Towards Cyber Physical Networks: Joint Design of Network and Control

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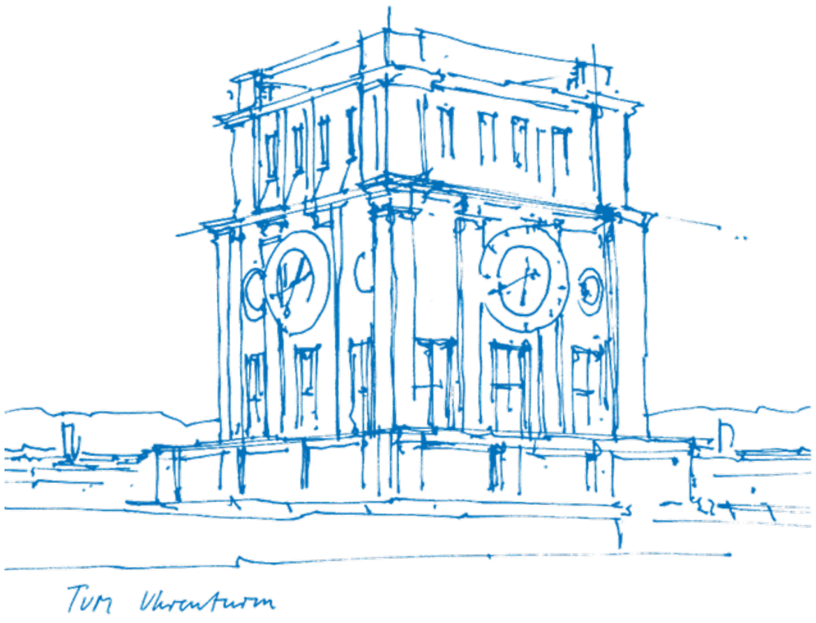

Overview

- Motivation & Framework
- Problem statement
- Stability Analysis
- Numerical Evaluation
- Adaptive Scheduler

Networked Control Systems

- Tactile Internet applications: healthcare, robotics, manufacturing, smart grid, etc., rely on Control Systems [Fet14]
- Distributed, large scale systems must be interconnected: Networked Control Systems [WTJ+11]
- Separate treatment of application and network - inefficient
- Event-triggered control paradigm [MAB+03, BHP09] $\rightarrow$ Non-deterministic transmission patterns $\rightarrow$ no static resource allocation / reservation

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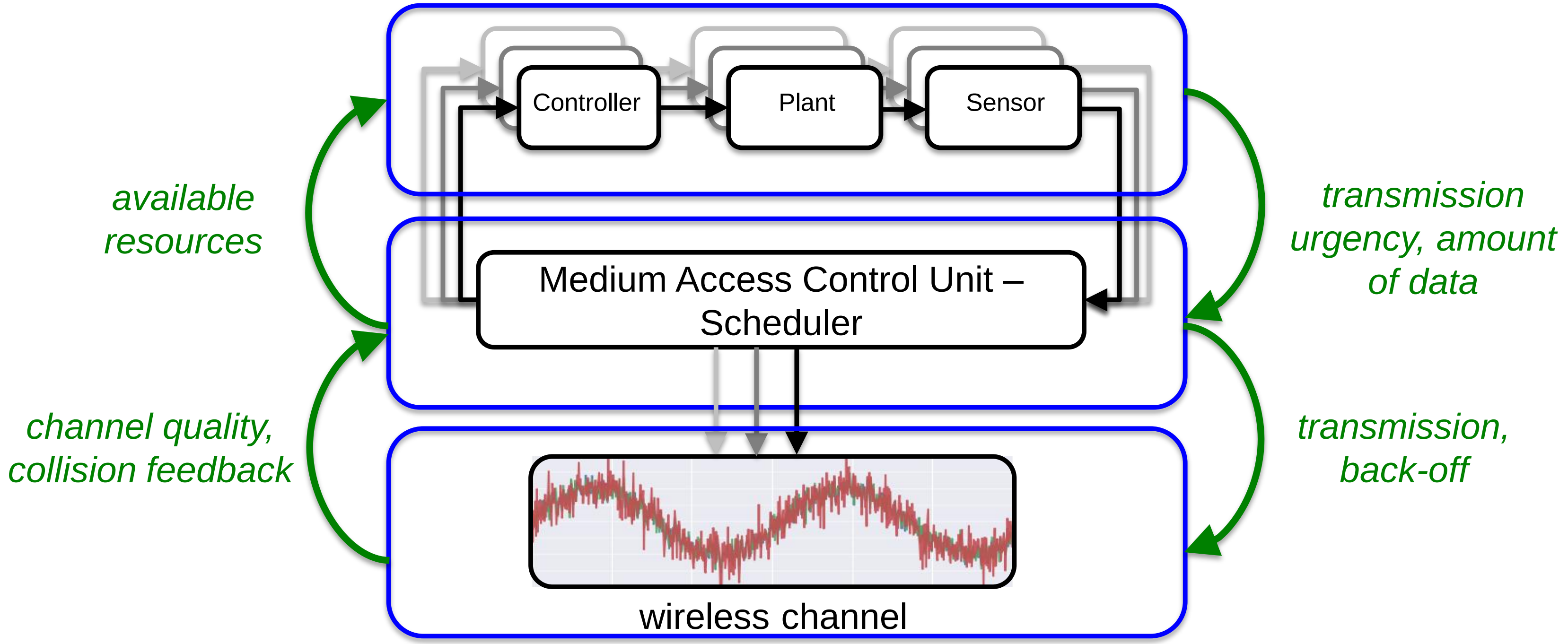
Idea: Exploit Control System properties for Efficient Medium Access Design

Framework of cross-layer design



Problem Statement: scenario

- NCS of N heterogeneous LTI control loops with the plant process:

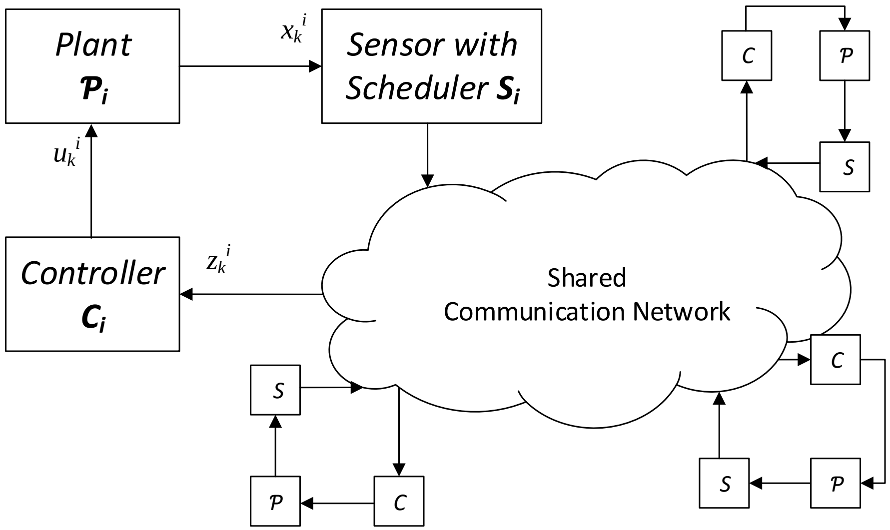
$$x_{k+1}^i = A_i x_k^i + B_i u_k^i + w_k^i$$

- Local scheduler S_i deciding:

$$\delta_k^i = \begin{cases} 1, & x_k^i \text{ sent through the channel} \\ 0, & x_k^i \text{ blocked.} \end{cases}$$

- Shared network $\rightarrow$ sub-systems can collide:

$$\gamma_k^i = \begin{cases} 1, & x_k^i \text{ successfully received} \\ 0, & x_k^i \text{ collided.} \end{cases}$$



From this slide on: [VMKH16]

Network Model

- Homogeneous sampling period k
- **Network state** – available channels (TX opportunities) M_k per sampling period k
- Multichannel Slotted ALOHA [Yue91]
- Thus, received signal at the controller side is:

$$z_k^i = \begin{cases} x_k^i, & \theta_k^i = 1 \\ \varnothing, & \text{otherwise,} \end{cases}$$

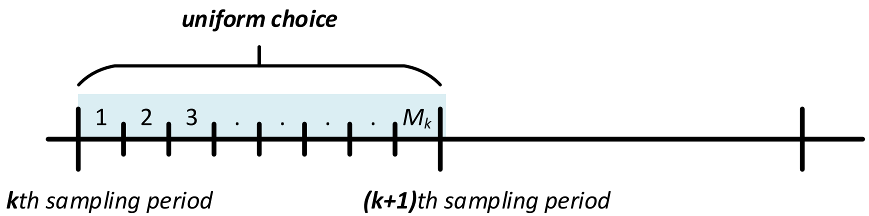
where, $\theta_k^i = \delta_k^i \gamma_k^i$.

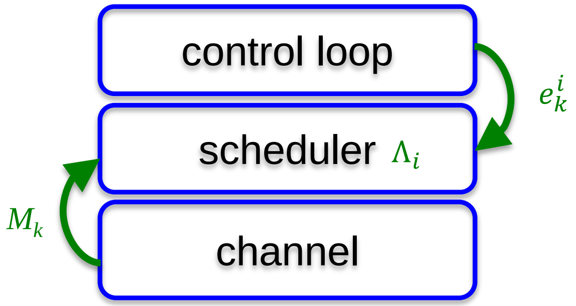
- Control law:

$$u_k^i = \vartheta_k^i(Z_k^i) = -L_i \mathsf{E}\left[x_k^i | Z_k^i\right],$$

- If a transmission fails, use model-based estimator:

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





From: [VMKH16]

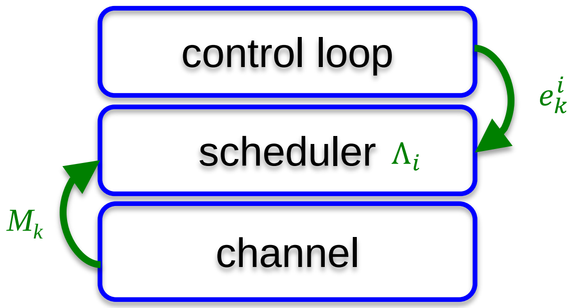
Threshold-based Scheduler

- *Network-induced estimation error* e_k^i:

$$e_k^i := x_k^i - \mathsf{E}\left[x_k^i | Z_k^i\right]$$

- Estimation error follows the dynamics:

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



- Local threshold-based scheduler with the policy:

$$\mathsf{P}[\delta_{k+1}^i = 1 | e_k^i] = \begin{cases} 0, & \text{if } \|e_k^i\| \leq \Lambda_i \\ 1, & \text{otherwise.} \end{cases}$$

- At time step k, local schedulers let g_k sub-systems transmit:

$$\mathsf{P}[\gamma_{k+1}^i = 1 | \|e_k^i\| > \Lambda_i] = \left(\frac{M_k - 1}{M_k}\right)^{g_k}$$

From: [VMKH16]

Stability Analysis

- Noise with unsupported distribution $\rightarrow$ stochastic stability notions

LSP:

given ξ, $\xi' > 0$: $\lim_{k\to\infty} \sup \mathsf{P}\left[e_k^{\mathsf{T}} e_k \geq \xi'\right] \leq \xi$

Proof outline

- Aggregated error state: $e_k = [e_k^{1\,T}, \ldots, e_k^{N\,T}]^T$
- Stability condition: at least one successful transmission
- Probability of all sub-systems to collide:

$$\mathsf{P}_{fail}^{k} \leq \frac{M^N + \sum_{j=1}^{min(N,M)} (-1)^j \cdot j! \binom{M}{j} \binom{N}{j} (M-j)^{N-j}}{M^N}$$

- Adjust M according to N to guarantee stability

From: [VMKH16]

Performance Evaluation: Metrics

- NCS performance: *average error variance*

$$\Sigma = \frac{1}{N}\sum_{i=1}^{N} \mathrm{var}[e_k^i]$$

- Network performance:
  - Average channel utilization (*throughput*):

$$T = \mathsf{E}\left[\frac{n_p^s}{M}\right]$$

  - Average *collision ratio*:

$$r_{coll} = \mathsf{E}\left[\frac{n_p^c}{n_p^c + n_p^s}\right]$$

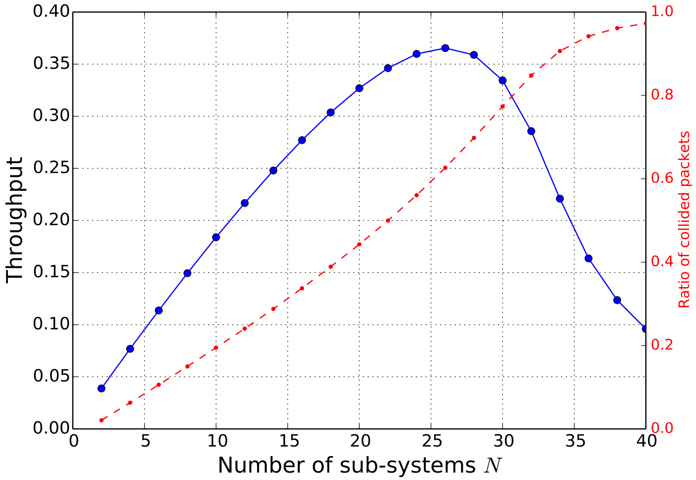
- For the following: global transmission threshold: $\Lambda_i := \Lambda', \quad \forall i \in N$
- Evaluation performed using numerical simulation*

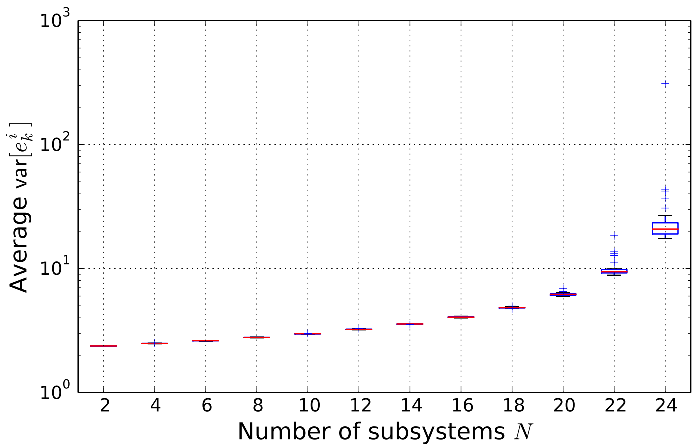
From: [VMKH16]

*Source code & repeatability instructions available: `https://github.com/mvilgelm/AdaptiveMAC`

Performance Evaluation: General

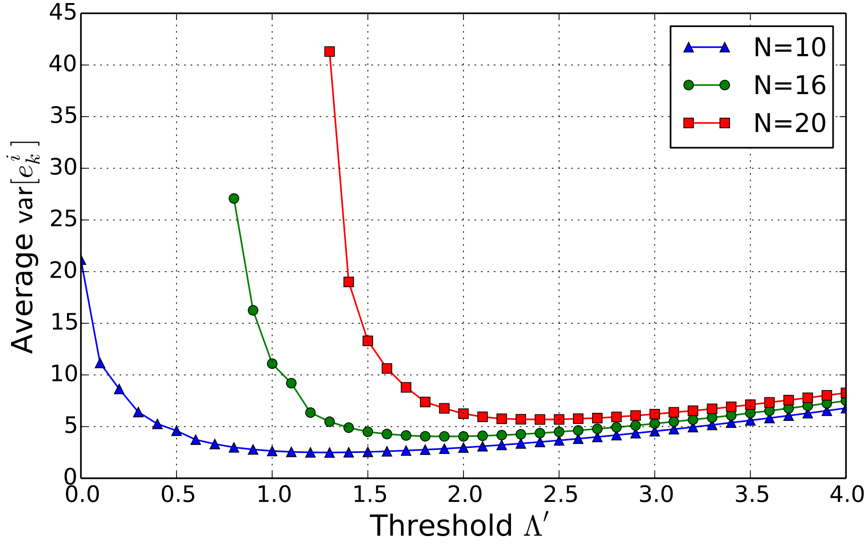
- Network performance: “classical” slotted ALOHA plot
- Exists a peak throughput
- Number of collisions grows with the number of sub-systems
- Average error variance grows with the number of sub-systems N
- After the peak throughput is reached – grows exponentially due to a very high collision rate





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



$\rightarrow$ to optimally use the network, adaptive scheduling policy is required

From: [VMKH16]

Scheduler with Threshold Adaptation

- Scenario: varying number of channels $M_k \in \{M_1, M_2\}$, $M_1 < M_2$:

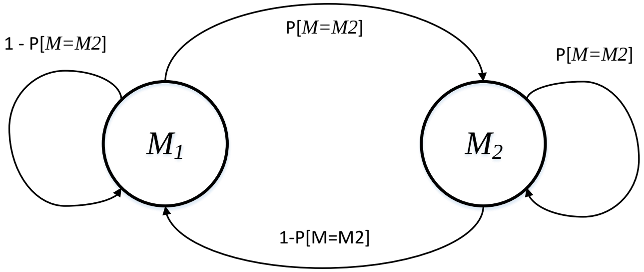
$$\mathsf{P}[M_k = M_1] = 1 - \mathsf{P}[M_k = M_2]$$

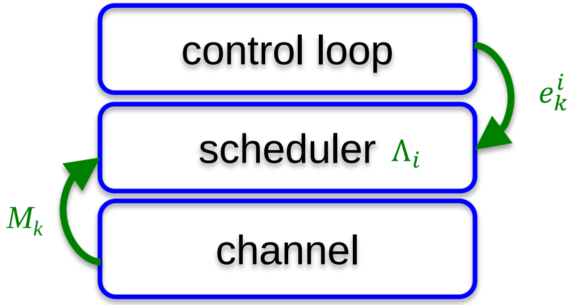
- Might occur in a case of dynamic resource allocation [LKY11, 3GP11]
- Adaptive scheduling policy:

$$\Lambda'_k = f(M_k)$$

- Optimal threshold for given N, M:

	Optimal Λ'						
N	4	6	8	10	12	14	16
$M = 5$	1.0	1.5	2.0	2.4	3.5	5.2	8.1
$M = 10$	0.6	0.8	1.0	1.2	1.4	1.6	1.8

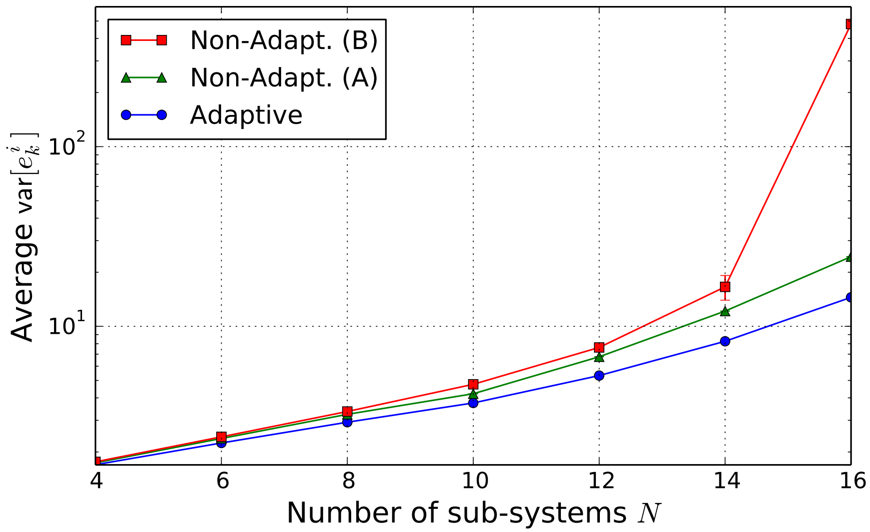




From: [VMKH16]

Scheduler with Threshold Adaptation (2)

- Comparison with non-adaptive: (A) chosen for M_1 and (B) chosen for M_2
- Gain from the adaptation depends on the number of sub-systems
- Gain is larger for non-adaptive targeting worse network state – scheduler (A) risks underutilization, while scheduler (B) risks high collision ratio



From: [VMKH16]

Conclusions

Contributions summary:

- Threshold-based scheduler & multi-channel slotted aloha
- Proved stochastic stability
- Numerically evaluated control and network performance
- Illustrated coupling of control & network via Λ'
- Proposed adaptive scheduling policy

Outlook

- Traffic Analysis of NCS
- Centralized Network- and Control-aware scheduler
- Design of control law based on the network knowledge

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Questions?