Chair of Communication Networks
Department of Electrical and Computer Engineering
Technical University of Munich

Joint Optimization of Control and Networking in Wireless Cyber Physical Systems

ECC, Naples, Italy

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based on joint work with

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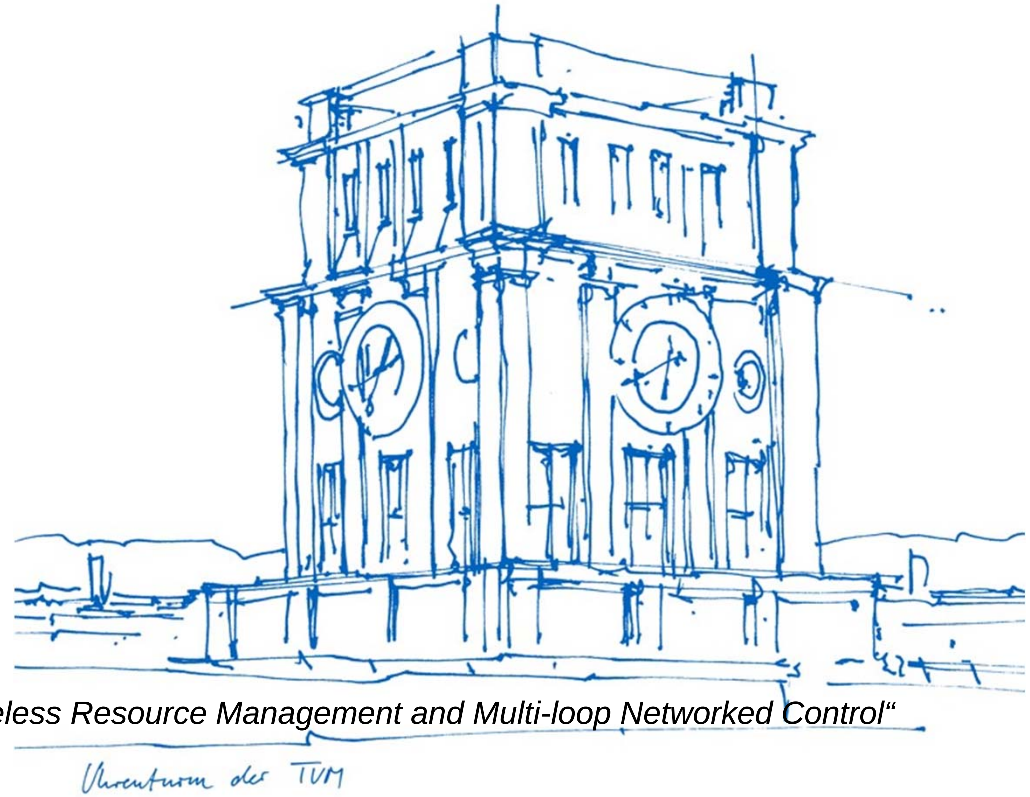


DFG SPP 1914 project „Optimal Co-Design of Wireless Resource Management and Multi-loop Networked Control“

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

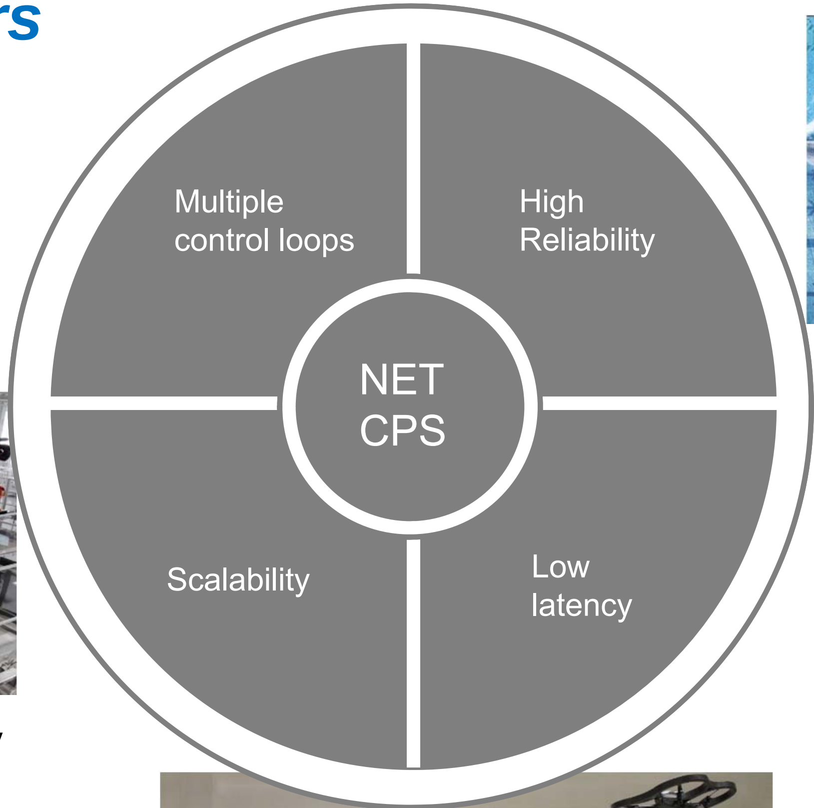
It is mostly machines that communicate over networks

Motivation: Control

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

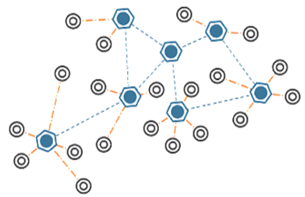
Control matters

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

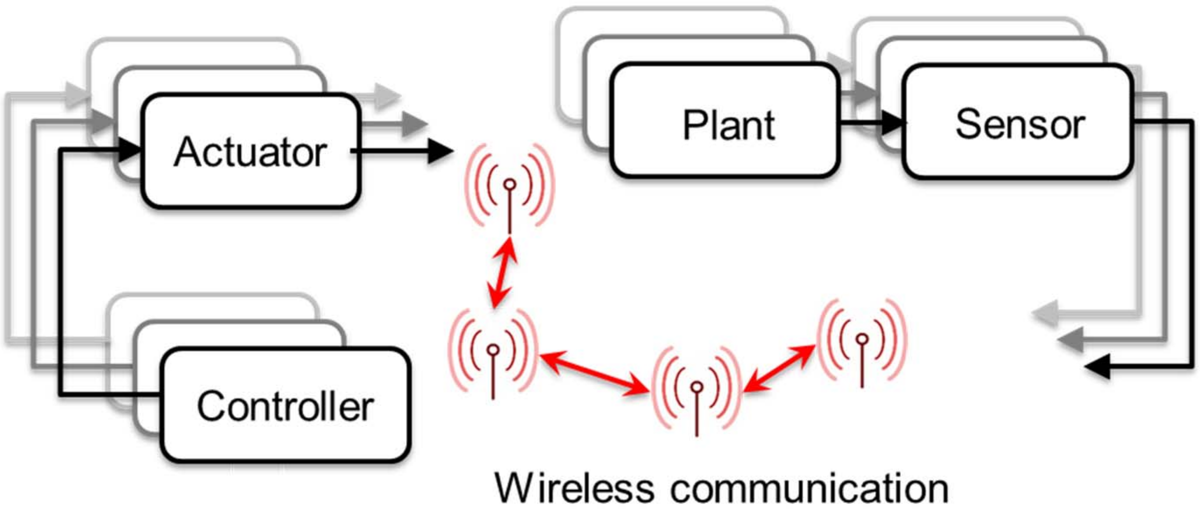
- Key challenge in design and analysis of cyber-physical systems: **Control over shared communication networks**
  – quality of control may be degraded due to the congestion while accessing the scarce communication resources

- **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 talk

- Support of control over shared wireless 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

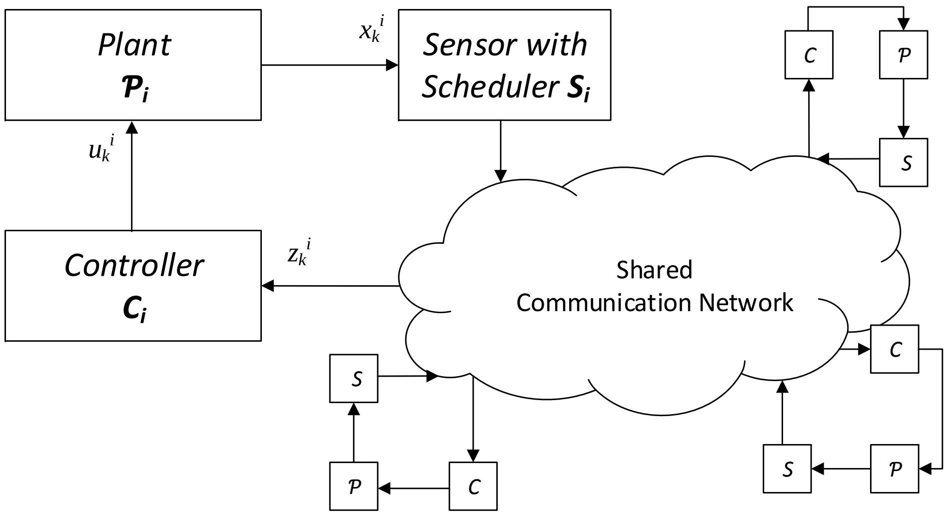
- Selected use cases and results
  - Decentralized wireless MAC & Control: Adaptive Random Access
  - Scheduled wireless access & Control: Age of Information vs. Value of Information

- NCS experience for everybody:
  Intro to NCS benchmark platform

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

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

Scenario & Problem Formulation

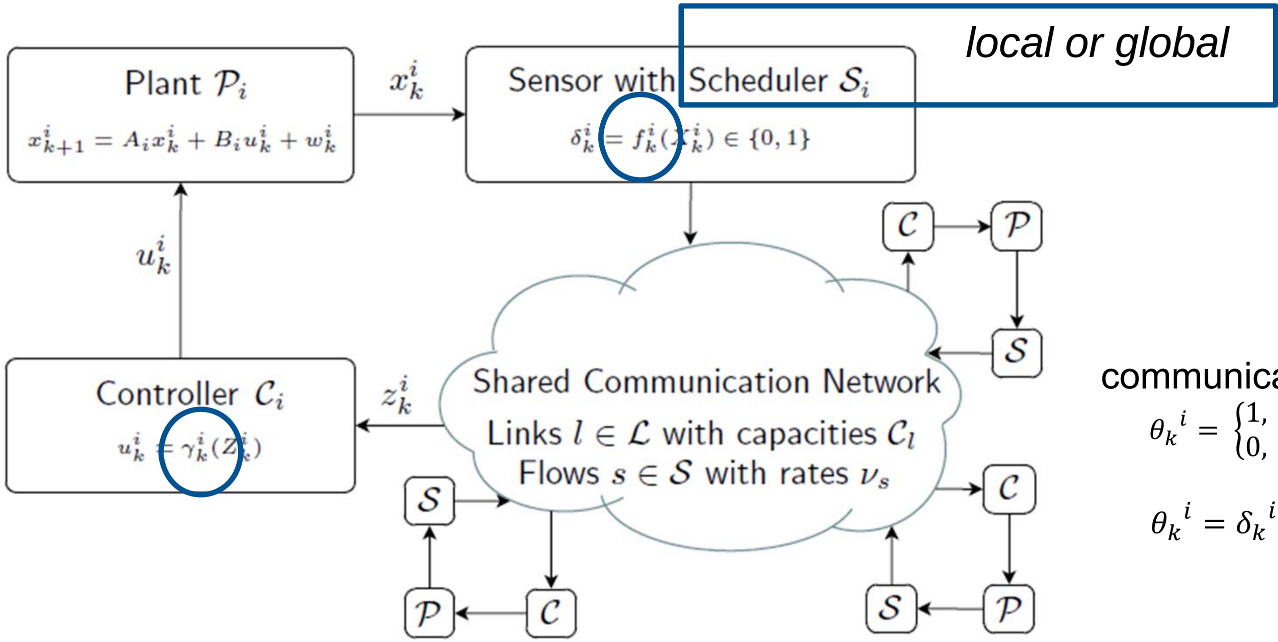
Generalized *optimization problem*:

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

QoC
Quality of Control

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

Event-triggered Control



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 $Z_k^i = \{z_o^i, \dots z_k^i\}$ 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)

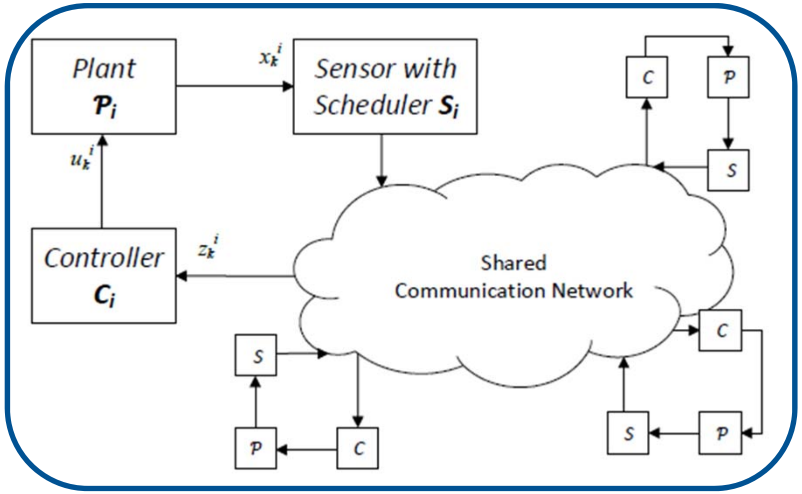
→*AoI and VoI based scheduling*

Decentralized wireless MAC & Control: Adaptive Random Access

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



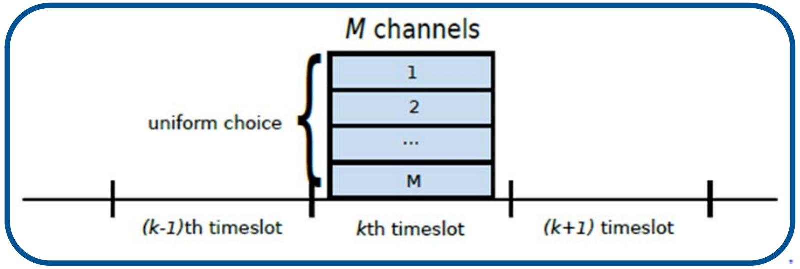
- LTI control loop

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

- 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 Λ_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: 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 δ_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: Eval. of Threshold

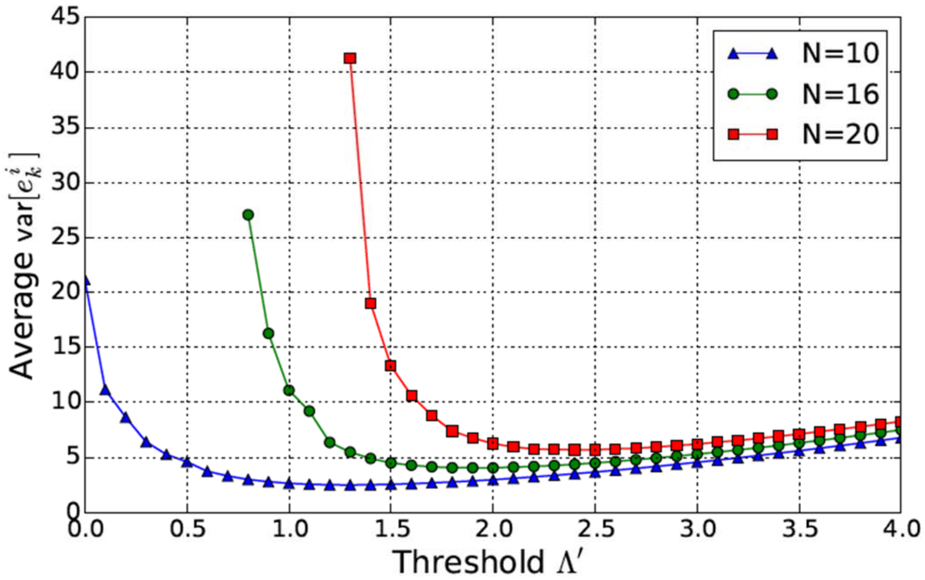
- Performance Evaluation: Threshold

• 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

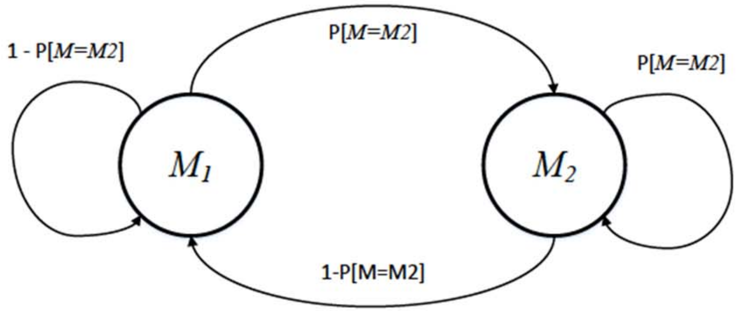


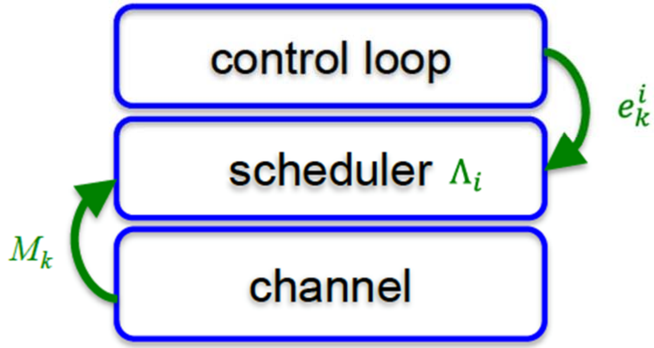
→ to optimally use the network, adaptive scheduling policy is required

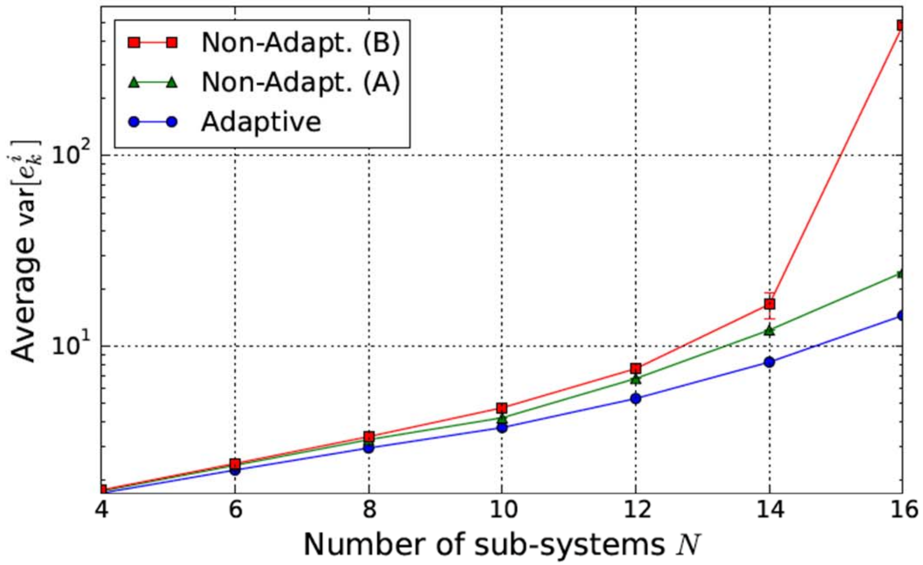
M. Vilgelm, M. H. Mamduhi, W. Kellerer, S. Hirche, *"Adaptive Decentralized MAC for Event-Triggered NCS,"* ACM HSCC, 2016

Adaptive Random Access: Adaptation

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







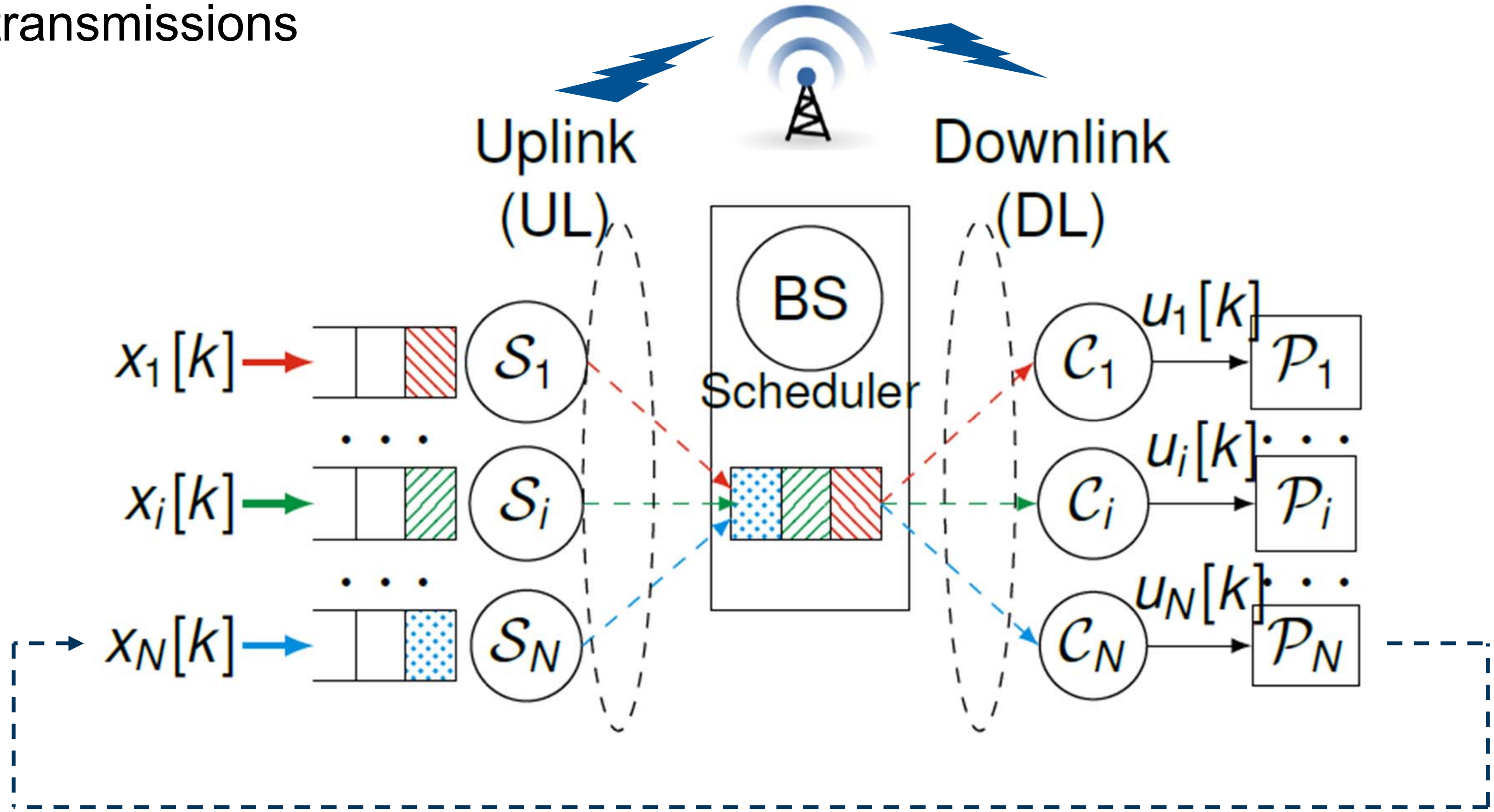
M. Vilgelm, M. H. Mamduhi, W. Kellerer, S. Hirche, *"Adaptive Decentralized MAC for Event-Triggered NCS,"* ACM HSCC, 2016

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

O. Ayan , M. Vilgelm, M. Klügel, S. Hirche, W. Kellerer, “Age-of-Information vs. Value-of-Information Scheduling for Cellular Networked Control Systems“, ACM/IEEE International Conference on Cyber-Physical Systems, Montreal, Canada, April 16 - 18, 2019.

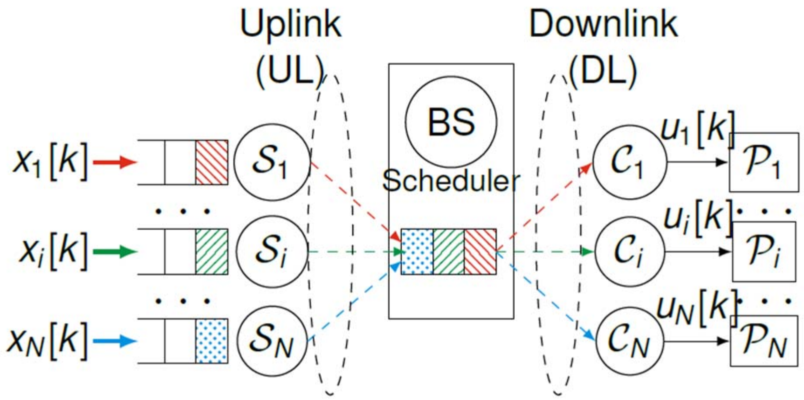
Scheduled wireless access: Scenario

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



Plant N is observed by Sensor N

Scheduled wireless access: Scenario

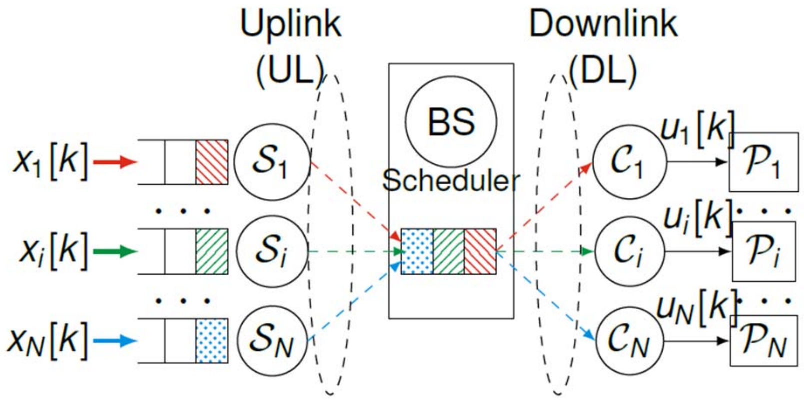


- *N* stochastic LTI control loops share the same network
- Each sub-system consists of sensor S_i , controller C_i and plant P_i
- Observed plant state $x_i[k_i]$ at time-step k_i is transmitted towards C_i
  - First on uplink (UL) from S_i to base station (BS)
  - Then on downlink (DL) from BS to C_i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

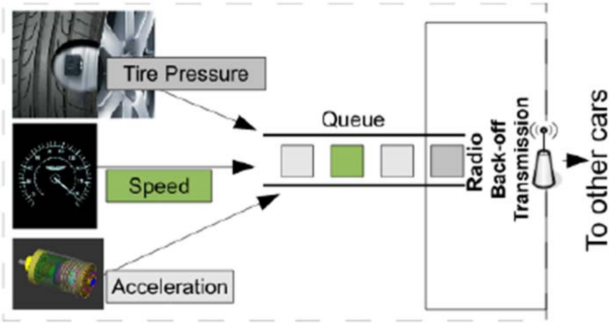
- Central scheduler has to consider the importance of a sensor value to decide for scheduling considering both hops



- 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)

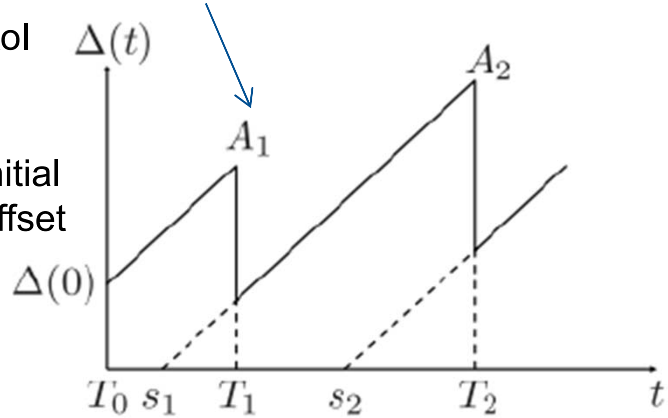
- a recently proposed performance metric that measures **information freshness** at the destination node
- proposed in 2011 by S. Kaul and R. Yates for vehicular networks [1,2]
  - [1]: “Average end-to-end (application-to-application) delay observed in any vehicle’s state”
  - [3]: “Time since last update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



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

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

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

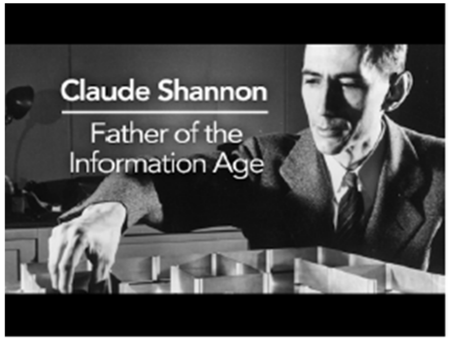


$s_i = u(t)$, *time* sensor value is taken

[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!

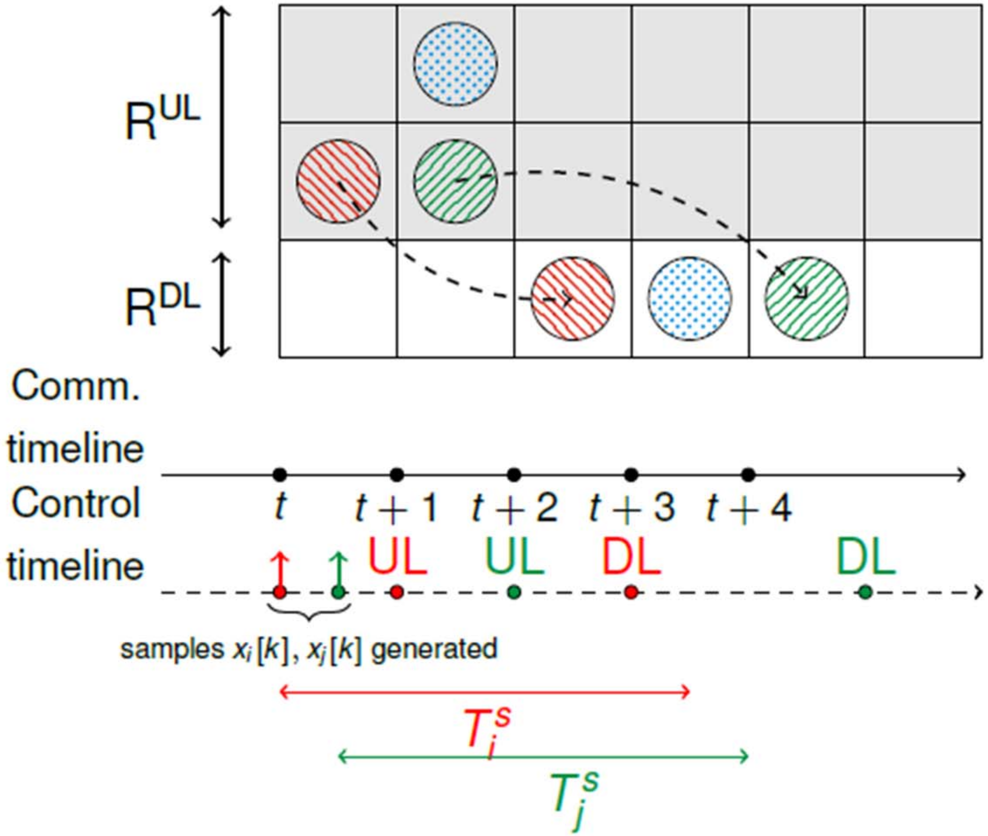
Value-of-Information

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

Network Model



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

R^{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:

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

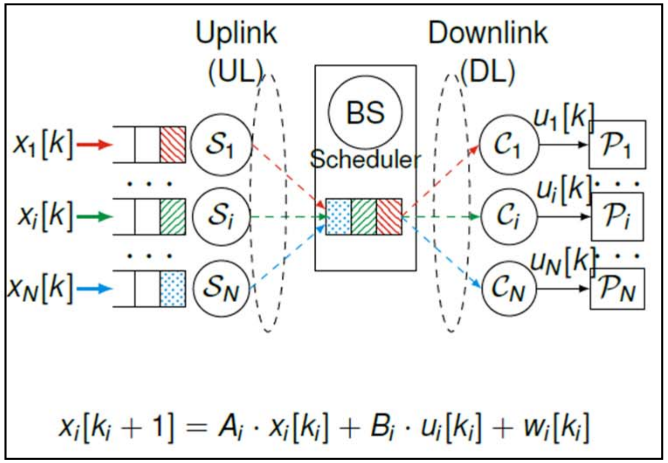
  with $x_i[0] = w_i[0]$ and $w_i \sim \mathcal{N}(0, W_i)$.

- 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 $\mathcal{C}_i$:

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

Age-of-Information

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

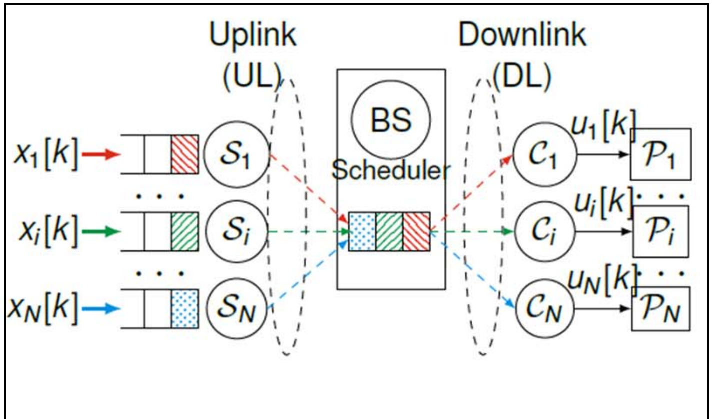
- Control input:

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

state feedback gain matrix L_i

Control Model

Sampling event (period T)



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

- 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 $\mathcal{C}_i$:

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

- Control input:

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

state feedback gain matrix L_i

Age-of-Information

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

current time

timestamp of most recent update

Age of Information and Value of Information

- Age-of-Information:

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

AoI = time difference to sensor value generation time

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:

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

VoI = expected value of squared estimation error

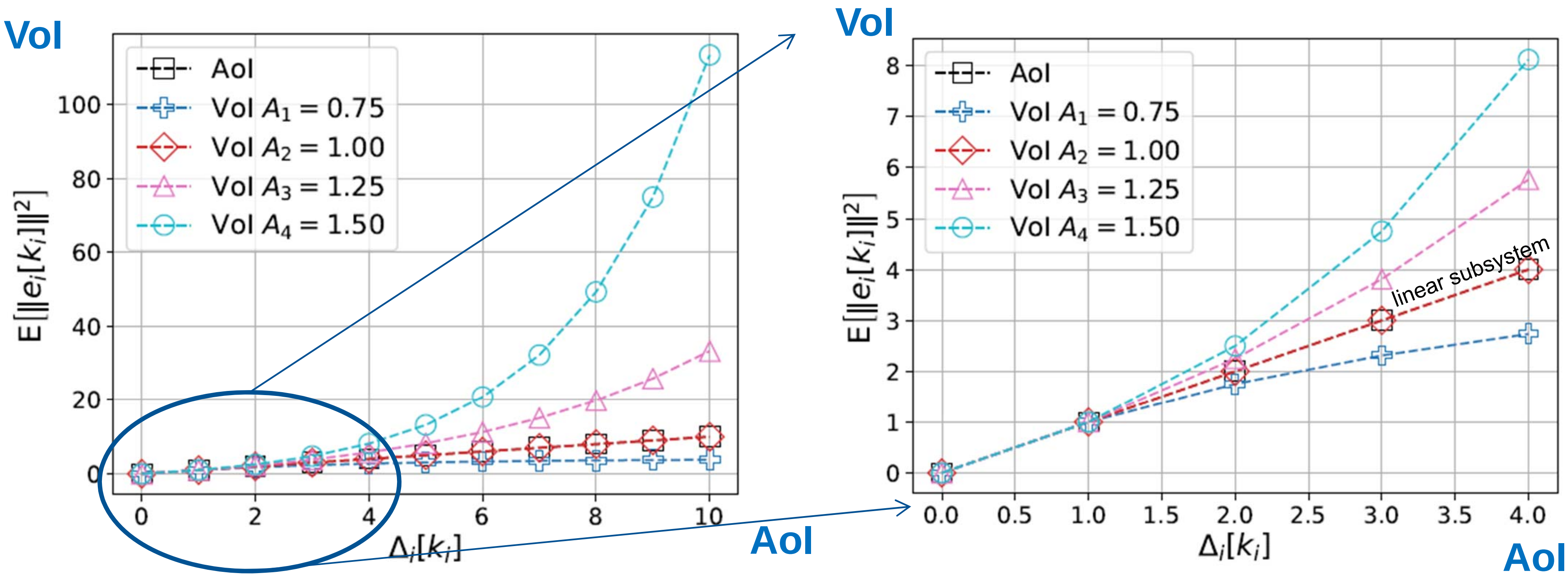
with:

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

is a function of AoI

tr(.): Trace operator

System Dependability of VoI



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

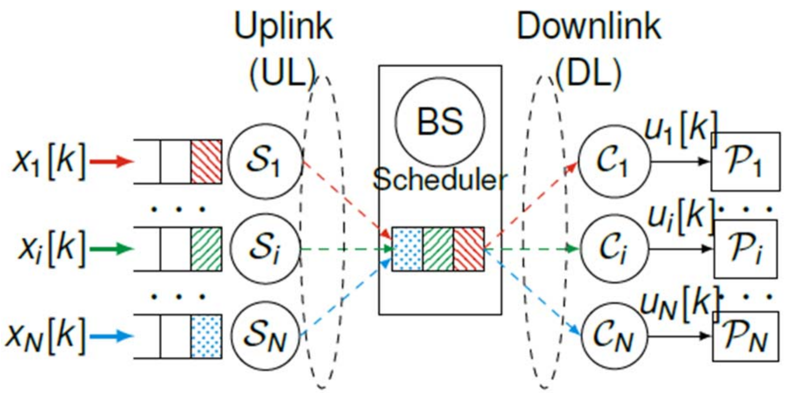
b) $\mathbb{E}\left[\|e_i[k_i]\|^2\right]$ for $\Delta_i[k_i] \in [0, 4]$, $W_i = 1$

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

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

- 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 $\mathcal{C}_i$:

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

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

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

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 $e_i^S[k_i] = 0$.

- Value of DL packets:

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

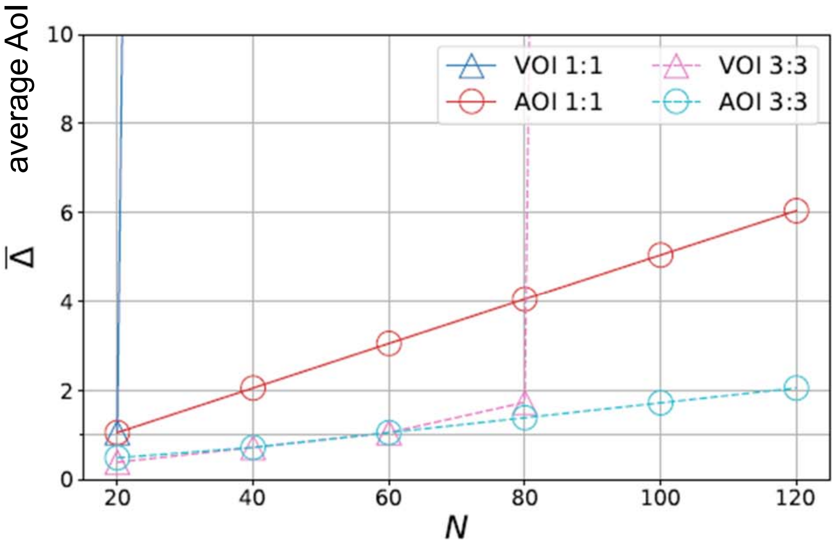
- UL Scheduling:

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

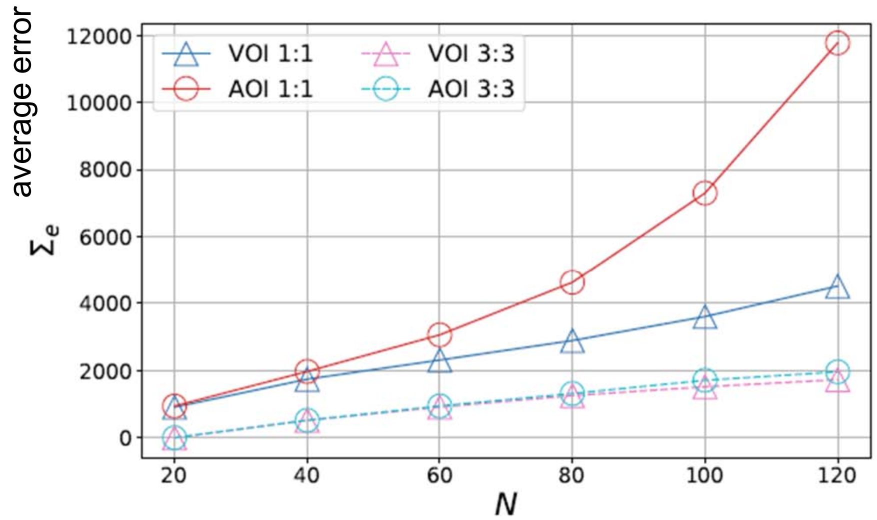
- DL scheduling:

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

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. $R^{UL} : R^{DL} = \{1:1,\ 3:3\}$

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

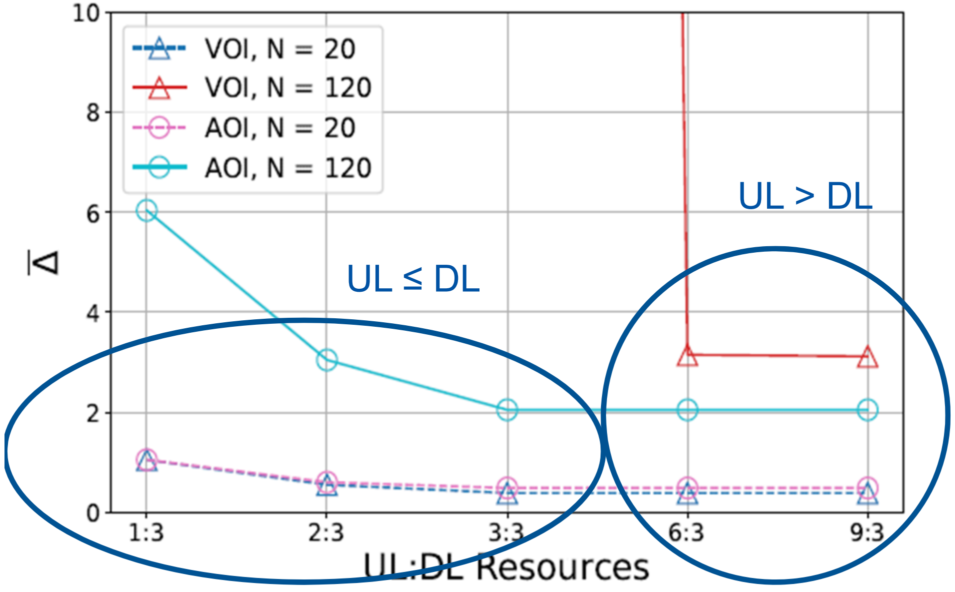
with simulation run-time T_{sim}

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

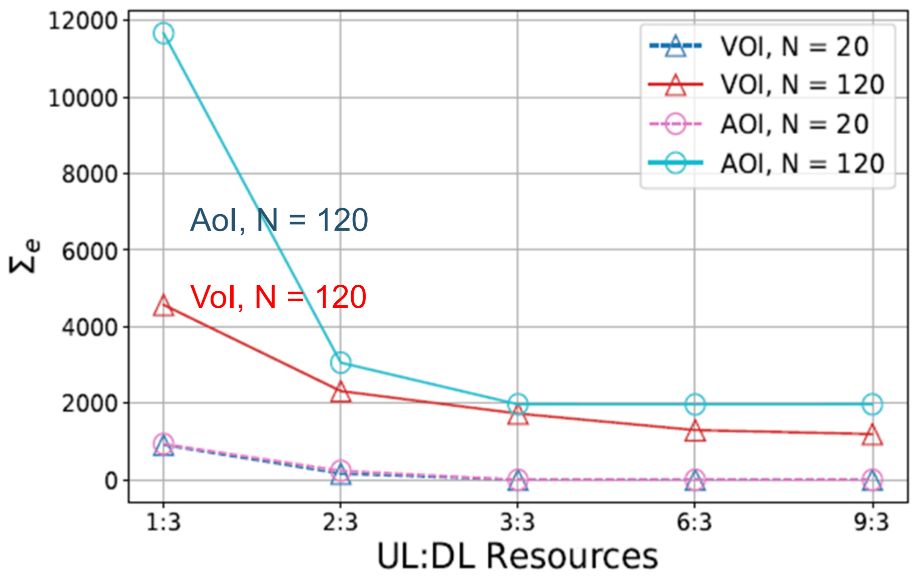
$A_{1,2,3,4} = \{0.75,\ 1.0,\ 1.25,\ 1.50\}$

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

NCS benchmark platform

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

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

Joint work with Jörg Raisch (TU Berlin) and Georg Carle (TUM) and their teams

https://git.io/fpaU4

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