# Control over Wireless Networks

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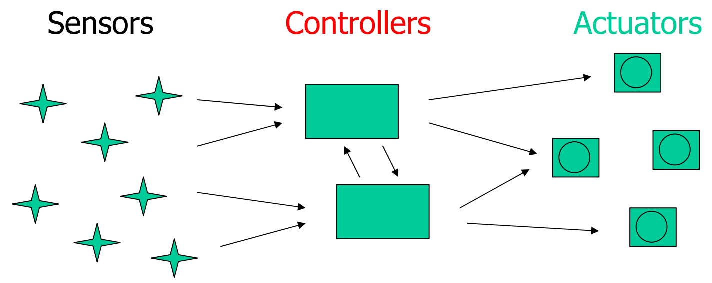
25th Benelux Meeting on Systems and Control
Heeze, The Netherlands, March 13-15, 2006

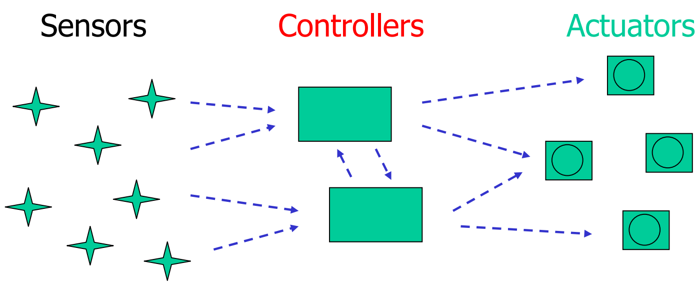
## Wireless control system




A collection of cooperating algorithms (controllers) designed to achieve a set of common goals, aided by interactions with the environment through distributed measurements (sensors) and actions (actuators)

 [Sangiovanni-V., 2005]

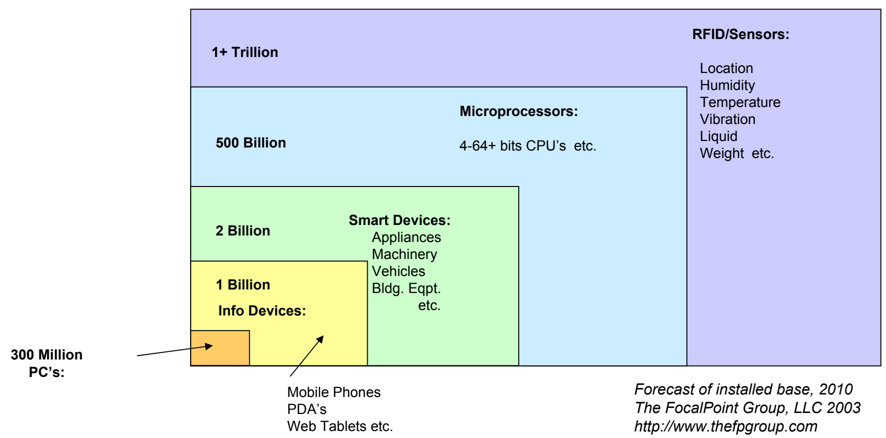
## Wireless control system






## Wireless control systems everywhere

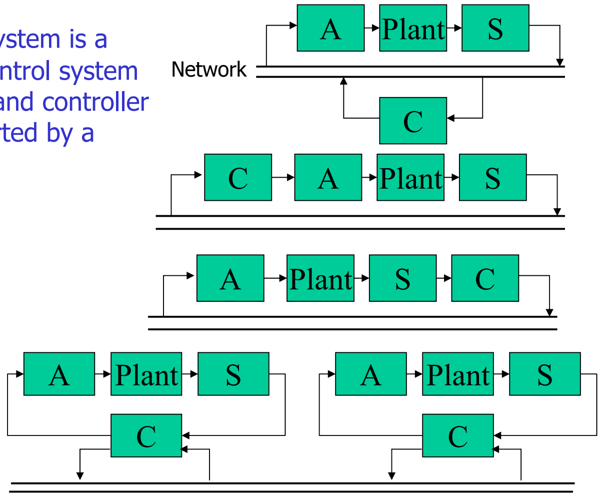
Machine-to-machine device population forecast 2010




*Forecast of installed base, 2010*
*The FocalPoint Group, LLC 2003*
*http://www.thefpgroup.com*

# Feedback control representations

A networked control system is a spatially distributed control system with sensor, actuator and controller communication supported by a network






# Outline: Control over wireless networks

- Motivating examples
- Benefits and barriers of networked control
- Control-aware networking
  - Layered communication models
  - Control of communication resources

**Today**

- Network-aware control
  - Control under limited communication
- Conclusions
- Acknowledgements
- Literature

**Tomorrow**



# Motivation for control over wireless networks

- Wireless industrial automation


- Information networks in vehicles

- Wireless sensor and actuator networks in rescue operations

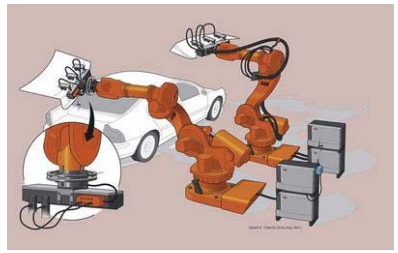


# Wireless industrial automation

- Communication cabling is subject to heavy wear and tear in industry robots and therefore requires frequent maintenance
- Replace wires between robot controller and gripper by wireless communication

*Removing cables undoubtedly saves cost, but often the real cost gains lie in the radically different design approach that wireless solutions permit. […] In order to fully benefit from wireless technologies, a rethink of existing automation concepts and the complete design and functionality of an application is required.*

Jan-Erik Frey, ABB

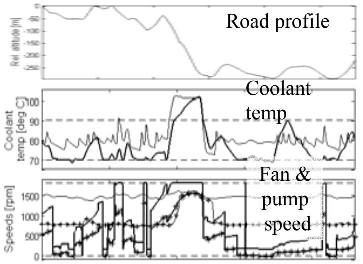


Wireless Actuator Sensor Interface

# Wireless information systems for improved fuel efficiency in vehicles

- Predict road and driving conditions based on emerging wireless information systems
  - E.g., congestion info through RDS, digital maps, GPS
- Control vehicle subsystems to improve fuel efficiency
  - E.g., cruise control, automated gear shifting, auxiliary systems

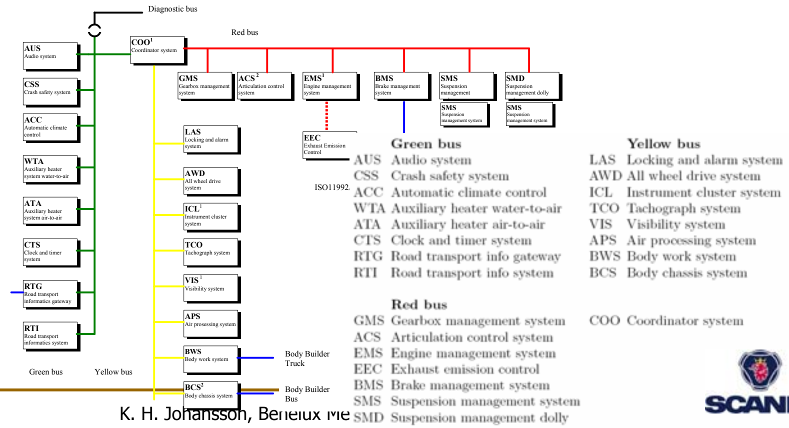

**Example**
Optimal control of cooling system based on road profile ahead and other predicted driver conditions




Benelux Meeting on Systems and Control, 2006 [Pettersson & J, 2006]

# Network architecture of a heavy vehicle

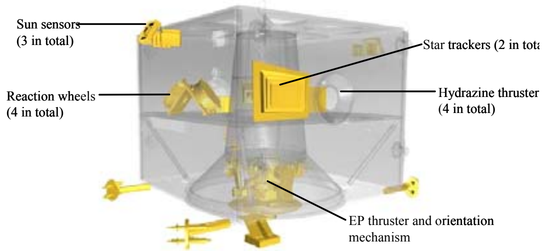
- Architecture based on three controller area networks (CANs)
- Link up to 40 control nodes
- Coloured by criticality




K. H. Johansson, Benelux Me

# Networked control architecture of SMART-1 spacecraft

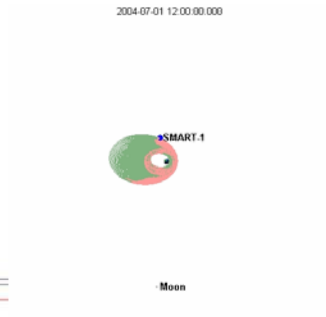
- First European lunar mission, launched Sep 2003

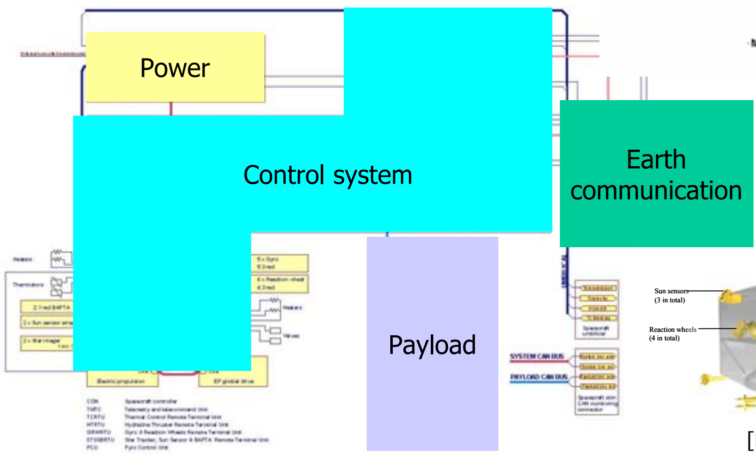



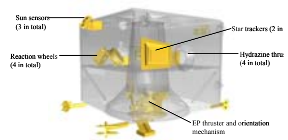

[Bodin, 2005]

# Networked control architecture of SMART-1 spacecraft

- First European lunar mission, launched Sep 2003
- Two CAN busses for control system and for scientific experiments (“payload”)
- Node and communication redundancies



[Bodin, 2005]

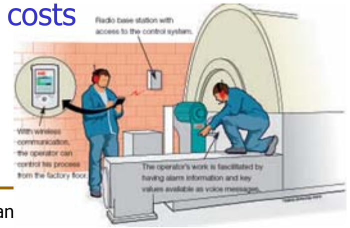
## Wireless sensor and actuator networks in rescue operation for road tunnel fire 2020


- Accident site equipped with a variety of wireless sensor networks
  - Vehicle area networks
  - Body area networks
  - Tunnel networks
- Firefighters and mobile robots use WSNs for making decisions and taking action


## Benefits of wireless networking in control systems

Several advantages with wireless networking control systems:

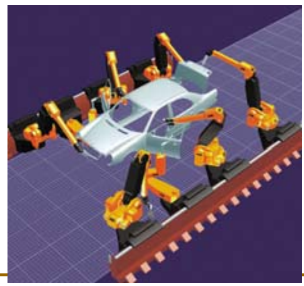

- Added flexibility
  - Sensor and actuator nodes can be placed more appropriately
  - Less restrictive maneuvers and control actions
  - More powerful control through distributed computations
- Reduced installation and maintenance costs
  - Less cabling
  - More efficient monitoring and diagnosis





## Barriers of wireless technology in automation and control

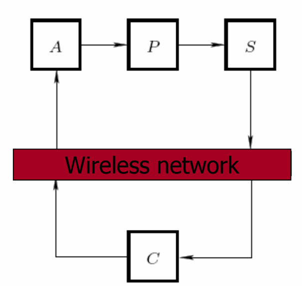
- Complexity
  - Systems designers and programmers need suitable abstractions to hide the complexity from wireless devices and communication
- Reliability
  - Systems should have robust and predictable behaviour despite characteristics of wireless networks
- Security
  - Wireless technology is vulnerable
  - Security mechanisms for control loops





## Influence of wireless communication on closed-loop control performance

- Communication of sensor and actuator data impose uncertainty, disturbances and constraints on control system
- Communication imperfections in single control loop include
  - Delay and jitter
  - Bandwidth limitations
  - Data loss and bit errors
  - Outages and disconnection



# Two complementary approaches to control over wireless networks

**Control-aware networking and communication**

- Modify network protocols and radio links for better real-time performance
  - E.g., CAN from Bosch and IWLAN from Siemens

*Let us discuss these two approaches based on proposals in the literature*

**Network-aware control**

- Modify control algorithms to cope with communication imperfections
  - E.g., control with time-stamped sensor data

Control application

Network

Radio



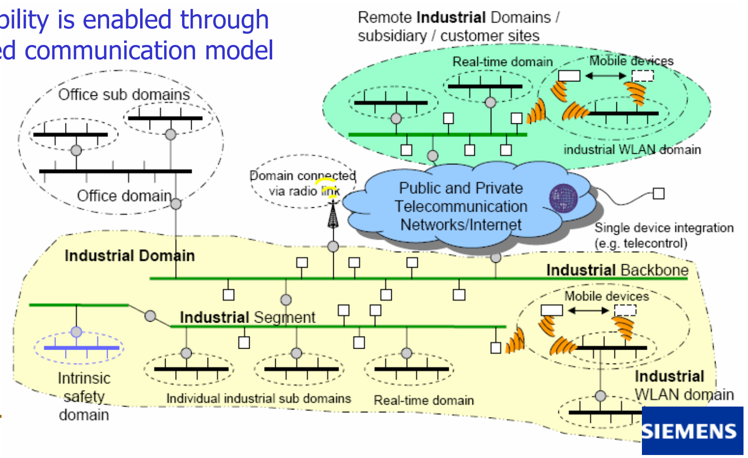
# Outline: Control over wireless networks

- Motivating examples
- Benefits and barriers of networked control
- **Control-aware networking**
  - **Layered communication models**
  - **Control of communication resources**
- Network-aware control
  - Control under limited communication
- Conclusions
- Acknowledgements
- Literature



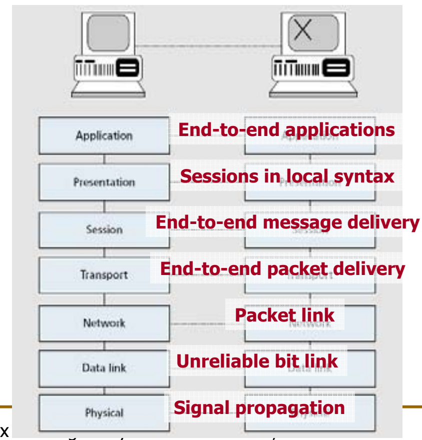
# How to deal with the heterogeneity of communication networks?

- A wide area network (e.g., Internet) is made up by interconnecting several local area networks
- Interoperability is enabled through layered communication model



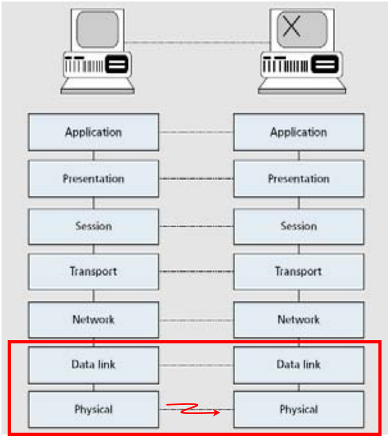

# The OSI model for communication


Open systems interconnection (OSI) model separates functional elements of a network into seven layers



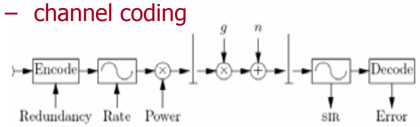
# Control of communication resources

- OSI model has allowed refinement of each layer independently
- Several feedback control mechanisms separate communication layers




**Example**

- Reliable data transfer over wireless link through suitable feedback control of
  - power
  - modulation
  - channel coding

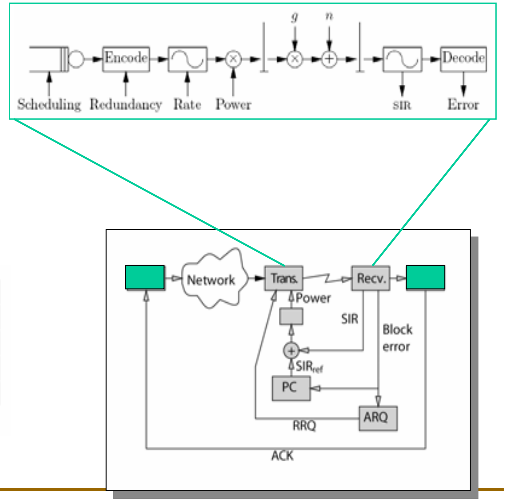


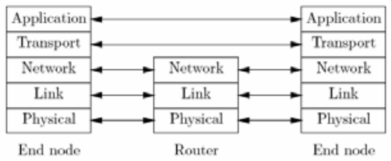



# Cascaded feedback control loops

Cascaded control loops separate lowest communication layers

- Inner and outer power controls
- Link-layer retransmission
- Forward error correction

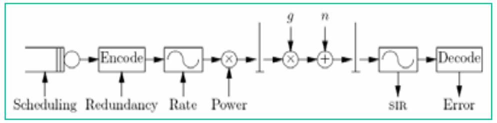


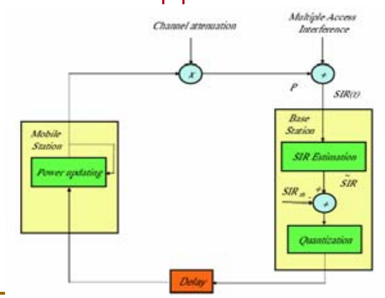

[Möller and J, 2003]

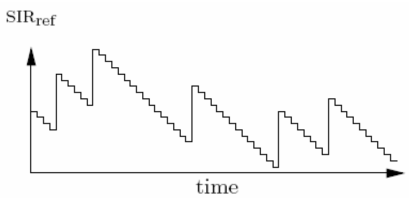


# Power control




- Objective of power control is to provide a good radio channel with minimum energy consumption
- Cascade control system
  - Outer-loop power control sets suitable Signal-to-Interference-Ratio (SIR) reference to avoid losses
  - Inner-loop power control tracks SIR reference





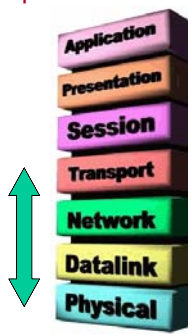

# Cross-layer interaction

- Existing resource control mechanisms are not always able to separate communication layers
- Undesirable cross-layer interaction may lead to performance deterioration
  - E.g., properties of wireless link influence end-to-end network performance

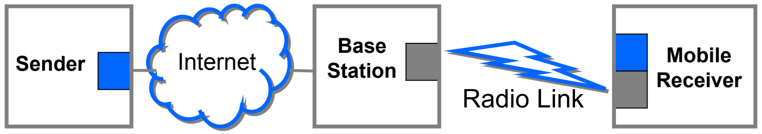
**Example**

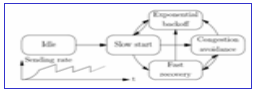
- Wireless Internet

Cross-layer interaction



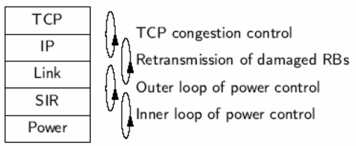
# Cross-layer interaction in wireless Internet



: TCP protocol    : RLC protocol

- Bandwidth and delay variations in radio link erroneously indicate network congestion to TCP
- Results in that TCP reduces the sending rate
- Gives poor link utilization and user experience



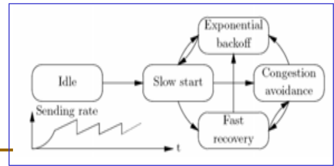

[Möller and J, 2003]



# Interaction between radio link delay and TCP reduces achievable end-to-end bandwidth

$P_{\text{TO}} = P(\text{RTT} > E\{\text{RTT}\} + 4\sigma\{\text{RTT}\})$

- Radio link gives small changes in delay distribution compared to wired link
- Leads to increaced time-out (TO) probability
  - Uniform distribution: $P_{\text{TO}} = 0$
  - Normal distribution: $P_{\text{TO}} \approx 0.006\%$
  - **Wireless link:** $0.2\% \lesssim P_{\text{TO}} \lesssim 1\%$
- TO triggers TCP slow start mechanism, which resets sending rate



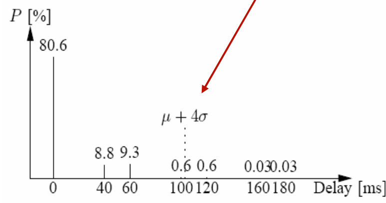




Fig. 6. Original delay distribution

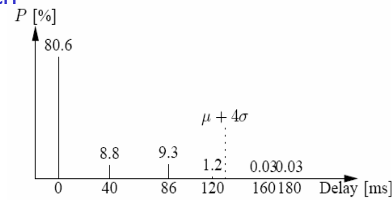



Fig. 7. Optimized delay distribution

[Möller et al., 2004]

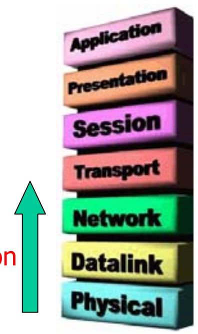


# Cross-layer adaptation

- Cross-layer adaptation is **desirable** signalling between communication layers to improve overall performance
- Application variables may depend on link-layer bandwidth, energy resources etc.

## Examples

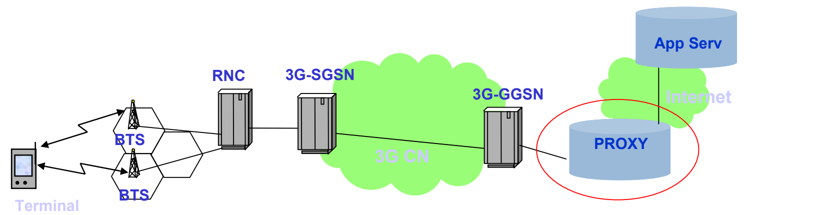
- Adapt control application based on available network resources
- Radio network feedback for wireless Internet






# Radio network feedback for wireless Internet

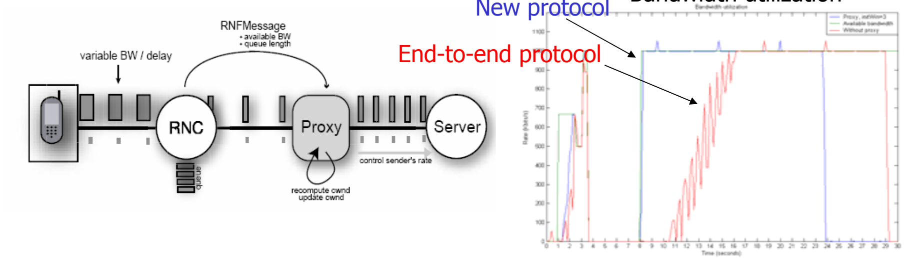
- Proxy between cellular system and Internet adapt sending rate to radio bandwidth variations obtained from radio network controller (RNC)




ERICSSON

## Cross-layer adaptation for wireless Internet

- Hybrid controller in proxy regulates sending rate based on
  - Events generated by radio bandwidth changes obtained from RNC
  - Sampled measurements of queue length in RNC
- Improved time-to-serve-user and link utilization compared to traditional end-to-end protocol




[Möller et al., 2005]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## Summary

- **Motivating examples**
- **Benefits and barriers of networked control**
- **Control-aware networking**
  - **Layered communication models**
  - **Control of communication resources**
- Network-aware control
  - Control under limited communication
- Conclusions
- Acknowledgements
- Literature

**Today**

**Tomorrow**



# Control over Wireless Networks Part II

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25th Benelux Meeting on Systems and Control
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## Two approaches to control over wireless networks

**Control-aware networking and communication**

- Modify network protocols and radio links for better real-time performance etc.

Yesterday

Today

**Network-aware control**

- Modify control algorithms to cope with communication imperfections

## Outline: Control over wireless networks

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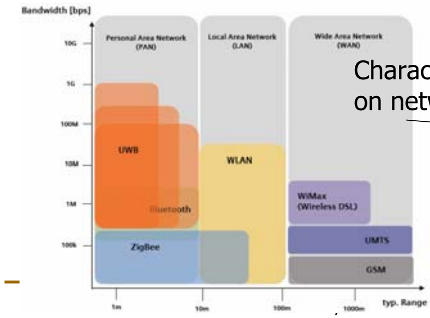
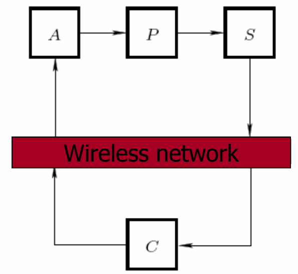
## Network-aware controllers

Modify controller to cope with communication imperfections

- Control under varying network delay
- Control under data loss
- Control under bandwidth limitation
- Control under topology constraints [F. Bullo]




Characteristics depend on network technology

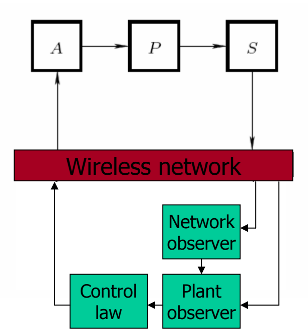





## Network-aware control architecture

- An architecture for control over wireless networks

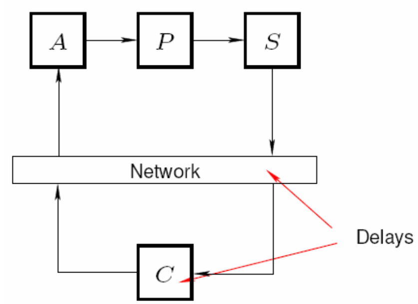
- Estimate network state
  - Network delay
  - Data loss probability
  - Bandwidth



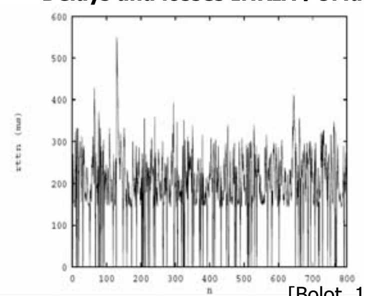



## Control under network delay

- Delays in communication due to buffering and propagation delays
- Delays are bad for control loops (avoid if possible)
- Delays can be fixed or varying, known (measurable) or unknown




**Delays and losses INRIA→UMd**



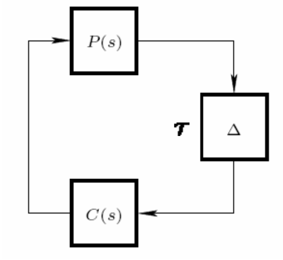

[Bolot, 1993]

- Vast literature, e.g., IFAC Workshop on Time-Delay Systems

# Unknown and fixed time delay

**Nyquist Criterion:** LTI control system with phase margin $\varphi_m$ at cross-over frequency $\omega_c$ is stable, if communication adds <u>fixed</u> time delay

$$\tau < \varphi_m / \omega_c$$





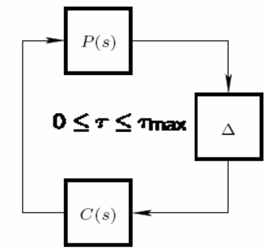

# Unknown and varying time delay

**Theorem:** LTI control system with time-varying delay

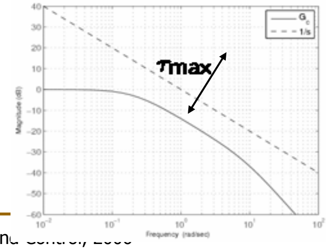
$$0 \le \tau(t) \le \tau_{\max}$$

is stable, if

$$\left| \frac{P(i\omega)C(i\omega)}{1 + P(i\omega)C(i\omega)} \right| < \frac{1}{\tau_{\max}\omega}$$




**Remark:** Closed-loop gain should be small.
Easy to check through Bode plot.

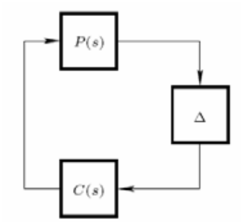


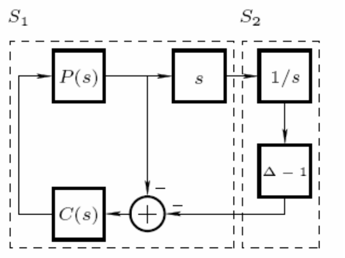

[Kao and Lincoln, 2004]



# Proof

**Redraw block diagram:**




**Small Gain Theorem:** $\gamma(S_1)\gamma(S_2) < 1 \Rightarrow$ stability gives the result with

$$S_1(s) = \frac{sP(s)C(s)}{1 + P(s)C(s)}, \qquad S_2(s) = \frac{e^{-s\tau} - 1}{s},$$

$$\gamma(S_1) = \sup_{\omega \in \mathbb{R}} \left| \frac{\omega P(i\omega)C(i\omega)}{1 + P(i\omega)C(i\omega)} \right|, \quad \gamma(S_2) \le \tau_{\max}$$



# Relation to Nyquist Criterion

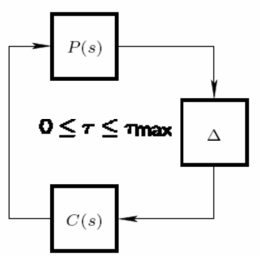
**At $\omega = \omega_c$, we have**

$$\left| \frac{P(i\omega)C(i\omega)}{1 + P(i\omega)C(i\omega)} \right| = \frac{1}{|1 - e^{i\varphi_m}|} \approx \frac{1}{\varphi_m}$$

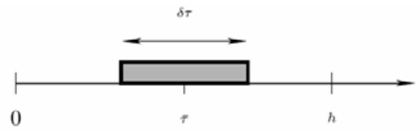
**Theorem inequality imposes**

$$\frac{1}{\varphi_m} < \frac{1}{\tau_{\max}\omega_c}$$

**Corresponds to the Nyquist Criterion for fixed $\tau(t) \equiv \tau_{\max}$**



# Unknown and varying delay jitter




**Jitter $\delta\tau$ is delay variation:**

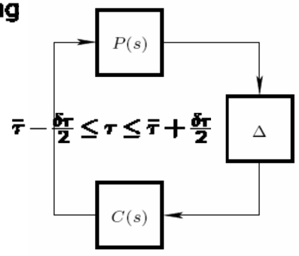
$$\delta\tau = \tau_{\max} - \tau_{\min}$$

**Theorem:** LTI control system with time-varying delay

$$0 \le \bar{\tau} - \frac{\delta\tau}{2} \le \tau(t) \le \bar{\tau} + \frac{\delta\tau}{2} \le h$$

is stable, if

$$\left| \frac{P(i\omega)C(i\omega)}{1 + P(i\omega)C(i\omega)e^{-i\omega\bar{\tau}}} \right| < \frac{\sqrt{2}}{\delta\tau\omega}$$

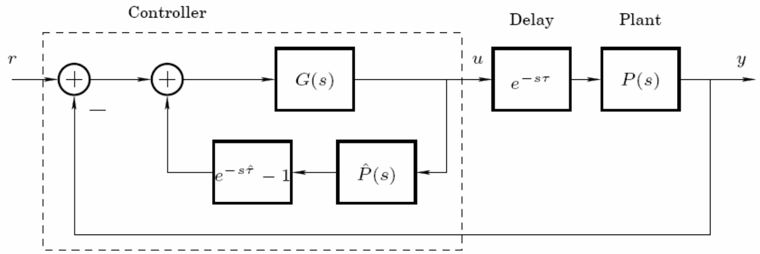



[Kao and Lincoln, 2004]



# Known time delay

Known time delays can be compensated by **Smith predictor**




Closed-loop system with $\hat{P} = P$ and $\hat{\tau} = \tau$

$$y = \frac{PG}{1 + PG} e^{-s\tau} r$$

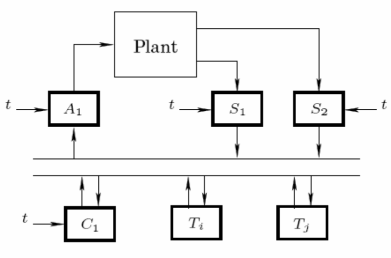
Design controller as if there were no time delay and then implement structure above



# Time stamps and synchronization

**Delays can be estimated from time-stamped data $(y(t), t)$ if nodes are synchronized**

- Major improvement in control performance if delays are measurable (or can be estimated)




**Example**

- CAN is event-triggered and does not give timing guarantees
- TTCAN (Time-triggered communication on CAN) is an extension to the CAN standard targeting the need for time-synchronized nodes

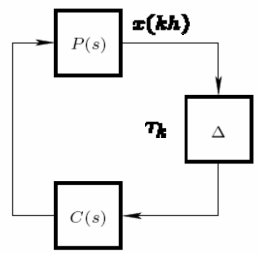


# Compensating known delays: State feedback controller

**Plant with state output $P(s) = (sI - A)^{-1}B$**

**Sensor node sends $x(kh)$ at $t = kh$**

**Control node receives $x(kh)$ at $t = kh + \tau_k$ where $\tau_k = \tau(kh) < h$**




**In control node, compute state feedback**

$$u(kh + \tau_k) = -L\bar{x}(kh + \tau_k)$$

$$\bar{x}(kh + \tau_k) = e^{A\tau_k} x(kh) + \int_{kh}^{kh+\tau_k} e^{A(kh+\tau_k - s)} Bu(s) ds$$

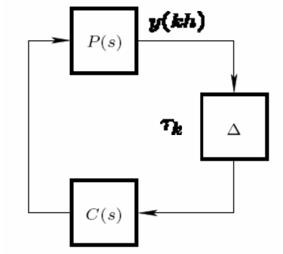
# Compensating known delays: Output feedback controller

Plant with $P(s) = C(sI - A)^{-1}B$

Sensor node sends $y(kh)$ at $t = kh$

Control node receives $y(kh)$ at $t = kh + \tau_k$
where $\tau_k = \tau(kh) < h$

In control node, compute estimate and feedback in the following order:




$$\bar{x}(kh) = \hat{x}(kh) + K[y(kh) - C\hat{x}(kh)]$$

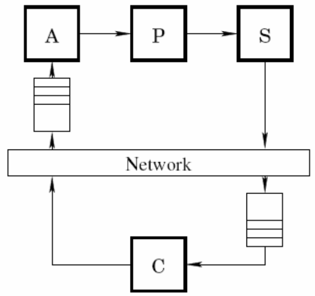
$$\bar{x}(kh+\tau_k) = e^{A\tau_k}\bar{x}(kh) + \int_{kh}^{kh+\tau_k} e^{A(kh+\tau_k-s)}Bu(s)ds$$

$$u(kh+\tau_k) = -L\bar{x}(kh+\tau_k)$$

$$\hat{x}(kh+h) = e^{A(h-\tau_k)}\bar{x}(kh+\tau_k) + \int_{kh+\tau_k}^{kh+h} e^{A(kh+h-s)}Bu(s)ds$$

[Zhang et al., 2001]

# Large delays and out-of-order delivery

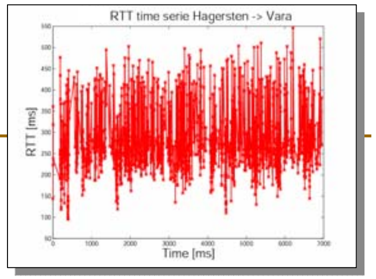



$\tau(kh) \geq h$: Large known delays can be treated as before by extending the estimator state (one dim per extra sampling period delay)

- Buffers can handle out-of-order delivery, but may increase delays
- "Don't wait for late data, but use them to adjust old estimates"



# Delay estimation

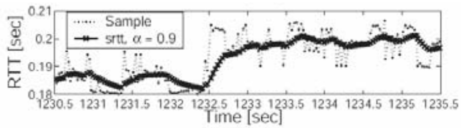



- Internet round-trip time (RTT) data are noisy with piecewise constant average
- Complex network dynamics hard to model
- RTT estimation in TCP:

$$\hat{x}_t = \alpha\hat{x}_{t-1} + (1-\alpha)y_t$$

- Improved estimation thru Kalman filter with hypothesis test (CUSUM filter)

$$\hat{x}_t = \hat{x}_{t-1} + K_t(y_t - \hat{x}_{t-1})$$
$$K_t = \frac{P_{t-1}}{P_{t-1} + R_e}$$
$$P_t = (1 - K_t)P_{t-1} + R_v$$
$$\epsilon_t = y_t - \hat{x}_{t-1}$$
$$g_t = \max(g_{t-1} + \epsilon_t - \xi, 0)$$
$$\delta_t = 1 : R_v \neq 0, \text{alarm if } g_t > h$$
$$\delta_t = 0 : R_v = 0$$
After an alarm, reset $g_t = 0$




[Jacobsson et al., 2004] K. H. Johansson, Benelux Meetin

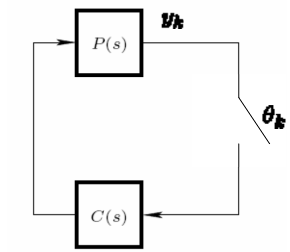
# Control under data loss

**Plant model**

$$x_{k+1} = Ax_k + Bu_k + w_k$$
$$y_k = Cx_k + v_k$$

**Network model**

Stochastic process $\theta_k \in \{0, 1\}$:
$\theta_k = 1$ if $y_k$ reaches its destination
$\theta_k = 0$ otherwise




- Estimation under data loss
- Control under data loss
- Controlled data loss

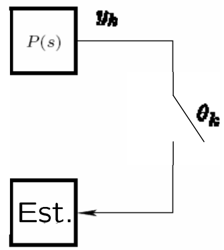
# Optimal estimation under data loss

Optimal estimate $\hat{x}_{k|j} = E[x_k \mid y_\ell, \forall \ell \le j \text{ s.t. } \theta_\ell = 1]$

can be computed as

$$\begin{aligned}
\hat{x}_{k|k} &= \hat{x}_{k|k-1} + \theta_k F_k (y_k - c\hat{x}_{k|k-1}) \\
\hat{x}_{k+1|k} &= A\hat{x}_{k|k} \\
F_k &= \theta_k P_k C^T (C P_k C^T + R_v)^{-1} \\
P_{k+1} &= A P_k A^T + R_w - A F_k (C P_k C^T + R_v) F_k^T A^T
\end{aligned}$$

since $\theta_k$ is indenpendent from $w$ and $v$




**Theorem**

Suppose $\theta_k$ Bernoulli with $p := \Pr[\theta_k = 0]$.

There exists $p_c \in (0, 1]$, such that

$\forall p \ge p_c: \ \exists P_0 \ge 0$ for which $E[P_k]$ is unbounded

$\forall p < p_c$ and $\forall P_0 \ge 0$, $E[P_k]$ is uniformly bounded

[Sinopoli et al., 2004]



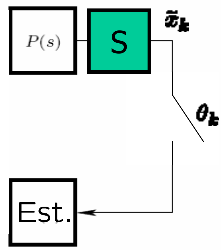
# Estimation using smart sensor

Estimate $\bar{x}_{k|k} = E[x_{k|k} \mid y_\ell, \forall \ell \le k]$ in sensor

Transmit $\bar{x}_{k|k}$ (instead of raw measurement)

Estimate $\hat{x}_{k|j} = E[x_k \mid \bar{x}_{\ell|\ell}, \forall \ell \le j \text{ s.t. } \theta_\ell = 1]$ remotely:

$$\hat{x}_{k+1|k} = (1-\theta_k) A \hat{x}_{k|k-1} + \theta_k A \bar{x}_{k|k}$$




**Theorem**

Suppose $\theta_k$ Bernoulli with $p := \Pr[\theta_k = 0]$.

If $p < 1/\lambda_{\max}(A)$, $\sup_k E\|x_k - \hat{x}_{k|k-1}\|^2 < \infty$

[Hu & Hespanha, 2005]



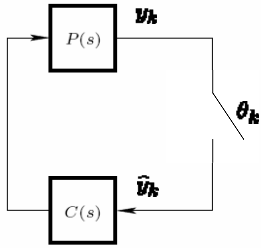
# Control under data loss

Restrict to the case $\tilde{y}_k = \theta_k y_k + (1-\theta_k)\tilde{y}_{k-1}$

Introduce

$$\Phi_\theta = \begin{pmatrix} e^{Ah} + \theta\Gamma(h-\tau)BC & e^{A(h-\tau)}\Gamma(\tau)B + (1-\theta)\Gamma(h-\tau)B \\ \theta C & (1-\theta)I \end{pmatrix}$$

where $\Gamma(s) = \int_0^s e^{At}dt$, $h$ sampling period and $\tau < h$ network delay




**Theorem**

Suppose $\theta_k$ Bernoulli with $p := \Pr[\theta_k = 0]$.

If there exists $Z = Z^T > 0$ such that

$$\begin{pmatrix} Z & \sqrt{p}(\Phi_0 Z)^T & \sqrt{1-p}(\Phi_1 Z)^T \\ \sqrt{p}(\Phi_0 Z) & Z & 0 \\ \sqrt{1-p}(\Phi_1 Z) & 0 & Z \end{pmatrix} > 0$$

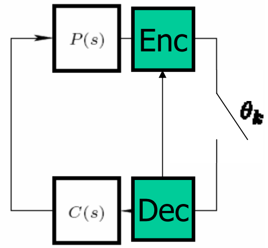
then closed-loop system is exponentially mean-square stable.

[Seiler & Sengupta, 2001]



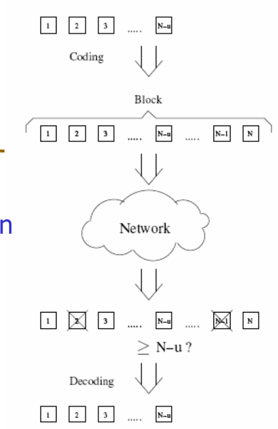
# Controlled data loss

- Compensate data loss through added redundancy
- Base amount of redundancy on feedback information from decoder
  - Adaptive forward error correction

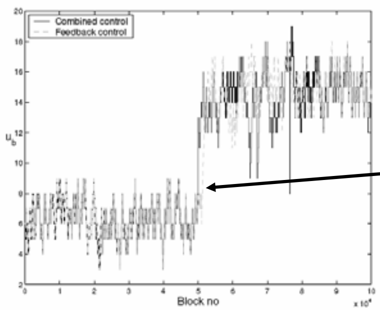


# Controlled data loss

- Compensate data loss through added redundancy
- Base amount of redundancy on feedback information





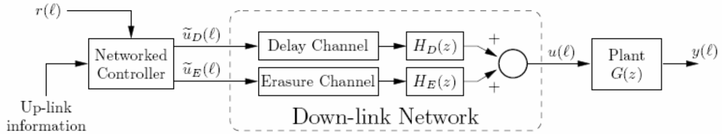



Track network variations through variable redundancy

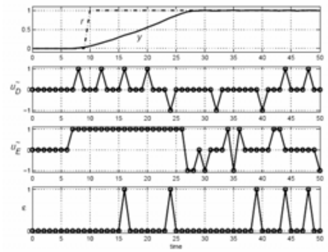
[Flärdh et al., 2005]



# Control under either delay or data loss




- Communication channel with two modes:
  - Error-free transmission, but delay
  - Transmission errors, but no delay



- Receding horizon control optimized under communication constraints

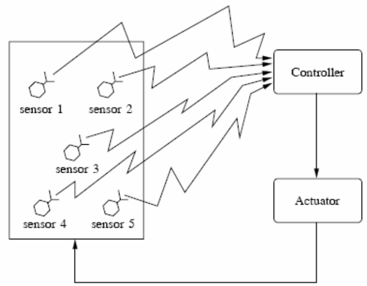
[Quevedo & Goodwin, 2005]



# Control under bandwidth limitation

- Control using wireless sensor network should maximize sensor sleeping to maximize battery lifetime
- Periodically sampled sensors waste resources

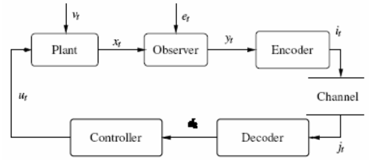
**Idea:** Event-based sensing with optimized use of communication bandwidth



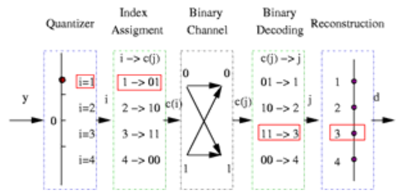



# Encoder-decoder design for event-triggered feedback control over bandlimited channels

- Optimize closed-loop performance based on plant model and disturbance statistics

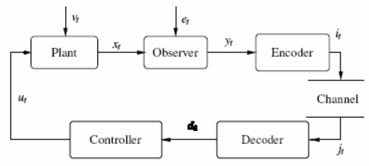



- Model of communication system

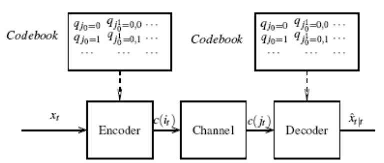


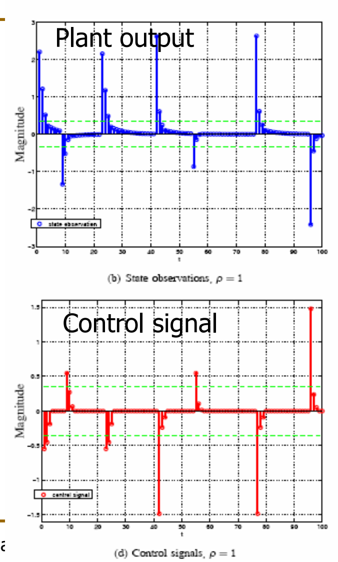

[Bao et al., 2006]

## Encoder-decoder design for event-triggered feedback control over bandlimited channels




- Train encoder and decoder through sequential Monte Carlo estimation




[Bao et al., 2006]



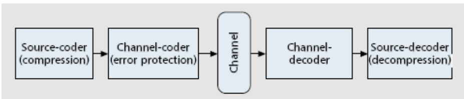
## Outline: Control over wireless networks

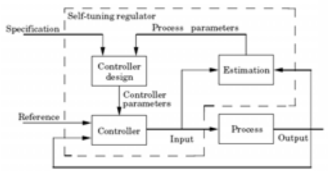
- Motivating examples
- Benefits and barriers of networked control
- Control-aware networking
  - Layered communication models
  - Control of communication resources
- Network-aware control
  - Control under limited communication
- **Conclusions**
- Acknowledgements
- Literature

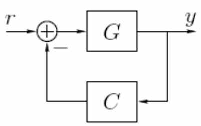


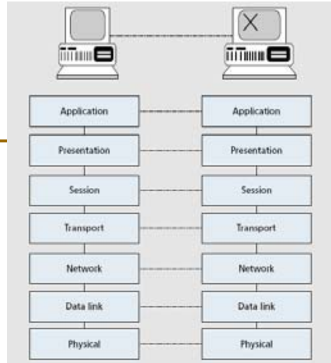
## An open question on system abstraction

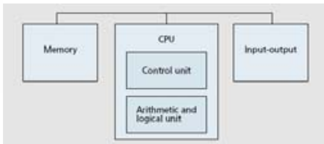
Classical abstractions in systems design:



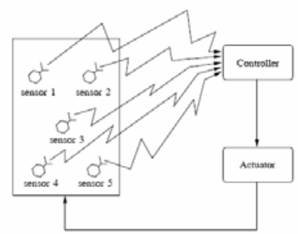




What is a suitable system abstraction to support the design of emerging complex wireless control systems?

 [Kawadia & Kumar,2005]

## Conclusions

- Control over wireless networks has a rapidly growing application domain, e.g., industrial automation, vehicles
- Several open research problems related to complexity, reliability and security
- A need for an integrated approach:
  - Control-aware networking
  - Network-aware control
- Challenge traditional approaches in control and communication theory




Updated slides and other material at
**http://www.ee.kth.se/~kallej**

# Acknowledgements

Presented work was done together with colleagues and students at KTH:

- Lei Bao, Carlo Fischione, Oscar Flärdh, Håkan Hjalmarsson, Krister Jacobsson, Mikael Johansson, Niels Möller, Niklas Pettersson, Mikael Skoglund

Financially supported by

- Swedish Research Council
- Swedish Foundation for Strategic Research
- Swedish Programme Council for Vehicle Research
- European Commission IST 6th Framework Programme
  - RUNES Integrated Project
  - HYCON Network of Excellence

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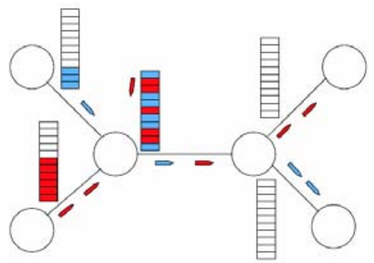
# Network models

- Communication networks are traditionally modelled as either
  - an event-driven discrete packet delivery, or
  - a time-driven continuous data flow

**Packet model**



**Fluid model**