Communication-Aware Networked Control Systems

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ACCESS Linnaeus Center

Sweden's largest university research center in communication and networked systems

- 40 senior researchers and 80 PhD students
- Basic funding from VR on 12 MEUR for 10 years
- Total research budget about 6 MEUR per year
- Extensive industrial and international collaborations

ACCESS

Acknowledgments

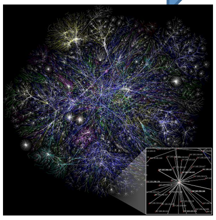
Based on joint work with Yassine Ariba, Jose Araujo, Phoebus Chen, Carlo Fischione, Erik Henriksson, Magnus Lindhé, Piergiuseppe di Marco, Mikael Johansson, Pangun Park, Oriol Prats, Maben Rabi, Chithrupa Ramesh, Henrik Sandberg, Milos Stankovic, André Teixeira

Financial support:

Wireless control as an enabling technology

- Internet
- WWW
- Ubiquitous computing

Info Web



The Internet

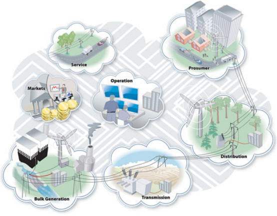
- Remote sensing
- Monitoring environments
- Wireless sensor networks

Sensor Web

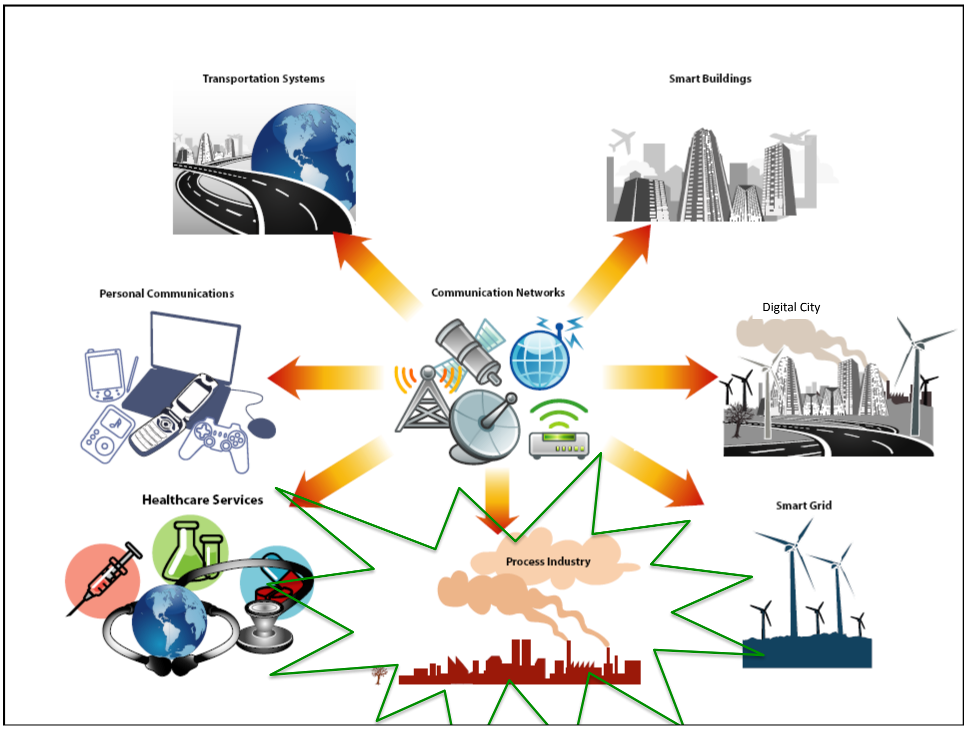
Monitoring storm petrels at Great Duck Island

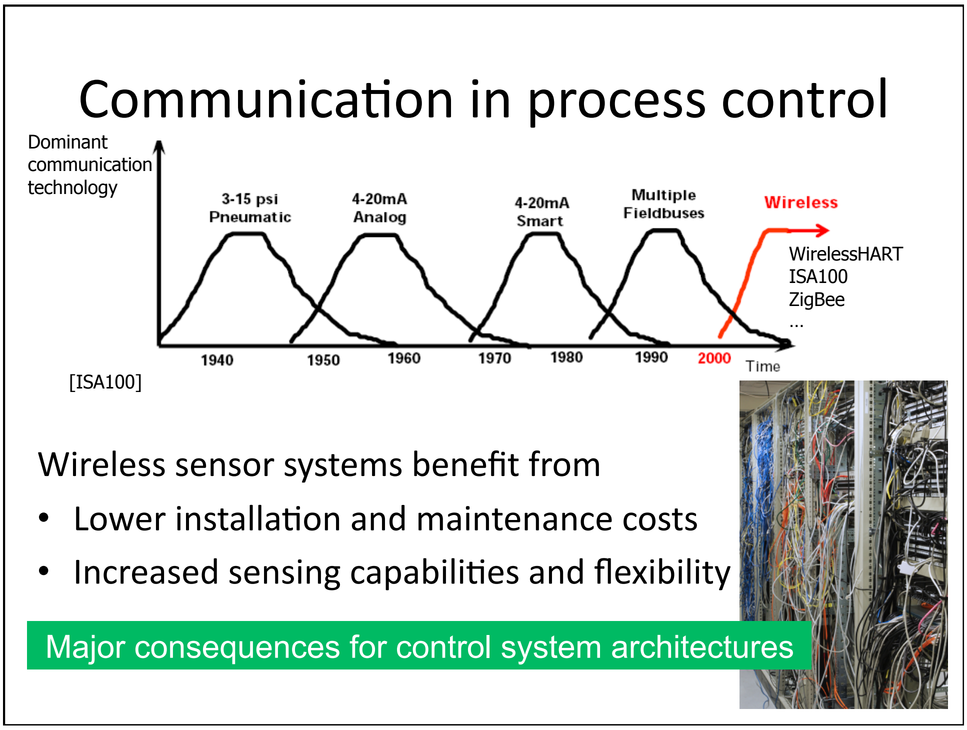
- Cyber-physical systems
- Critical infrastructures
- Humans-in-the-loop

Action Web



The smart energy grid





Communication in process control

[ISA100]

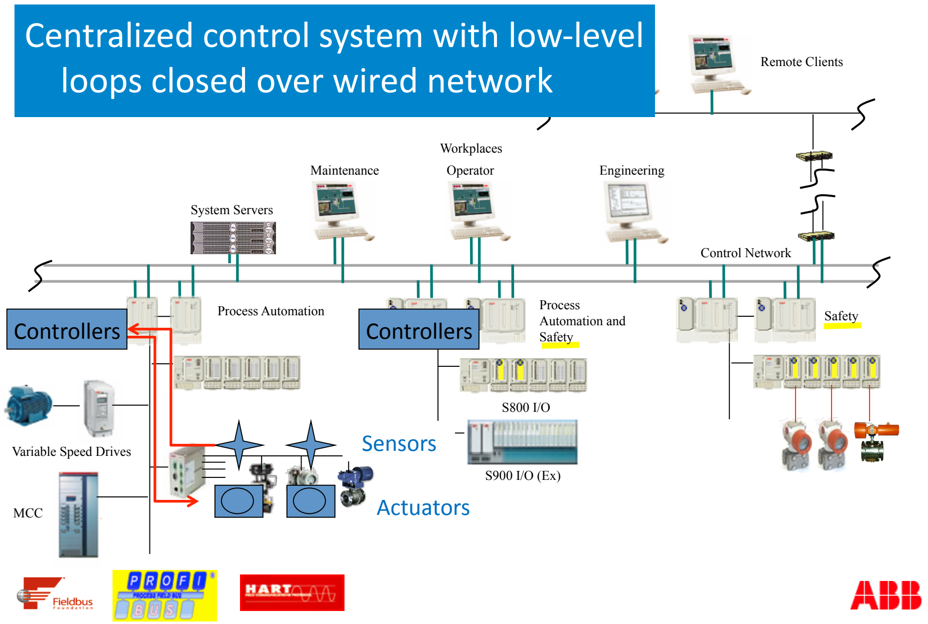
Wireless sensor systems benefit from

- Lower installation and maintenance costs
- Increased sensing capabilities and flexibility

Major consequences for control system architectures

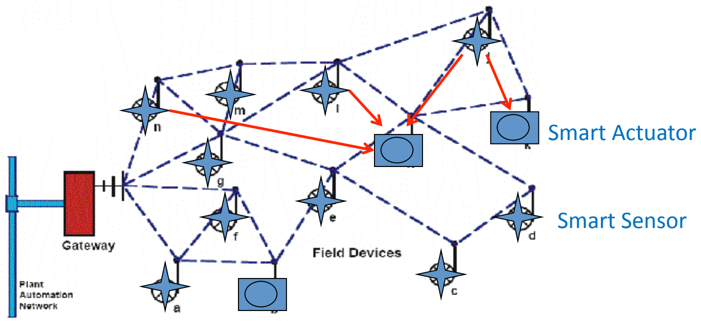
Today's industrial communication architecture

Centralized control system with low-level loops closed over wired network



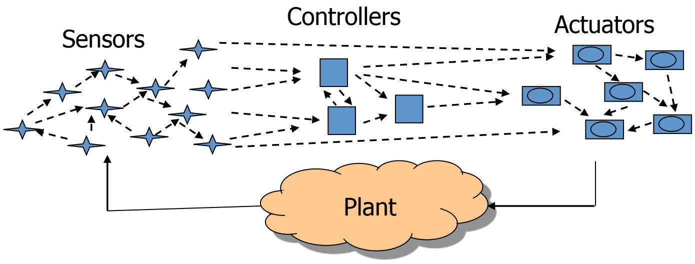
Wireless sensor and actuator network architecture

- Local control loops closed over **wireless multi-hop network**
- Potential for a dramatic change:
  - From fixed hierarchical centralized system to flexible distributed
  - Move intelligence from dedicated computers to sensors/actuators



Wireless control system

How to share common network resources while maintaining guaranteed control performance?

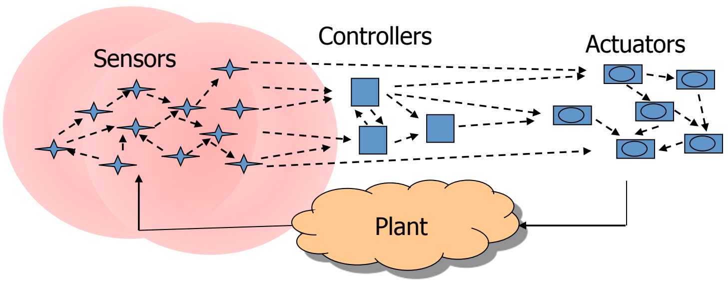


Outline

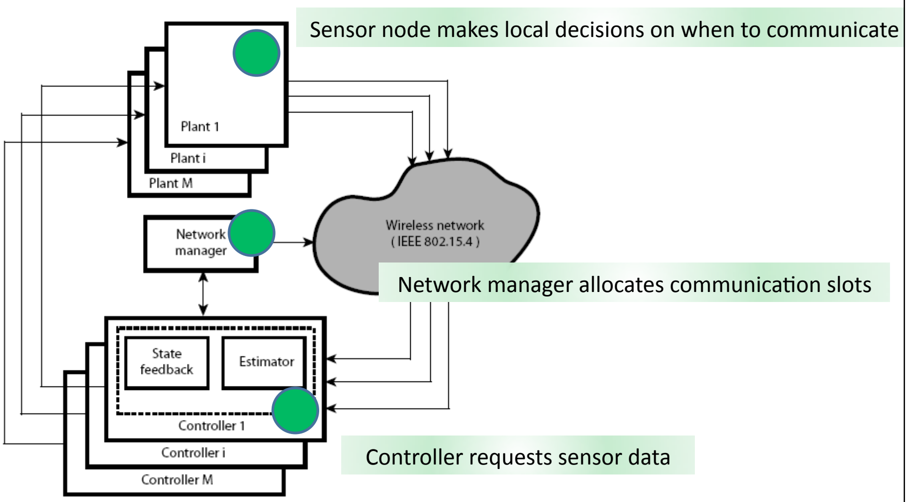
- Motivation
- Wireless control system
- Medium access for networked control
- Hybrid control for hybrid medium access
- Communication-aware motion planning
- Conclusions

Medium access control

Data are lost if a radio channel is accessed by more than one node within interference range



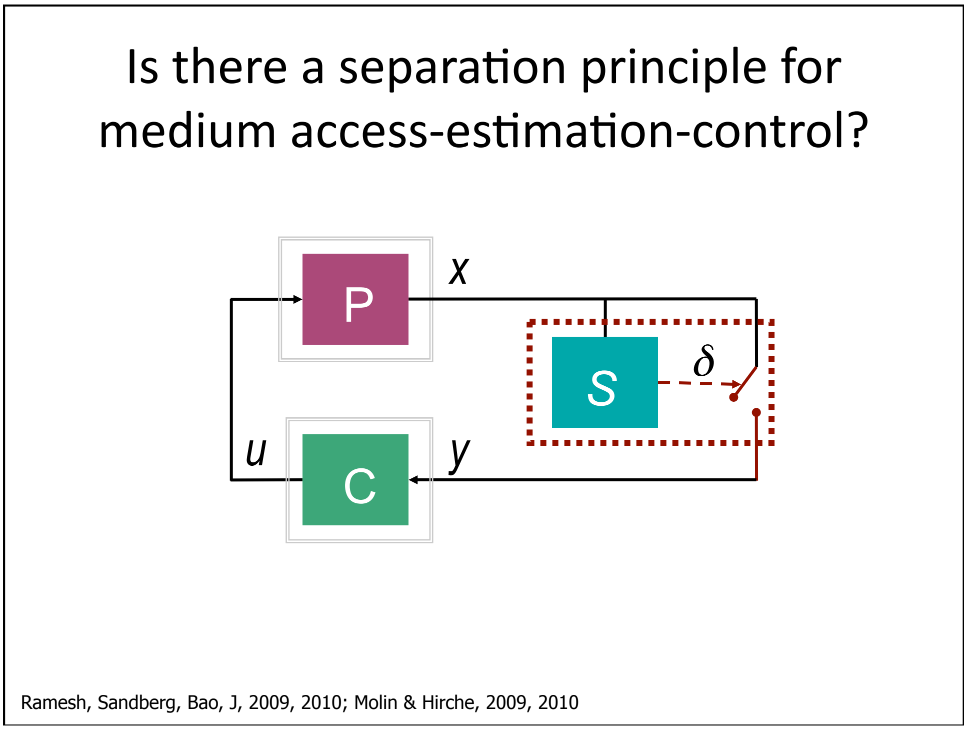
Where to take medium access decisions?



Sensor node makes local decisions on when to communicate

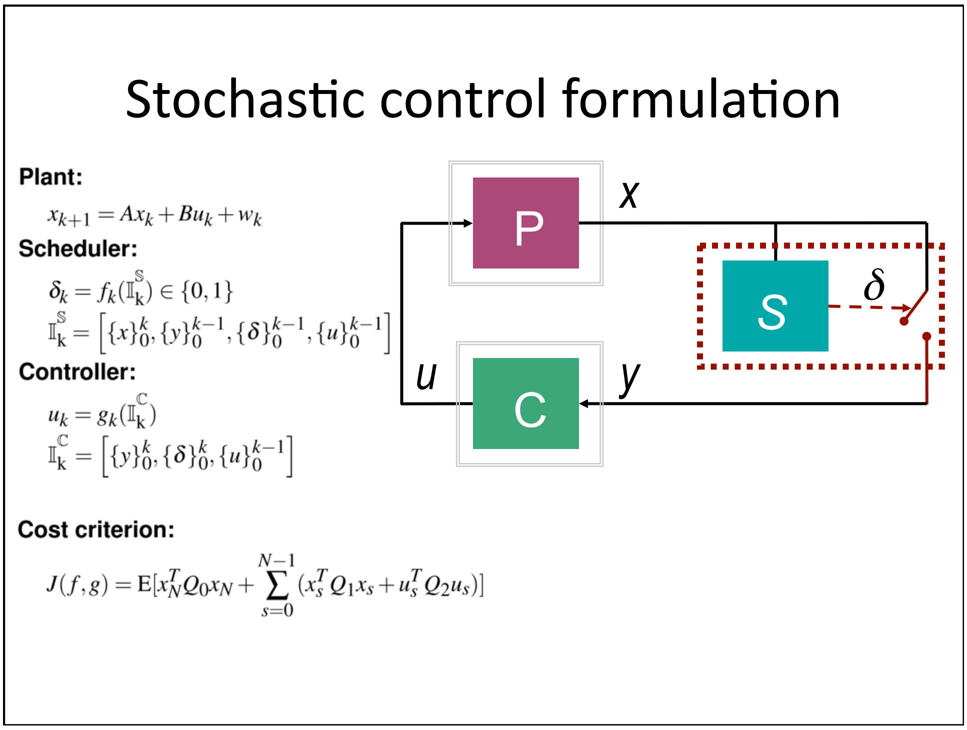
Network manager allocates communication slots

Controller requests sensor data



Is there a separation principle for medium access-estimation-control?

Ramesh, Sandberg, Bao, J, 2009, 2010; Molin & Hirche, 2009, 2010



Stochastic control formulation

Plant:

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

Scheduler:

$$\delta_k = f_k(\mathbb{I}_{\mathrm{k}}^{\mathbb{S}}) \in \{0,1\}$$

$$\mathbb{I}_{\mathrm{k}}^{\mathbb{S}} = \left[\{x\}_0^k, \{y\}_0^{k-1}, \{\delta\}_0^{k-1}, \{u\}_0^{k-1}\right]$$

Controller:

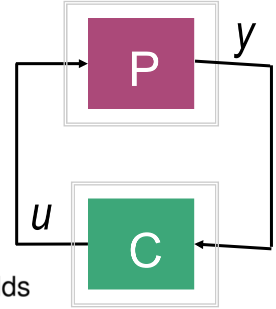
$$u_k = g_k(\mathbb{I}_{\mathrm{k}}^{\mathbb{C}})$$

$$\mathbb{I}_{\mathrm{k}}^{\mathbb{C}} = \left[\{y\}_0^k, \{\delta\}_0^k, \{u\}_0^{k-1}\right]$$

Cost criterion:

$$J(f,g) = \mathrm{E}[x_N^T Q_0 x_N + \sum_{s=0}^{N-1} (x_s^T Q_1 x_s + u_s^T Q_2 u_s)]$$

Certainty equivalence revisited



Definition Certainty equivalence holds if the closed-loop optimal controller has the same form as the deterministic optimal controller with x_k replaced by the estimate $\hat{x}_{k|k} = \mathrm{E}[x_k|\mathbb{I}_{\mathrm{k}}^{\mathbb{C}}]$.

Theorem [Bar-Shalom–Tse] Certainty equivalence holds if and only if $\mathrm{E}[(x_k - \mathrm{E}[x_k|\mathbb{I}_{\mathrm{k}}^{\mathbb{C}}])^2|\mathbb{I}_{\mathrm{k}}^{\mathbb{C}}]$ is independent of past controls $\{u\}_0^{k-1}$ (no dual effect).

Feldbaum, 1965; Åström, 1970; Bar-Shalom and Tse, 1974

State-based scheduler

Plant:

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

Scheduler:

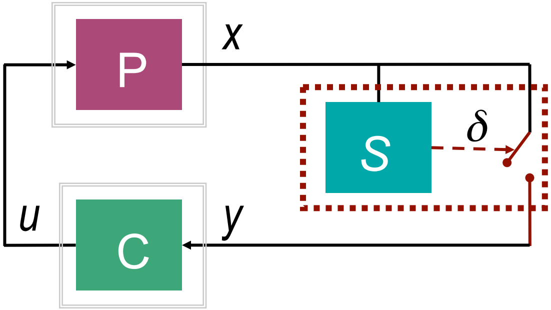
$$\delta_k = f_k(\mathbb{I}_{\mathrm{k}}^{\mathbb{S}}) \in \{0,1\}$$

$$\mathbb{I}_{\mathrm{k}}^{\mathbb{S}} = \left[\{x\}_0^k, \{y\}_0^{k-1}, \{\delta\}_0^{k-1}, \{u\}_0^{k-1}\right]$$

Controller:

$$u_k = g_k(\mathbb{I}_{\mathrm{k}}^{\mathbb{C}})$$

$$\mathbb{I}_{\mathrm{k}}^{\mathbb{C}} = \left[\{y\}_0^k, \{\delta\}_0^k, \{u\}_0^{k-1}\right]$$



Corollary The control u_k for the optimal closed-loop system has a dual effect.

The separation principle does not hold for the optimal closed-loop system, so the scheduler, estimator, and controller cannot be designed separately

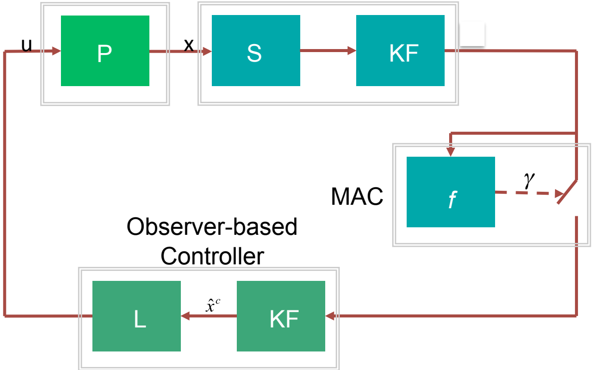
Ramesh, Sandberg, Bao, J, 2009, 2010

Symmetric scheduler

Proposition If the scheduler $f = f(\sum_{s=1}^{k-\tau_k} A^{s-1} w_{k-s})$ is a symmetric map:

- The CE controller is optimal
- The observer has low complexity

Supports threshold-based (Lebesque) sampling in scheduler (MAC)



Ramesh, Sandberg, Bao, J, 2009, 2010

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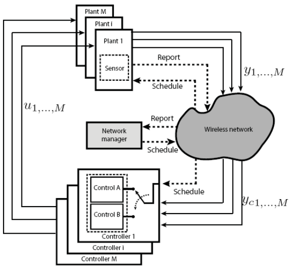
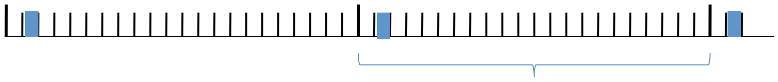
Hybrid MAC protocol



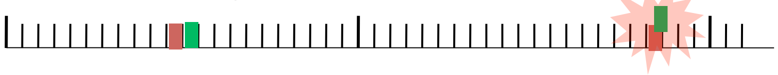
MAC protocol standards have both
contention-free and contention access periods

Contention-free period for TDMA scheduled communication



Periodic superframe of N slots

Contention access period for random CSMA communication



Cf., real-time embedded systems literature: Kopetz' time-triggered architecture; Benveniste's LTTA; Sifakis etc

TDMA = Time division multiple access, CSMA/CA = Carrier Sense Multiple Access with Collision Avoidance

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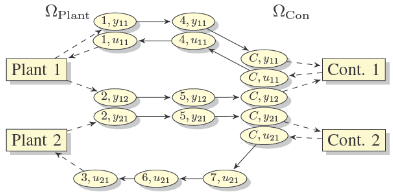
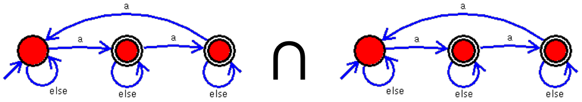
TDMA communication and control



- Leads to hybrid closed-loop system

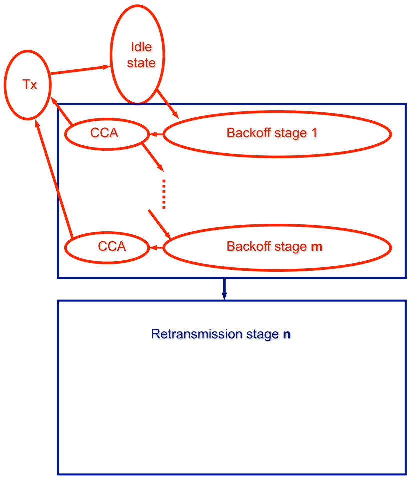
$$x(t+1) = \hat{A}(s(t))x(t), \qquad \hat{A}(e,m) := \begin{pmatrix} A_i & B_i \cdot O_{\text{Plant}} & 0 \\ I^T_{\text{Plant}} \cdot C_i & \text{Adj}(\langle V_{\mathfrak{R}}, e\rangle)^{\text{T}} & O^T_{\text{Con}} \cdot \tilde{C}_i(m) \\ 0 & \tilde{B}_i(m) \cdot I_{\text{Con}} & \tilde{A}_i(m) \end{pmatrix}$$

- Schedules for each loop can represented as automata
- Feasible overall schedules computed as intersections of automata



Alur, D'Innocenzo, J, Pappas, Weiss, 2009

CSMA/CA mechanism of a node in an IEEE 802.15.4 wireless network

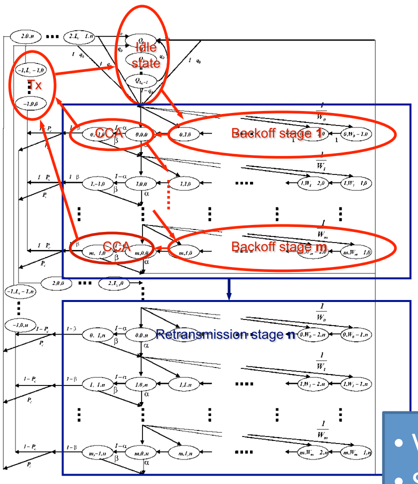


- A transmitting node delays for a random number of backoff periods in [0 , 2^{m_0} - 1], where m_0 is the initial backoff exponent.
- If two consecutive clear channel assessments (CCA) are idle, the node starts the transmission and waits for an ACK
- If the channel is busy, the procedure is repeated increasing the backoff windows until a maximum backoff exponent m_b.
- After a maximum number of backoffs m the packet is discarded.
- In case of collision the procedure is restarted and repeated until a retry limit n

Park, Di Marco, Soldati, Fischione, J, 2009

Cf., 802.11 model by Bianchi, 2000; Pollin et al, 2008; etc

Markov chain model of CSMA/CA

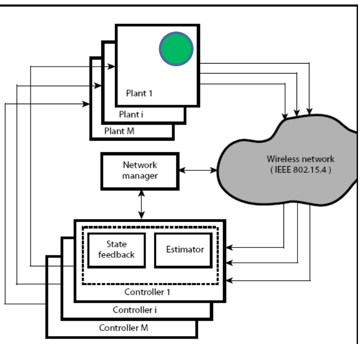


- Markov state (s,c,r)
  - s: backoff stage
  - c: state of backoff counter
  - r: state of retransmission counter
- Model parameters
  - q_0: traffic condition (q_0=0 saturated)
  - m_0, m, m_b, n: MAC parameters
- Computed characteristics
  - α: busy channel probability during CCA1
  - β: busy channel probability during CCA2
  - P_c: collision probability

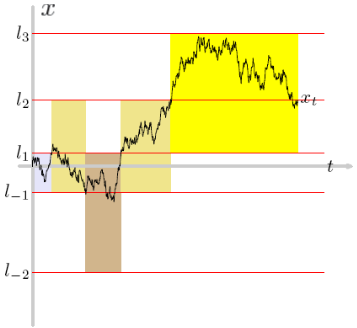
- Validated in simulation and experiment
- Simplified model used for design

Park, Di Marco, Soldati, Fischione, J, 2009

CSMA/CA communication and control



- Make communication decisions based on state level crossings
- Leads to event-based control with packet drops



Åström & Bernhardsson, 1999; Rabi, J, Johansson, 2008; Cervin & Henningsson, 2008; etc

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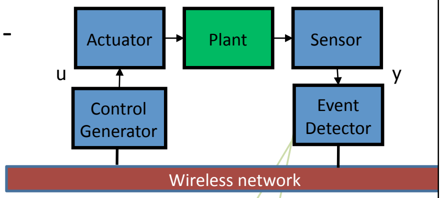
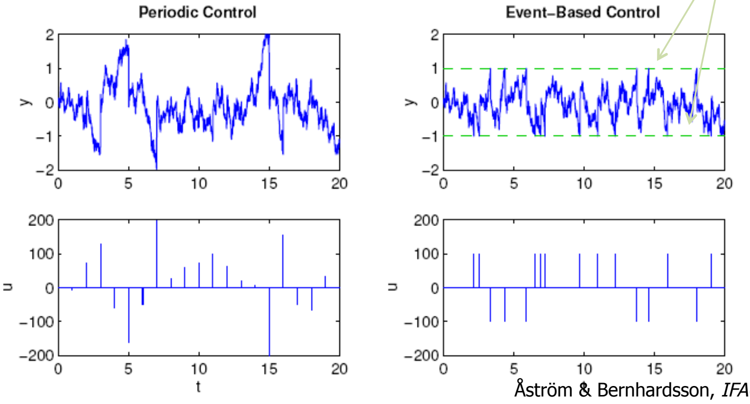
Fixed threshold with impulse control

- Event-detector implemented as fixed-level threshold at sensor
- Event-based impulse control better than periodic impulse control


Actuator
Plant
Sensor
u
y
Control Generator
Event Detector
Wireless network

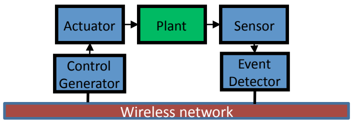


Åström & Bernhardsson, *IFAC*, 1999

System model and performance measure

Plant $$dx_t = dW_t + u_t dt,\ x(0) = x_0,$$

Sampling events $$\mathcal{T} = \{\tau_0, \tau_1, \tau_2, \ldots\},$$

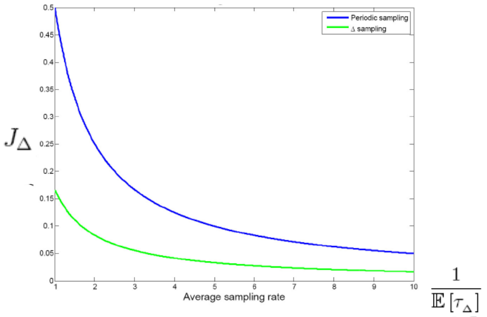


Impulse control $$u_t = \sum_{n=0}^{\infty} x_{\tau_n} \delta(\tau_n)$$

Average sampling rate $$R_\tau = \limsup_{M\to\infty} \frac{1}{M} \mathbb{E}\left[\int_0^M \sum_{n=0}^{\infty} \mathbf{1}_{\{\tau_n \le M\}} \delta(s-\tau_n)\, ds\right]$$

Average cost $$J = \limsup_{M\to\infty} \frac{1}{M} \mathbb{E}\left[\int_0^M x_s^2 ds\right]$$

Comparison between time- and event-based control



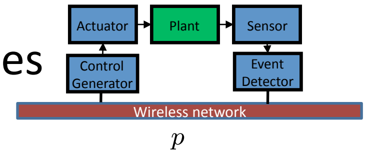
$T = \Delta^2$ gives equal average sampling rate for periodic control and event-based control

Event-based impulse control is three times better than periodic

Åström & Bernhardsson, 1999

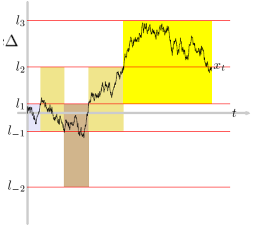
What about the influence of communication losses?
Is event-based sampling still better?

Event-based control with losses



Theorem

If packet losses are independent and identically distributed with probability p,
then level-triggered sampling gives



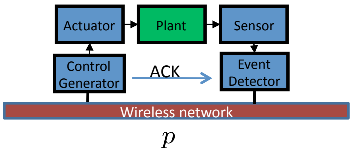
$$J_p = \frac{\Delta^2 (5p+1)}{6(1-p)}$$

Event-based control better than periodic control if loss probability

$$p < 0.25$$

Rabi and J, *2009*

Communication acknowledgements



If controller perfectly acknowledges packets to sensor, event detector can adjust its sampling strategy

Let $\Delta(l) = \sqrt{l+1}\Delta_0$

where $l \geq 0$ number of samples lost since last successfully transmitted packet

Gives that $\mathbb{E}\left[\tau_{i+1}^{\dagger} - \tau_i^{\dagger}\right]$ becomes independent of i.

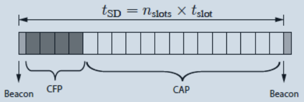
Better performance than fixed $\Delta(l)$ for same sampling rate:

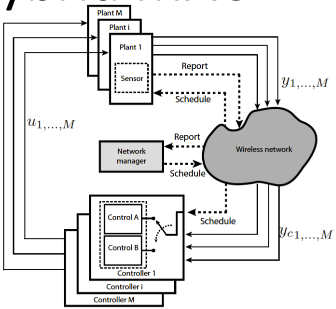
$$J_p^{\dagger} = \frac{\Delta^2 (1+p)}{6(1-p)} \leq \frac{\Delta^2 (1+5p)}{6(1-p)} = J_p.$$

Rabi and J, *2009*

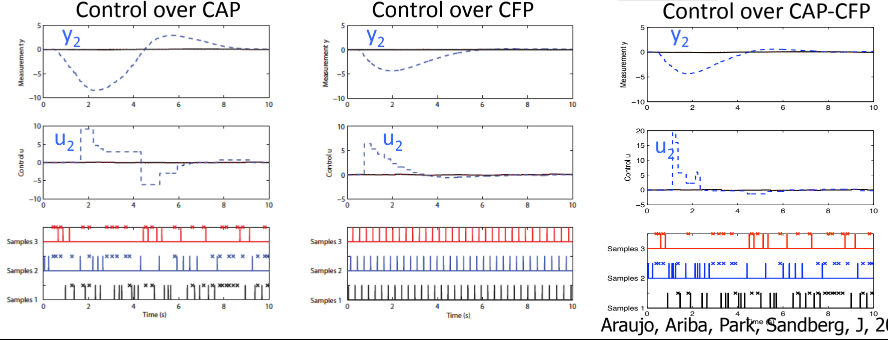
Hybrid control for hybrid MAC

Utilize that hybrid MAC has both contention-free period (CFP) and contention access period (CAP):





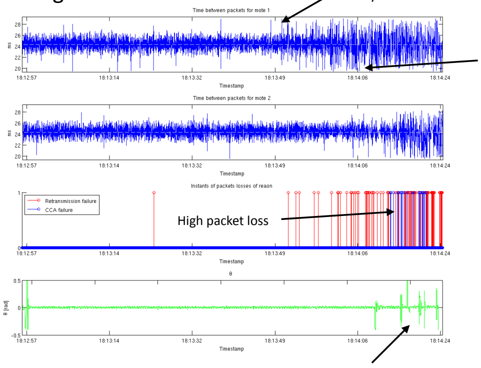
Example Disturbance rejection in plant 2



Araujo, Ariba, Park, Sandberg, J, 2009

Wireless control of inverted pendulum

Angle Sensor

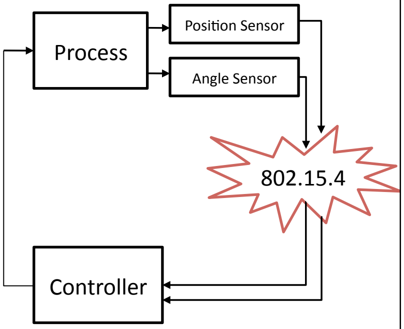


Interference node starts transmitting every 100 ms

Interference node starts transmitting every 10 ms

High packet loss

Pendulum suffers large oscillations


Process
Position Sensor
Angle Sensor
802.15.4
Controller

MOVIE

- Sensor sampling period 25 ms
- Protocol with retransmissions leads to large delays during interference

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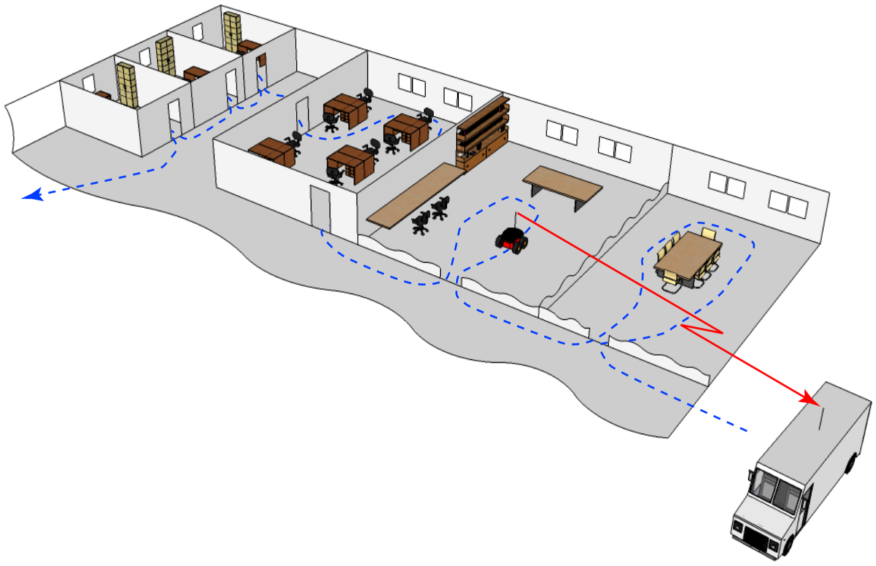
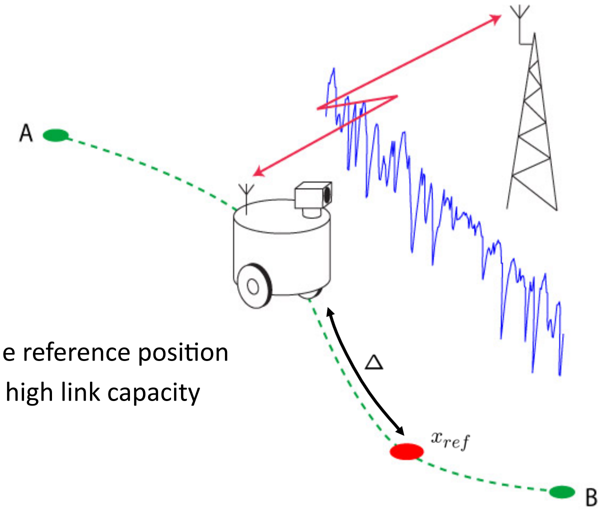
Indoor surveillance scenario



Katsilieris, Lindhe, Dimarogonas, Ögren, J, ICRA 2010

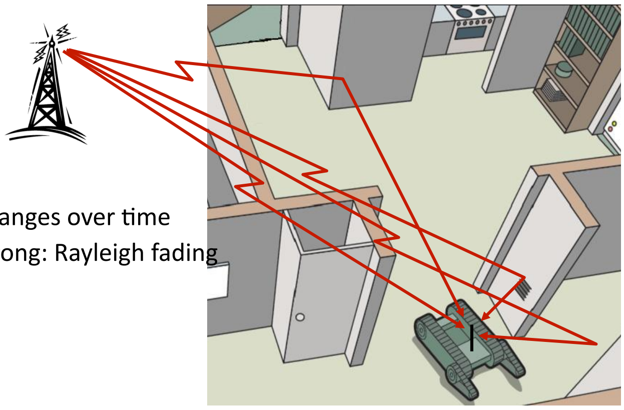
Exploiting Multipath Fading



- Follow the reference position
- Maintain high link capacity

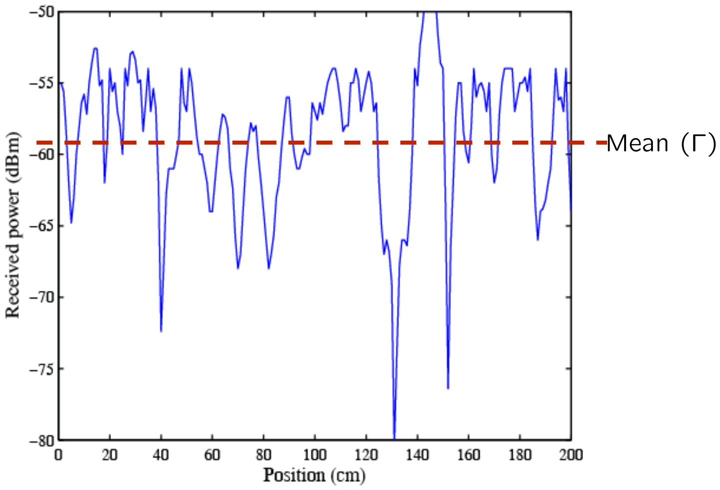
Lindhe & J, IEEE Wireless Comm. 2009, ICRA 2010

Multipath Fading



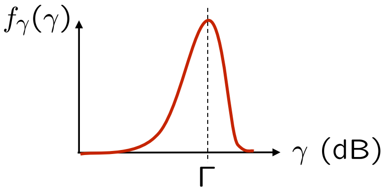
- Static fading: Nothing changes over time
- All reflections equally strong: Rayleigh fading

Multipath Fading



Rayleigh Fading

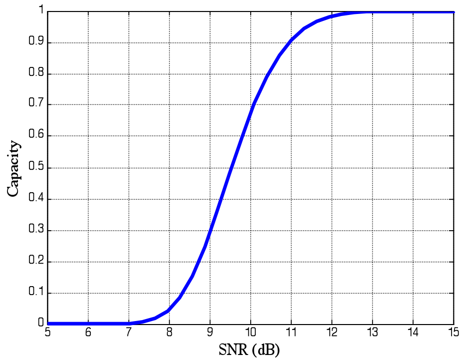
The SNR (γ) is exponentially distributed:



$$f_\gamma(\gamma) = \frac{1}{\Gamma} e^{-\gamma/\Gamma}$$

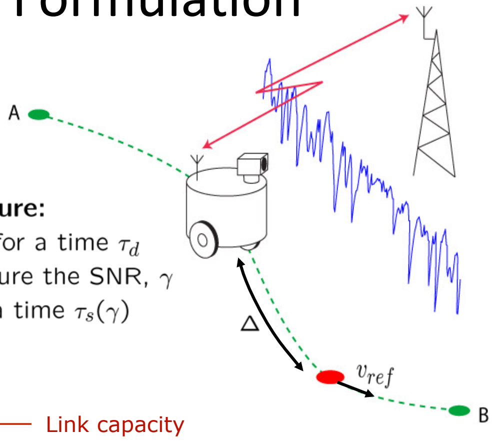
Samples more than $\lambda/2$ apart are independent.

Link Capacity Depends on SNR



Capacity = packet reception rate:
$c(\gamma) = [1 - Q(\gamma)]^{8B}$ (B bits/packet)

Problem Formulation



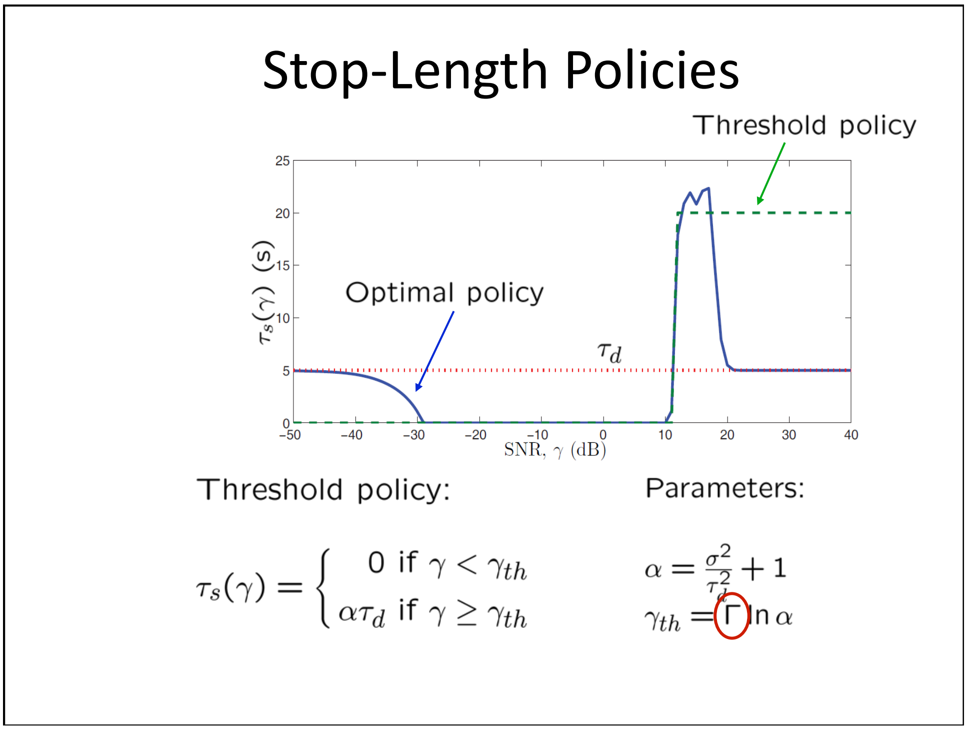
Stop&go procedure:

1. Drive at $2v_{ref}$ for a time τ_d
2. Stop and measure the SNR, γ
3. Stand still for a time $\tau_s(\gamma)$

Problem:

$\max_{\tau_s(\gamma)} \mathrm{E}\{c\}$ ← Link capacity

s.t. $\mathrm{E}\{\tau_s\} = \tau_d$
$\mathrm{Var}\{\tau_s\} \leq \sigma^2$ } Reference tracking



Stop-Length Policies

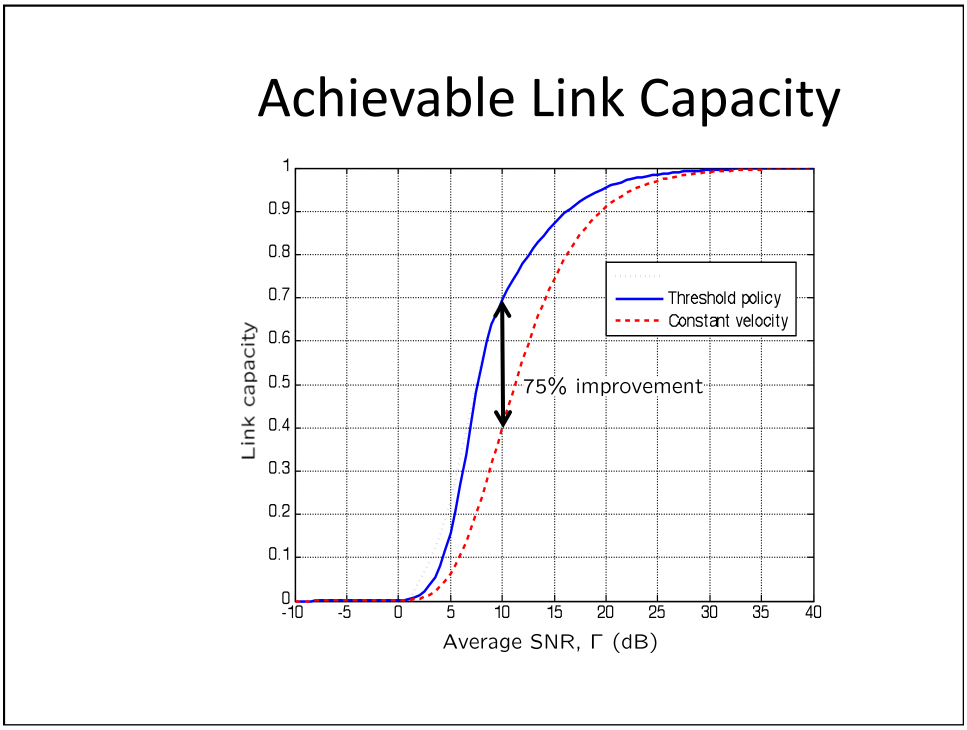
Threshold policy:

$$\tau_s(\gamma) = \begin{cases} 0 \text{ if } \gamma < \gamma_{th} \\ \alpha\tau_d \text{ if } \gamma \geq \gamma_{th} \end{cases}$$

Parameters:

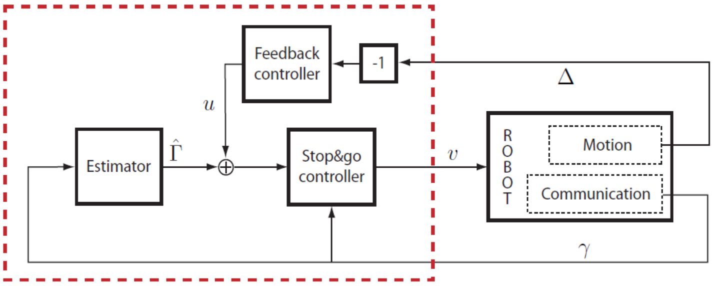
$$\alpha = \frac{\sigma^2}{\tau_d^2} + 1$$

$$\gamma_{th} = \Gamma \ln \alpha$$



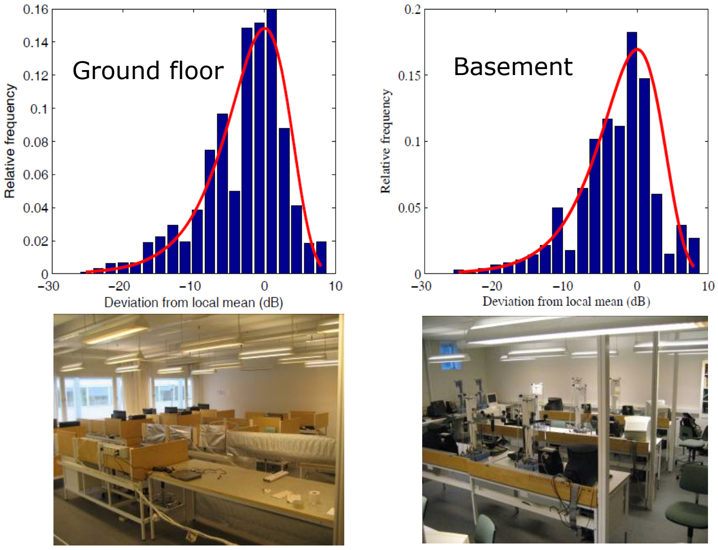
Achievable Link Capacity

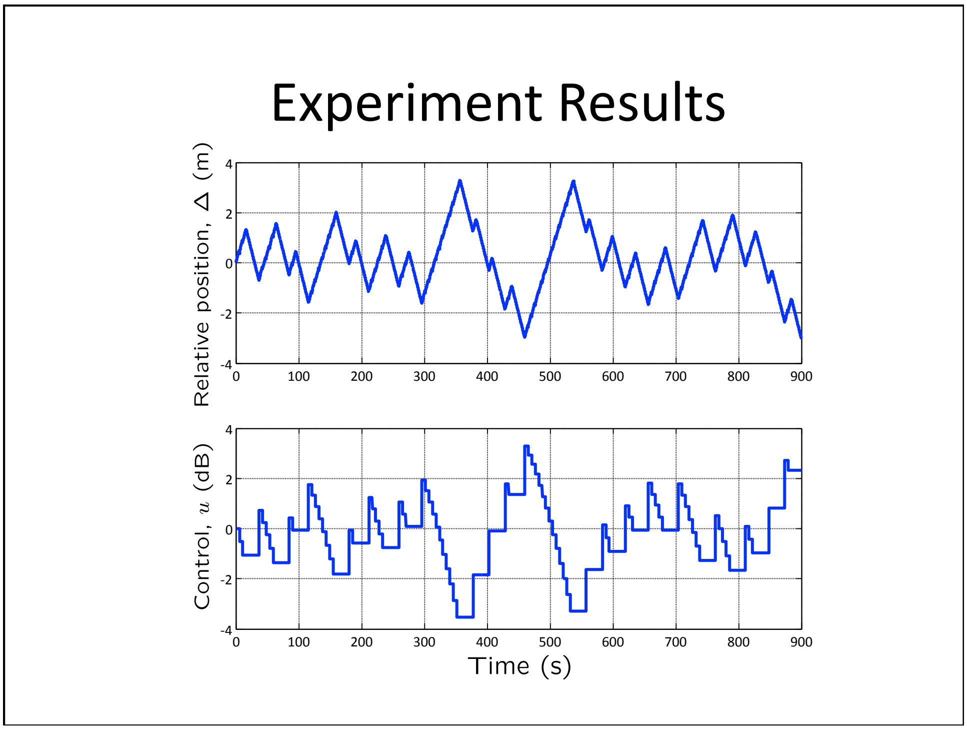
Control Architecture



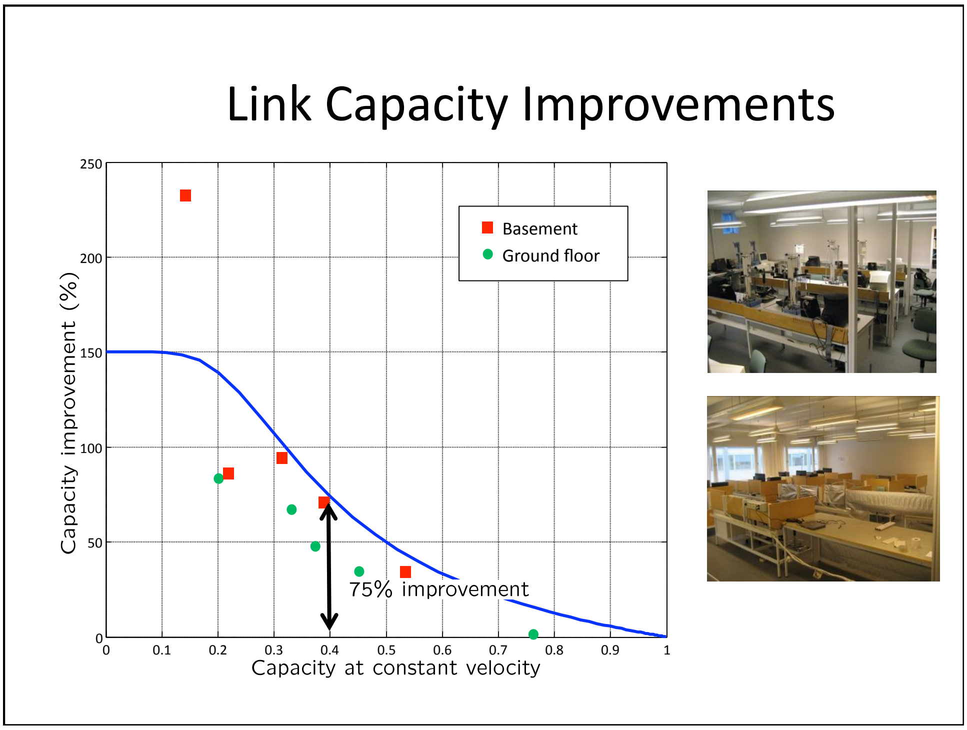
- Stop&go controller uses $\tau_s(\gamma)$
- Estimator for average SNR, Γ
- Feedback controller for reference tracking

Model Validation



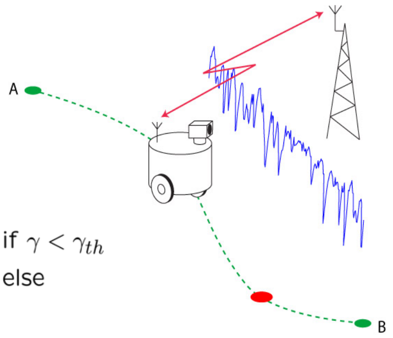


Experiment Results



Link Capacity Improvements

Communication-aware motion planning



Assumptions:
- Static environment
- Rayleigh fading

Stop&go procedure:
1. Drive for a time τ_d
2. Stop, measure the SNR, γ
3. Stand still for a time $\tau_s(\gamma) = \begin{cases} 0 \text{ if } \gamma < \gamma_{th} \\ \alpha\tau_d \text{ else} \end{cases}$

Architecture:
- Estimator for channel estimation
- Feedback controller for tracking and robustness

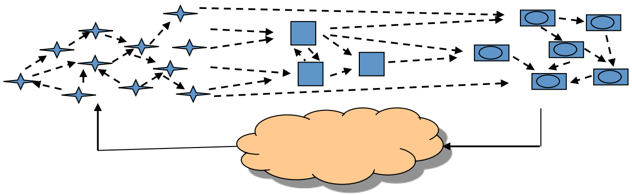
Result:
- Link capacity improvements up to 100%
- Stable tracking error

Outline

- Motivation
- Wireless control system
- Medium access for networked control
- Hybrid control for hybrid medium access
- Communication-aware motion planning
- Conclusions

Conclusions

- Wireless control is an enabling technology in many emerging application domains
- Fundamental challenges related to
  - event-driven, asynchronous, ad hoc wireless networking, vs
  - time-driven, synchronous, sampled data control
- New control paradigms and system architectures
  - E.g., communication-aware motion planning



http://www.ee.kth.se/~kallej