Event-based Control for Distributed Systems

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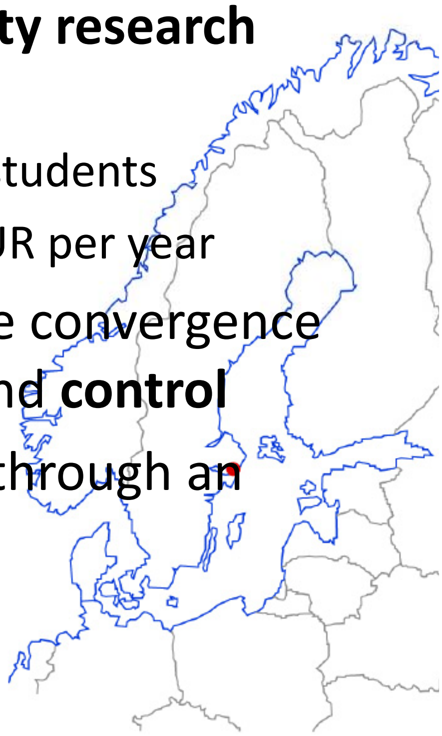
ACCESS Linnaeus Centre

- One of Europes's largest **university research center** in networks
  - 35 senior researchers and 80 PhD students
  - Total research budget about 6 MEUR per year
- Cross-disciplinary research on the convergence of **computing**, **communication** and **control**
- Strong **industrial collaborations** through an industrial partnership program
- Extensive **mobility program**



Outline

- **Introduction**
- **Motivation:** Control over wireless networks
- **Architecture** for event-based control
- **Design** of event detector and control generator
- **Extensions**
- **Conclusions**

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- **Introduction**
- **Motivation:** Control over wireless networks
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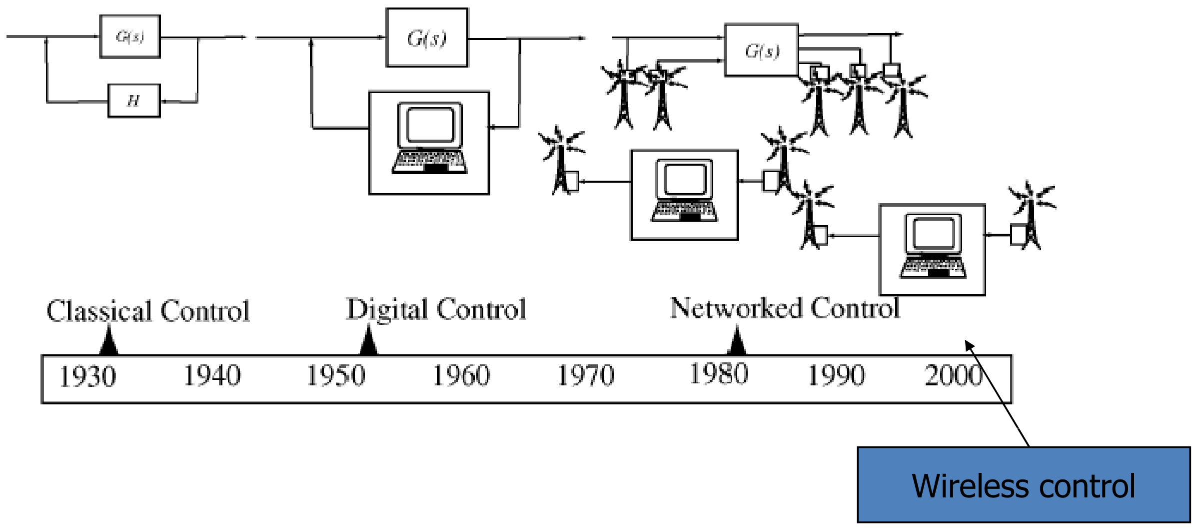
- **Extensions**
  - – Multiple control loops
  - – Influence of communication losses
  - – Event-based PID control
- **Conclusions**

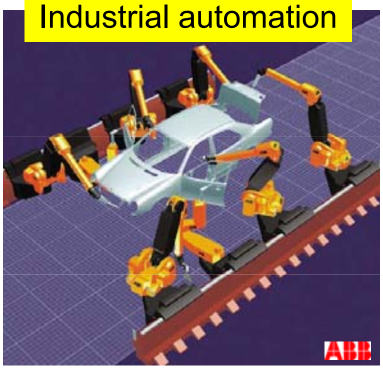
A history of control



[Baillieul & Antsaklis, 2007]

Today's wireless control systems

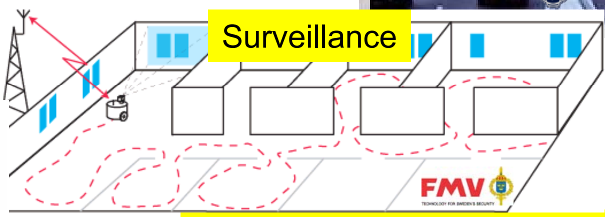
Industrial automation



Home automation

Transportation networks

Surveillance

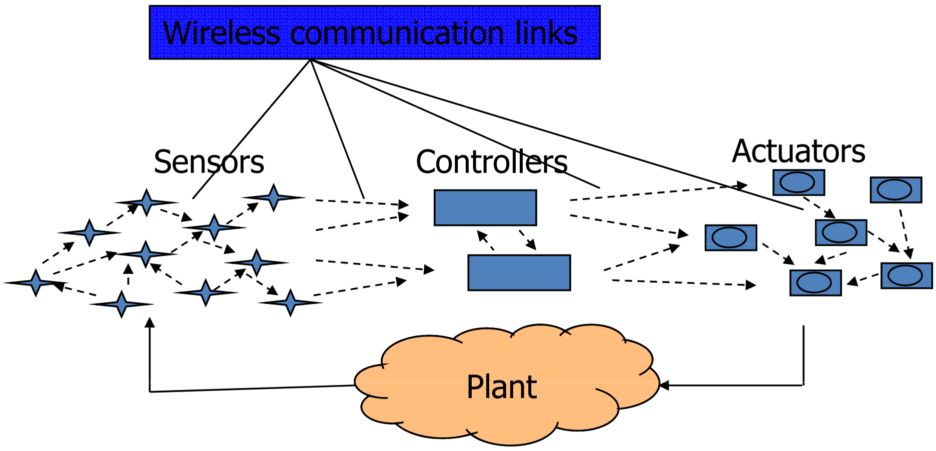


Marine habitat mapping

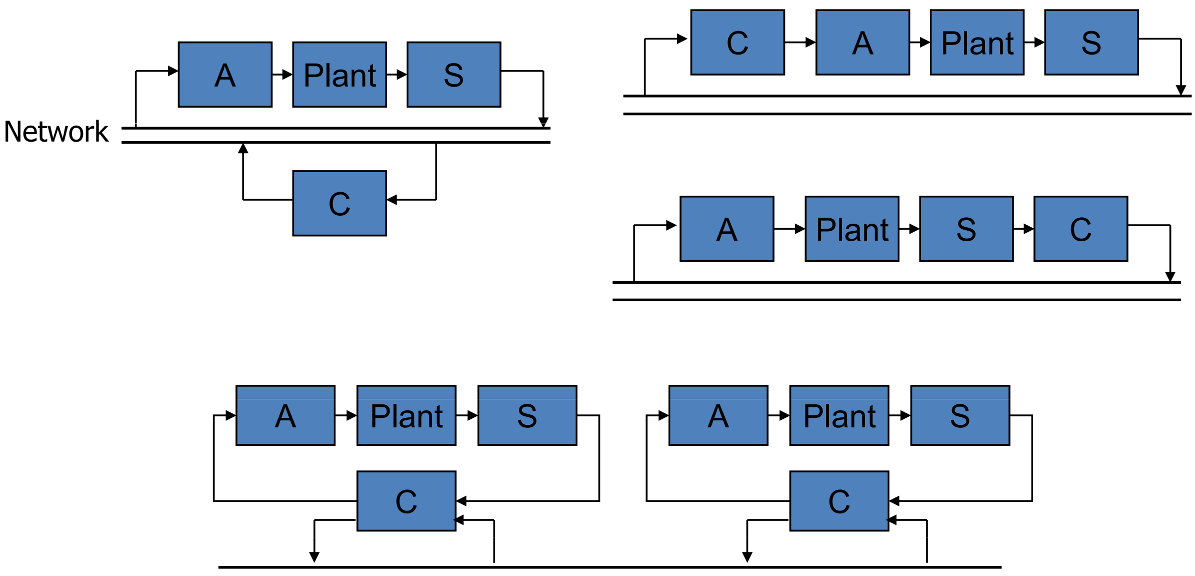
Environmental monitoring

Control over wireless networks

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

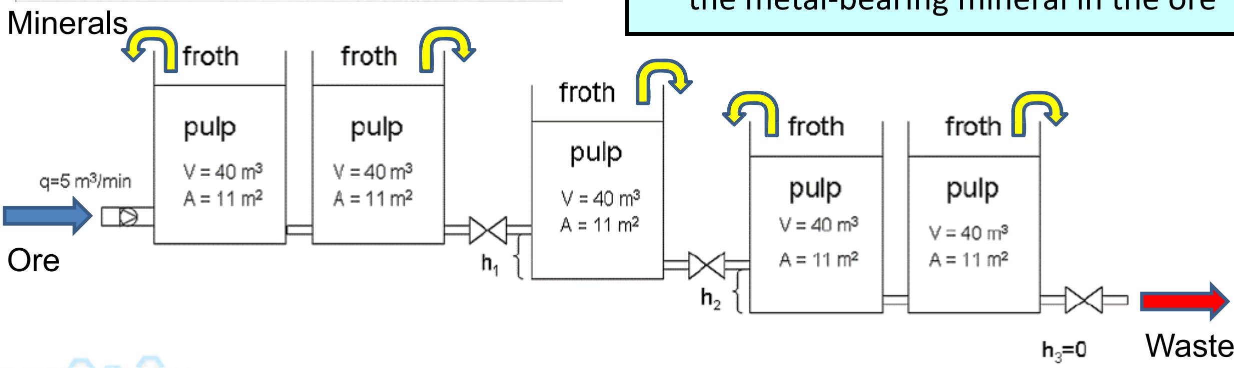


Networked control architectures



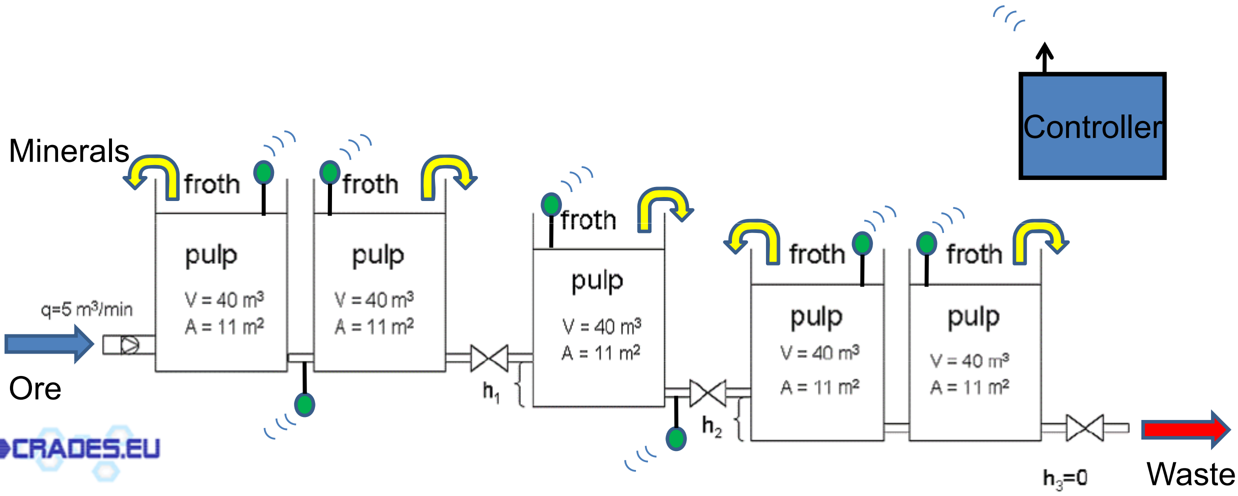
Example: Froth flotation process

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

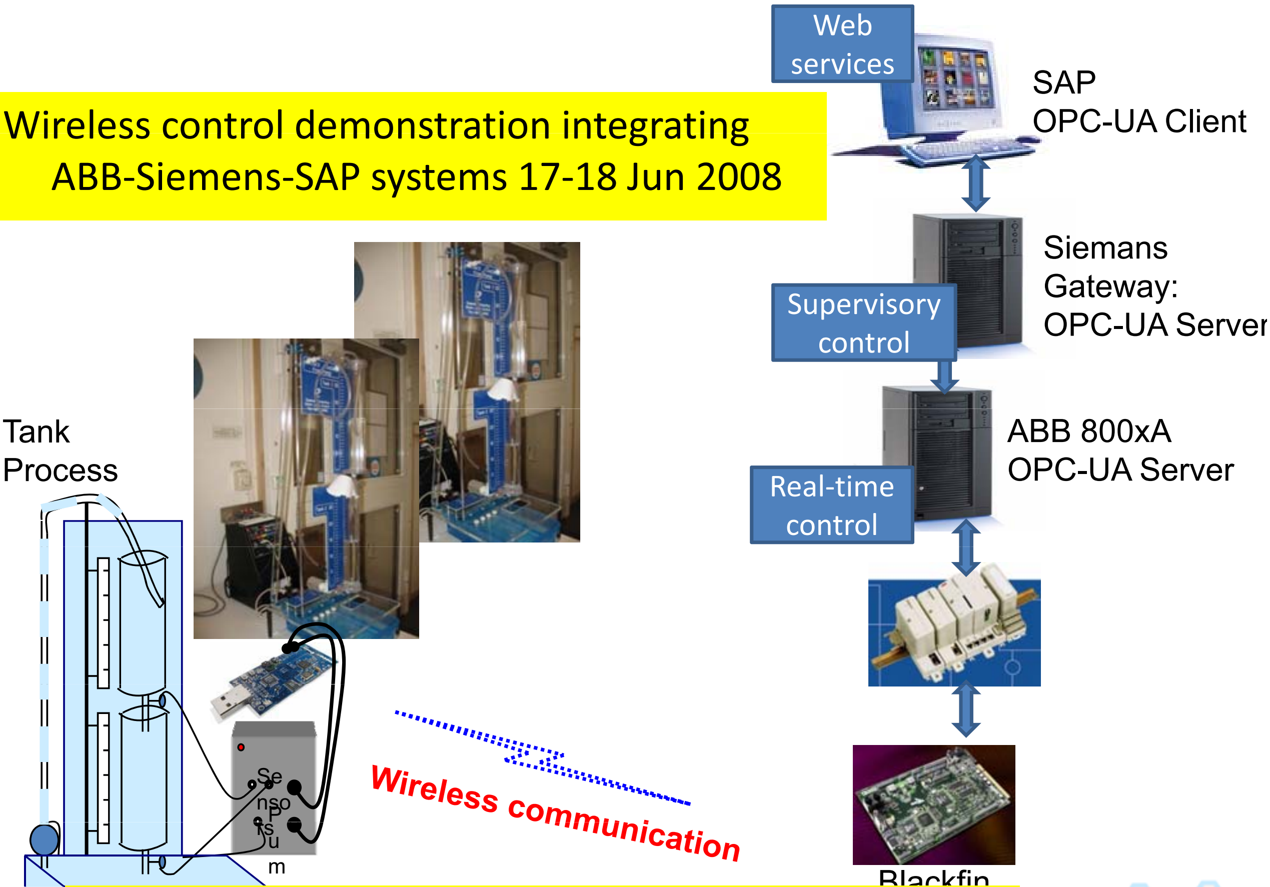


Wireless control of flotation process

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



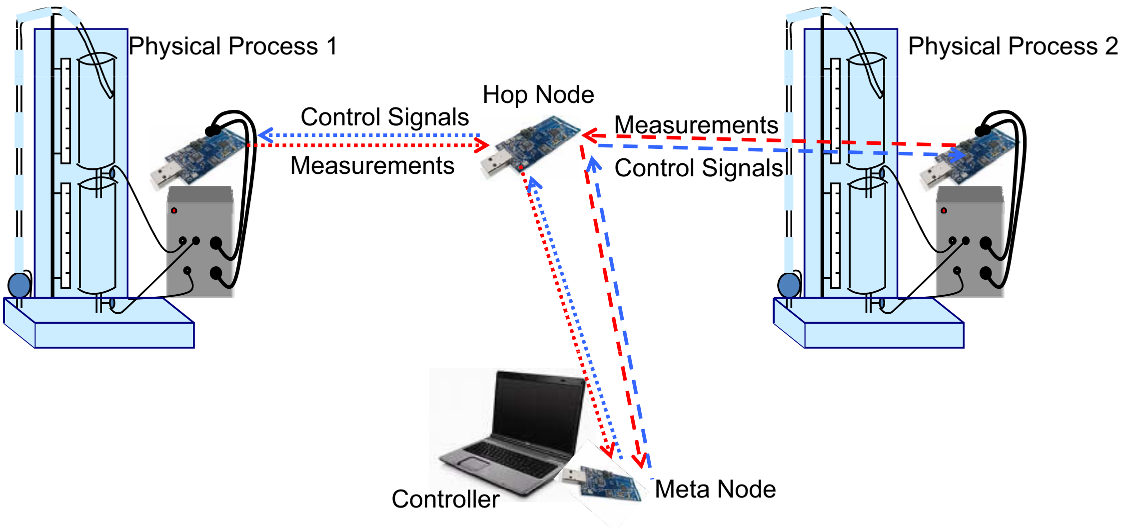
Wireless control demonstration integrating ABB-Siemens-SAP systems 17-18 Jun 2008



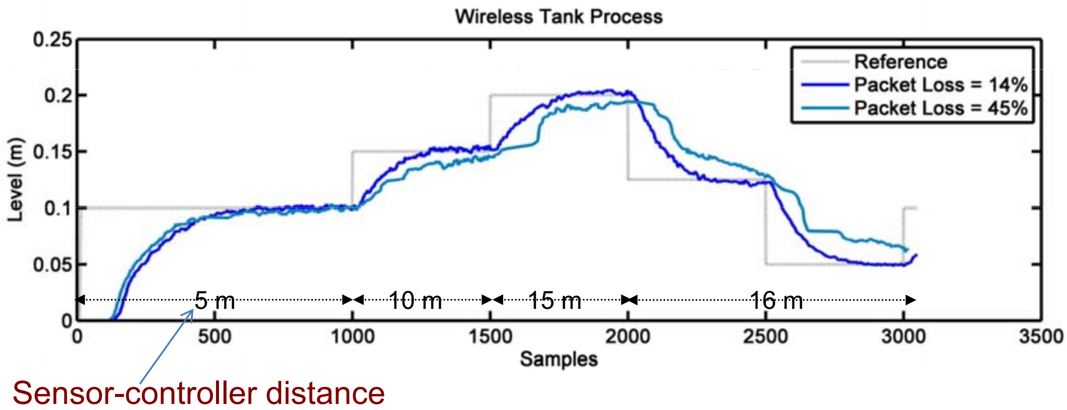
Froth flotation process demo at Boliden in Aug 2009

S●CRADES.EU

Experimental setup for demo on control over multi-hop network



Effect of packet loss

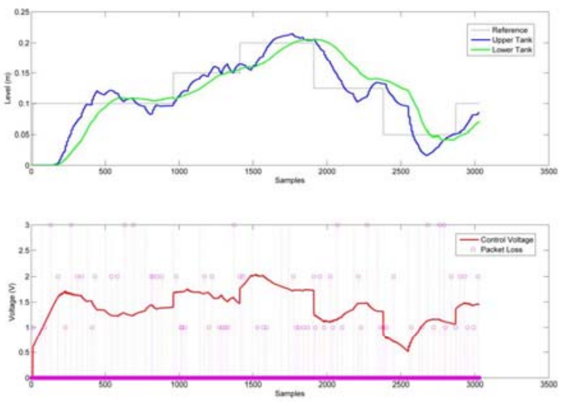


Effect of radio interference

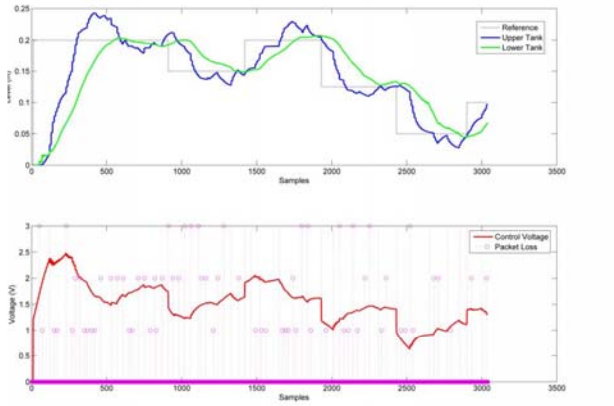
Interference from multiple motes transmitting and receiving simultaneously to tank processes 1 and 2

Packet loss = 45%, Sampling time = 1 s

Tank Process 1



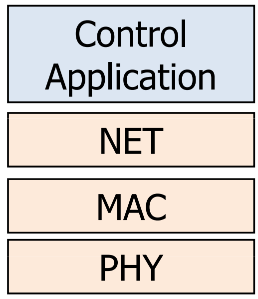
Tank Process 2

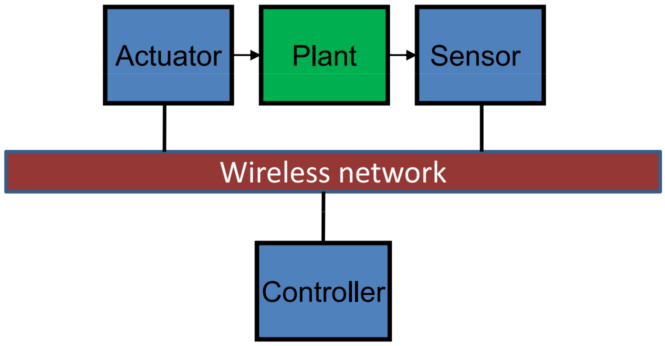


A communication or a control problem?

Approaches to control over wireless networks:

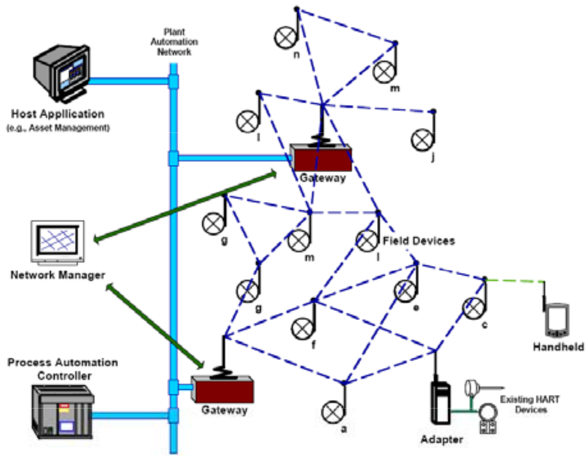
1. Communication protocol suitable for control
2. Control application that compensates for communication imperfections
3. Integrated design of control application and communication layers

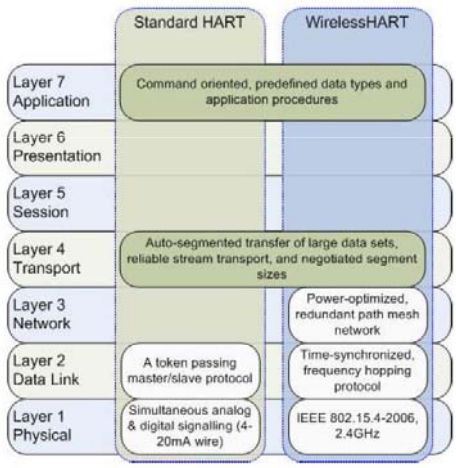


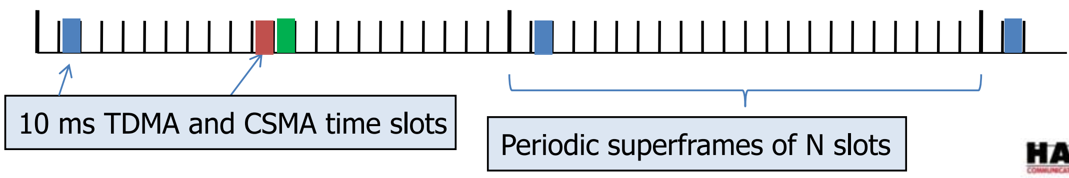


WirelessHART

Wireless networking protocol standard (2007) designed for sensing and control applications

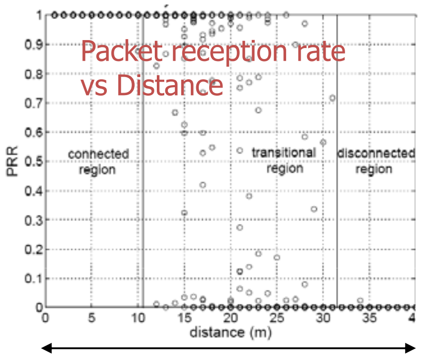






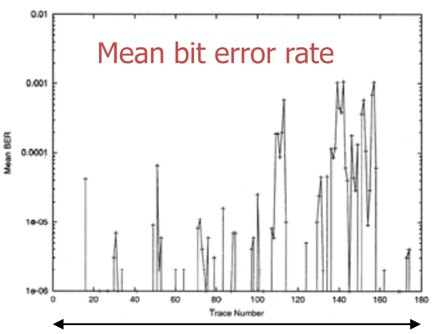
HART

Wireless channels may deteriorate control performance

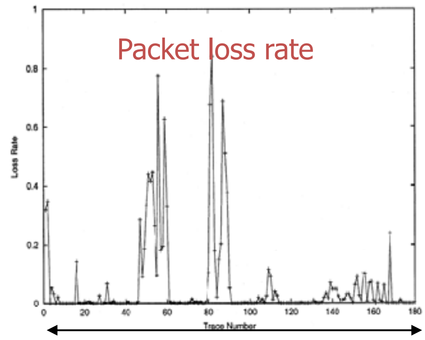


40 m

Zuniga & Krishnamachari, *SECON*, 2004

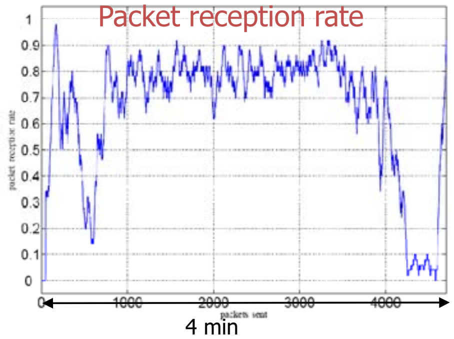


4 h



4 h

Willig et al., *IEEE Trans. Ind. Electron.*, 49, 6, 2002

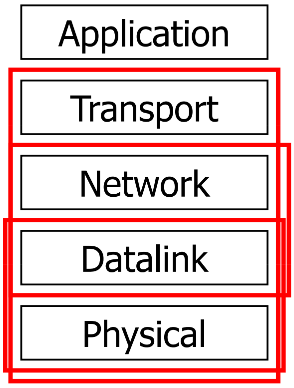


4 min

Park et al., KTH, 2007

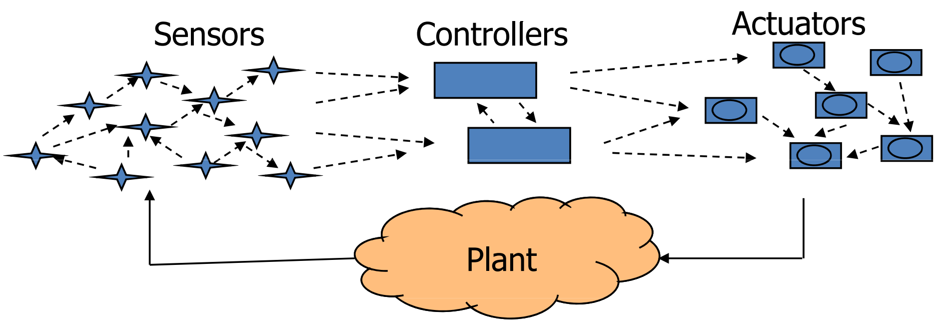
Large variations in

- Connectivity
- Bit and packet delivery
- End-to-end delivery



How trade-off network resources and control performance?

How move intelligence from central units to local devices?



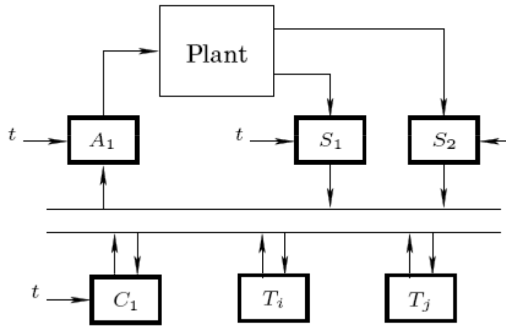
A fundamental challenge in wireless control

A traditional conflict between

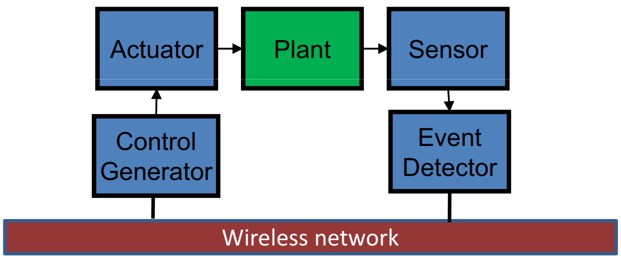
- time-driven, synchronous, sampled data **control engineering**

and

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



A new architecture for wireless control



Rabi and J., *WICON, 2008*

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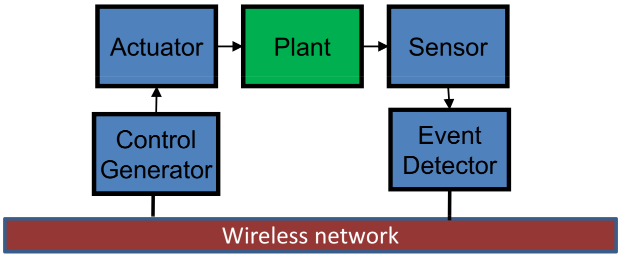
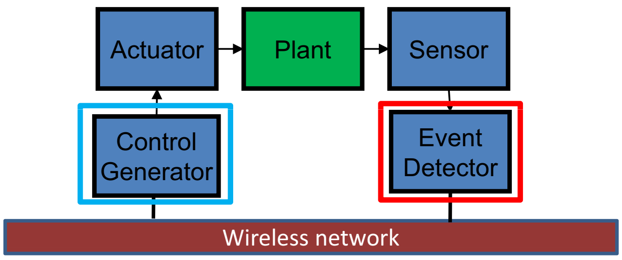
Architecture for event-based control



Åström, *2007,* Rabi and J., *WICON, 2008*

When to transmit?

- Medium access control-like mechanism at sensor
  - E.g., threshold crossing



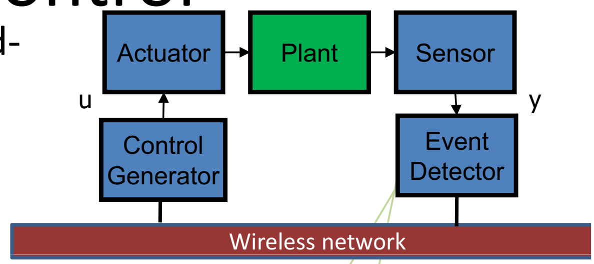
How to control?

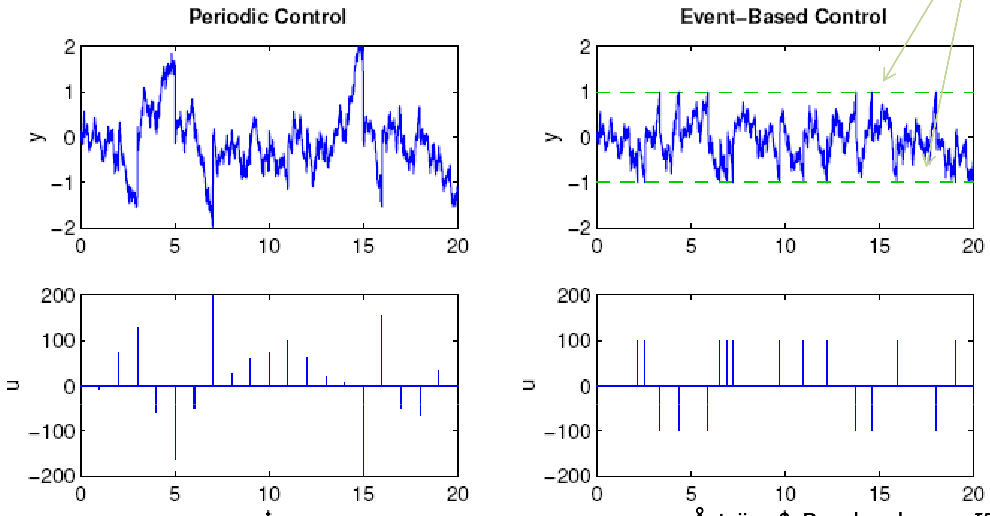
- Execute control law over fixed control alphabet
  - E.g., piecewise constant controls, impulse control

Rabi et al., *2008*

Example: Fixed threshold with impulse control

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





Åström & Bernhardsson, *IFAC,* 1999

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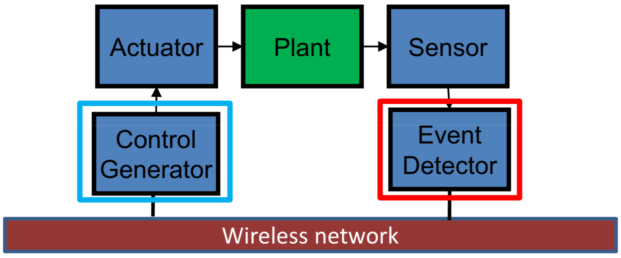
Design of control generator and event detector

1. Impulse
2. Zero order hold
3. Higher order hold

1. Fixed threshold
2. Adaptive sampling



Plant model and control cost

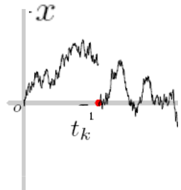
Plant $dx = u dt + dv,$

v is a Wiener process: $E(v(t+s) - v(t))^2 = |s|$

Cost function $V = \frac{1}{T} E \int_0^T x^2(t) dt.$

Discussion later on how to treat general dynamics, sensor noise etc

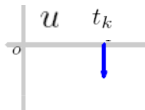
Periodic impulse control



Impulse applied at events t_k

$$u(t) = -x(t_k)\delta(t - t_k),$$

Periodic reset of state every event.



State grows linearly as

$$E(v(t+s) - v(t))^2 = |s|$$

between sample instances, because $dx = udt + dv,$

Average variance over sampling period h is $\frac{1}{2}h$ so the cost is

$$V_{PIH} = \frac{1}{2}h.$$

Åström, 2007

Periodic ZoH control

Traditional sampled-data control theory gives that

$V = \frac{1}{h}\int_0^h Ex^2(t)\,dt$ is minimized for the sampled system

$$x(t+h) = x(t) + hu(t) + e(t),$$

with

$$u = -Lx = \frac{1}{h}\frac{3+\sqrt{3}}{2+\sqrt{3}}x$$

derived from

$$S = \Phi^T S\Phi + Q_1 - L^T RL, \quad L = R^{-1}(\Gamma^T S\Phi + Q_{12}^T), \quad R = Q_2 + \Gamma^T S\Gamma,$$

The minimum gives the cost

$$V_{PZOH} = \frac{3+\sqrt{3}}{6}h$$

Åström, 2007

Event-based impulse control with fixed threshold

Suppose an event is generated whenever

$$|x(t_k)| = a$$

generating impulse control

$$u(t) = -x(t_k)\delta(t - t_k),$$

One can show that the average time between two events is

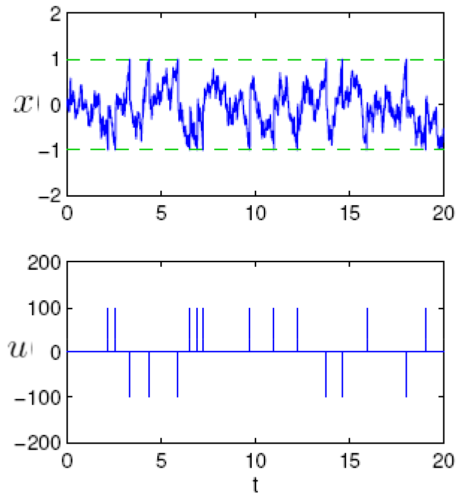
$$h_E := E(T_{\pm d}) = E(x^2_{T_{\pm d}}) = a^2$$

and that the pdf of x is triangular:

$$f(x) = (a - |x|)/a^2$$

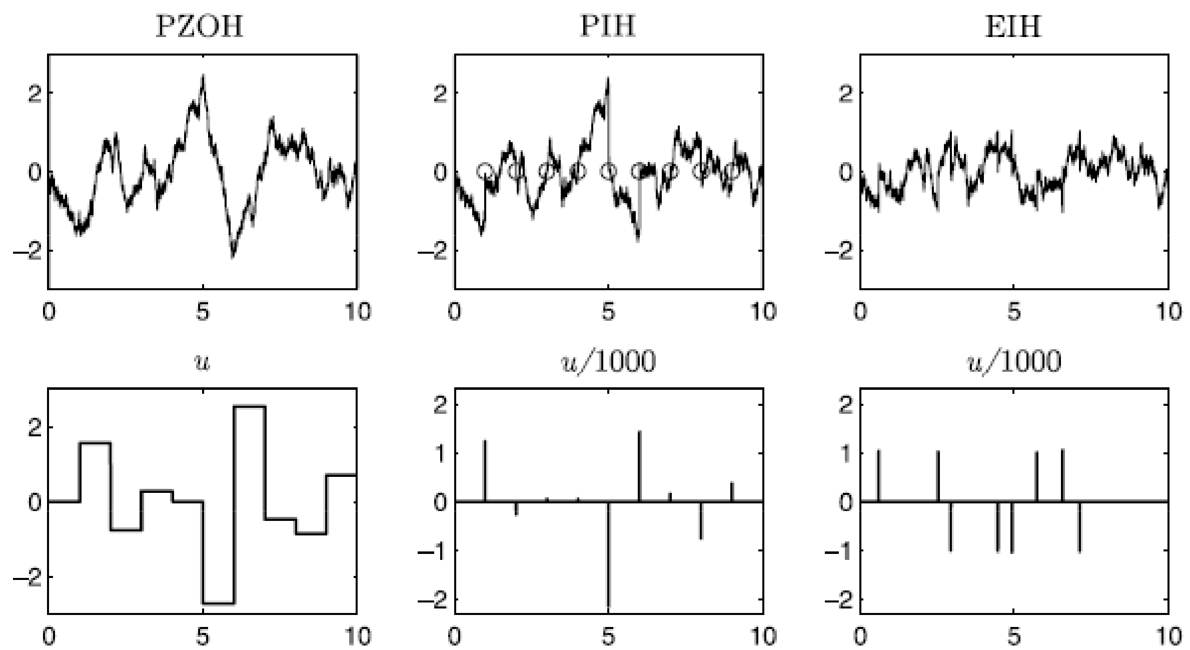
The cost is

$$V_{EIH} = \frac{a^2}{6} = \frac{h_E}{6}$$



Åström, 2007

Comparison



Åström, 2007

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Background: Wireless technologies, nowadays a commodity in personal and data communication, have the potential of providing significant benefits in factory and industrial automation systems. The wireless way of communicating makes plant setup and modification easier, more flexible and cost-efficient. It provides a natural approach for communication with mobile machines and robots, where fixed cables are in constant danger of breaking. The industrial interest in wireless solutions is growing rapidly: standardization efforts such as Wireless HART and ISA 100 are underway, and hardware for embedded wireless is dropping in price. It is expected that wireless technologies will be integrated into distributed control systems on a broad scale. However, there are still open issues about reliability, performance, and data security of the wireless control loop that may limit the rate of adoption.

The goal of the special section is to attract theoretical and practical papers attacking the main issues and problems regarding the adoption of wireless technologies for networked control, ranging from theoretical foundations to the reporting of implementation experiences and applications.

Topics for the special section include, but are not limited to, the following:

- **Industrial wireless networking** for efficient, reliable and timely data transmission: low-layer (MAC/link/physical-layer) protocols and multi-hop (routing, transport) protocols
- **Theory and methodology** for reliable and robust wireless networked control
- **Novel solutions** for re-configurable, resilient and fault tolerant wireless control
- **Security** for industrial wireless systems
- **Middleware and higher-layer support** for wireless networked control systems
- **Hybrid wired/wireless networked control systems**
- **Experiences from industrial deployments** of wireless control
- **Innovative wireless networked control applications**

Submissions must represent original material that have been neither submitted to, nor published in, any other journal. Extended versions of papers previously published in conference proceedings may be eligible for consideration, provided that the authors inform the Special Section Guest Editors at the time of submission.

Manuscript preparation and submission: Follow the guidelines in "Information for Authors" in http://ieee-ies.org/tii/

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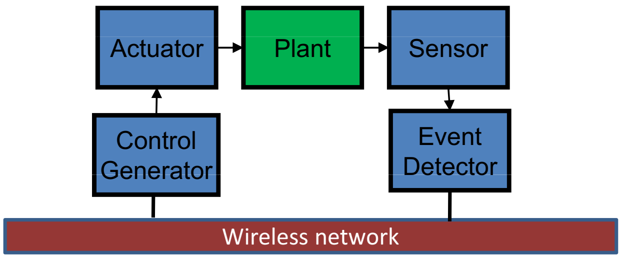
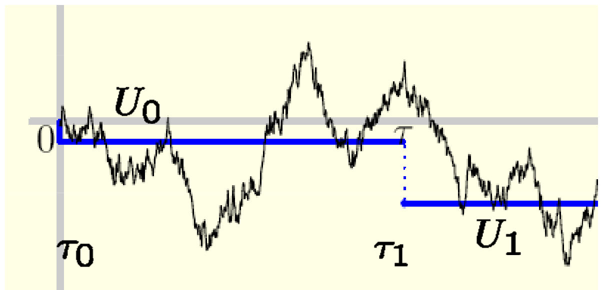
Paper submission deadline: October 31, 2009

Expected publication date: November 2010 (tentative)

Note: The recommended papers for the section are subject to final approval by the Editor in Chief. Some papers may be published outside the special section, at his discretion.

Event-based ZoH control with adaptive sampling



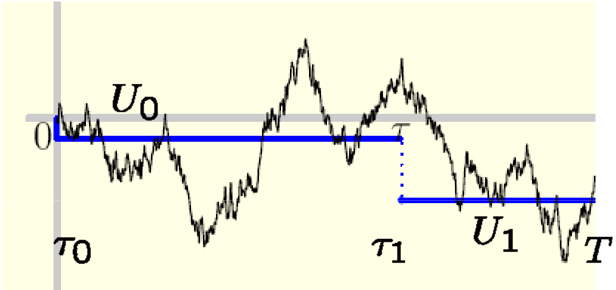


How choose $\{U_i\}$ and $\{\tau_i\}$ to minimize $V = \frac{1}{T} E \int_0^T x^2(t)dt.$

Rabi et al., *2008*

Controlled Brownian motion with one sampling event

$$dx_t = u_t dt + dB_t$$



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

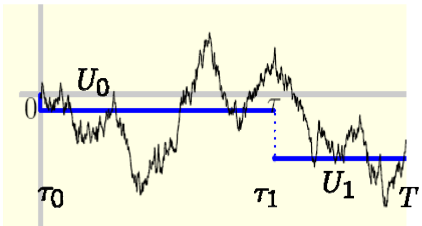
$$= \min_{U_0,U_1,\tau} \left[\mathbf{E}\int_0^\tau x_s^2 ds + \mathbf{E}\int_\tau^T x_s^2 ds\right]$$

A joint optimal control and optimal stopping problem

Rabi et al., *2008*

$$dx_t = u_t dt + dB_t$$

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



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

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

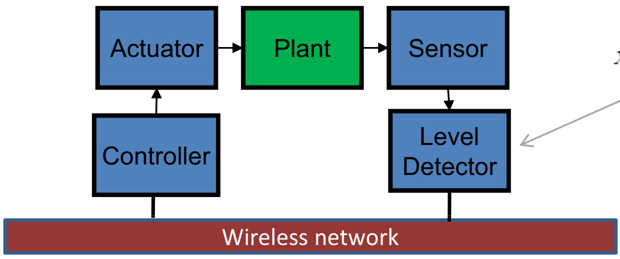
If τ is event-driven (depending on x_t) and $x_0 = 0$:

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

$$\tau^* = \inf\{t : \underbrace{x_t^2 \geq \sqrt{3}(T-t)}\}$$

Envelope defines optimal level detector

Optimal level detector



$$dx_t = u_t dt + dB_t$$

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

Proof

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

$$\mathbf{E}\left\{ \int_\tau^T x_s^2 ds \Big| \tau, x_\tau, U_1 \right\} = \left[x_t = x_\tau + \int_\tau^t U_1 ds + \int_\tau^t dB_s \right]$$

$$= \int_\tau^T \mathbf{E} \left\{ \left[x_\tau^2 + U_1^2 (t-\tau)^2 + (B_t - B_\tau)^2 + 2x_\tau U_1 (t-\tau) \right. \right.$$

$$\left. \left. + 2x_\tau (B_t - B_\tau) + 2U_1 (t-\tau)(B_t - B_\tau) \right] \right\} dt$$

$$= \left[\mathbf{E} B_t = 0, \ \mathbf{E} B_t^2 = t, \ \delta := T - \tau \right] = \delta x_\tau^2 + \frac{\delta^3}{3} U_1 + \frac{\delta^2}{2} + \delta^2 x_\tau U_1$$

$$= \frac{\delta}{4} x_\tau^2 + \delta \left(\frac{x_\tau \sqrt{3}}{2} + \frac{\delta U_1}{\sqrt{3}} \right) + \frac{\delta^2}{2}$$

Hence, optimal control $U_1^* = U_1^*(x_\tau, T - \tau) = -\dfrac{3x_\tau}{2(T-\tau)}$

$$J(U_0, U_1^*, \tau) = \mathbf{E}\int_0^\tau x_s^2 ds + \mathbf{E}\left\{\frac{T-\tau}{4}x_\tau^2 + \frac{(T-\tau)^2}{2}\right\}$$

If τ chosen deterministically **(not depending on x_t) and $x_0 = 0$:**

$$J(U_0, U_1^*, \theta) = \frac{\theta^3}{3}U_0^2 + \frac{\theta^2}{2} + \frac{T-\theta}{4}(U_0^2\theta^2 + \theta) + \frac{(T-\theta)^2}{2}$$

Hence,

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

which gives

$$J(U_0^*, U_1^*, \tau^*) = \frac{5T^2}{16}$$

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

$$J(U_0, U_1^*, \tau) = \mathbf{E}\int_0^\tau x_s^2 ds + \mathbf{E}\left\{\frac{T-\tau}{4}x_\tau^2 + \frac{(T-\tau)^2}{2}\right\} = \cdots$$

$$= \frac{T^2}{2} + \frac{U_0^2 T^3}{3} - \mathbf{E}\left\{\left(\frac{x_\tau\sqrt{3}}{2} + \frac{(T-\tau)U_0}{\sqrt{3}}\right)^2 (T-\tau)\right\}$$

$$= \frac{T^2}{2} - \frac{3}{4}\mathbf{E}\left\{x_\tau^2(T-\tau)\right\}$$

because from symmetry $U^* = 0$.

Find τ that maximizes $f(x_\tau, \tau) = \mathbf{E}\left\{x_\tau^2(T-\tau)\right\}$

Find τ that maximizes $f(x_\tau, \tau) = \mathbf{E}\left\{x_\tau^2 (T-\tau)\right\}$

Suppose there exists smooth $g(x,t)$ such that

$$g(x,t) \geq x^2(T-t)$$

$$\frac{1}{2} g_{xx}(x,t) + g_t(x,t) = 0$$

Then, for $0 \leq t \leq \tau \leq T$,

$$f(x_\tau,\tau) = \mathbf{E}\left\{x_\tau^2(T-\tau)\right\} \leq \mathbf{E}\left\{g(x_\tau,\tau)\right\} = g(x_t,t) + \mathbf{E}\int_t^\tau dg(x_\tau,\tau)$$

$$= [\text{Ito formula}] = g(x_t,t) + \mathbf{E}\int_t^\tau \left(\frac{1}{2} g_{xx} + g_t\right) dt$$

$$= g(x_t,t)$$

Hence, g is an upper bound for the expected reward.

We next show that equality can be achieved.

$$g(x_t,t) = \frac{\sqrt{3}}{1+\sqrt{3}} \left(\frac{x_t^4}{6} + x_t(T-t) + \frac{(T-t)^2}{2}\right)$$

is a solution to

$$\frac{1}{2} g_{xx}(x,t) + g_t(x,t) = 0$$

Moreover,

$$g(x_t,t) - x_t^2(T-t) = \frac{1}{2(1+\sqrt{3})}\left(\frac{x_t^4}{3} - \frac{2}{\sqrt{3}} x_t^2 (T-t) + (T-t)^2\right)$$

$$= \frac{1}{2(1+\sqrt{3})}\left(\frac{x_t^4}{\sqrt{3}} - (T-t)^2\right) = 0$$

if $x_t^2 = \sqrt{3}(T-t)$.

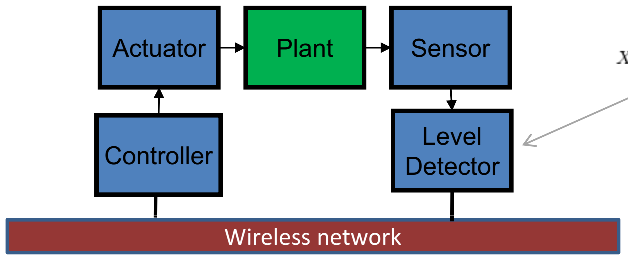
Hence, the optimal sampling time is

$$\tau^* = \inf\{t:\ x_t^2 \geq \sqrt{3}(T-t)\}$$

which gives

$$J(U_0^*, U_1^*, \tau^*) = \frac{T^2}{8}$$

Optimal level detector



$$dx_t = u_t dt + dB_t$$

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

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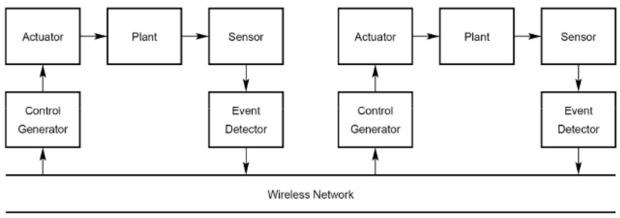
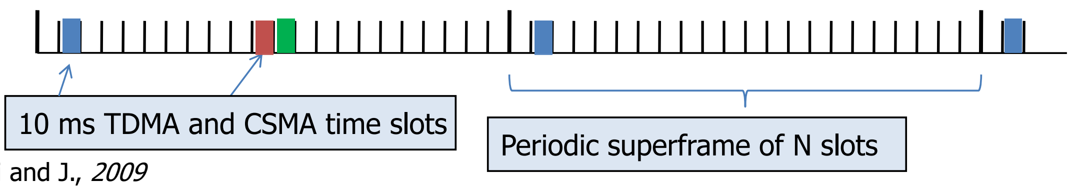
Multiple control loops

- N control loops sharing the same wireless network



- Time Division Multiple Access or contention-based medium access



Rabi and J., *2009*

System model and performance measures

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

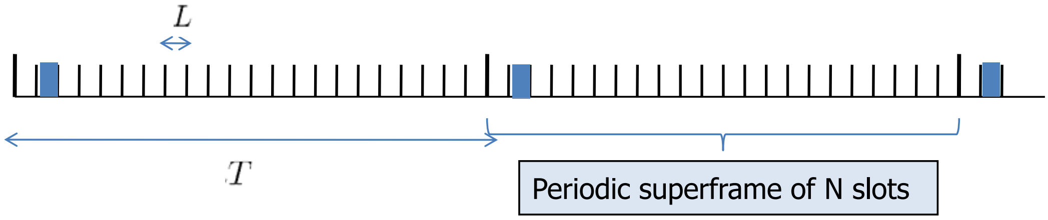
Periodic sampling of multiple loops

Sampling events $\tau_n = nT \quad \text{for} \quad n \ge 0$

Slot length L gives $T = NL$

Average sampling rate $R_{\text{Periodic}} = \frac{1}{T}$

Average cost $J_{\text{Periodic}} = \frac{T}{2}$

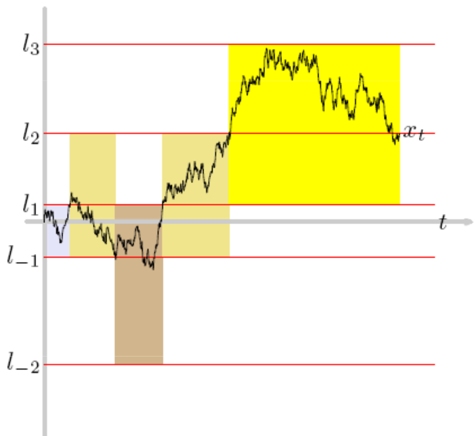


Level-triggered control

Ordered set of levels $\mathcal{L} = \{\ldots, l_{-2}, l_{-1}, l_0, l_1, l_2, \ldots\}$ $l_0 = 0$

Multiple levels needed because we allow packet loss

Lebesgue sampling $\tau = \inf\left\{\tau \middle| \tau > \tau_i, x_\tau \in \mathcal{L}, x_\tau \notin x_{\tau_i}\right\}$



Level-triggered control

For Brownian motion, equidistant sampling is optimal

$$\mathcal{L}^* = \left\{k\Delta \middle| k \in \mathbb{Z}\right\}$$

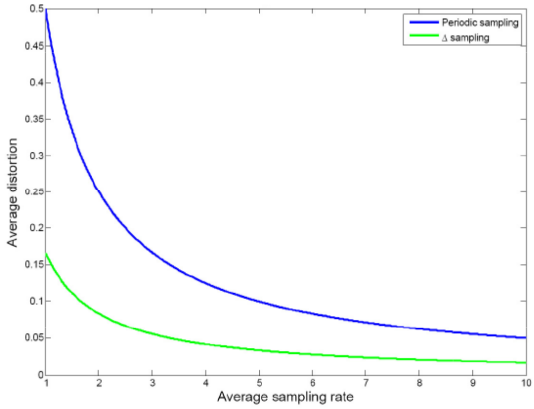
First exit time

$$\tau_\Delta = \inf\left\{\tau \middle| \tau \geq 0, x_\tau \notin (\xi - \Delta, \xi + \Delta), x_0 = \xi\right\}$$

Average sampling rate $R_\Delta = \dfrac{1}{\mathbb{E}[\tau_\Delta]} = \dfrac{1}{\Delta^2},$

Average cost $J_\Delta = \dfrac{\mathbb{E}\left[\int_0^{\tau_\Delta} x_s^2 ds\right]}{\mathbb{E}[\tau_\Delta]} = \dfrac{\Delta^2}{6}.$

Comparison between periodic and event-based control



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

Event-based impulse control is 3 times better than periodic impulse control

What about the influence of communication losses?
When is event-based better and vice versa?

Influence of communication losses

Times when packets are successfully received $\rho_i \in \{\tau_0 = 0, \tau_1, \tau_2, \ldots\}$,

$$\{\rho_0 = 0, \rho_1, \rho_2, \ldots\}. \qquad \rho_i \geq \tau_i,$$

Average rate of packet reception

$$R_\rho = \limsup_{M\to\infty} \frac{1}{M}\mathbb{E}\left[\int_0^M \sum_{n=0}^{\infty} \mathbf{1}_{\{\rho_n \leq M\}} \delta(s - \rho_n)\, ds\right] = p \cdot R_\tau$$

Define the times between successful packet receptions $\rho_{(p,\Delta)}$

Average cost $J_p = \limsup_{T\to\infty} \frac{1}{T}\mathbb{E}\left[\int_0^T x_s^2 ds\right] = \frac{\mathbb{E}\left[\int_0^{\rho_{(p,\Delta)}} x_s^2 ds\right]}{\mathbb{E}\left[\rho_{(p,\Delta)}\right]}$

Rabi and J., *2009*

IID losses

Proposition

Suppose packet losses are IID. Then,

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

Remark

Event-based control is better than period control under IID losses if

$$\frac{(1+5p)}{3(1-p)} \;\geq\; 1$$

So if the loss probability

$$p \geq 0.25$$

then traditional periodically sampled control is preferable.

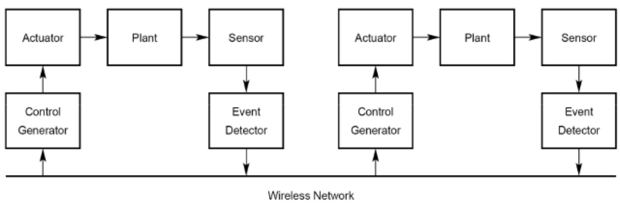
Rabi and J., *2009*

Losses depending on the other loops

Suppose the loss processes across the different loops are independent, so that the sample streams of the other sensors only matter through their average behaviour (cf., *Poisson arrivals see time averages*, PASTA)

The likelihood that a sample generated in one loop faces at least one competing transmission is then

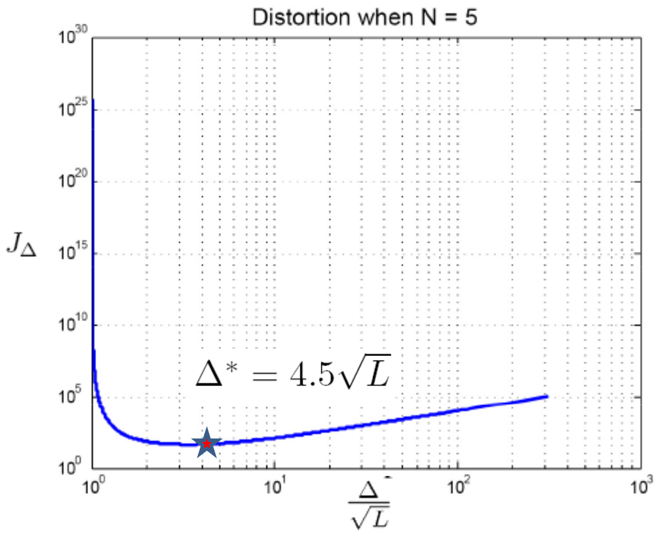
$$p = 1 - \left(1 - \frac{L}{\Delta^2}\right)^{N-1}$$



Losses depending on the other loops

Average cost $J_\Delta = \frac{L\left(6 - 5\beta^{N-1}\right)}{6\beta^{N-1}\left(1-\beta\right)}$ $\beta = 1 - \frac{L}{\Delta^2}$

gives trade-off between control performance and network resources



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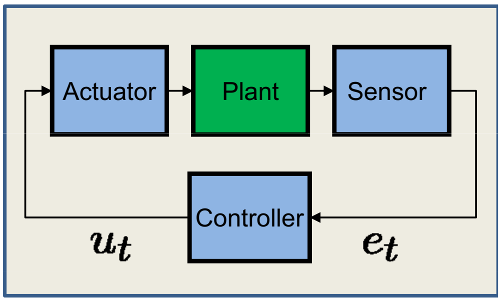
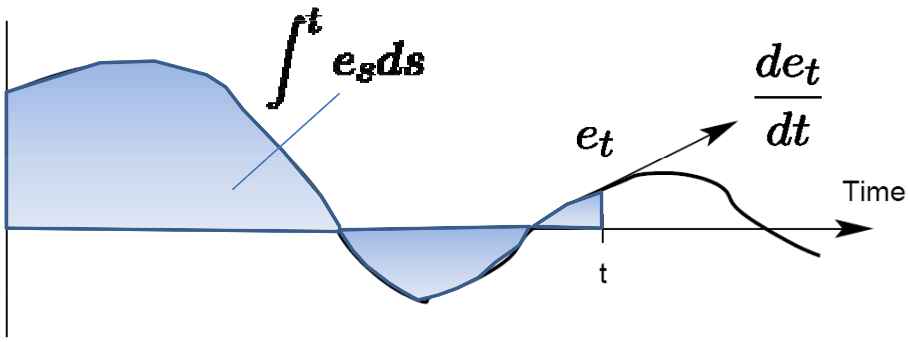
Proportion-Integral-Derivative control

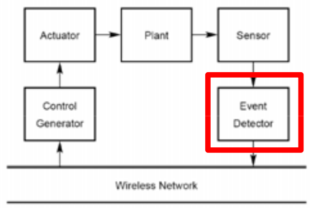


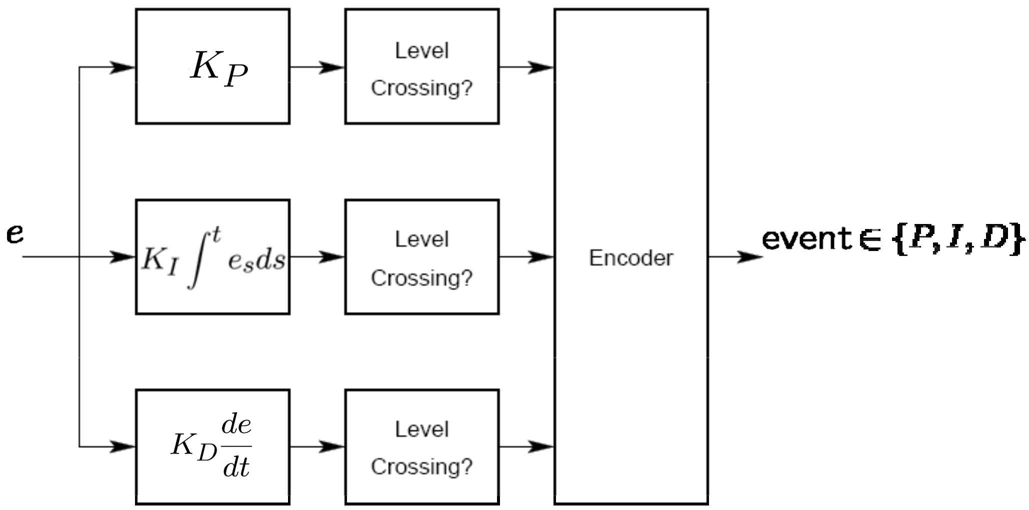
$$u_t = K_P e_t + K_I \int^t e_s ds + K_D \frac{de_t}{dt}$$



How extend PID control to event-based control?

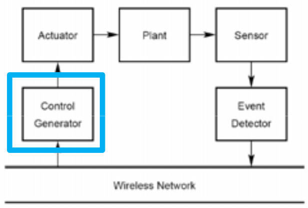
Event-detector for PID control

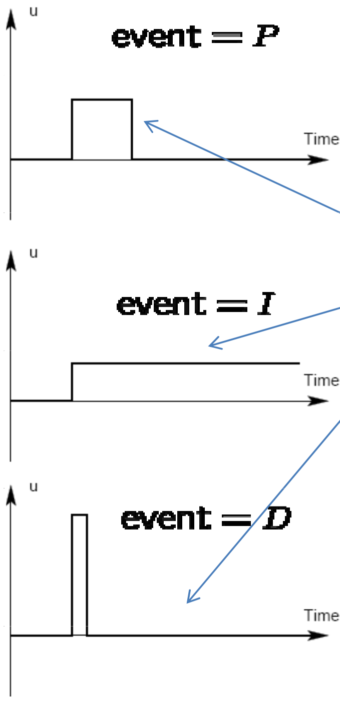




Rabi and J., *WICON, 2008*

Control generator for PID control

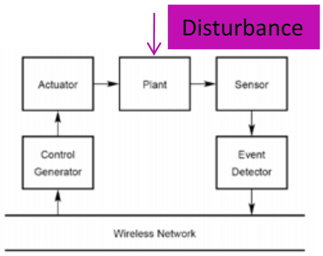


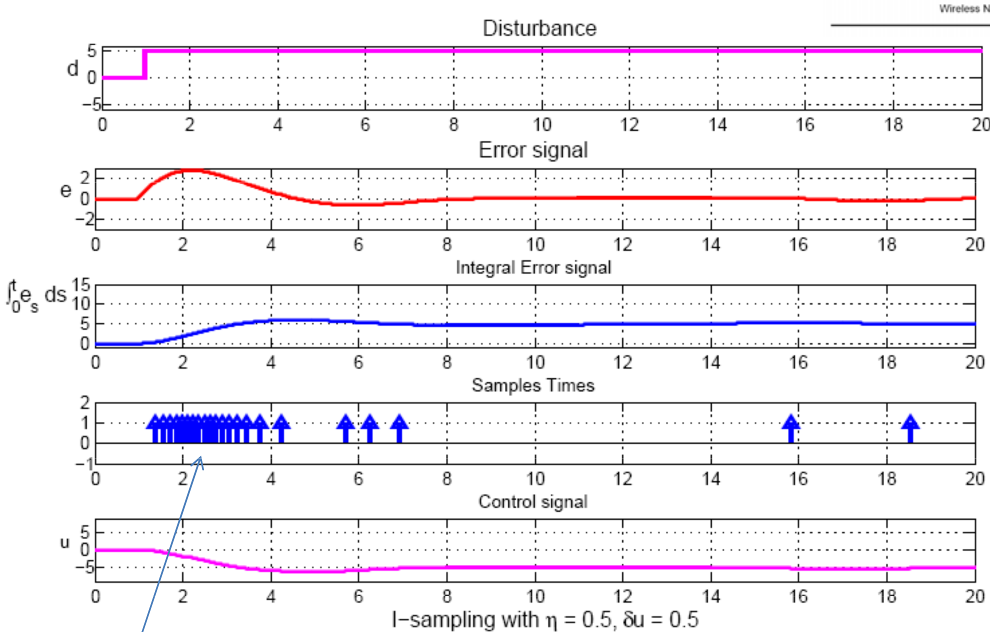


Control alphabet consists of three symbols, which are activated depending on the event

Rabi and J., *WICON, 2008*

Example: Integral control





Communicate only when integral error triggers events

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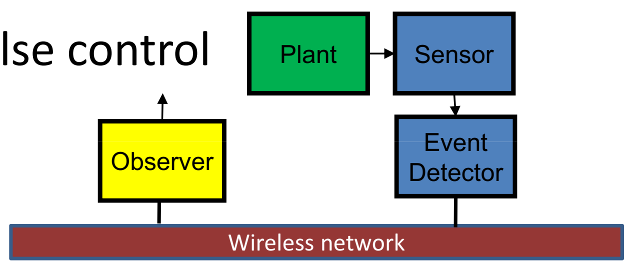
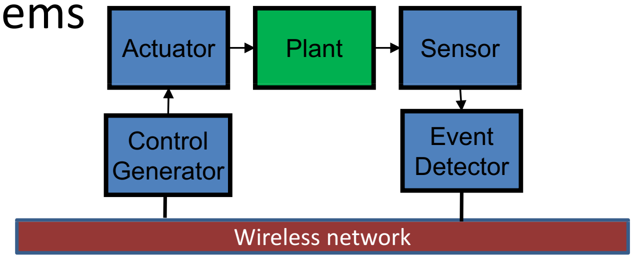
What was not covered?

- Observations with sensor noise
- Linear and nonlinear plant dynamics
  – Adaptive sampling based on policy iterations
- Deterministic setting: Lyapunov stability etc
  – See Reading recommendations
- Event-based estimation
  – Similarities with impulse control



Conclusions

- Wide range of emerging wireless control applications
- Event-based control to support asynchronous networking
  – “If it ain’t broken, don’t fix it” [Åström]
- Event-based control architecture allows network nodes to take local decisions
- Event detector and control generator choice leads to interesting theoretical problems



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

Reading recommendations

Lectures are mainly based on the following material:

- K. J. Åström and B. Bernhardsson, “Comparison of periodic and event based sampling for first-order stochastic systems”, IFAC World Congress, 1999.
- K. J. Åström and B. Bernhardsson, “Comparison of Riemann and Lebesgue sampling for first order stochastic systems”, IEEE CDC, 2002.
- M. Rabi, “Packet based Inference and Control”, PhD thesis, University of Maryland, 2006
- K. J. Åström, “Event based control”, In Analysis and Design of Nonlinear Control Systems: In Honor of Alberto Isidori. Springer Verlag. 2007.
- T. Henningsson, “Event-Based Control and Estimation with Stochastic Disturbances”, Lic Thesis, Lund University, 2008.
- M. Rabi and K. H. Johansson, “Event-triggered strategies for industrial control over wireless networks”, WICON, 2008.
- M. Rabi, K. H. Johansson, and M. Johansson, “Optimal stopping for event-triggered sensing and actuation”, IEEE CDC, 2008.
- M. Rabi and K. H. Johansson, “Optimal stopping for updating controls”, International Workshop on Sequential Methods, 2009.
- M. Rabi and K. H. Johansson, “Scheduling packets for event-triggered control”, ECC, 2009.

Reading recommendations

Stochastic control and optimal stopping:

- Bernt K. Øksendal. Stochastic Differential Equations: An Introduction with Applications. Berlin: Springer, 2003
- Karl Johan Åström, Introduction to Stochastic Control Theory, Dover, New York, 2006. Reprint. Originally published by Academic Press 1970
- Harold J. Kushner, On the optimum timing of observations for linear control systems with unknown initial state, IEEE Trans. Automatic Control, AC-9 (1964), pp. 144–150.
- Goran Peskir and Albert Shiryaev, Optimal stopping and free-boundary problems, Lectures in Mathematics ETH Z¨urich, Birkh¨auser Verlag, Basel, 2006.

Related recent work but in deterministic settings:

- Dimos Dimarogonas, MIT; Maurice Heemels, TUE ; Michael Lemmon, UND; Paulo Tabuada, UCLA; etc.