# Closing the Loop over Wireless Networks: Fundamentals and Applications

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**Mikael Johansson, Pan Gun Park, Emmanuel Witrant**

WiOpt 2008, Berlin, 1-3 Apr

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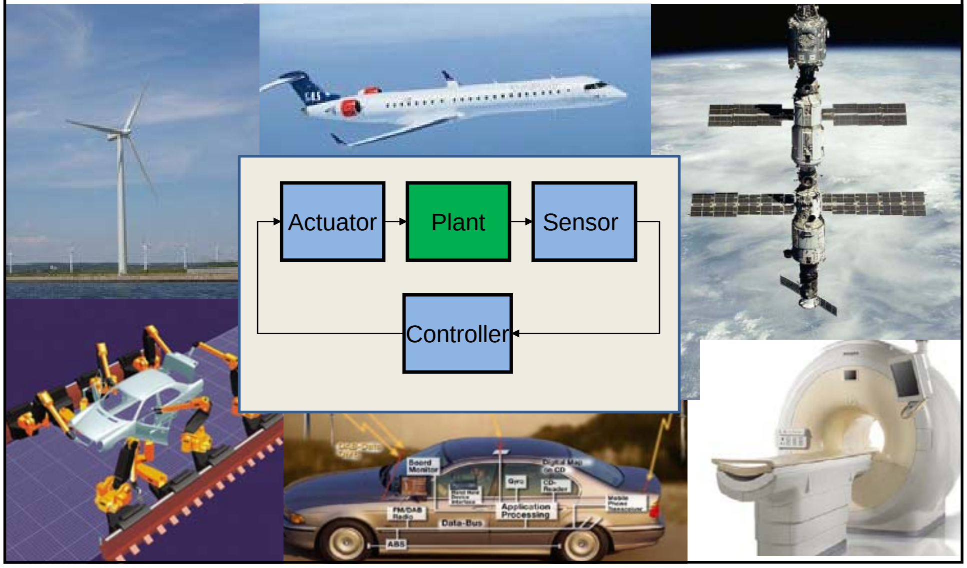
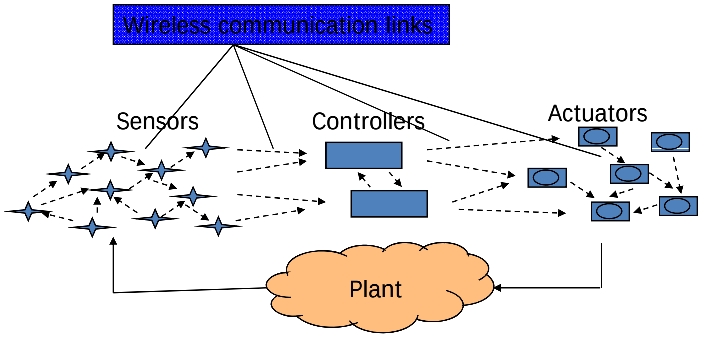
# Feedback control systems everywhere



# Control over wireless networks

How to control a plant when sensor, actuator and controller nodes are wireless network devices?

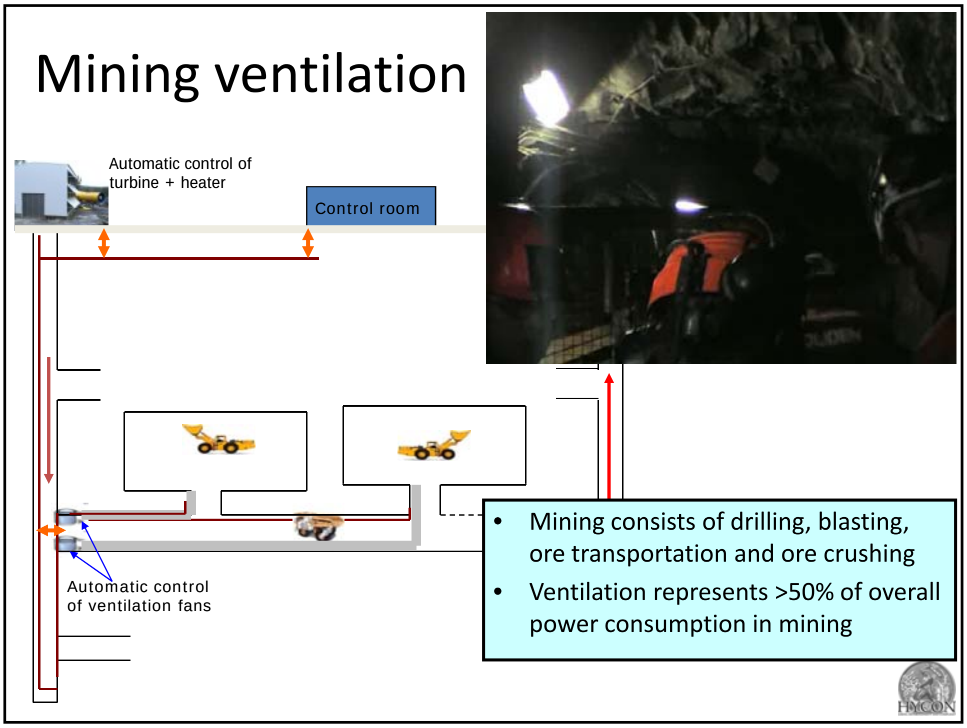


# Outline

- Emerging applications
- Control over wireless networks
  - A communication or a control problem?
  - Time- or event-driven communication?
- Event-driven control
- Predictive outage compensation
- Conclusions

# Emerging applications

- Wireless **mining** ventilation control BOLIDEN ABB
- Wireless control of flotation process BOLIDEN ABB
- **Vehicle** fuel efficiency with networked sensing SCANIA
- **Disaster relief** support using mobile sensors ERICSSON
- **Surveillance** with networked autonomous vehicles FOI SAAB



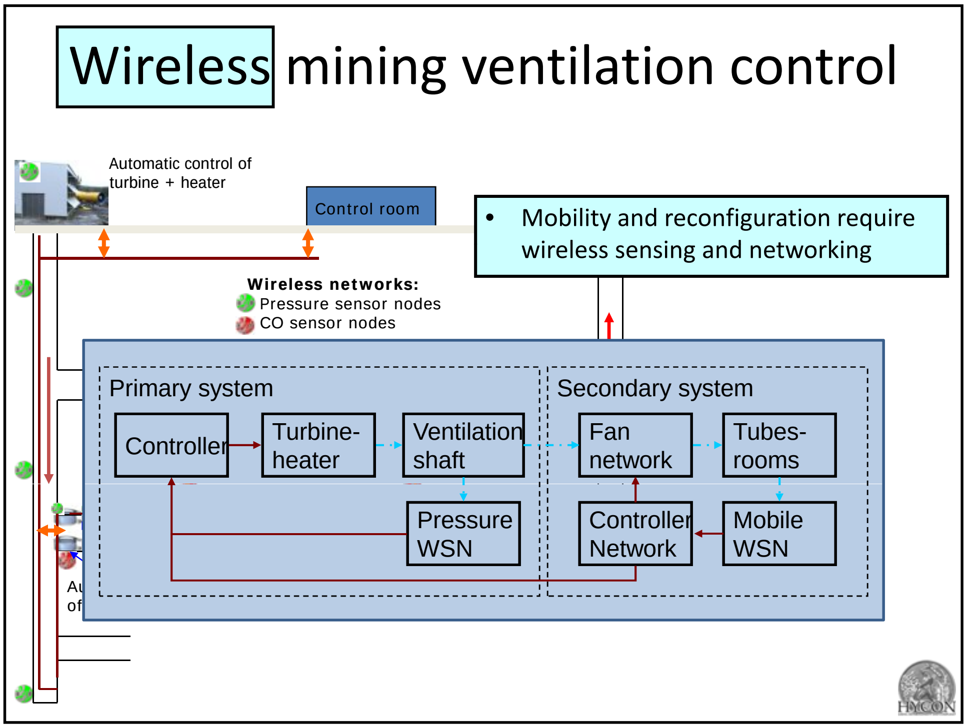
# Mining ventilation

Automatic control of turbine + heater

Control room

Automatic control of ventilation fans

- Mining consists of drilling, blasting, ore transportation and ore crushing
- Ventilation represents >50% of overall power consumption in mining



# Wireless mining ventilation control

Automatic control of turbine + heater

Control room

- Mobility and reconfiguration require wireless sensing and networking

**Wireless networks:**
🟢 Pressure sensor nodes
🔴 CO sensor nodes

Primary system

Controller

Turbine-heater

Ventilation shaft

Pressure WSN

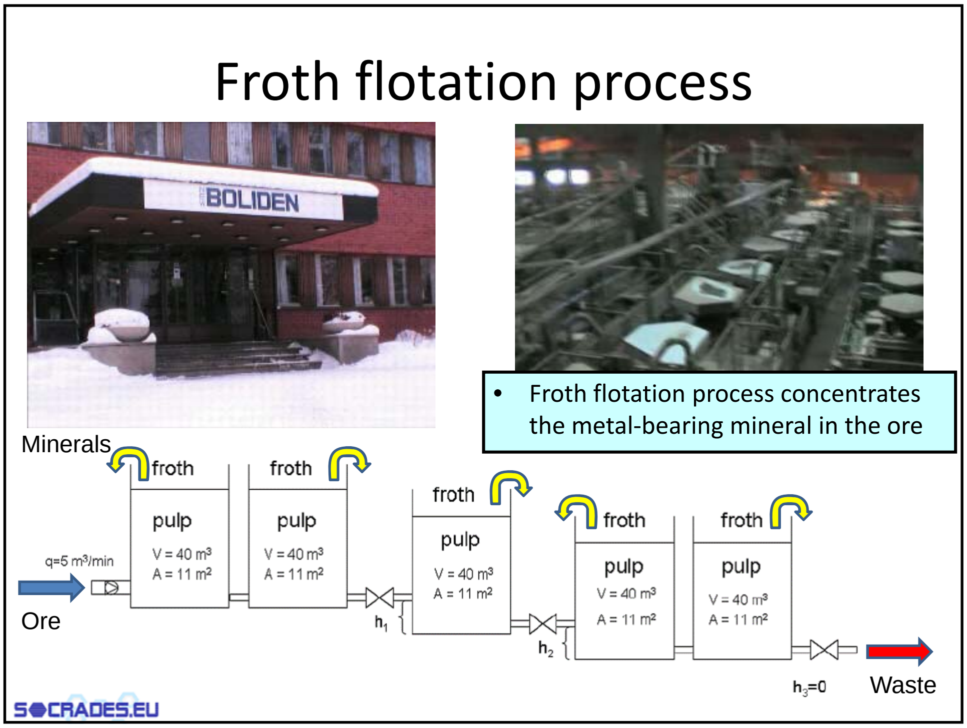
Secondary system

Fan network

Tubes-rooms

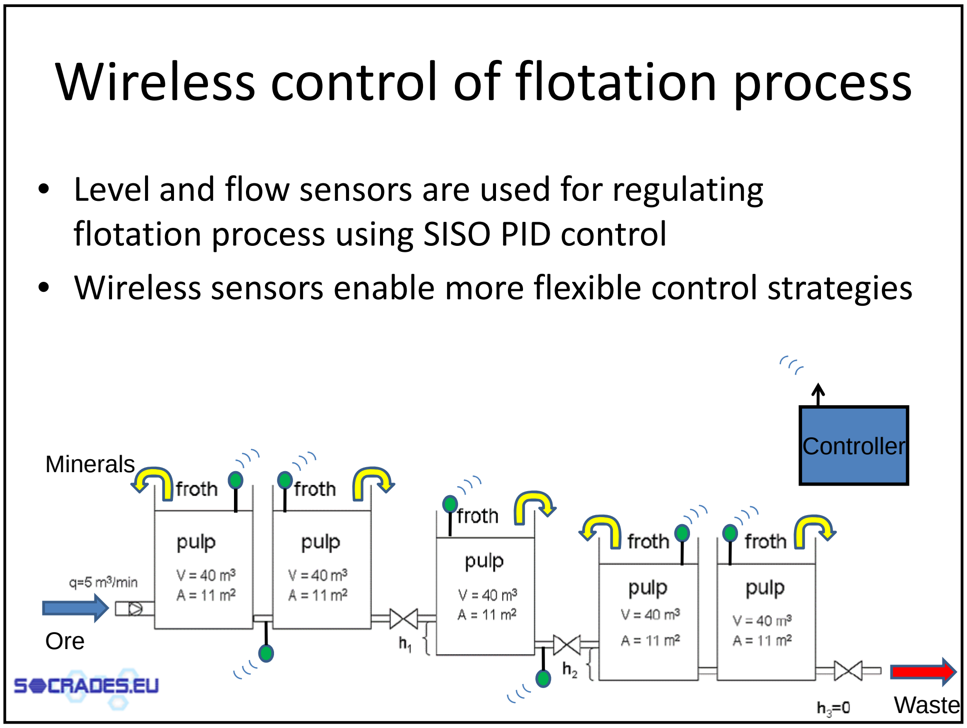
Controller Network

Mobile WSN



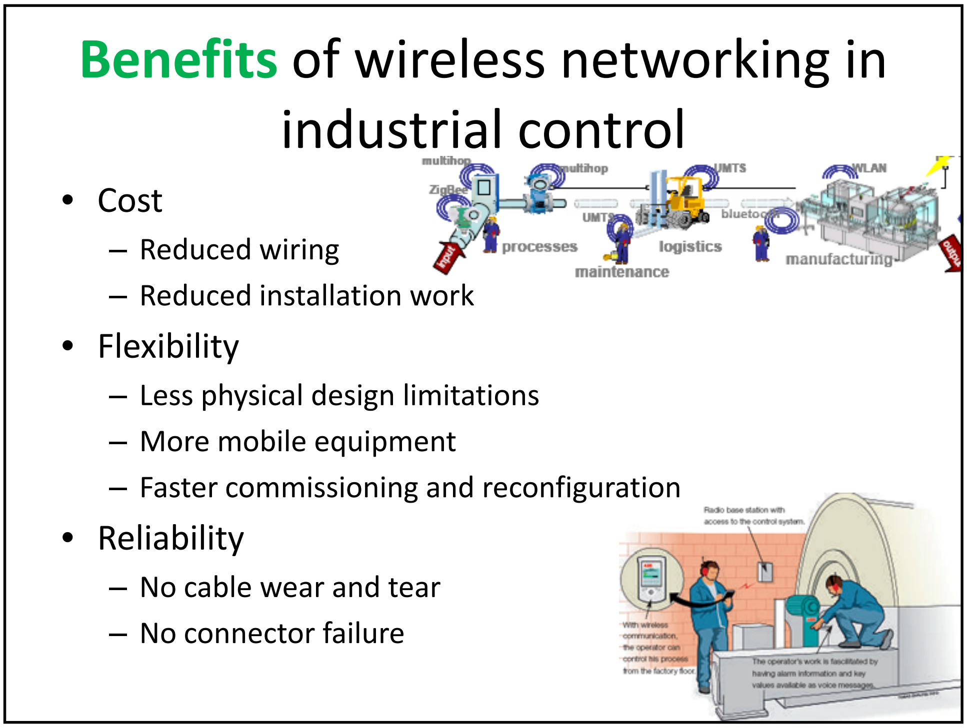
## Froth flotation process

- Froth flotation process concentrates the metal-bearing mineral in the ore



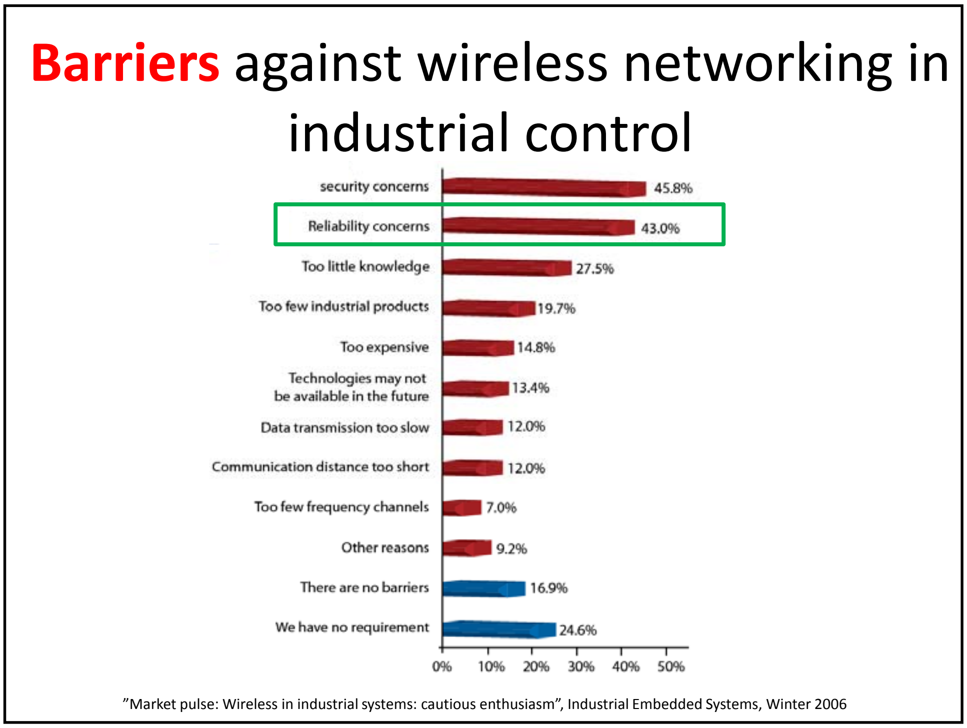
## Wireless control of flotation process

- Level and flow sensors are used for regulating flotation process using SISO PID control
- Wireless sensors enable more flexible control strategies



# Benefits of wireless networking in industrial control

- Cost
  - Reduced wiring
  - Reduced installation work
- Flexibility
  - Less physical design limitations
  - More mobile equipment
  - Faster commissioning and reconfiguration
- Reliability
  - No cable wear and tear
  - No connector failure



# Barriers against wireless networking in industrial control

”Market pulse: Wireless in industrial systems: cautious enthusiasm”, Industrial Embedded Systems, Winter 2006

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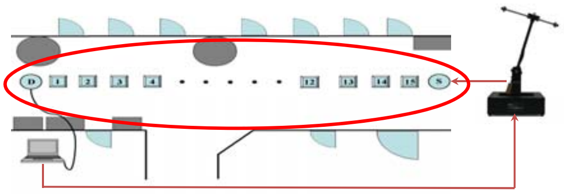
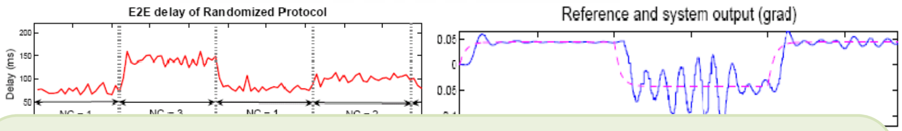
# Influence of wireless networking on feedback control performance





There is a conflict between traditional
- time-driven, synchronous, sampled data **control theory**

and
- event-driven, asynchronous, ad hoc **networking**

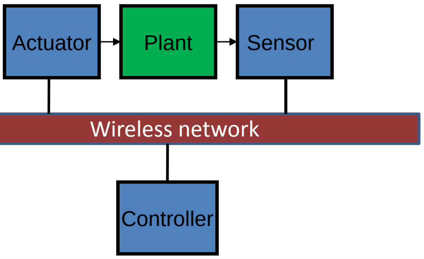
Witrant et al., *IEEE CCA,* 2007

# A communication or a control problem?

**Approaches to control over wireless networks**

1. Communication protocol suitable for control
2. Control application that compensates for communication imperfections
3. Cross-layer solution with integrated design of application and communication layers

Control Application
NET
MAC
PHY



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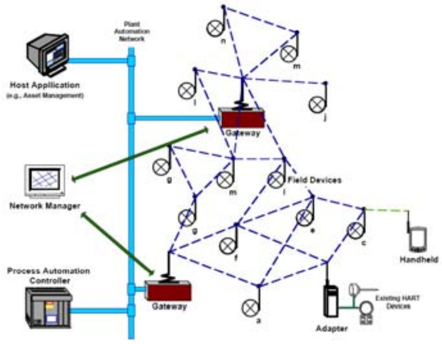
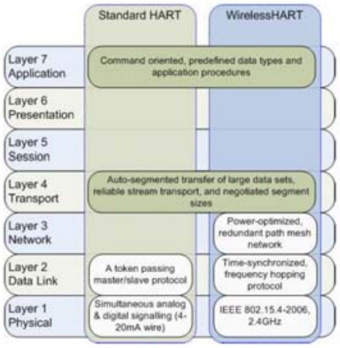
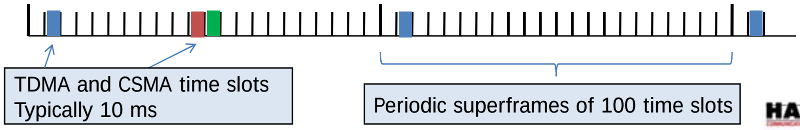
# WirelessHART

- New wireless networking protocol designed for control applications





<table>
<tr><th></th><th>Standard HART</th><th>WirelessHART</th></tr>
<tr><td>Layer 7 Application</td><td colspan="2">Command oriented, predefined data types and application procedures</td></tr>
<tr><td>Layer 6 Presentation</td><td></td><td></td></tr>
<tr><td>Layer 5 Session</td><td></td><td></td></tr>
<tr><td>Layer 4 Transport</td><td colspan="2">Auto-segmented transfer of large data sets, reliable stream transport, and negotiated segment sizes</td></tr>
<tr><td>Layer 3 Network</td><td></td><td>Power-optimized, redundant path mesh network</td></tr>
<tr><td>Layer 2 Data Link</td><td>A token passing master/slave protocol</td><td>Time-synchronized, frequency hopping protocol</td></tr>
<tr><td>Layer 1 Physical</td><td>Simultaneous analog & digital signalling (4-20mA wire)</td><td>IEEE 802.15.4-2006, 2.4GHz</td></tr>
</table>

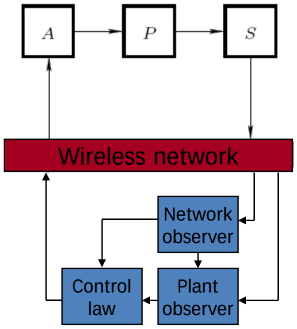


TDMA and CSMA time slots
Typically 10 ms

Periodic superframes of 100 time slots

# A network-aware control architecture

- Compensate communication imperfections in controller
  - Packet losses and bit errors
  - Outages
  - Delay and jitter
  - Bandwidth limitations



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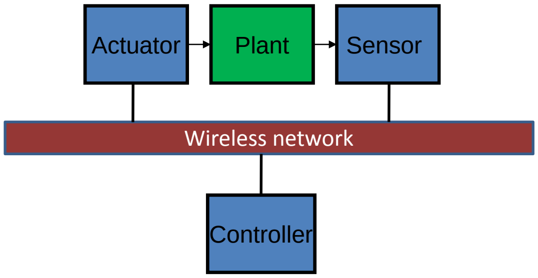
# Event-driven control

- Transmit information only when needed:
  - “If it ain’t broke, don’t fix it” [Åström]



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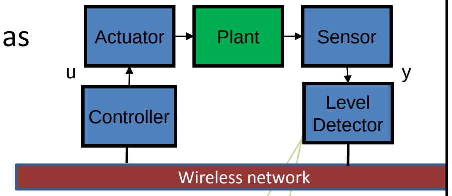
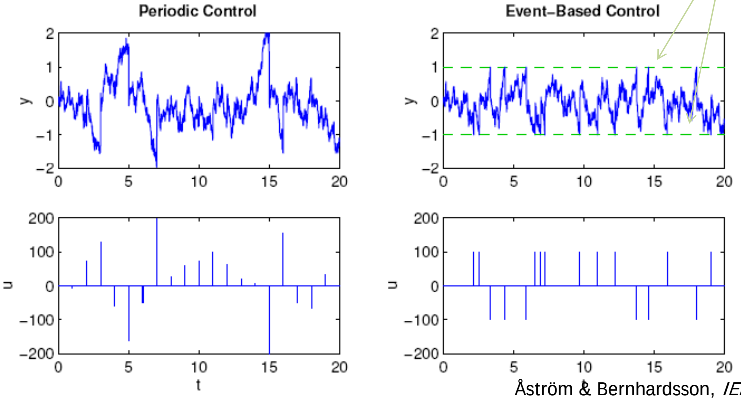
# Time- vs. event-driven control

- Event-driven control implemented as fixed-level detector at sensor
- Outperforms periodic control



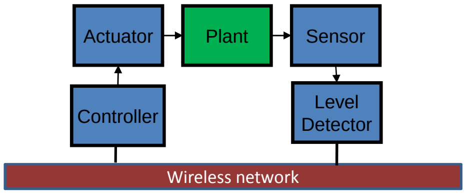

Periodic Control

Event-Based Control

Åström & Bernhardsson, *IEEE CDC*, 2002

## When to transmit?

- Simple medium access mechanism at sensor, e.g., level detector



Actuator

Plant

Sensor

Controller

Level Detector

Wireless network

## How to control?

- Apply control law from fixed control alphabet, e.g., piecewise constant controls

Rabi et al., *IEEE CDC, 2006* Johannesson et al., *HSCC, 2007* Cervin & Henningsson, *2008* Rabi et al., *2008*

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# Mathematical framework

$$dx_t = f(x_t, u_t)dt + g(x_t, u_t)dB_t$$

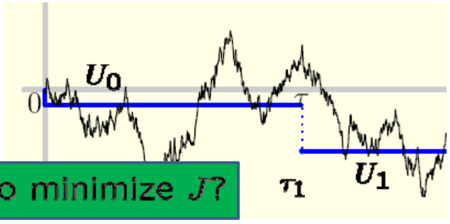
$x_t$ state

$u_t$ control

$B_t$ Brownian motion

Piecewise constant controls: $u_t = \sum_{i=0}^{N} U_i \cdot \mathbf{1}_{\tau_i \le t < \tau_{i+1}}$

Cost: $J = \mathbf{E} \int_0^T L(x_s, u_s) ds$

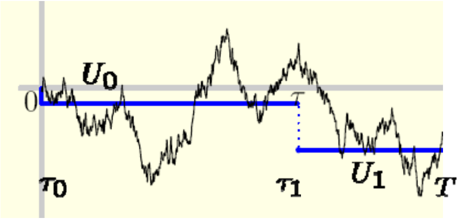


How choose $\{U_i\}$ and $\{\tau_i\}$ to minimize $J$?

Rabi et al., *2008*

# Controlled Brownian motion with one sampling event

$$dx_t = u_t dt + dB_t$$



$$\min_{U_0,U_1,\tau} J = \min_{U_0,U_1,\tau} \mathbf{E} \int_0^T x_s^2 ds$$

$$= \min_{U_0,U_1,\tau} \left[ \mathbf{E} \int_0^\tau x_s^2 ds + \mathbf{E} \int_\tau^T x_s^2 ds \right]$$

A joint optimal control and optimal stopping problem

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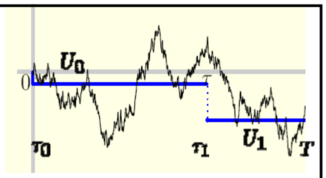
$$dx_t = u_t dt + dB_t$$

$$\min_{U_0,U_1,\tau} J = \min_{U_0,U_1,\tau} \mathbf{E} \int_0^T x_s^2 ds$$



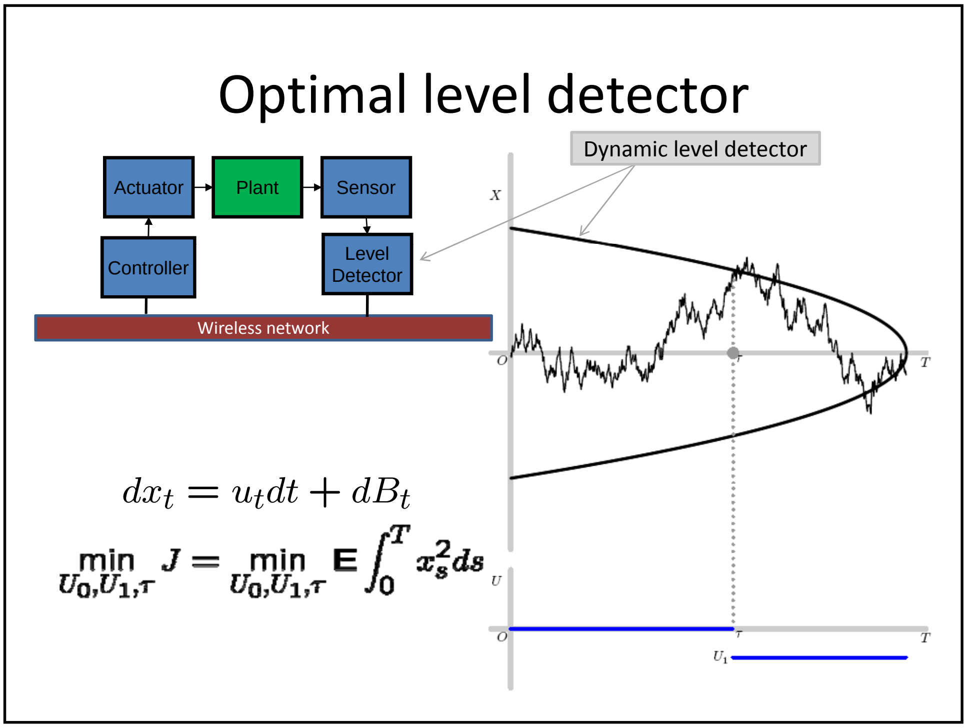
If $\tau$ chosen deterministically (not depending on $x_t$) and $x_0 = 0$:

$$U_0^* = 0 \qquad U_1^* = -\frac{3x_{T/2}}{T} \qquad \tau^* = T/2$$

If $\tau$ is event-driven (depending on $x_t$) and $x_0 = 0$:

$$U_0^* = 0 \qquad U_1^* = -\frac{3x_{\tau^*}}{2(T-\tau^*)}$$

$$\tau^* = \inf\{t : \underbrace{x_t^2 \geq \sqrt{3}(T-t)}_{\text{Envelope defines optimal level detector}}\}$$



# Optimal level detector

Actuator

Plant

Sensor

Controller

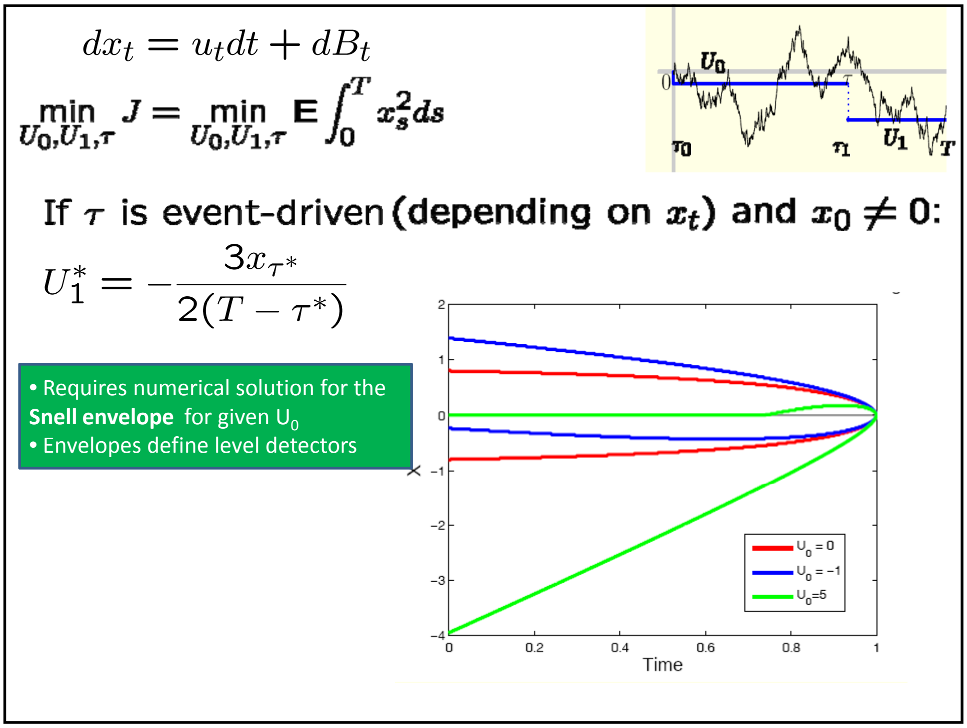
Level Detector

Wireless network

Dynamic level detector

$$dx_t = u_t dt + dB_t$$

$$\min_{U_0,U_1,\tau} J = \min_{U_0,U_1,\tau} \mathbf{E}\int_0^T x_s^2 ds$$



$$dx_t = u_t dt + dB_t$$

$$\min_{U_0,U_1,\tau} J = \min_{U_0,U_1,\tau} \mathbf{E}\int_0^T x_s^2 ds$$

If $\tau$ is event-driven (depending on $x_t$) and $x_0 \neq 0$:

$$U_1^* = -\frac{3x_{\tau^*}}{2(T-\tau^*)}$$

- Requires numerical solution for the **Snell envelope** for given $U_0$
- Envelopes define level detectors

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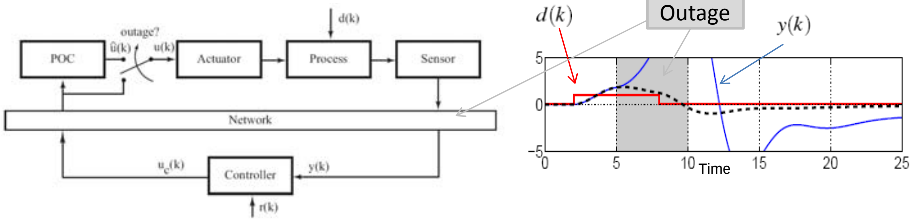
# Predictive outage compensation

- Compensate for communication outages by model-based extrapolation of control commands



Unknown piecewise constant disturbance

$$y(k) = P(q)\big(u(k)+d(k)\big) = \frac{B(q)}{A(q)}\big(u(k)+\boxed{d(k)}\big)$$

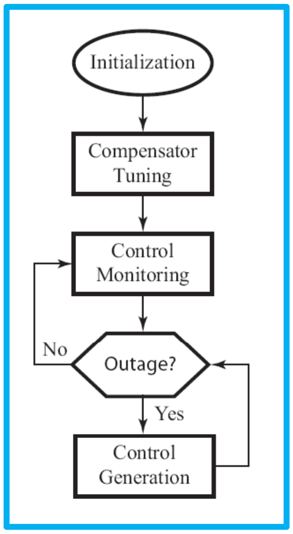
$$u(k) = \begin{cases} u_c(k) & \text{Command from controller received} \\ \hat{u}(k) & \text{Command from controller lost} \end{cases}$$

$$u_c(k) = C(q)\big(r(k)-y(k)\big) = \frac{S(q)}{R(q)}\big(r(k)-y(k)\big)$$

$$\hat{u}(k) = G(q)\hat{d}(k) = \frac{E(q)}{F(q)}\hat{d}(k)$$

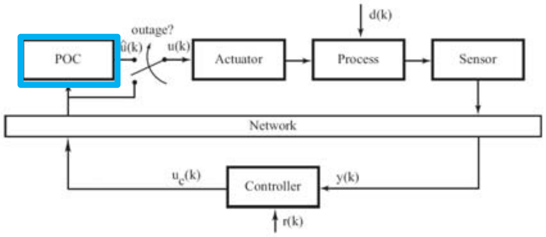
Henriksson et al., *2008*

# Predictive outage compensation



$\sup_{k \in \text{Outage}} |u_c(k) - \hat{u}(k)|$ depends on

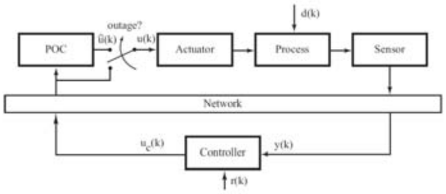
- Communication outage length
- Uncertainty of closed-loop system
- Complexity of POC filter $\hat{u}(k) = G(q)\hat{d}(k)$
- Uncertainty of class of disturbances $d(k)$

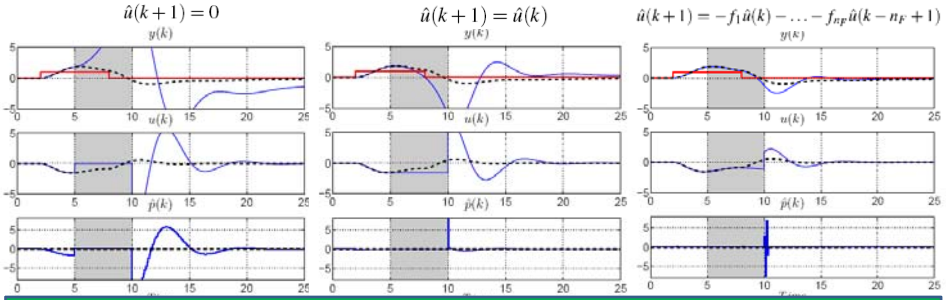


# Example

$$P(q) = \frac{1}{(q-1)^2}$$

$$C(q) = \frac{1.95q^2 - 3.80q + 1.85}{q^2 - 1.82q + 0.82}$$





$\hat{u}(k+1) = 0$

$\hat{u}(k+1) = \hat{u}(k)$

$\hat{u}(k+1) = -f_1\hat{u}(k) - \ldots - f_{n_F}\hat{u}(k - n_F + 1)$

Predictive outage compensation compensates for substantial outages

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# Conclusions

- Wide range of emerging wireless control applications:

- Need integrated view of control and wireless networking
  - Event-triggered control to support asynchronous networking
  - Outage compensation for control under varying radio conditions

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