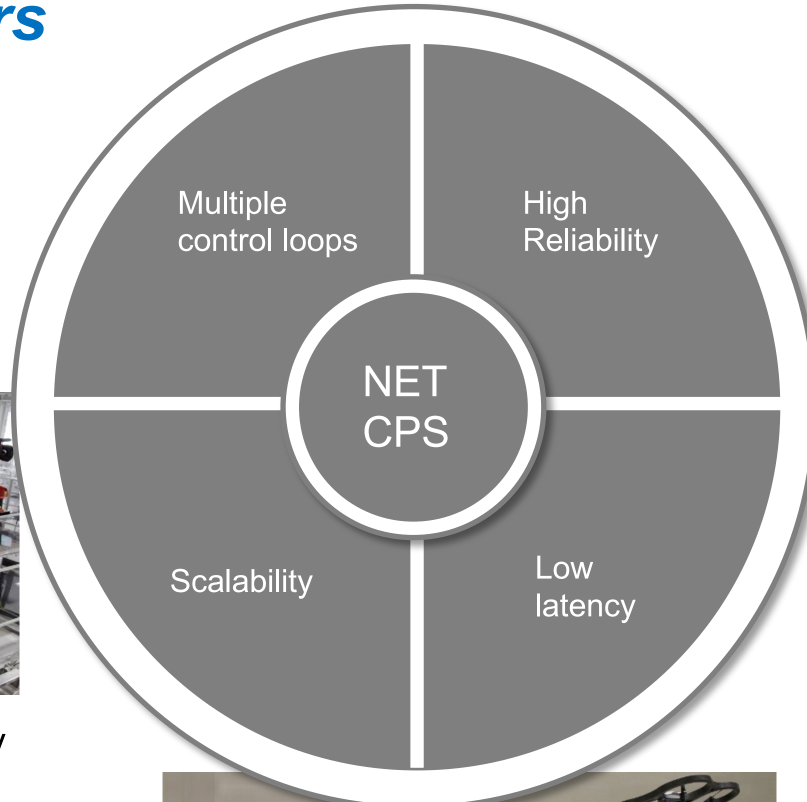



# Motivation: Control

- Networked Machines → Networked Cyber Physical Systems (NET CPS)

***Control matters***

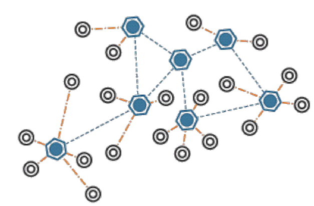
Industry 4.0, Tesla Factory
http://www.nytimes.com





Trucks platooning, Scania
www.scania.com

Robot cooperation
http://iridia.ulb.ac.be/~mathews



# Motivation: Cyber Physical Networking

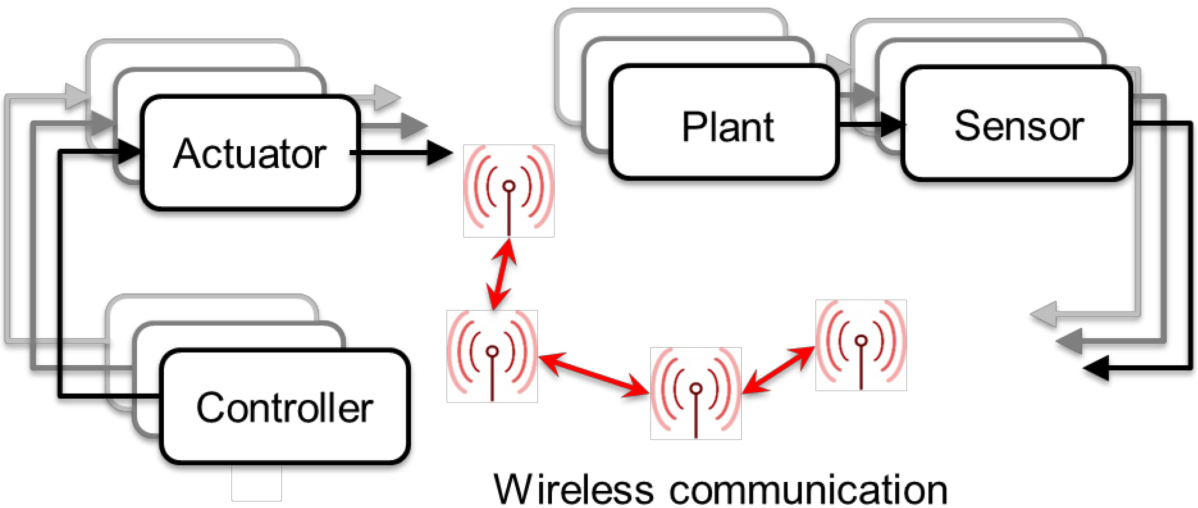
- Key challenge in design and analysis of cyber-physical systems: **Control over shared communication networks**
  - quality of control may be degraded due to the congestion while accessing the scarce communication resources

- **Cyber Physical Networking**: joint consideration of control and networking concepts to improve the system performance
- possibly involving
  - all network layers (cross-layer design,…)
  - all communicating nodes between devices (edge computing,…)
  - multiple control loops with different control strategies

# Focus of this tutorial

- Support of control over shared communication networks

- Focus on
  - **Communication**: Medium Access Control (MAC)
  - **Control**: multi-loop networked control system (NCS), all control loops share a communication network



# Outline

- System model: Networked Control System
  - Including a short primer on control

- Selected use cases and results
  - Decentralized wireless MAC & Control: Adaptive Random Access
  - Scheduled wireless access & Control: Age of Information vs. Value of Information

- NCS experience for everybody:
  Intro to NCS benchmark platform

- … with a break in between

# DFG SPP 1914 Cyber Physical Networking

- **DFG Priority Programme Cyber-Physical Networking (SPP 1914)**
  https://www.spp1914.de/

- Understanding the fundamental trade-offs btw. communication and control systems
  - Fundamental limits for communication latency, reliability, efficiency, and control performance including the role of feedback/side information
  - Joint analysis methods and joint optimisation metrics defining the interfaces
  - Mathematical models and analysis of interacting communication and control dynamics

- Design methods for horizontal/vertical coordination and control, surpassing the limitations of todays abstraction
  - Co-design and adaptive feedback mechanisms for control and protocols over unreliable communication channels such as wireless
  - Distributed control and communication in large-scale systems
  - Latency-aware horizontal/vertical coordination: interfaces, integration of network, operating system and applications

# DFG SPP Cyber Physical Networking

Project areas

- Cooperative control and networking for wireless networks (e.g., topology control, consensus-based control, multi-agent systems, event-based c.)
- Co-design of control and networking/ communications (e.g., information exchange between control and networking, model predictive CPN)
- Higher layer network aspects (e.g., latency, resilience-aware networking, co-designed architecture for in-network control)
- Performance measurements and modeling

**https://www.spp1914.de**

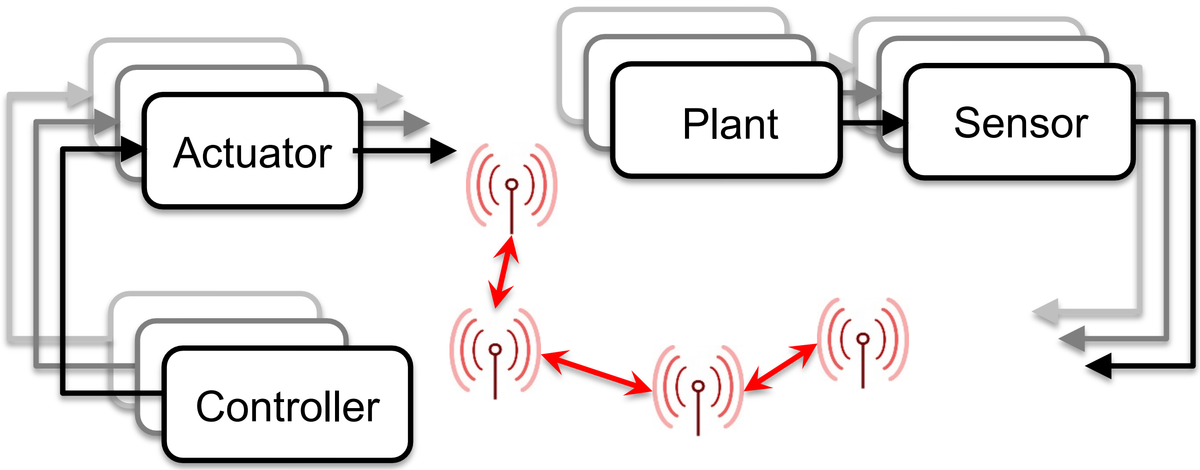
in **interdisciplinary teams** of control/automation and communication/ network experts

# Networked Control Systems

# Networked Control Systems

- Machine-to-Machine: Sensing & Actuation
- Control systems, coupled via communication networks

→ **Networked Control Systems**

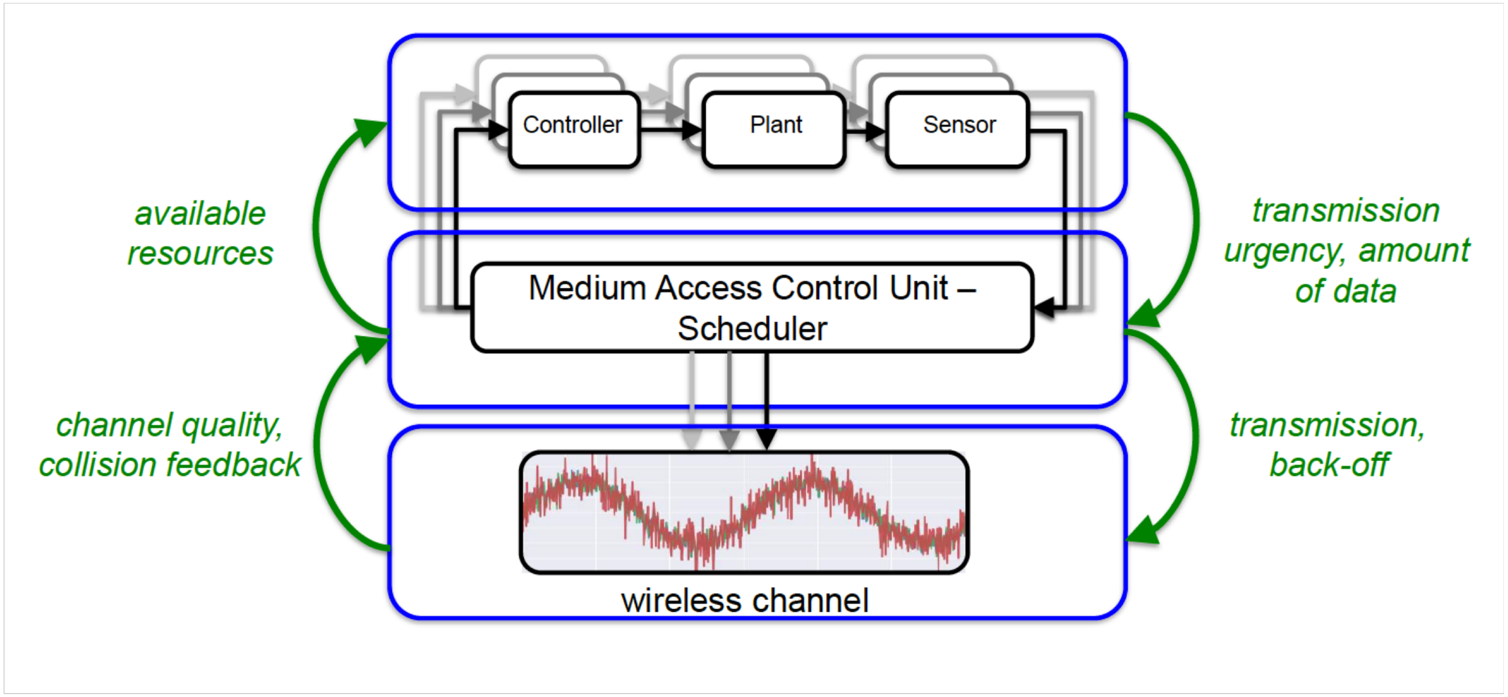



Wireless communication

The following system model is based on the view of the DFG SPP 1914 Cyber-Physical Networks project *„Optimal Co-Design of Wireless Resource Management and Multi-loop Networked Control*" (Hirche, Kellerer)

# Cross-Layer Design Framework

- Optimal Network & Control – Global Optimization Problem



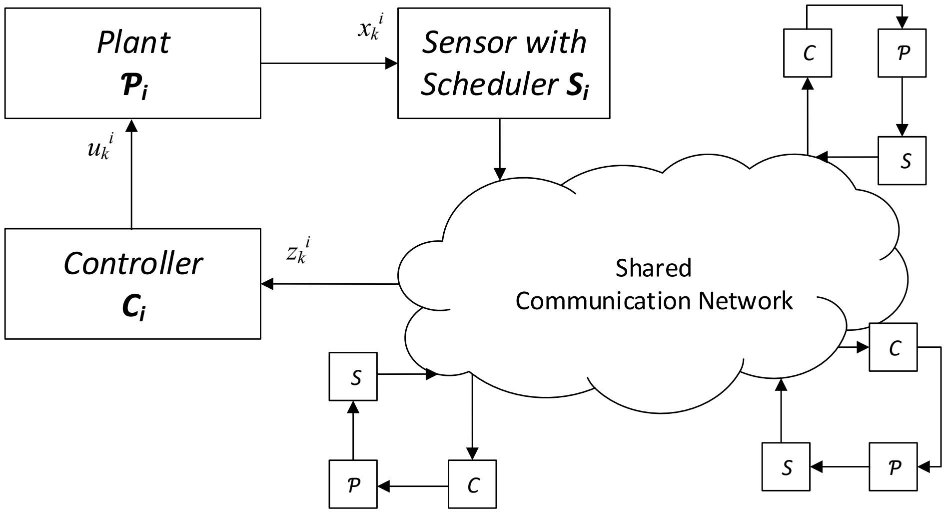

- Control and network protocols: distributed solutions to global OP

# Scenario & Problem Formulation

- *N* stochastic Linear Time Invariant (LTI) systems

$$x_{k+1}^i = A^i x_k^i + B^i u_k^i + w_k^i$$

- Colocated Controller - (Actuator) - Plant




- Plant state is sensed remotely, e.g., camera

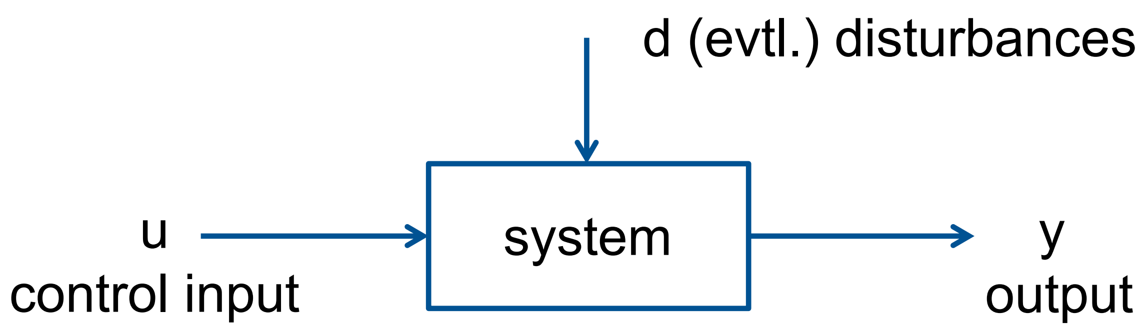
- Shared network: blocking / collisions / packet errors

$$\theta_k{}^i = \begin{cases} 1, & \text{if OK} \\ 0, & \text{otherwise} \end{cases}$$

# Excursion: Quick Introduction to Control (1)

- Control: use of algorithms & feedback in engieering systems; usually for dynamic system

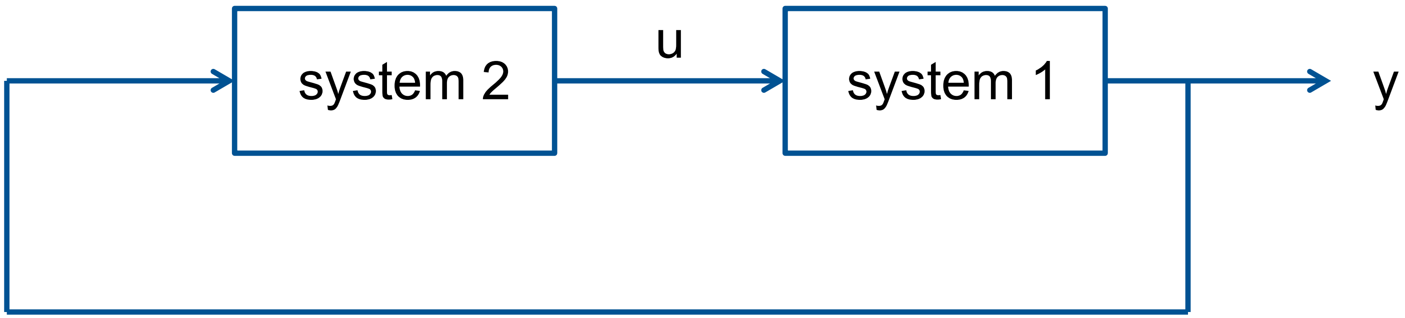
- Dynamic system: a system whose behavior changes over time, often in response to external stimulation




Based on a tutorial given by Sebastian Trimpe, MPI für Intelligente Systeme, 2018.
Textbook: Carl Johan Aström, Richard M. Murray, "Feedback Systems", Princeton University Press

# Quick Introduction to Control (2)

- Feedback: two (or more) dynamic systems connected such that they influence each other

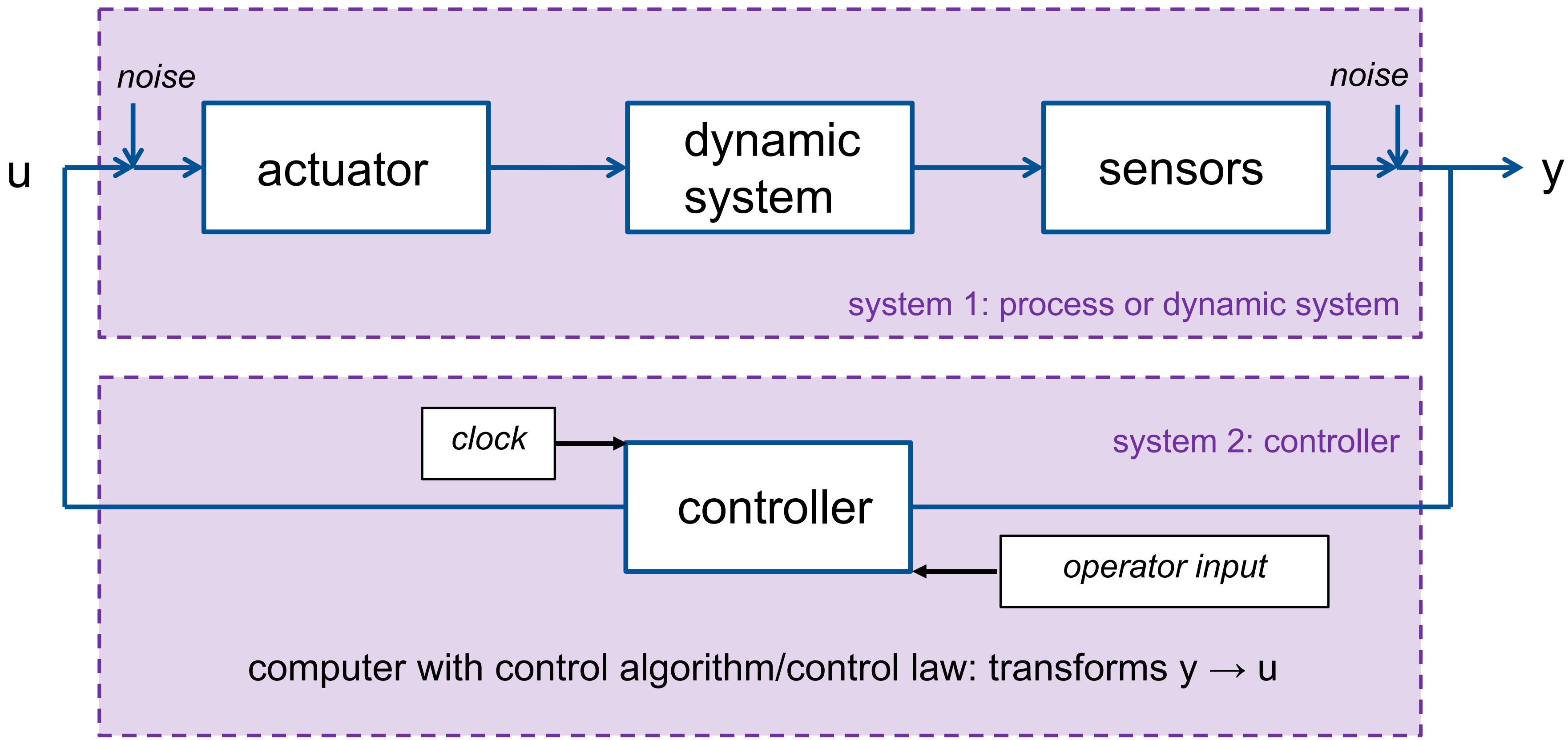



closed loop (with feedback)

- Control System: design a dynamic system “the controller“ (= system 2) to influence the process (= system 1) in a desired way

# Quick Introduction to Control (3)

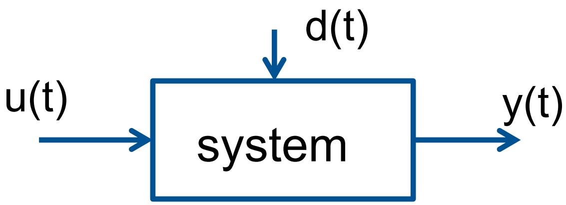
- Control System
  - design a dynamic system “the controller“ (= system 2) to influence the process (= system 1) in a desired way
  - modern control systems: controller is an algorithm running on a computer



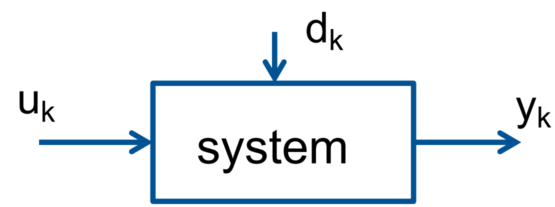
# Quick Introduction to Control (4)

- Typical representations of Dynamic Systems

<u>(a) continuous time</u>




<u>(b) discrete time</u>




- x(t): system state
- Differential equation:

$$\dot{x}(t) = \frac{dx}{dt} = f(x(t), u(t), d(t))$$
$$y(t) = x(t)$$

- Difference equation

$$x_{k+1} = f(x_k, u_k, d_k)$$
$$y_k = x_k$$

Here: discrete-time linear time-invariant (LTI) systems

$$x_{k+1} = Ax_k + Bu_k + w_k$$

# Quick Introduction to Control (5)

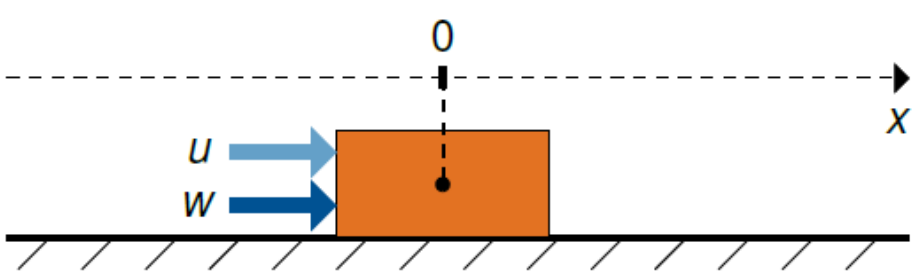
Discrete-time Linear Time-Invariant (LTI) stochastic Networked Control Systems (NCS)

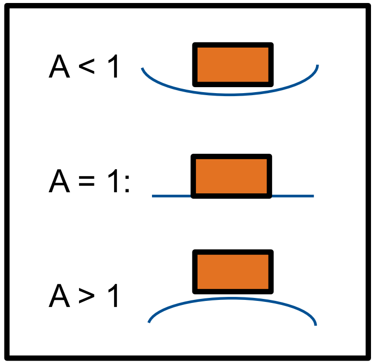
$$x_{k+1} = Ax_k + Bu_k + w_k$$
$$x[k+1] = Ax[k] + Bu[k] + w[k]$$

- $k \in \{0,1,2,\dots\}$ discrete time-step
- $x \in \mathbb{R}^n$: system state, $A \in \mathbb{R}^{n\times n}$: state matrix
- $u \in \mathbb{R}^m$: control input, $B \in \mathbb{R}^{n\times m}$: input matrix
- $w \in \mathbb{R}^n$: random noise vector

Special: 1-dim.

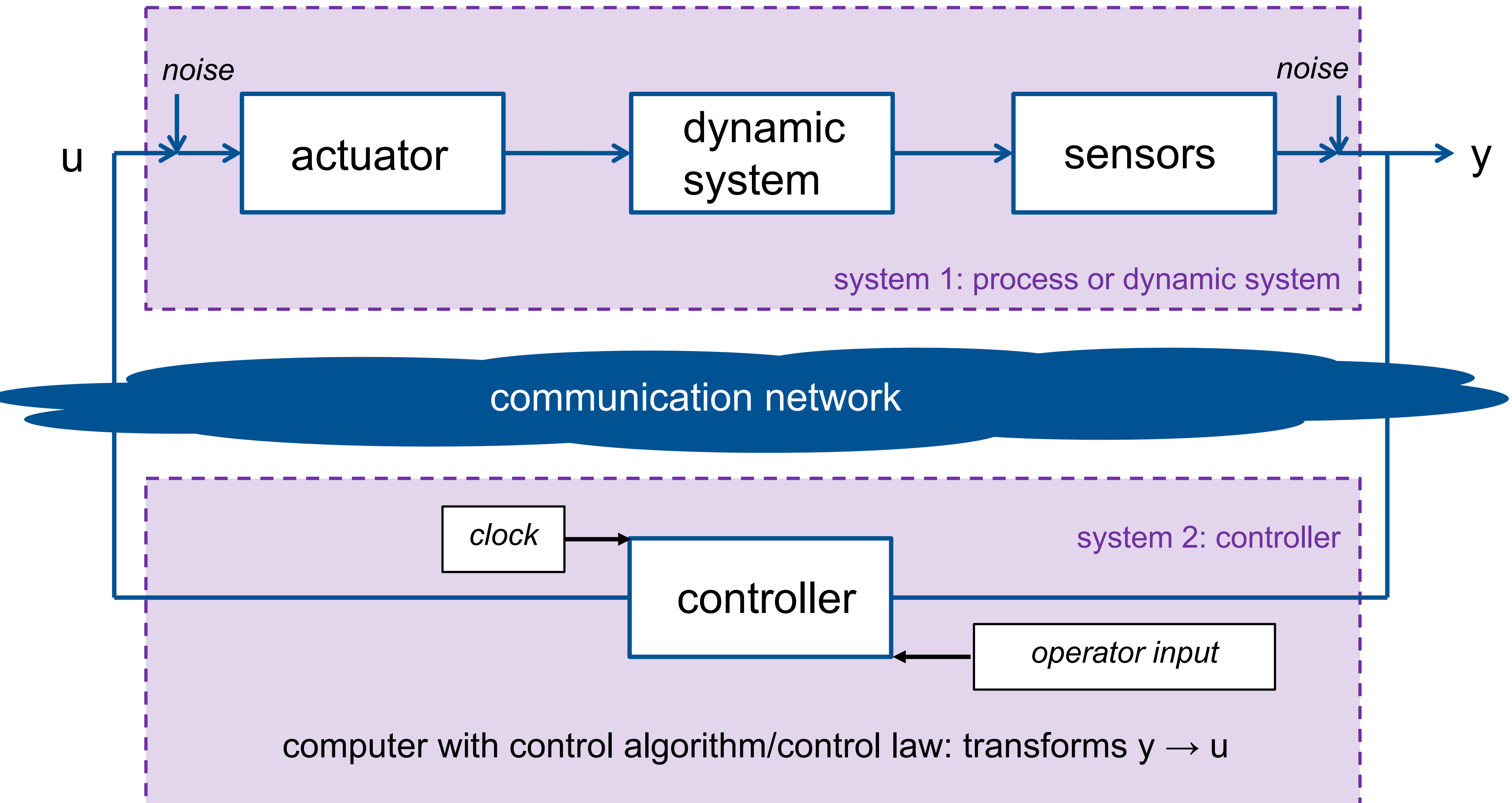
- $x[0] = 0$
- $A = 1 \in \mathbb{R}^{1\times 1}$



# Quick Introduction to Control (6)

- Networked Control System (NCS)



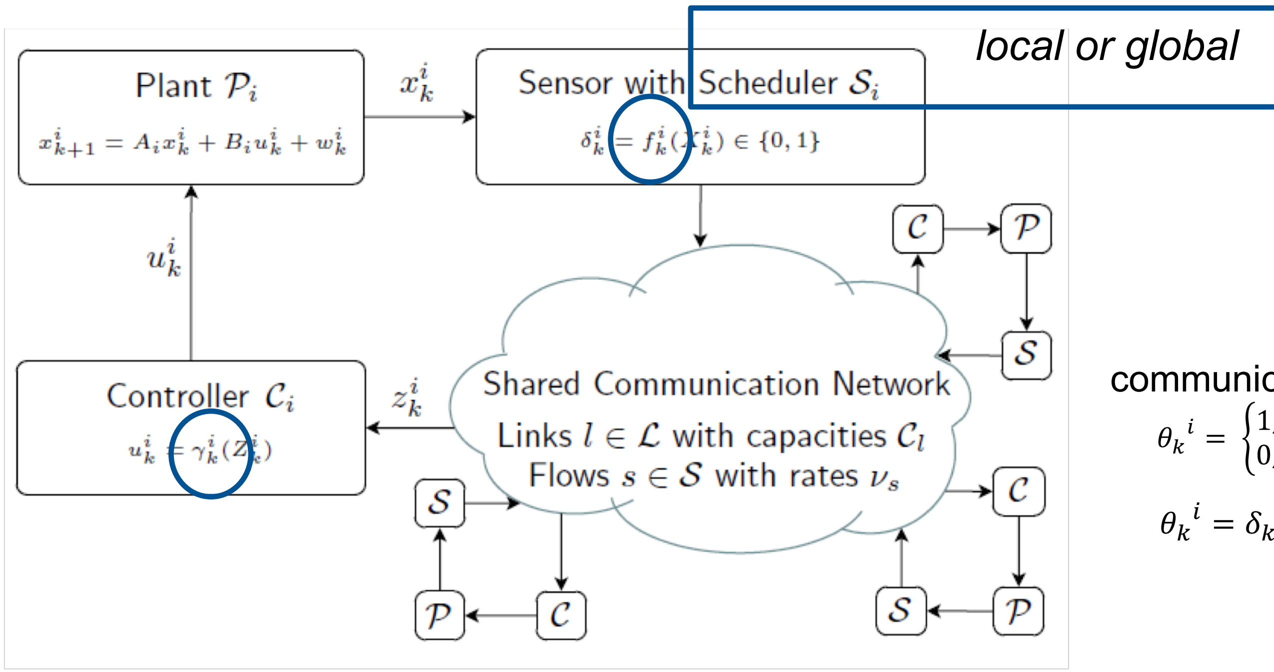
# Scenario & Problem Formulation

## Generalized *optimization problem*:

- with control and scheduling/link access policies as optimization problem variables

*QoC*
*Quality of Control*

$$\max_{\mathbf{f},\boldsymbol{\gamma}} QoC(\mathbf{x},\mathbf{u},\boldsymbol{\delta}) \quad \text{s.t.} \sum_{s\in S} \delta_l(s)\nu_s \le C_l \quad \text{and} \quad \mathrm{x}_{k+1} = A\mathrm{x}_k + B\mathrm{u}_k + w_k$$




communication success

$$\theta_k{}^i = \begin{cases} 1, & \text{if OK} \\ 0, & \text{otherwise} \end{cases}$$

$$\theta_k{}^i = \delta_k{}^i \gamma_k{}^i$$

# Scenario & Problem Formulation

- Dead-beat control law
  (linear discrete-time control: feedback → stable state)

$$u_k^i = -L_i \mathrm{E}\left[x_k^i \middle| Z_k^i\right],$$

with $Z_k^i = \left\{z_o^i, \dots z_k^i\right\}$ and $L_i$ - arbitrary stabilizing feedback gain

- Model-based estimation (if $\theta_k^i = 0$ *i.e. communication failed*):

$$\mathrm{E}\left[x_k^i \middle| Z_k^i\right] = (A_i - B_i L_i)\mathrm{E}\left[x_{k-1}^i \middle| Z_{k-1}^i\right]$$

- *Network Induced Error (~estimation error)* [MTH15]

$$e_{k+1}^i = \left(1 - \theta_k^i\right) A_i e_k^i + w_k^i$$

# Scenario & Problem Formulation

- *Network Induced Error (~estimation error)* [MTH15]

$$e_{k+1}^{i} = \left(1 - \theta_k^i\right) A_i e_k^i + w_k^i$$

**→Separation of Control and Communication problems**

Two application examples:

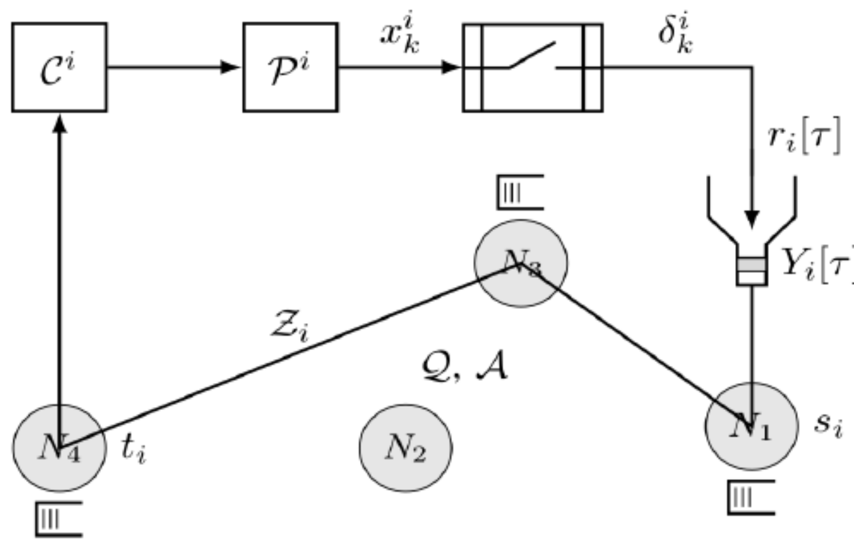
(1) <u>Decentralized</u> wireless MAC & Control

(2) <u>Scheduled</u> wireless access & Control (up-/downlink scheduling)

# Outlook: Global Optimization Problem

Generalization of the above problem

- Multi-loop
- Single-hop → Multi-hop
  - Base station (2 hop, central)
  - Multiple hops (wireless and wired)
- MAC → Multi-layer
  - Routing (topology, node buffering)
  - Transport (TCP congestion control)
- Network functions
  - Edge computing (location/migration of controller)

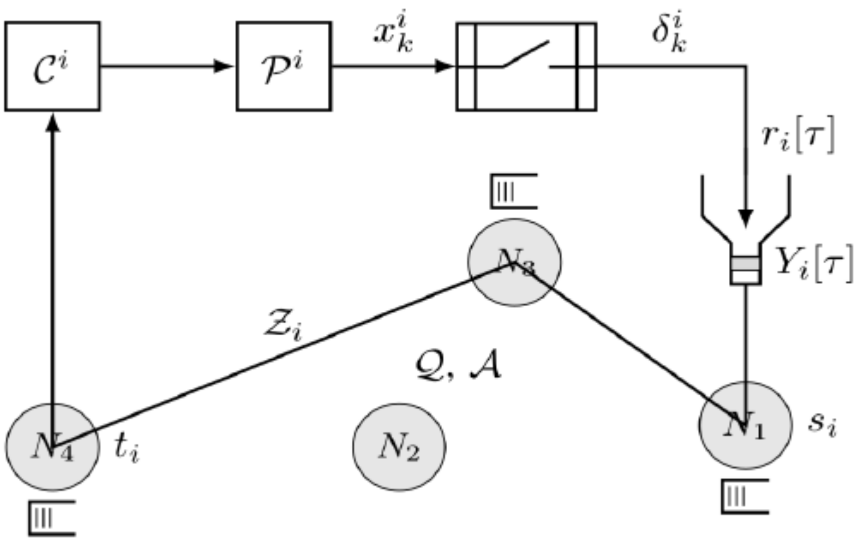



=> computationally very hard to solve – decomposition needed

# Global Optimization Problem

- Cost function

$$J_i = \lim_{K \to \infty} \frac{1}{K} \mathbb{E} \left[ \sum_{k=0}^{K-1} x_k^{i\top} Q_x^i x_k^i + u_k^{i\top} Q_u^i u_k^i \right]$$




- Nodes are linked according to the topology *Q*
- Action set *A*
- Transmission determined by a choice of (*Q*;*A*)

$$\min_{\psi,\pi,\varphi,\xi} \sum_i w_i J_i$$

$$\text{s.t. } \psi \in \Psi, \varphi \in \Phi, \pi \in \Pi, \xi \in \Xi$$

- $\psi$: congestion control law from the admissible set $\Psi$
- $\pi$: scheduling law from the admissible set $\Pi$
- $\varphi$: sampling law from the admissible set $\Phi$
- $\xi$: control law from the admissible set $\Xi$

# Outline

- System model: Networked Control System
  - Including a short primer on control

- **Selected use cases and results**
  - **Decentralized wireless MAC & Control: Adaptive Random Access**
  - **Scheduled wireless access & Control: Age of Information vs. Value of Information**

- NCS experience for everybody:
  Intro to NCS benchmark platform

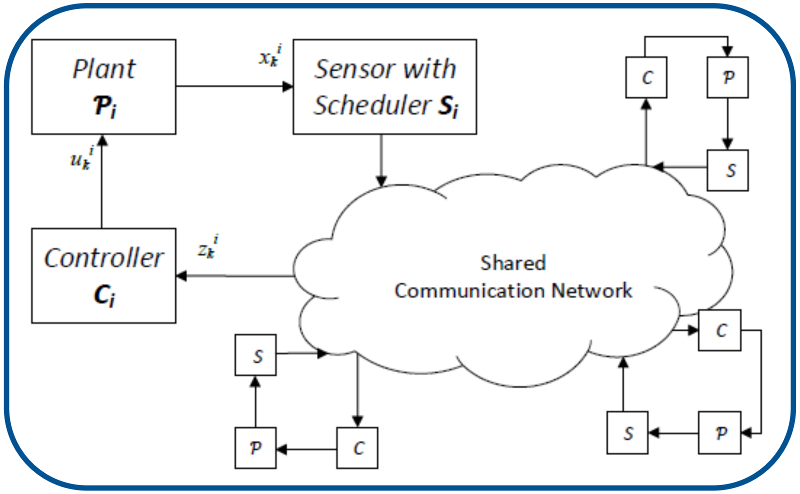
# Decentralized wireless MAC & Control: Adaptive Random Access

# Adaptive Random Access: Scenario

- Adaptive decentralized MAC for Event-Triggered NCS

- LTI control loop

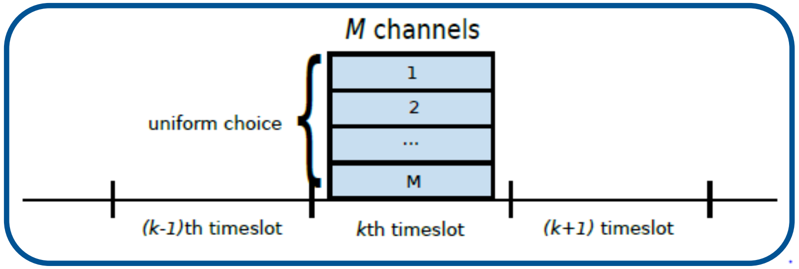
$$x_{k+1}^i = A_i x_k^i + B_i u_k^i + w_k^i,$$




- State dynamics → estimation error dynamics

$$e_{k+1}^i = (1 - \theta_k^i) A_i e_k^i + w_k^i.$$

- Local scheduler: event-based with threshold $\Lambda_i$




- Decentralized medium access with $M_k$ channels
  - *timeslot == control period*
  - uniform choice of the channels
  - collision occurs if the same channel is chosen
  - channel feedback: *collision (1,0)*, $M_k$

Vilgelm M, Mamduhi MH, Kellerer W, Hirche S. Adaptive Decentralized MAC for Event-Triggered Networked Control Systems, ACM HSCC, 2016

# Adaptive Random Access: Scenario

- Adaptive decentralized MAC for Event-Triggered NCS

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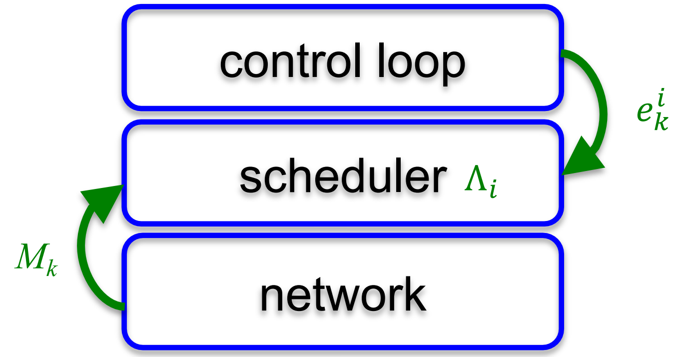



Vilgelm M, Mamduhi MH, Kellerer W, Hirche S. Adaptive Decentralized MAC for Event-Triggered Networked Control Systems, ACM HSCC, 2016

# Adaptive Random Access: Treshold-based Trigger

- Event-triggered NCS and Multichannel Slotted ALOHA
  - Communication delay ≈ connection establishment delay
- Threshold-based event triggering:

$$\mathrm{P}[\delta_k^i = 1 | e_k^i] = \begin{cases} 0, & \text{if } ||e_k^i|| \leq \Lambda_i \\ 1, & \text{otherwise} \end{cases}$$

with $\delta_k^i$ (local) scheduling variable.

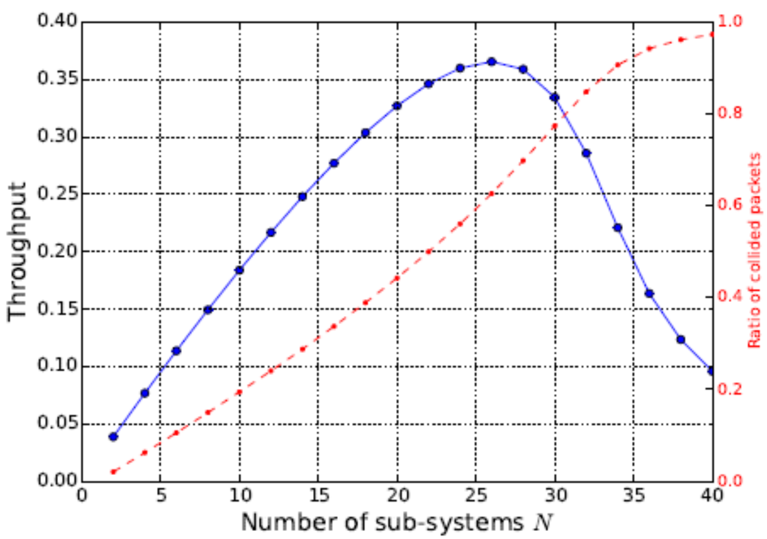
- Successful reception: $\theta_k^i = \delta_k^i \gamma_k^i$ with

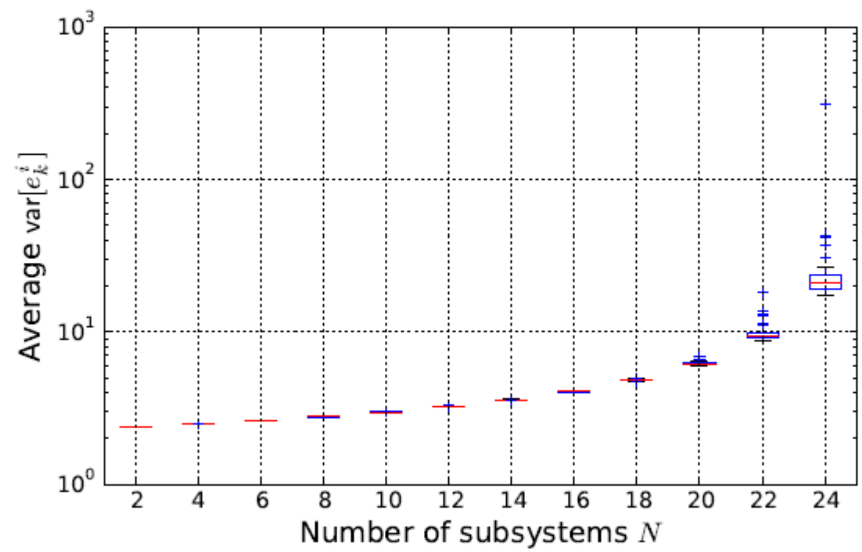
$$\mathrm{P}\left[\gamma_k^i = 1 \middle| \delta_k^i = 1\right] = \left(\frac{M_k - 1}{M_k}\right)^{g_k}$$

M. Vilgelm, M. H. Mamduhi, W. Kellerer, S. Hirche, *“Adaptive Decentralized MAC for Event-Triggered NCS,”* ACM HSCC, 2016

# Adaptive Random Access: Initial Evaluation

- Given $N$ subsystems with $A_i$, $W_i$, and $M_k$ channels
  - Network performance depends on control loop & $\Lambda_i$
  - Control loop performance depends on network & $\Lambda_i$
    - Metric: variance of an estimation error



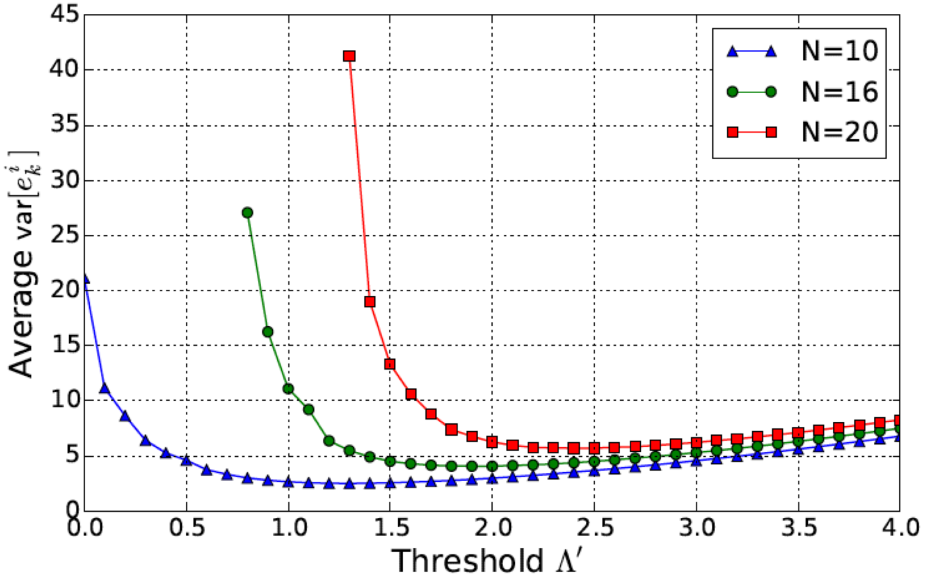

M=10, A=2

Vilgelm M, Mamduhi MH, Kellerer W, Hirche S. Adaptive Decentralized MAC for Event-Triggered Networked Control Systems, ACM HSCC, 2016

# Adaptive Random Access: Eval. of Threshold

- Performance Evaluation: Threshold

- Network and control performance are *coupled via the threshold*
- If the threshold is set too low, performance degrades drastic due to *collision*
- If the threshold is set too high, performance degrades slowly due to *underutilized network*
- Always exists a threshold (global), for which control and network performance are optimal

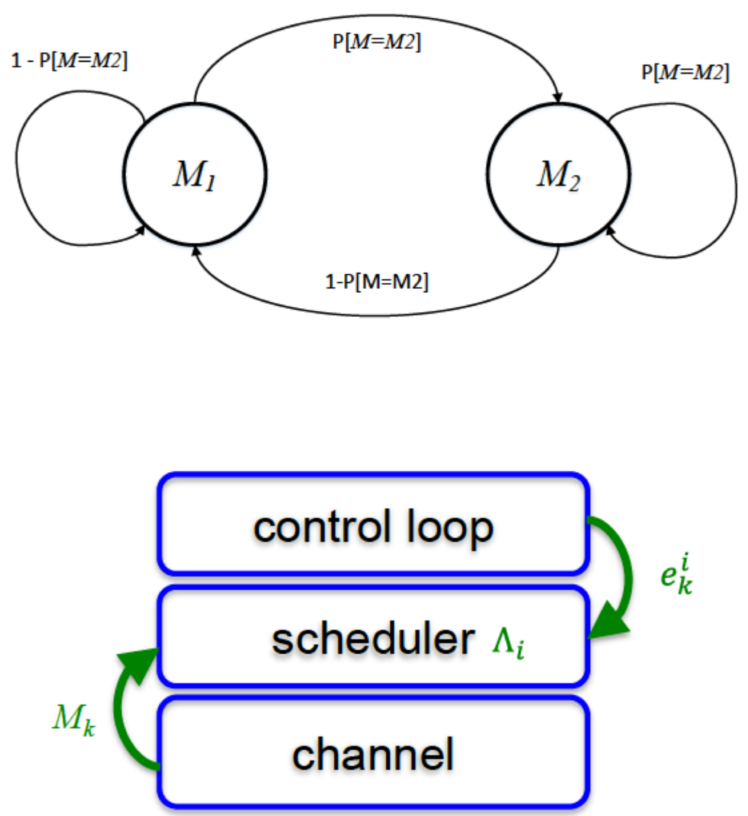


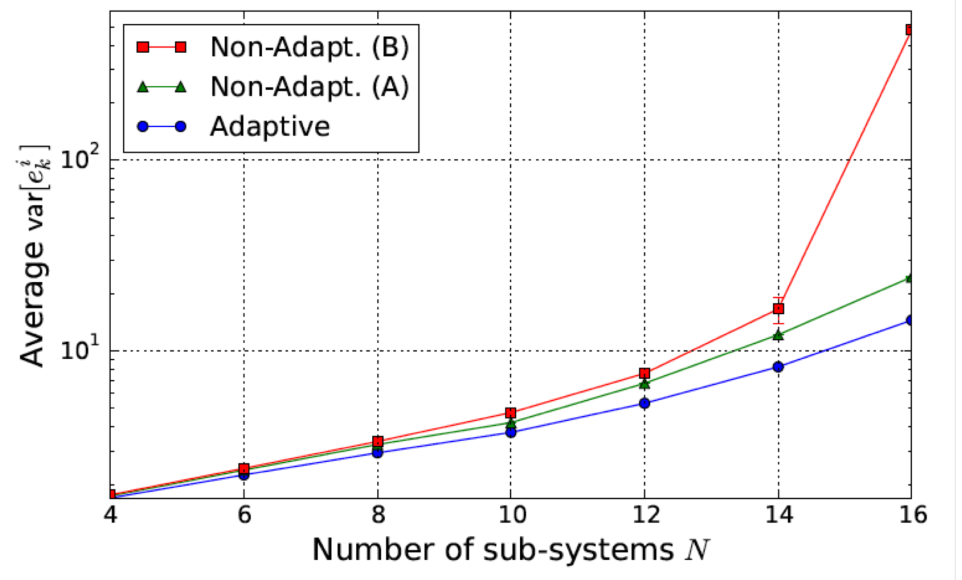

→ to optimally use the network, adaptive scheduling policy is required

[C3] M. Vilgelm, M. H. Mamduhi, W. Kellerer, S. Hirche, *"Adaptive Decentralized MAC for Event-Triggered NCS,"* ACM HSCC, 2016

# Adaptive Random Access: Adaptation

- Adapting to varying number of channels – *network state*



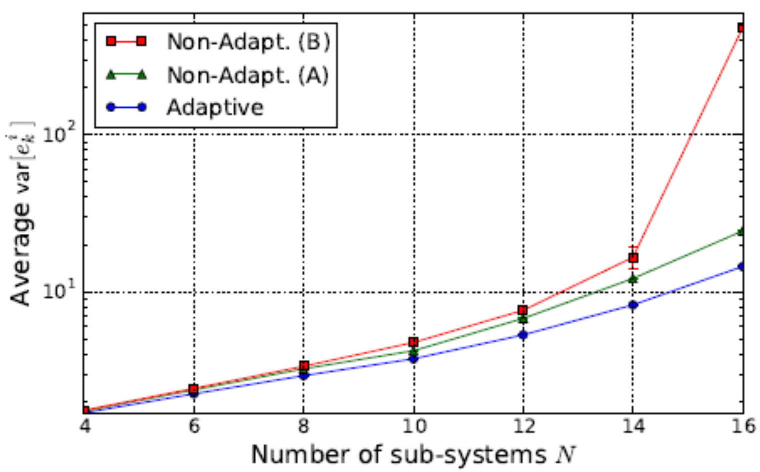

[C3] M. Vilgelm, M. H. Mamduhi, W. Kellerer, S. Hirche, *"Adaptive Decentralized MAC for Event-Triggered NCS,"* ACM HSCC, 2016

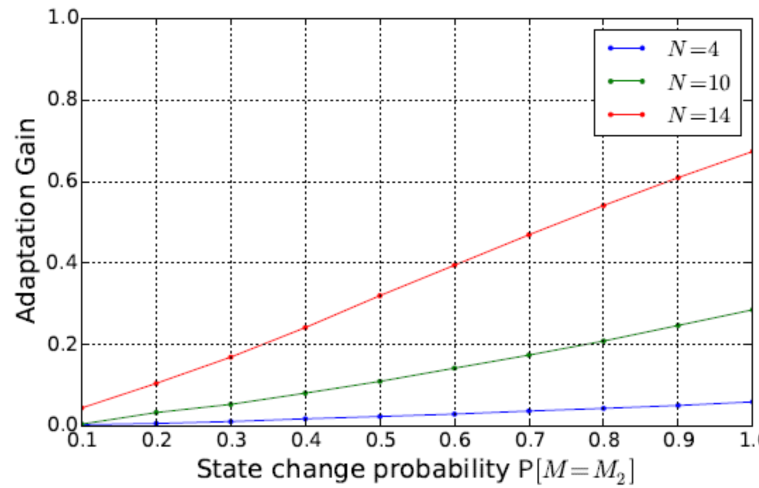
# Adaptive Random Access: Adaptation gain

- Adaptive choice of the threshold based on available channels

$$\Lambda' = f(M),$$

- Relative gain from adaptation depends on the variability of the number of channels





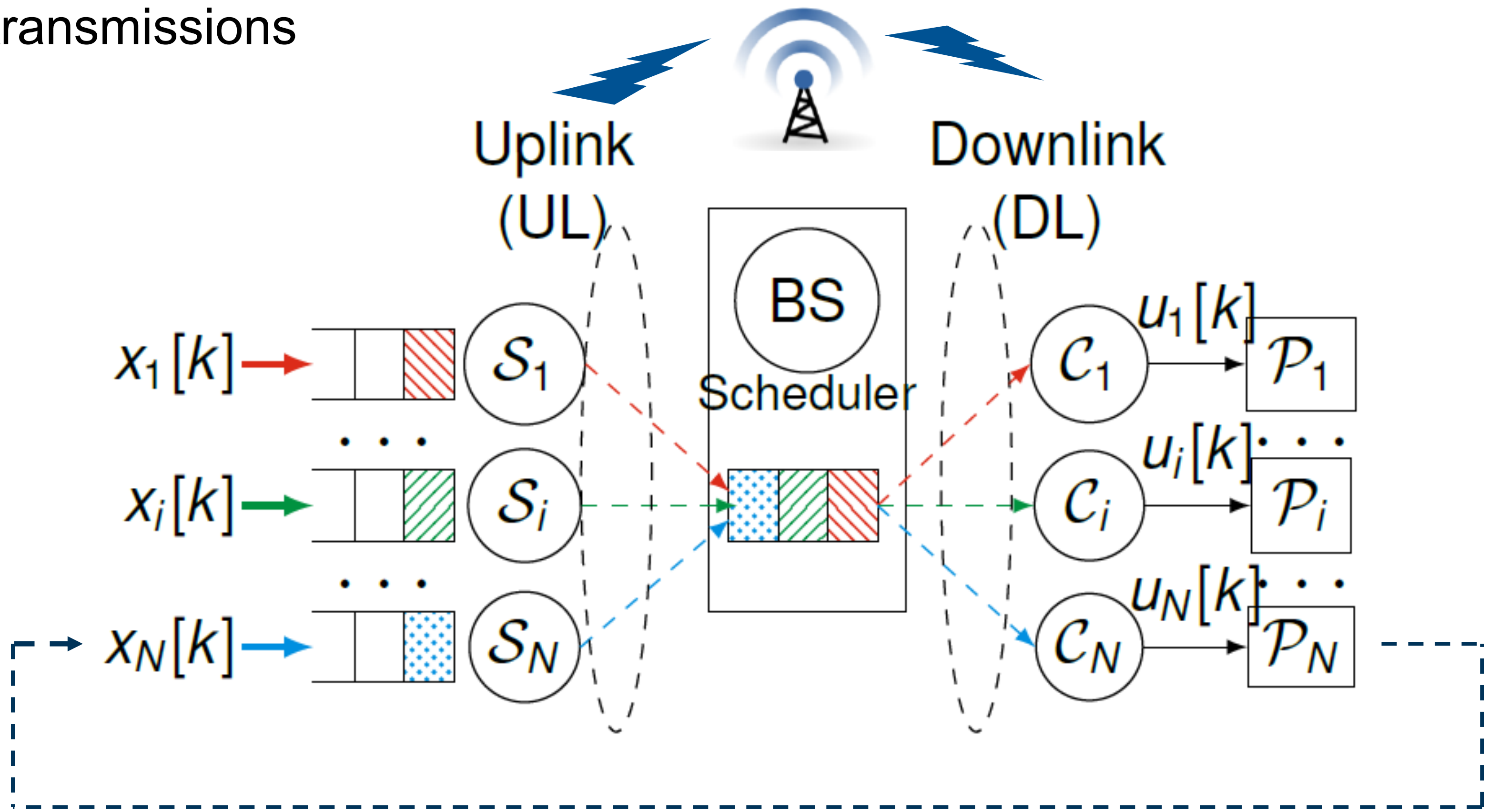
Vilgelm M, Mamduhi MH, Kellerer W, Hirche S. Adaptive Decentralized MAC for Event-Triggered Networked Control Systems, ACM HSCC, 2016

# Scheduled wireless access and control: Age of Information vs. Value of Information

„Age-of-Information vs. Value-of-Information Scheduling for Cellular Networked Control Systems“

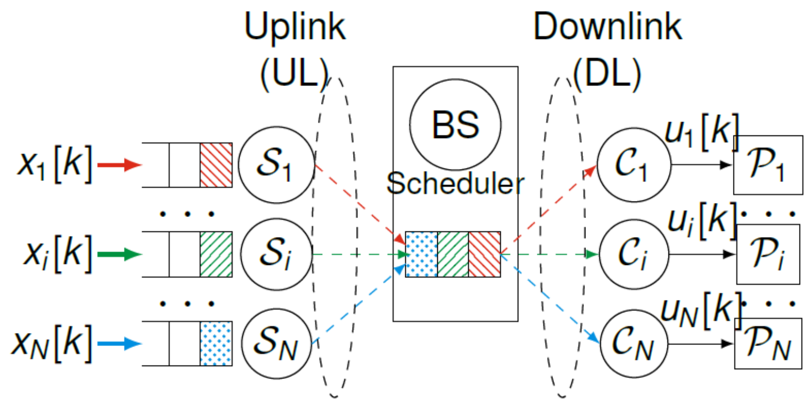
# Scheduled wireless access: Scenario

- $N$ stochastic LTI control loops share the same network
- Centralized scheduler in Base Station (BS) determines UL and DL transmissions




*Plant N is observed by Sensor N*

# Scheduled wireless access: Scenario

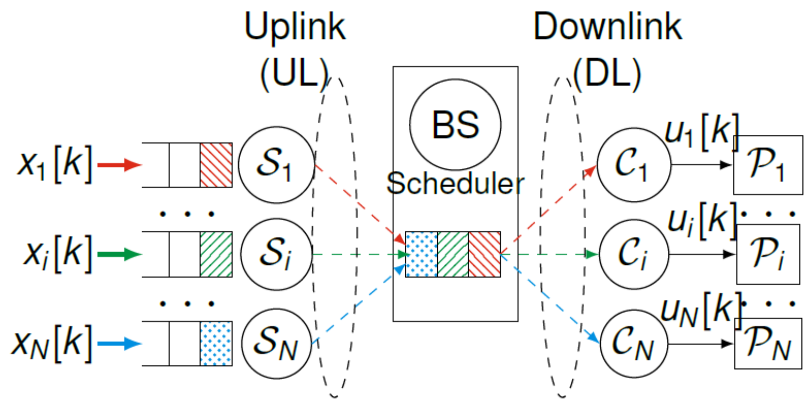



- *N* stochastic LTI control loops share the same network
- Each sub-system consists of sensor $S_i$ , controller $C_i$ and plant $P_i$
- Observed plant state $x_i[k_i]$ at time-step $k_i$ is transmitted towards $C_i$
  - First on uplink (UL) from $S_i$ to base station (BS)
  - Then on downlink (DL) from BS to $C_i$
- *Only the latest generated measurement is stored in the packet queue*
- *Centralized* scheduler determines UL and DL transmissions

*How to distribute (schedule) the UL and DL resources among the sub-systems (control loops)?*

# Challenge: two-hop communication system

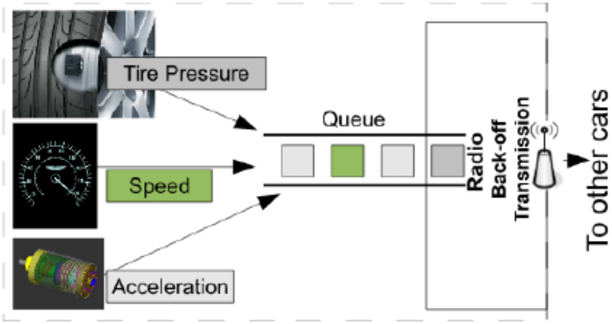
- Central scheduler has to consider the importance of a sensor value to decide for scheduling considering both hops




- Possible “importance“ metrics:
  - Delay → **Age of Information (AoI)**
  - Meaning of content of sensor value → **Value of Information (VoI)**
- We compare both in this example: *Age-of-Information vs. Value-of-Information Scheduling for Cellular Networked Control Systems*

# Age of Information (AoI)

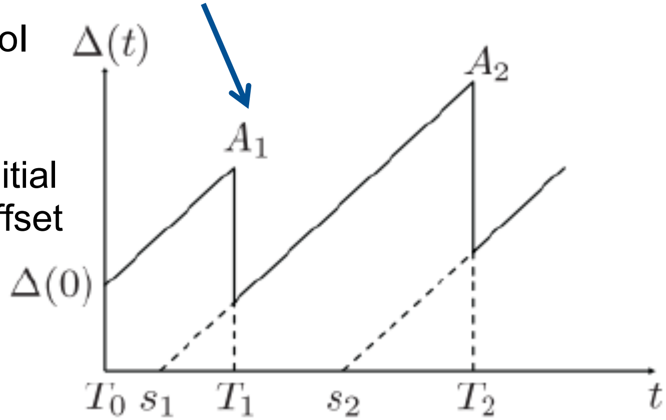
- a recently proposed performance metric that measures **information freshness** at the destination node
- proposed in 2011 by S. Kaul and R. Yates for vehicular networks [1,2]
  - [1]: "Average end-to-end (application-to-application) delay observed in any vehicle's state"
  - [3]: "Time since last update was received"




- Age of Information $\Delta(t)$:

$$\Delta(t) = t - u(t)$$

- *t*: current time
- *u(t)*: time-stamp of the most recent update

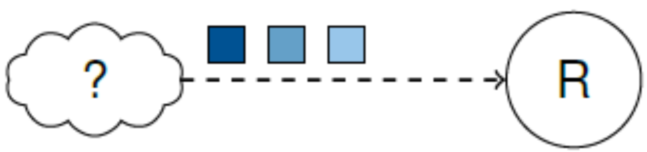


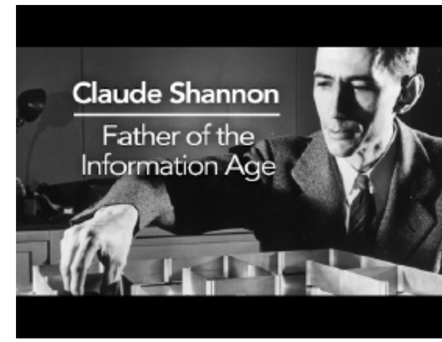

$s_i = u(t)$, *time* sensor value is taken

[1] Kaul, et al. Minimizing age of information in vehicular networks. 8th IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks, 2011.
[2] Kaul, Yates, Gruteser, Real-time status: How often should one update? IEEE INFOCOM, 2012.
[3] Talak et al. Minimizing age-of-information in multi-hop wireless networks. 55th Annual Allerton Conference on Communication, Control, and Computing, 2017.

# Value of Information (VoI)

- deals with the **content** of a new update independently of its timeliness
- VoI stems from information theory (Shannon)
- The amount of reduction in the uncertainty of a stochastic process at the recipient




Not of the Age-of-Information!

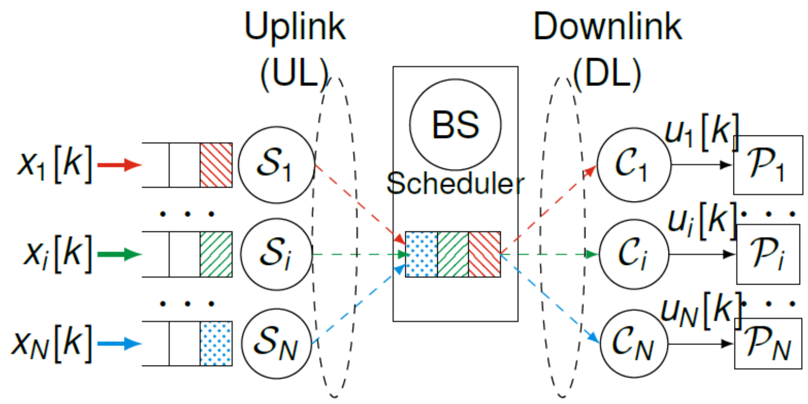
**Value-of-Information**

deals with the **content** of a new update independently of its timeliness

**Age-of-Information**

deals with the **freshness** of a new update independently of its content

# Back to our scenario




- *N* stochastic LTI control loops share the same network
- Each sub-system consists of sensor $S_i$ , controller $C_i$ and plant $P_i$
- Observed plant state $x_i[k_i]$ at time-step $k_i$ is transmitted towards $C_i$
  - First on uplink (UL) from $S_i$ to base station (BS)
  - Then on downlink (DL) from BS to $C_i$
- Only the latest generated measurement is stored in the packet queue
- Centralized scheduler determines UL and DL transmissions

*How to distribute (schedule) the UL and DL resources among the sub-systems (control loops)?*

# Recap: Stochastic LTI Networked Control Systems

- as also before:

Discrete linear time-invariant (LTI) stochastic NCSs are modeled as:

$$x[k+1] = A \cdot x[k] + B \cdot u[k] + w[k]$$

$k \in \{0, 1, 2, \dots\}$ discrete time-step

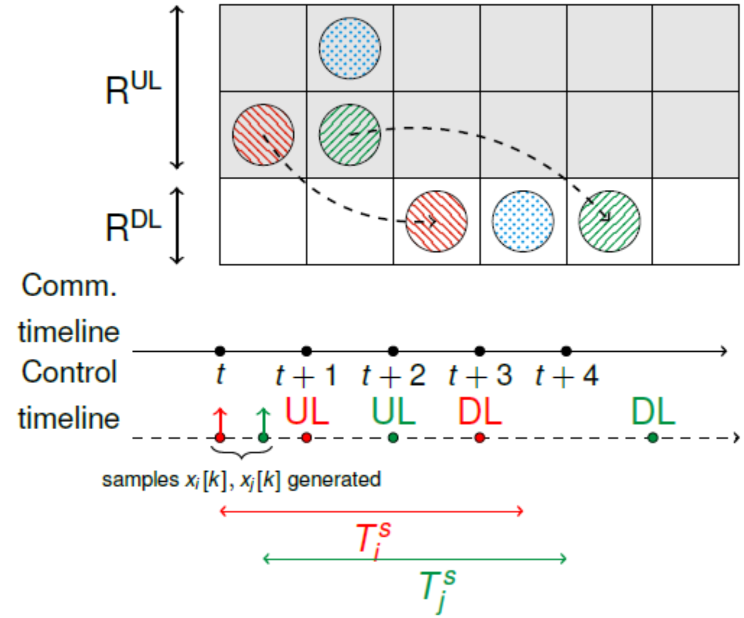
$x \in \mathbb{R}^n$: System state, $A \in \mathbb{R}^{n \times n}$: State matrix

$u \in \mathbb{R}^m$: Control input, $B \in \mathbb{R}^{n \times m}$: Input matrix

$w \in \mathbb{R}^n$: Random noise vector

# Network Model

- Faster networking than control $\Rightarrow$ $T_i^s \geq t \quad, \forall i$
- UL/DL schedules $\pi^{UL/DL}(t) \in \{0, 1\}^N$
  - $\pi_i^{UL/DL}(t) = 1 \iff$ sub-system $i$ transmits at $t$
- $\mathcal{R}^{UL}$, $\mathcal{R}^{DL}$ set of UL and DL resources
  - $|\mathcal{R}^{UL}| = \mathrm{R}^{\mathrm{UL}} < \infty$
  - $|\mathcal{R}^{DL}| = \mathrm{R}^{\mathrm{DL}} < \infty$
  - $\mathcal{R}^{UL} \cap \mathcal{R}^{DL} = \emptyset \Rightarrow$ Frequency-Division Duplex (FDD)
- Reception at the end of the slot




$\mathrm{R}^{\mathrm{UL}}$: Number of UL resources (per slot)

$\mathrm{R}^{\mathrm{DL}}$: Number of DL resources (per slot)

$T_i^s$: Sampling period of the $i$-th sub-system

# Control Model (1)

- Stochastic LTI control systems:

$$x_i[k_i + 1] = A_i \cdot x_i[k_i] + B_i \cdot u_i[k_i] + w_i[k_i]$$

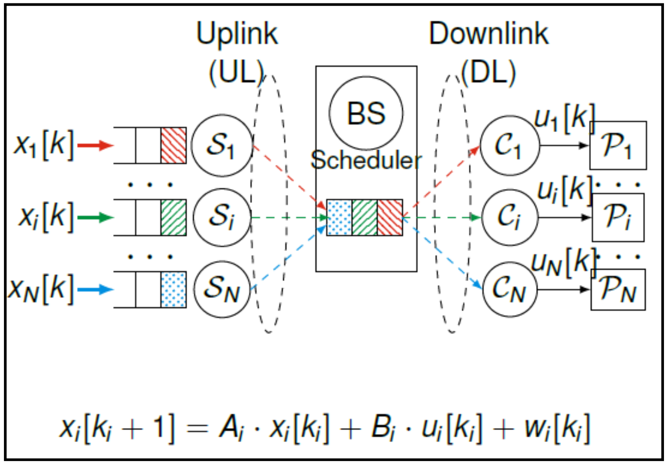
  with $x_i[0] = w_i[0]$ and $w_i \sim \mathcal{N}(0, W_i)$.

- Periodic sampling with sampling period $T_i^s$ slots with initial sampling $T_i^o \sim U(0, T_i^s)$
- Stairwise system evolution:

$$k_i(t) = \left\lfloor \frac{t - T_i^o}{T_i^s} \right\rfloor$$

- Sampling events at slots $\{k \cdot T_i^s + T_i^o\}, k \in \mathbb{N} \quad \Rightarrow \quad$ TX-Buffer update at sensor $\mathcal{S}_i$

# Control Model (2)




- Packet reception indicator variable $\delta_i[k_i] \in \{0, 1\}$:

$$z_i[k_i] = \begin{cases} x_i[k_i] & \text{, if } \delta_i[k_i] = 1 \\ \emptyset & \text{, if } \delta_i[k_i] = 0. \end{cases}$$

- Information set $\mathcal{I}_i[k_i]$ available at $\mathcal{C}_i$:

$$\mathcal{I}_i[k_i] = \{k_i,\ z_i[0],\ \ldots,\ z_i[k_i],\ u_i[0],\ \ldots,\ u_i[k_i - 1]\}$$

- State estimation at $\mathcal{C}_i$:

$$\hat{x}_i[k_i] = \mathbb{E}\left[x_i[k_i] \,\middle|\, \mathcal{I}_i[k_i]\right]$$

**Age-of-Information**

$$\Delta_i(k_i) = k_i - s_i[k_i]$$

- Control input:

$$u_i[k_i] = -L_i \hat{x}_i[k_i]$$

state feedback gain matrix $L_i$

# Age of Information and Value of Information

AoI =
*time difference to sensor value generation time*

- Age-of-Information:

$$\Delta_i(k_i) = k_i - s_i[k_i]$$

with $s_i[k_i] = \sup\{s \in \mathbb{N} : s \leq k_i,\ z_i[s] \neq \emptyset\} \ \Leftrightarrow\ s_i[k_i]$: Generation time of the most recent received information

- Estimation error:

$$e_i[k_i] = x_i[k_i] - \hat{x}_i[k_i]$$

- Value-of-Information:

VoI =
*expected value of squared estimation error*

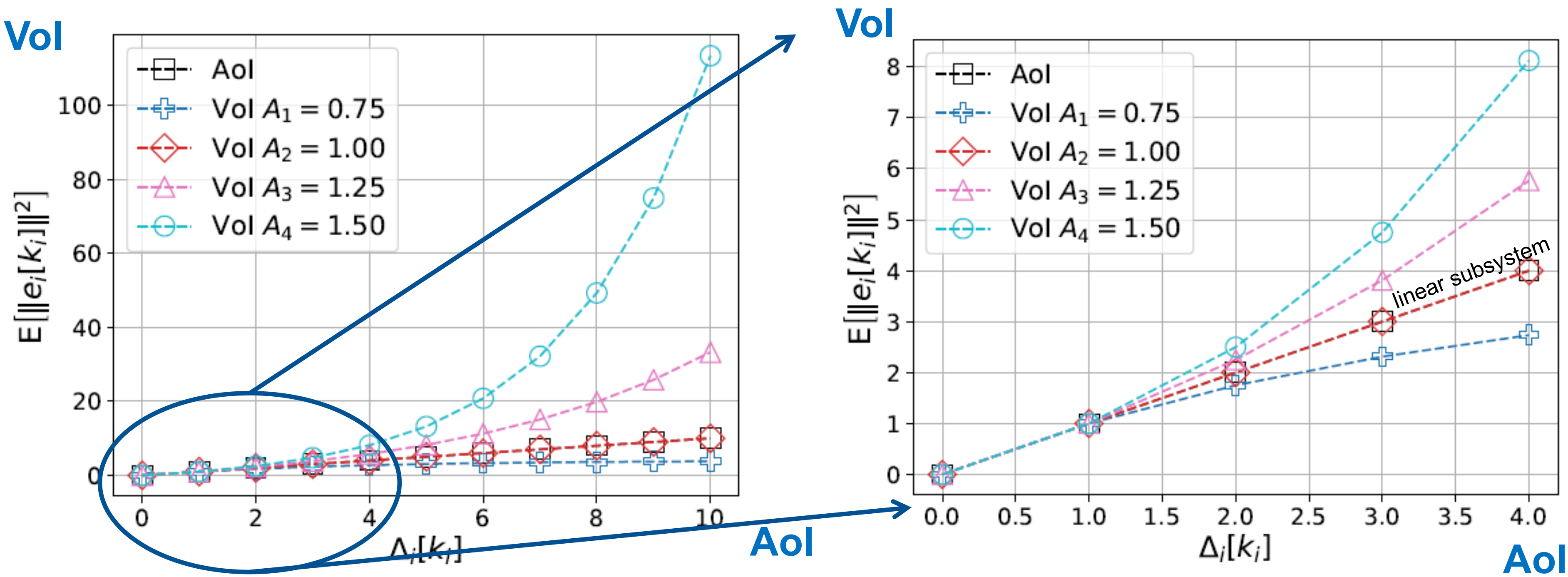
$$\mathbb{E}\left[\|e_i[k]\|^2\right] = \begin{cases} 0 & \text{, if } \Delta_i[k] = 0 \\ g\left(\Delta_i[k_i]\right) & \text{, if } \Delta_i[k_i] > 0 \end{cases},$$

with:

$$g(\Delta_i[k]) \triangleq \sum_{r=0}^{\Delta_i[k]-1} \operatorname{tr}\left((A_i^T)^r A_i^r W_i\right)$$

tr(.): Trace operator

# System Dependability of VoI




a) $\mathbb{E}\left[\|e_i[k_i]\|^2\right]$ for $\Delta_i[k_i] \in [0,\ 10]$, $W_i = 1$

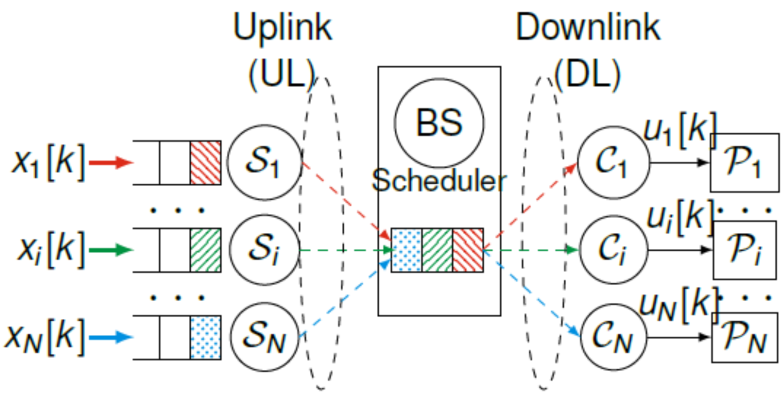
b) $\mathbb{E}\left[\|e_i[k_i]\|^2\right]$ for $\Delta_i[k_i] \in [0,\ 4]$, $W_i = 1$

$$\mathbb{E}\left[\|e_i[k]\|^2\right] = \begin{cases} 0 & \text{, if } \Delta_i[k] = 0 \\ g\left(\Delta_i[k_i]\right) & \text{, if } \Delta_i[k_i] > 0 \end{cases},$$

$$g(\Delta_i[k]) \triangleq \sum_{r=0}^{\Delta_i[k]-1} \operatorname{tr}\left(\left(A_i^T\right)^r A_i^r W_i\right)$$

- VoI depends on plant dynamics (system matrix A)
- A < 1: sub systems tend to stability / A > 1: plant dynamics require control

# Value-of-Information on UL / DL




- Reception variable:

$$z_i[k_i] = \begin{cases} x_i[k_i] & \text{, if } \delta_i[k_i] = 1 \\ \emptyset & \text{, if } \delta_i[k_i] = 0. \end{cases}$$

- Information set $\mathcal{I}_i[k_i]$ available at $\mathcal{C}_i$:

$$\mathcal{I}_i[k_i] = \{k_i,\, z_i[0],\, \dots,\, z_i[k_i],\, u_i[0],\, \dots,\, u_i[k_i - 1]\}$$

- State estimation at $\mathcal{C}_i$:

$$\hat{x}_i[k_i] = \mathbb{E}\left[x_i[k_i] \;\middle|\; \mathcal{I}_i[k_i]\right]$$

**Assumption 1.** The scheduler at the BS observes the content of any packet it receives on the UL.

**Assumption 2.** The scheduler is aware of system parameters $A_i, W_i, B_i, L_i, T_i^s, T_i^o, \forall i$

- Reception variable $\delta_i^B[k_i] = \{0, 1\}$
- Age-of-Information $\Delta_i^B[k_i]$ available at BS:
  - $\Delta_i^B[k_i] \leq \Delta_i[k_i]$
- Information set $\mathcal{I}_i^B[k_i]$ available at BS:
  - $\mathcal{I}_i^B[k_i] \supseteq \mathcal{I}_i[k_i]\ \forall i, k_i$
- Analogously:

$$e_i^B[k_i] = x_i[k_i] - \hat{x}_i^B[k_i]$$
$$\hat{x}_i^B[k_i] = f(\Delta_i^B[k_i],\, \mathcal{I}_i^B[k_i])$$
$$\mathbb{E}\left[\left\|e_i^B[k_i]\right\|^2\right] = g(\Delta_i^B[k_i])$$

# Value-of-Information on UL / DL

- Value of UL packets:

$$v_i^{\mathrm{UL}}(t) = \mathbb{E}\left[\left\|e_i^B[k_i] - e_i^S[k_i]\right\|^2\right] = \mathbb{E}\left[\left\|e_i^B[k_i]\right\|^2\right]$$

with $k_i = k_i(t)$ and sensing error $e_i^S[k_i] = 0$.

- UL Scheduling:

$$\max_{\pi^{\mathrm{UL}}(t)} \quad \sum_{i=1}^{N} \pi_i^{\mathrm{UL}}(t) \cdot v_i^{\mathrm{UL}}(t)$$
$$\text{subject to} \quad \sum_{i=1}^{N} \pi_i^{\mathrm{UL}}(t) \leq \mathrm{R}^{\mathrm{UL}},$$

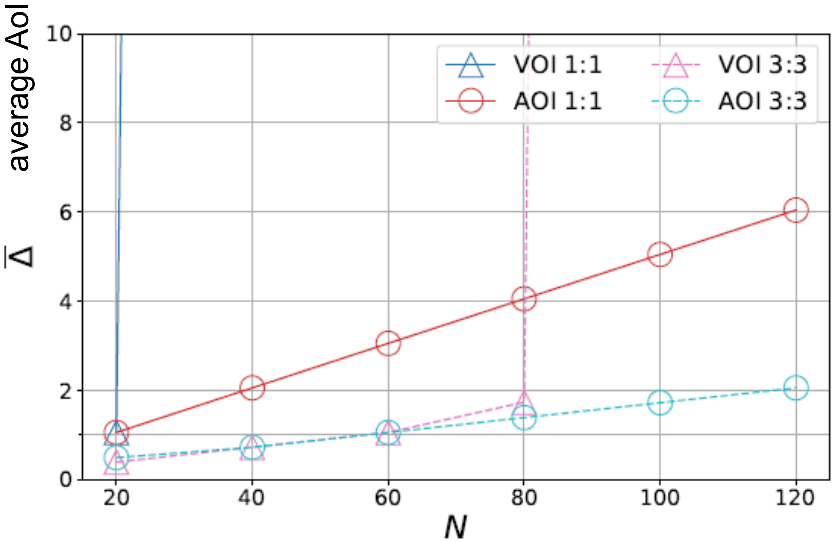
- Value of DL packets:

$$v_i^{\mathrm{DL}}(t) = \mathbb{E}\left[\left\|e_i[k_i] - e_i^B[k_i]\right\|^2\right] = \left\|\hat{x}_i^B[k_i] - \hat{x}_i[k_i]\right\|^2$$

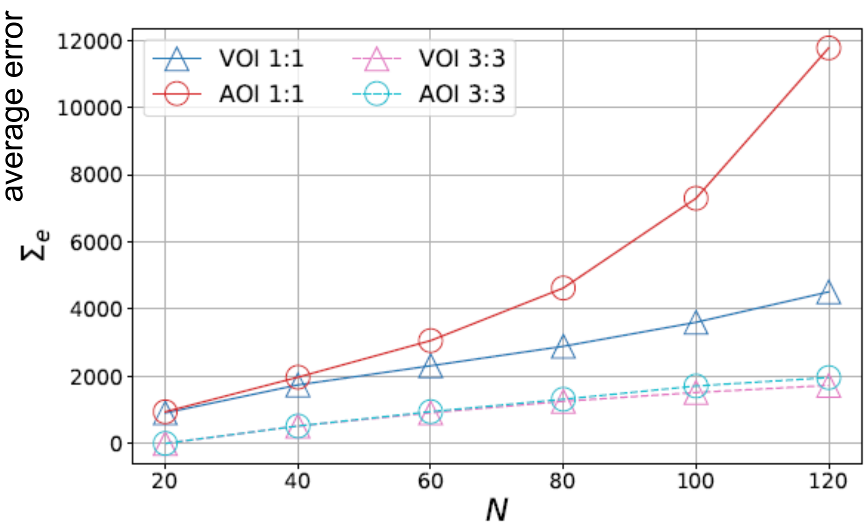
- DL scheduling:

$$\max_{\pi^{\mathrm{DL}}(t)} \quad \sum_{i=1}^{N} \pi_i^{\mathrm{DL}}(t) \cdot v_i^{\mathrm{DL}}(t)$$
$$\text{subject to} \quad \sum_{i=1}^{N} \pi_i^{\mathrm{DL}}(t) \leq \mathrm{R}^{\mathrm{DL}}.$$

# Simulation Results




a) Average Age-of-Information per sub-system over increasing $N$. $R^{UL}:R^{DL} = \{1:1,\ 3:3\}$




b) Average Integrated Absolute Error per sub-system over increasing $N$. $R^{UL}:R^{DL} = \{1:1,\ 3:3\}$

$$\overline{\Delta} = \frac{1}{N}\frac{1}{T_{sim}}\sum_{i=1}^{N}\sum_{t=0}^{T_{sim}-1}\Delta_i(t)$$

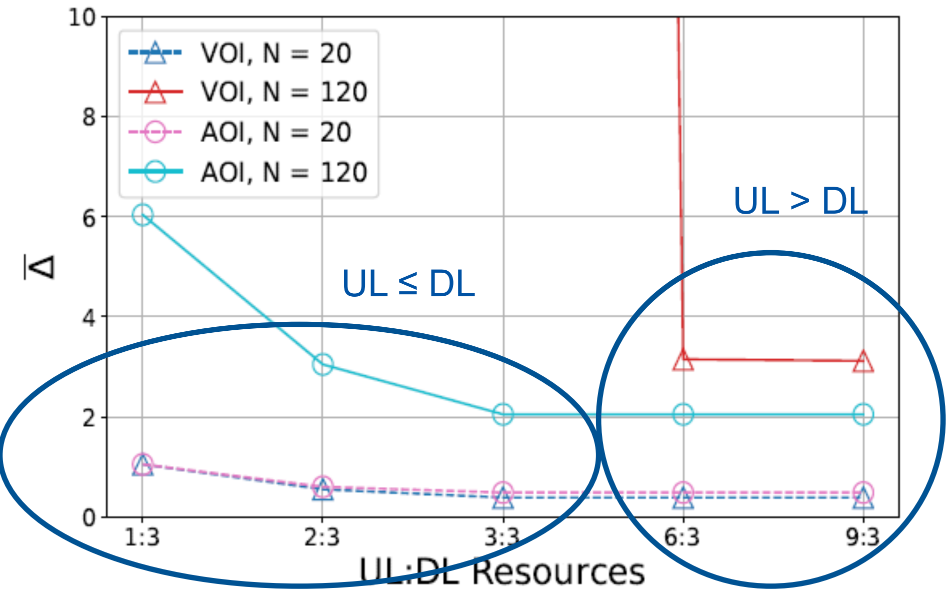
with simulation run-time $T_{sim}$

$$\Sigma_e = \frac{1}{N}\sum_{i=1}^{N}\sum_{t=0}^{T_{sim}-1}\|e_i[k_i(t)]\|$$

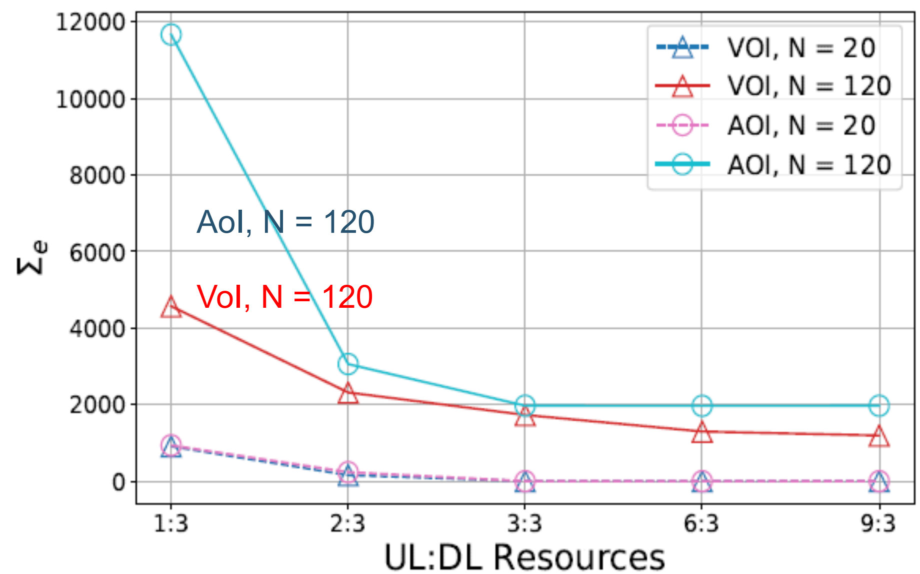
$A_{1,2,3,4} = \{0.75,\ 1.0,\ 1.25,\ 1.50\}$

- stable sub-systems (control loops) are less scheduled by VoI-scheduler (→ delay) with scarce resources (increasing N)
- VoI: less improvement expected from sensor values for stable loops

# Sensitivity to UL/DL Bottleneck Shift




a) Average Age-of-Information over changing $R^{UL}$. $R^{UL} : R^{DL} = \{1, 2, 3, 6, 9 : 3\}$




b) Average Integrated Absolute Error over changing $R^{UL}$. $R^{UL} : R^{DL} = \{1, 2, 3, 6, 9 : 3\}$

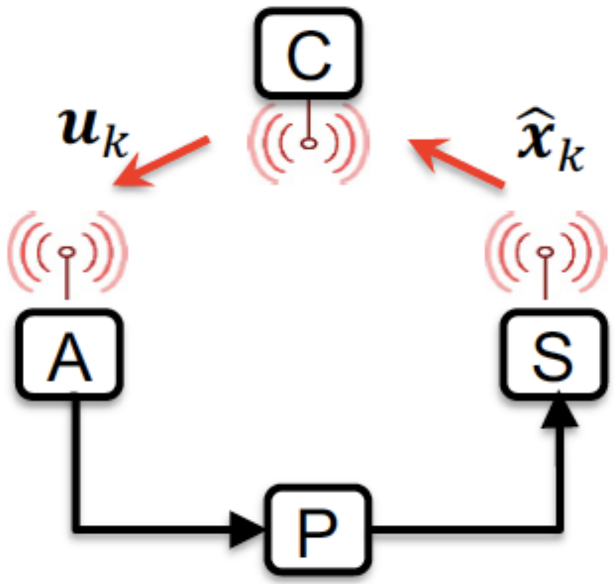
- Uplink (UL) capacity increased => bottleneck shifts from UL to downlink
- VoI-scheduler can better deal with scarce ressources (N=120)
- VoI buffers information that is not urgent (low VoI) (stable loops)

# Outline

- System model: Networked Control System
  - Including a short primer on control

- Selected use cases and results
  - Decentralized wireless MAC & Control: Adaptive Random Access
  - Scheduled wireless access & Control: Age of Information vs. Value of Information

- **NCS experience for everybody:**
  **Intro to NCS benchmark platform**

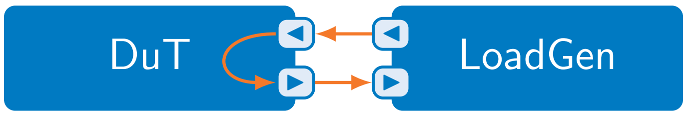



# NCS benchmark platform

https://github.com/tum-lkn/NCSbench

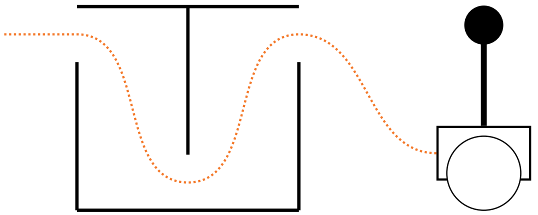
# Introduction & Motivation

Network Domain




Network domain has well-known benchmarks

Control Domain



Control domain has its own benchmarks

- We combined Network and Control domains
  - towards our **benchmarking** platform
    → *NCSbench*
  - in a **practical** approach
    → *Two-Wheeled Inverted Pendulum*

# NCSbench

- ... a ***Benchmarking*** Platform that is ...
  - Easy to recreate & affordable

    → Lego Mindstorm EV3

  - Easy to reproduce

    → Public GitHub Repository & Wiki

    → Step-by-step instructions for usage

    → Documentation for extension

https://git.io/fpaU4

# Current Status & Outcome

[1] *Benchmarking Networked Control Systems,*
**CPSBench, 2018**

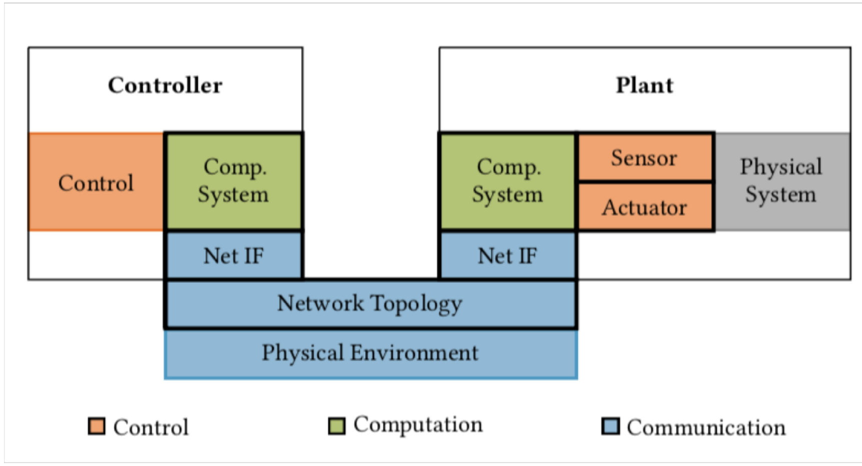
[2] *Reproducible Benchmarking Platform for Networked Control Systems,*
(under submission) => TR at TUM

[3] *Design Of a Networked Controller For a Two-Wheeled Inverted Pendulum Robot,*
(under submission)

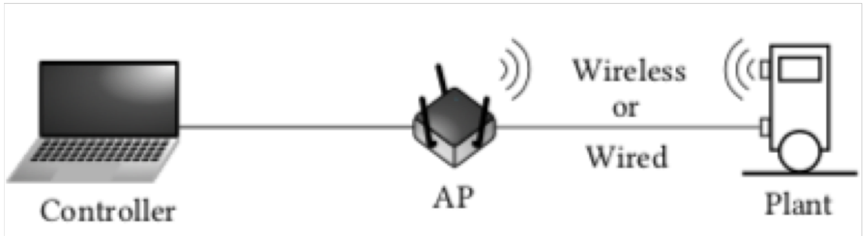
# NCSbench Platform – Implementation

- Flexible model of the CPS
  1. Computing System
  2. Communication Network
  3. Control Logic

  → allows the **performance analysis** of the individual components!

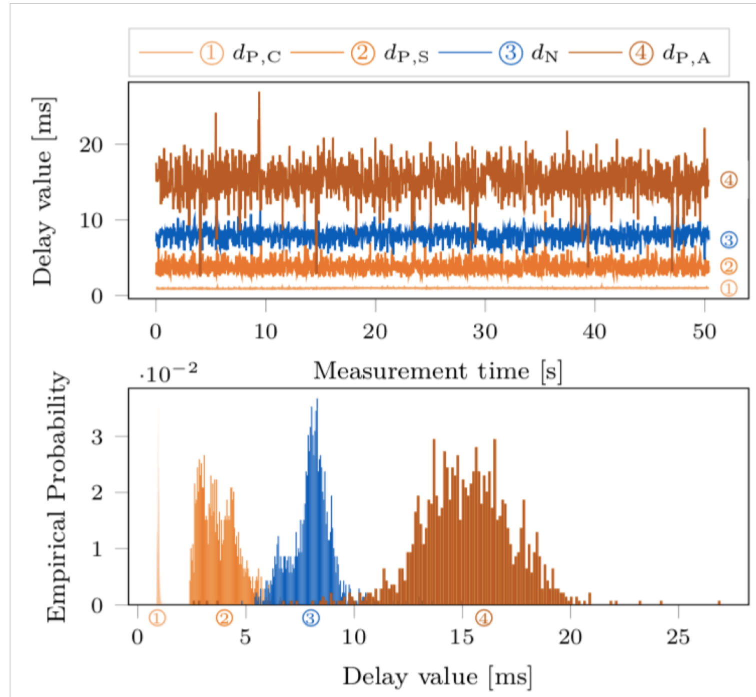



- In our implementation
  1. Lego Mindstorm & any PC
  2. Ethernet & Wi-Fi networks
  3. Delay & packet loss tolerant

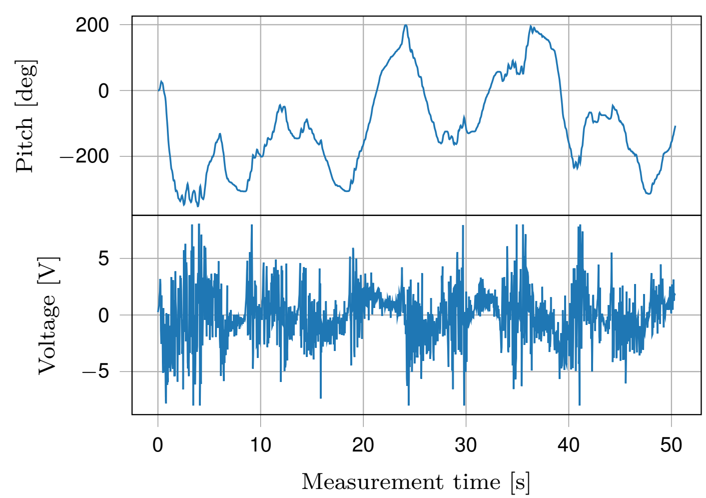


# NCSbench Platform – Performance

- Measures of  the **delays** of the NCS
  - Network delays ($d_N$)
  - Controller ($d_{P,C}$)
  - Sensor ($d_{P,S}$)
  - Actuator ($d_{P,A}$)
  - Computing system




- Measures of the **control performance**
  - Sensor → pitch angle, robot position (fig)
  - Actuation → motor voltage (fig)



# NCS Benchmark

- Measurement scenario:
  - Robot balancing for one minute
  - Data collection via scripts on Controller
  - Logging on Robot too expensive (only one CPU core, slow disk), data sent to Controller
  - Network: wired (Ethernet) & wireless (IEEE 802.11g, 2.4 GHz)

- KPIs:
  - Network:
    - Transmission Latency (in ms)
    - Jitter
  - Control:
    - Pitch angle of robot (gyro)
    - Rotation angle of motors
    - Motor voltage
    - Lost predictions

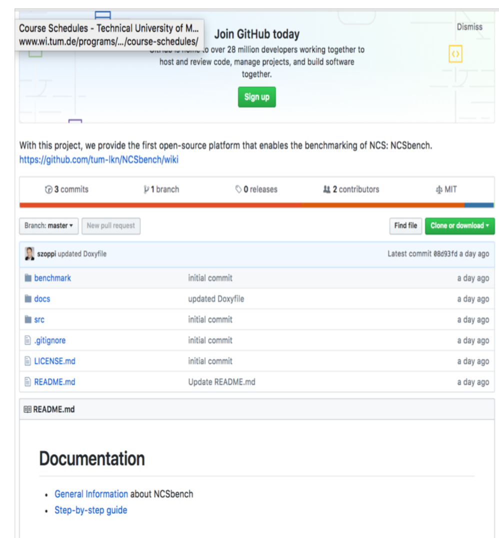
| Scenario | Median +- 95% | Q3 | 99.9% |
|---|---:|---:|---:|
| Wired | 4.38 +- 0.041 | 5.03 | 6.66 |
| Wireless | 8.09 +- 0.053 | 8.54 | 10.88 |

| Scenario | ∑Pitch | ∑Rot. | ∑Volt | Loss |
|---|---:|---:|---:|---:|
| Wired | 763 | 152090 | 2067 | 0 |
| Wireless | 938 | 217080 | 2637 | 10 |

cumulative deviations from reference value

# NCSbench: Summary

- Results:
  - Several publications directly based on the TWIP and the NCSbench
  - Collaboration between different project partners
  - Reproducible NCS benchmark combining Network & Control KPIs
- Open Source NCSbench framework ([https://git.io/fpaU4](https://git.io/fpaU4))
  - TWIP software
  - Measurement scripts
  - Plotting scripts
- Future Work
  - Benchmarking platform is currently limited by Robot's controller
  - Solution: Better hardware (Raspberry Pi-based)
  - Testing with different networks (WLAN 802.11ac, Bluetooth)
  - Better sensors
  - Extend the TWIP to a non-linearized controller



# Conclusion

- M2M Applications → Networked Control Systems
- NCS Model → Network Induced Error for Decoupling from Control
- Global Optimization model needs further decomposition

- Threshold-based policy for multi-channel ALOHA

- Network induced error → up-/downlink scheduling problem in a cellular network scenario

- NCSbench to experiment with your favorite
  - Control law
  - Communication network strategy

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[MMG19] Zenit Music, Fabio Molinari, Sebastian Gallenmüller, Onur Ayan, Samuele Zoppi, Wolfgang Kellerer, Georg Carle, Thomas Seel, Joerg Raisch, “Design of a Networked Controller for a Two-Wheeled Inverted Pendulum Robot”, (submitted)

[NCS19] https://github.com/tum-lkn/NCSbench

# Questions?