1st HYCON PhD School on Hybrid Systems

www.unisi.it

www.ist-hycon.org

Hybrid Control and Communication

Karl Henrich Johansson

KTH Stockholm, Sweden

kallej@s3.kth.se

HYSCOM

IEEE CSS Technical Committee on Hybrid Systems

Information Society Technologies

Siena, July 19-22, 2005 - Rectorate of the University of Siena

Hybrid Control and Communication

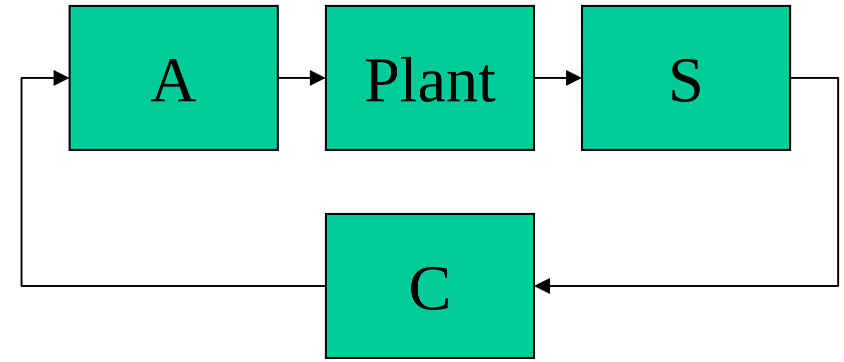
Karl H. Johansson
Department of Signals, Sensors and Systems
Royal Institute of Technology
Stockholm, Sweden
www.s3.kth.se/~kallej

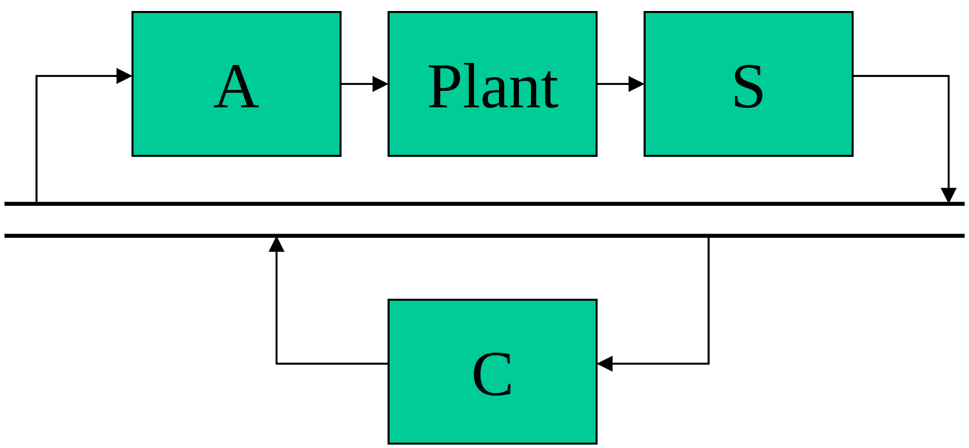
Outline

- Lecture I: Control under communication constraints
  - Motivating applications
  - Communication constraints
  - Compensation for delay and loss
  - Integrated design of control and communication
  - References
- Lecture II: Hybrid control of communication systems
  - Packet-switched networks
  - Hybrid model of congestion control
  - References
- [Lecture III (by L. Palopoli): Stabilization of quantized systems]

Lecture I:
Control under communication constraints

- Classical control theory are based on perfect exchange of information
- Modern control systems are often networked
  + added flexibility
  + cheaper implementation
- Sensor and actuator data are then transmitted over a shared network resource
  – added uncertainty
  – higher complexity



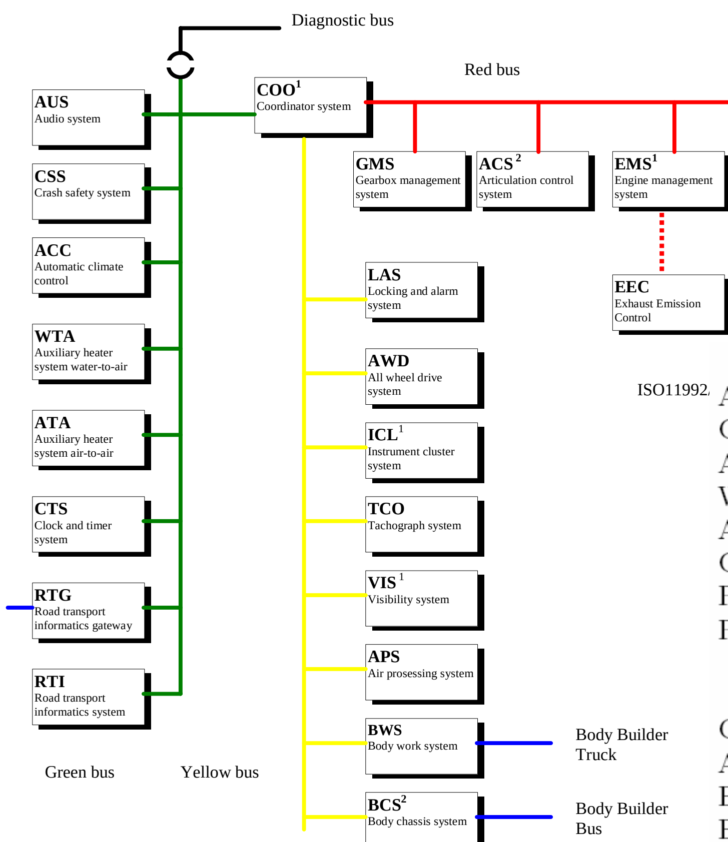


Motivating applications

- Scania truck
- Volvo XC90
- SMART-1 spacecraft
- Power control in wireless system
- Congestion control in communication network

Networked control architecture of a Scania truck

- Control units connected through 3 controller area networks (CANs) coloured by criticality
- CAN is a standard introduced by Bosch 1986

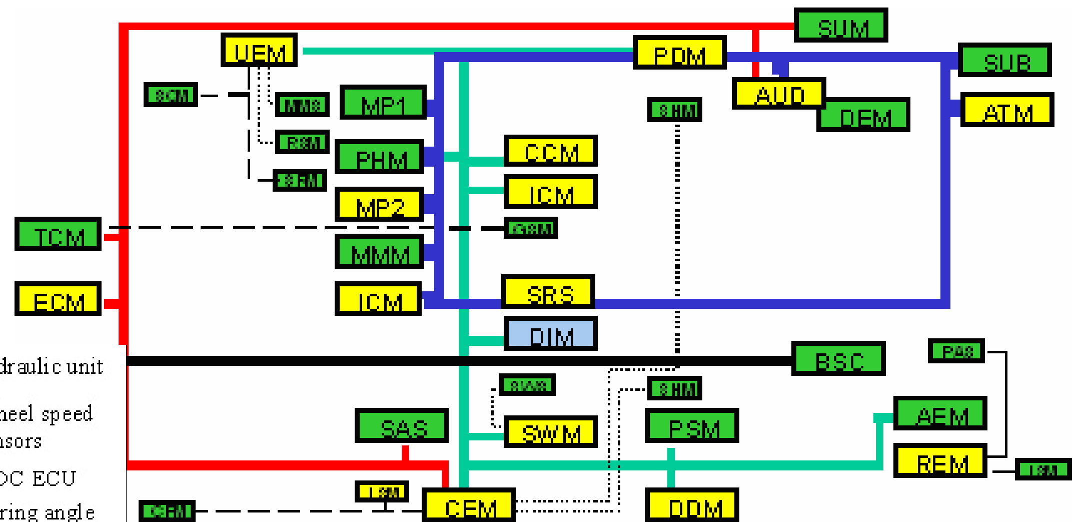


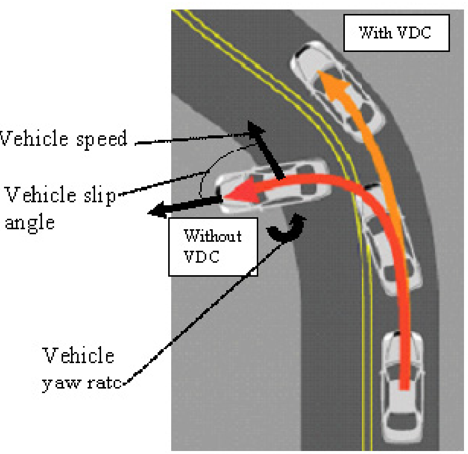
Green bus		**Yellow bus**	
AUS	Audio system	LAS	Locking and alarm system
CSS	Crash safety system	AWD	All wheel drive system
ACC	Automatic climate control	ICL	Instrument cluster system
WTA	Auxiliary heater water-to-air	TCO	Tachograph system
ATA	Auxiliary heater air-to-air	VIS	Visibility system
CTS	Clock and timer system	APS	Air processing system
RTG	Road transport info gateway	BWS	Body work system
RTI	Road transport info system	BCS	Body chassis system

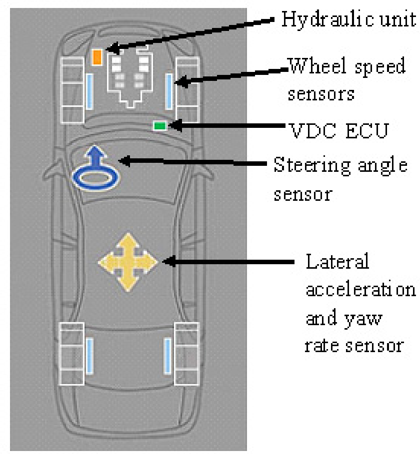
Red bus			
GMS	Gearbox management system	COO	Coordinator system
ACS	Articulation control system		
EMS	Engine management system		
EEC	Exhaust emission control		
BMS	Brake management system		
SMS	Suspension management system		
SMD	Suspension management dolly		

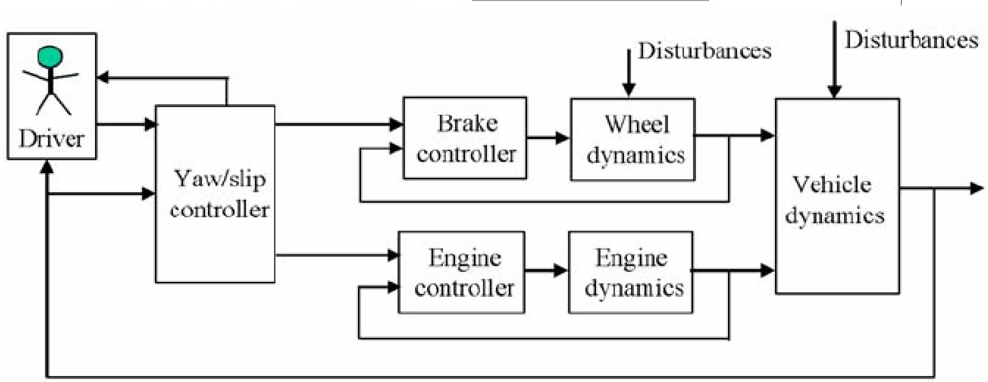
Networked control architecture of a Volvo XC90

- 3 CAN networks connect up to 40 control units
- Example of control system using CAN is vehicle dynamics control (electronic stability program)





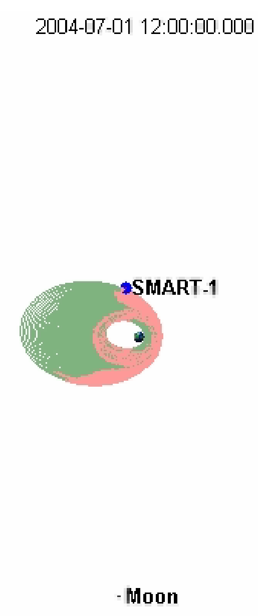


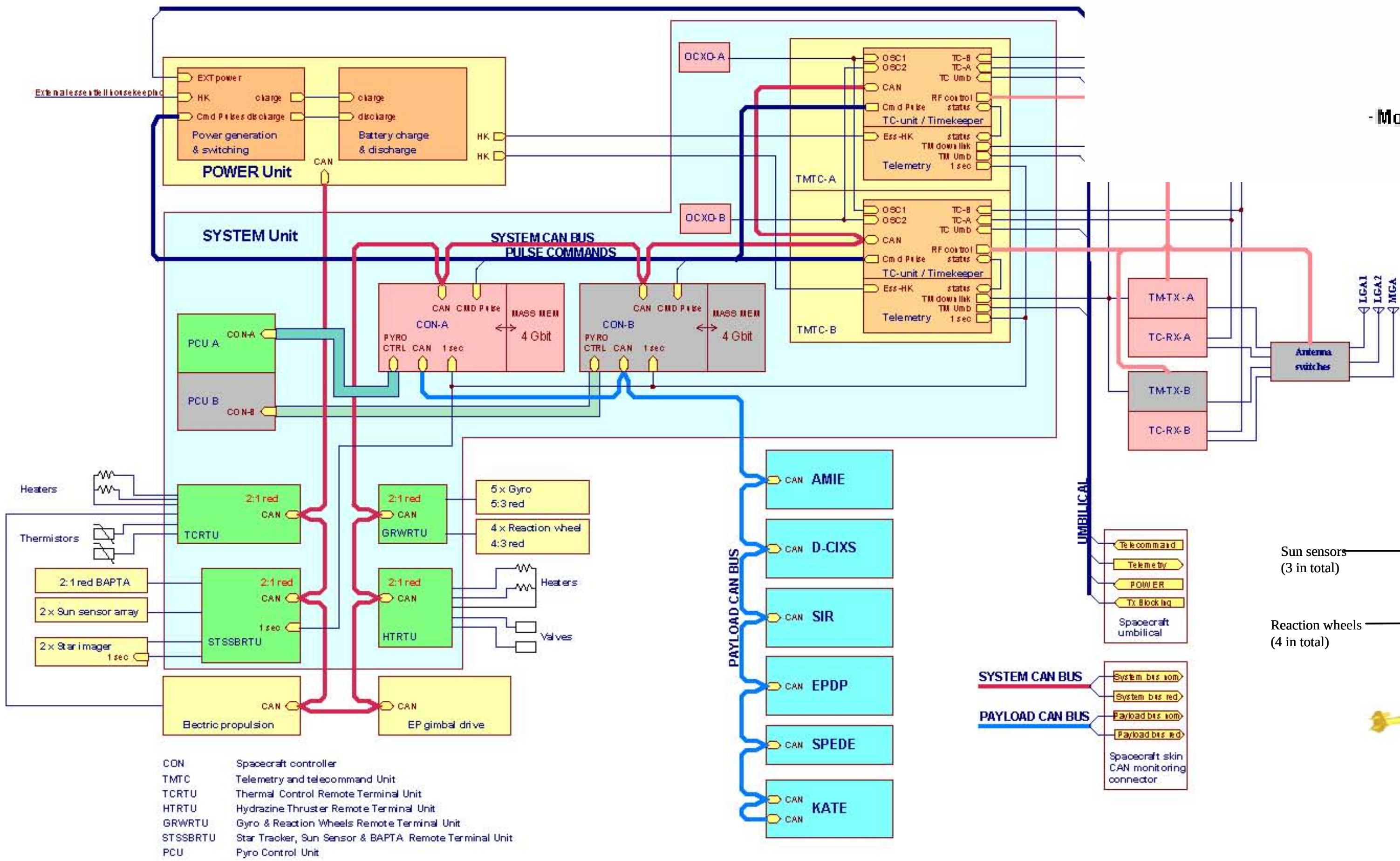


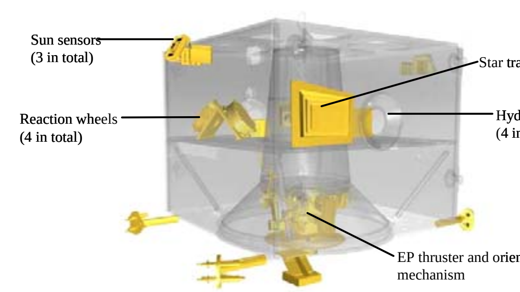
	Powertrain and chassis		Body electronics
TCM	Transmission control module	CEM	Central electronic module
ECM	Engine control module	SWM	Steering wheel module
BCM	Brake control module	DDM	Driver door module
BSC	Body sensor cluster	REM	Rear electronic module
SAS	Steering angle sensor	SWM	Steering wheel module
SUM	Suspension module	DDM	Driver door module
AUD	Audio module	PDM	Passenger door module
		REM	Rear electronic module
	Infotainment/Telematics	CCM	Climate control module
MP1,2	Media players 1 and 2	ICM	Infotainment control
PHM	Phone module	UEM	Upper electronic module
MMM	Multimedia module	DIM	Driver information module
SUB	Subwoofer	AEM	Auxiliary electronic
ATM	Antenna tuner module		

Networked control architecture of the SMART-1 spacecraft

- First European lunar mission, launched Sep 2003
- CAN networks for control system ("system") and for scientific experiments ("payload")
- Node and communication redundancies

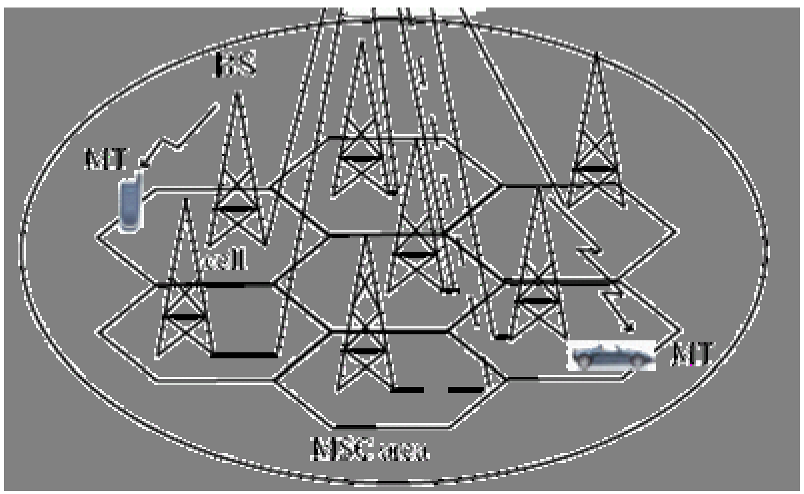


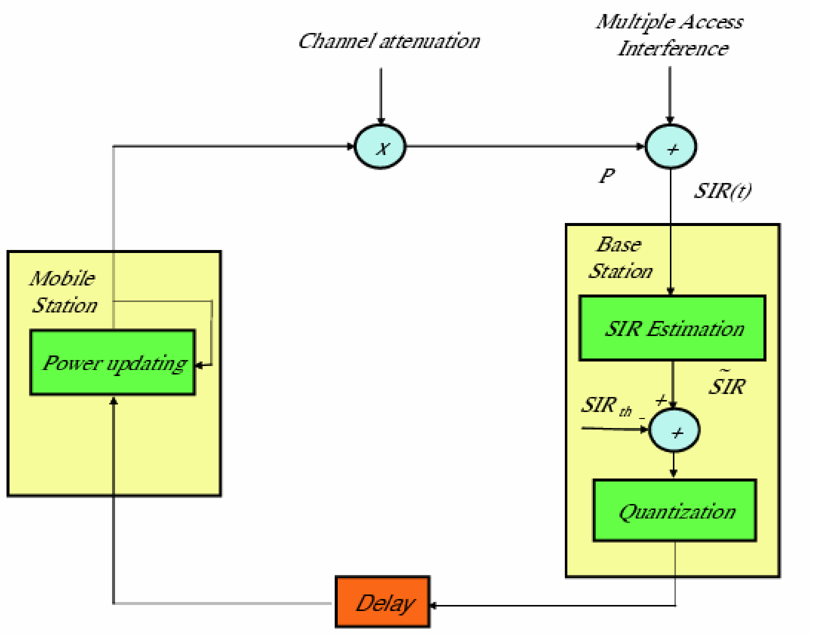




Distributed power control in cellular systems

- Power control in each mobile station tries to keep signal-to-interference ratio (SIR) at a threshold value
- Disturbances from channel fluctuations and interfering traffic
- Control in mobile station based on quantized estimate of SIR communicated from base station

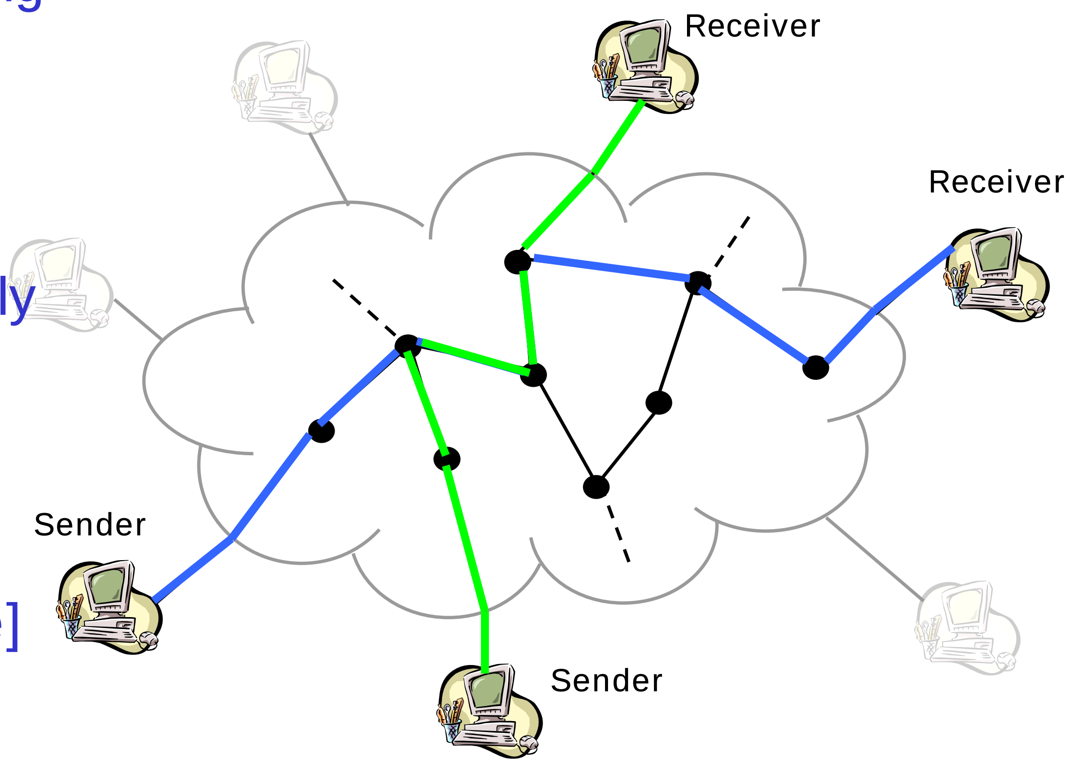




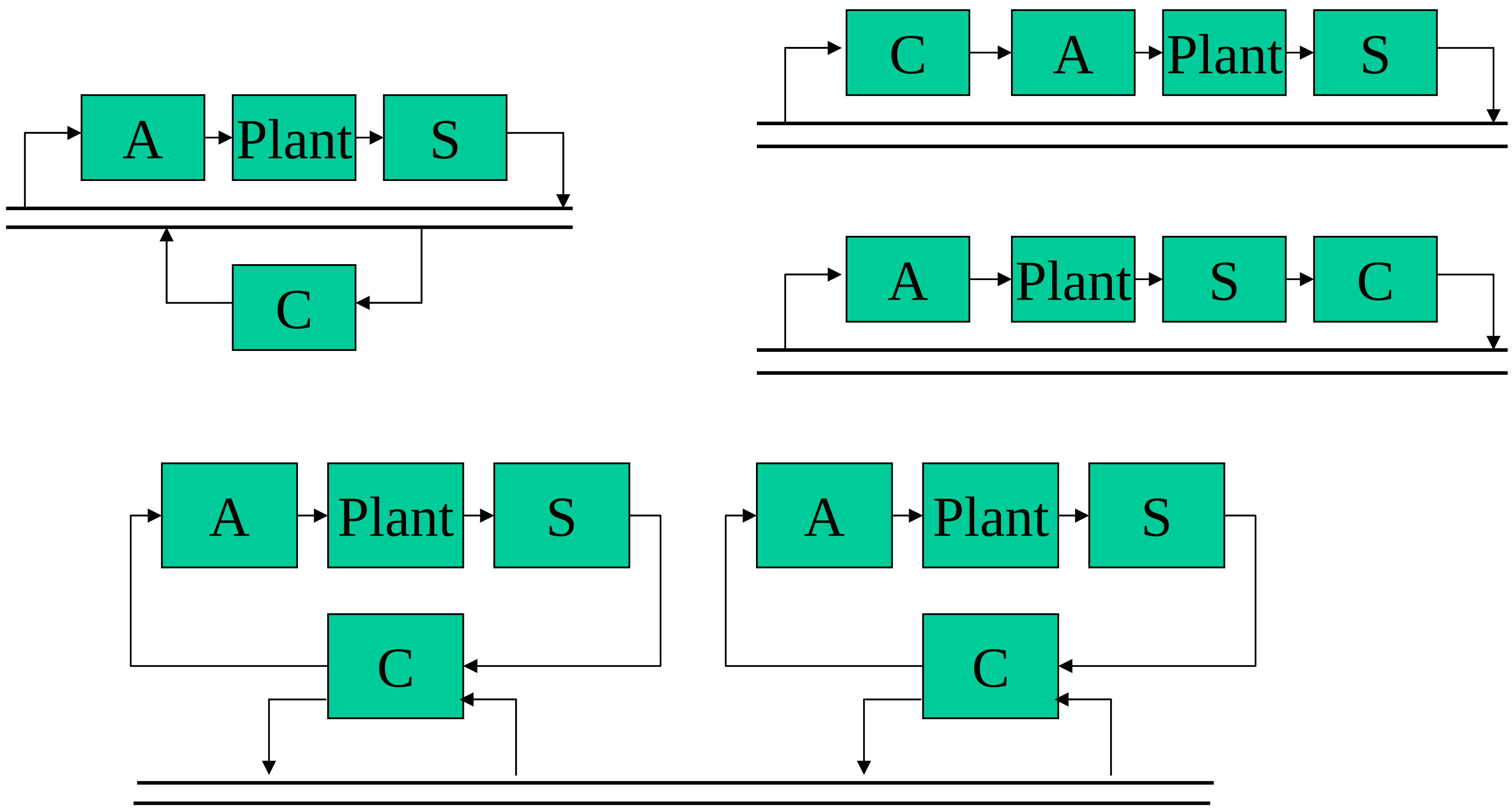
Congestion control in packet-switched data communication network

- Each sender regulates sending rate based on congestion information from receiver
- Variations in available bandwidth and traffic load
- Congestion indicated implicitly through missing acknowledgement packets
- Quantized control command

[Discussed in detail next lecture]

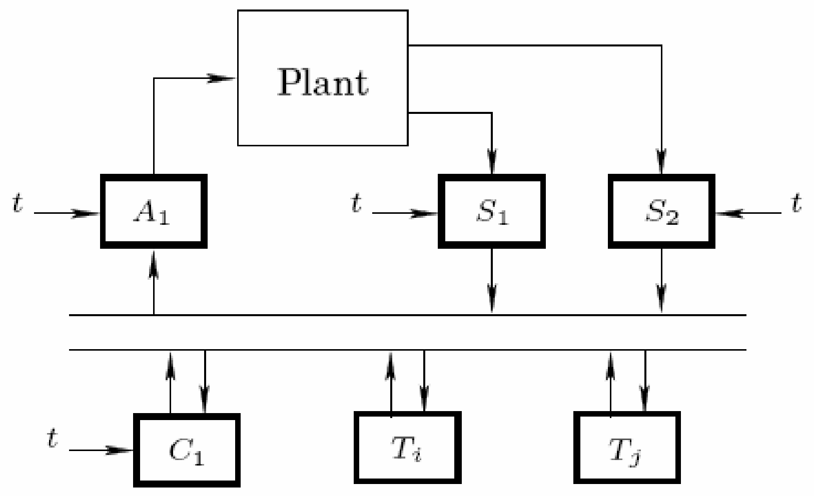


Examples of networked control architectures



What is hybrid in networked control?

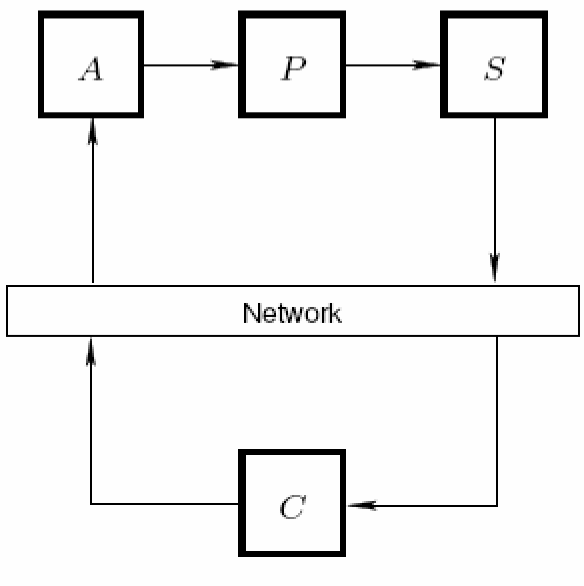
- Networked control systems are inherently hybrid, not only because interaction of physical plant and computer control, but also because they have
  - mixture of event- and time-triggered communication protocols
  - asynchronous network nodes (no global clock)
  - quantized sensor data to limit network traffic
  - symbolic control commands to simplify design and operation
- Now on we mainly discuss modelling and compensating some communication constraints, cf., Mitter's lecture



Control with constrained communication

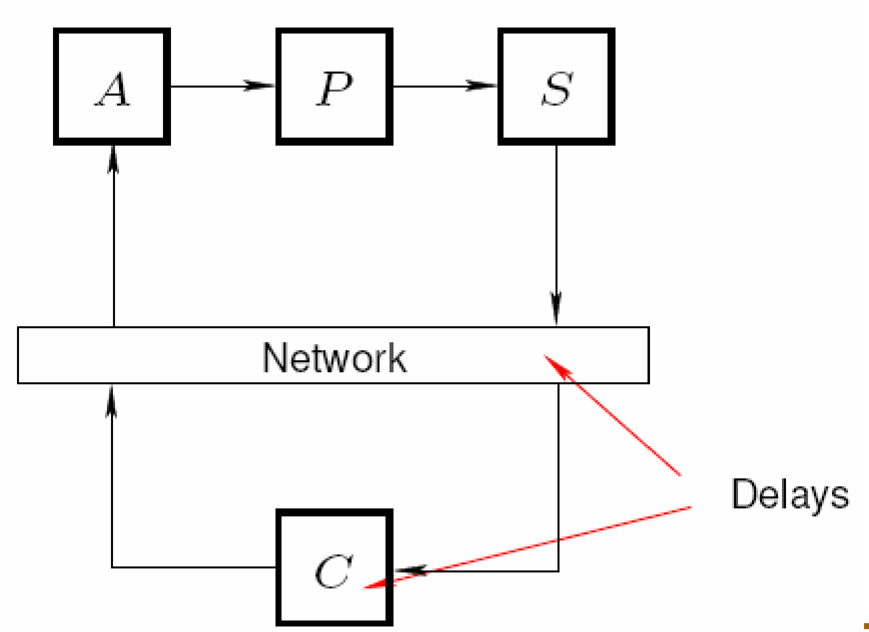
- Limitations in the communication of sensor and actuator data impose constraints on the control system

- Communication imperfections include
  - Delay and jitter
  - Quantization [Lecture by Palopoli]
  - Packet loss
  - Bit error
  - Outage (lost connection)



Time delays

- 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
- Data loss can be interpreted as infinity delay

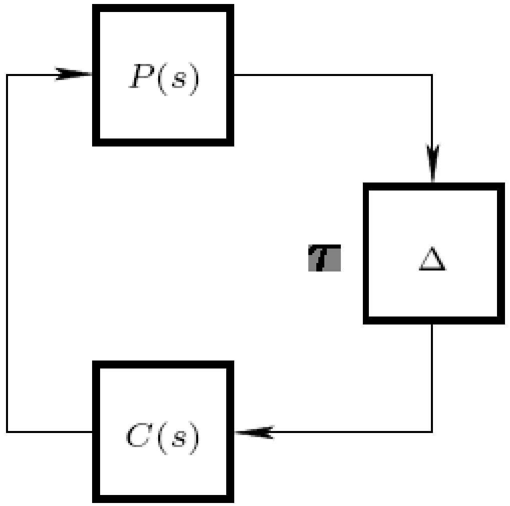


Unknown and fixed time delay

Theorem: LTI feedback control system with phase margin φ_m at cross-over frequency ω_c is stable, if communication adds fixed time delay

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

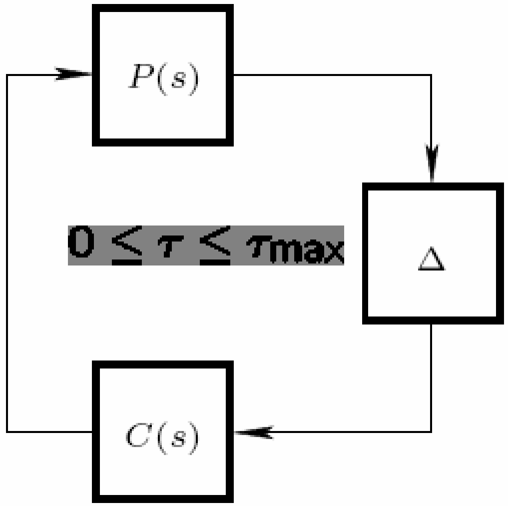
Proof: Nyquist Criterion



Unknown and varying time delay

Theorem [Lincoln]: LTI feedback control system with time-varying delay $0 \leq \tau(t) \leq \tau_{\max}$ is stable, if

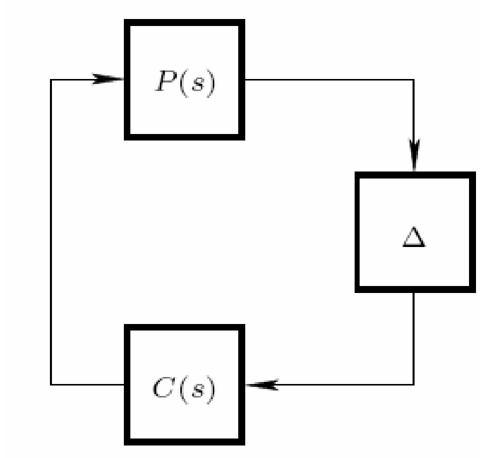
$$\left|\frac{P(i\omega)C(i\omega)}{1+P(i\omega)C(i\omega)}\right| < \frac{1}{\tau_{\max}\omega}$$

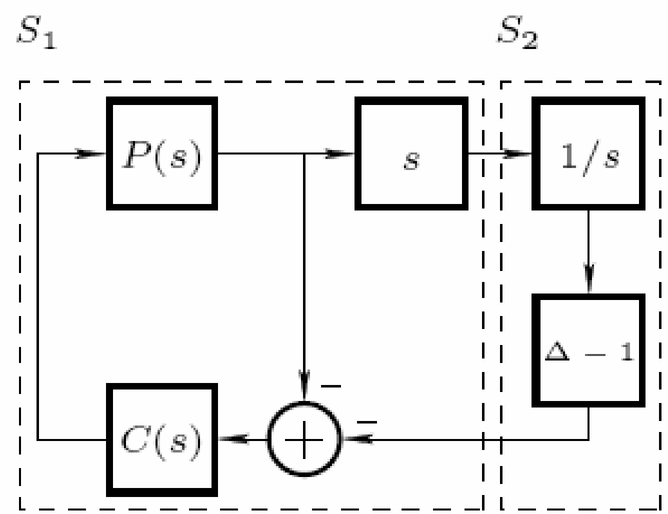


Remark: Closed-loop gain needs to be sufficiently small.
Easy to check through Bode plot.

Proof

Redraw block diagram:





Small Gain Theorem: $\gamma(S_1)\gamma(S_2) < 1 \Rightarrow$ stability

gives the result with

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

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

Relation to Nyquist Criterion

At $\omega = \omega_c$, we have

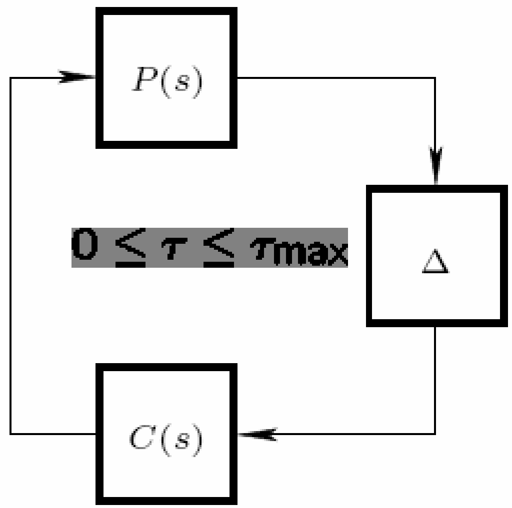
$$\left|\frac{P(i\omega)C(i\omega)}{1+P(i\omega)C(i\omega)}\right| = \frac{1}{|1-e^{i\varphi_m}|} \approx \frac{1}{\varphi_m}$$

Lincoln inequality imposes

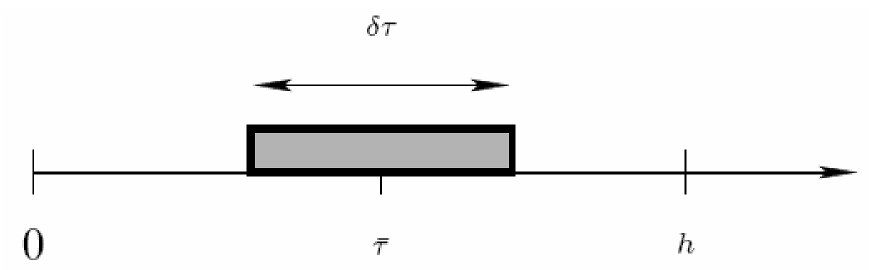
$$\frac{1}{\varphi_m} < \frac{1}{\tau_{\max}\omega_c}$$

Corresponds to the Nyquist Criterion

for fixed $\tau(t) \equiv \tau_{\max}$



Unknown and varying delay jitter



Jitter $\delta\tau$ is delay variation:

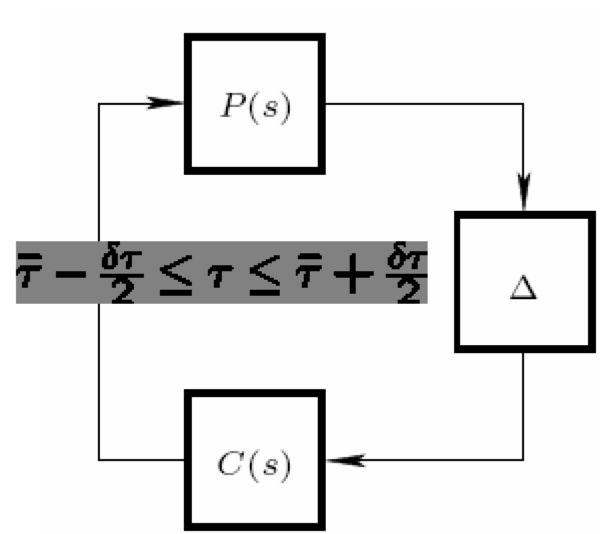
$$\delta\tau = \tau_{\max} - \tau_{\min}$$

Theorem [Lincoln]: LTI feedback control system with time-varying delay

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

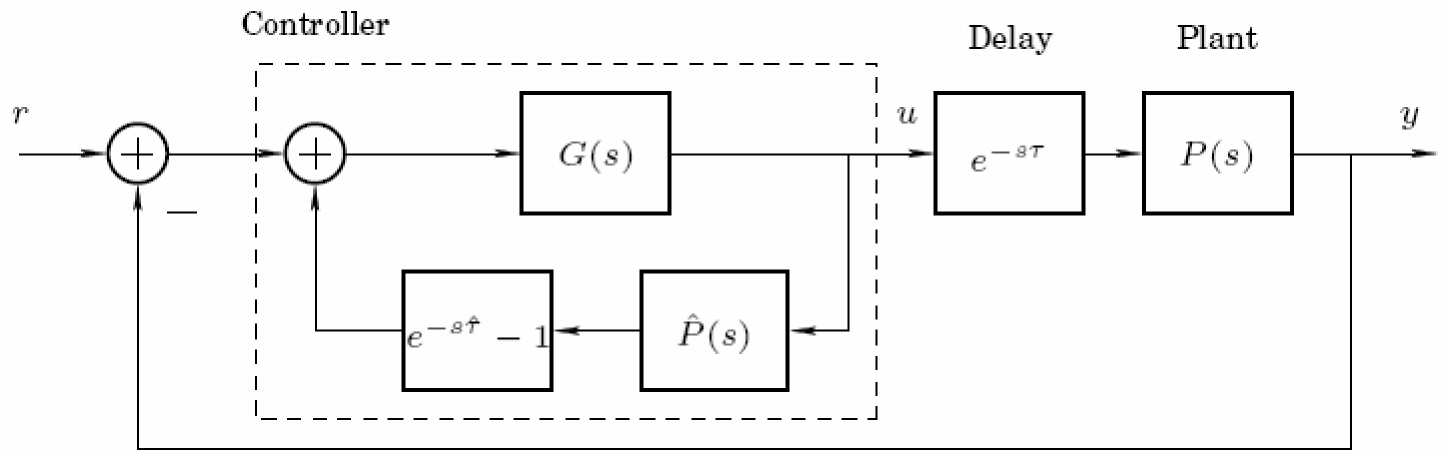
is stable, if

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



Known time delay

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



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

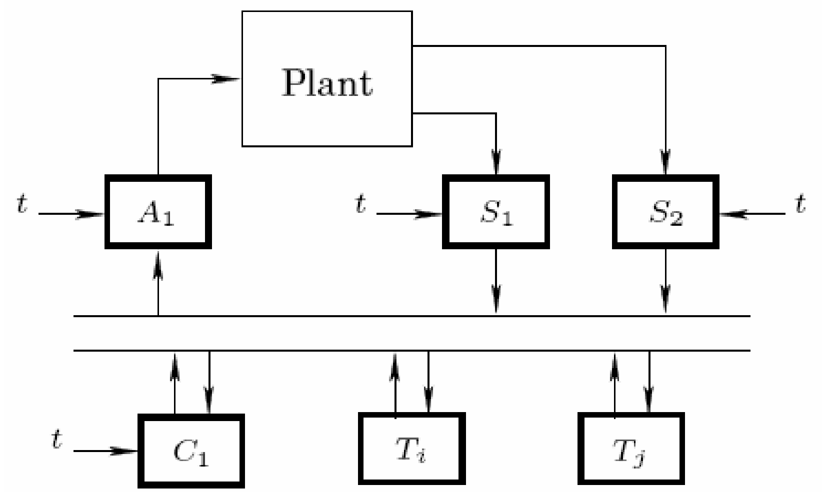
$$y = \frac{PG}{1 + PG} e^{-s\tau} r$$

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

Time delay estimation

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

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



Example

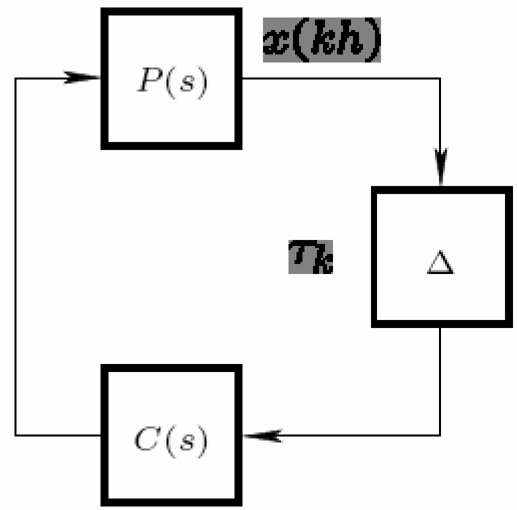
- CAN protocol (discussed earlier) is event-triggered and does not give timing guarantees in general
- TTCAN (Time-triggered communication on CAN) is an extension to the CAN standard targeting the need from sampled-data control

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 $\tau_k = \tau(kh) < h$

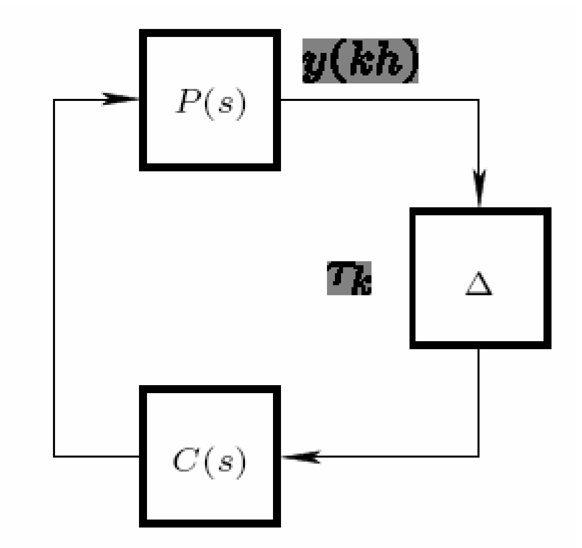


In control node, compute state feedback

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

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

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:

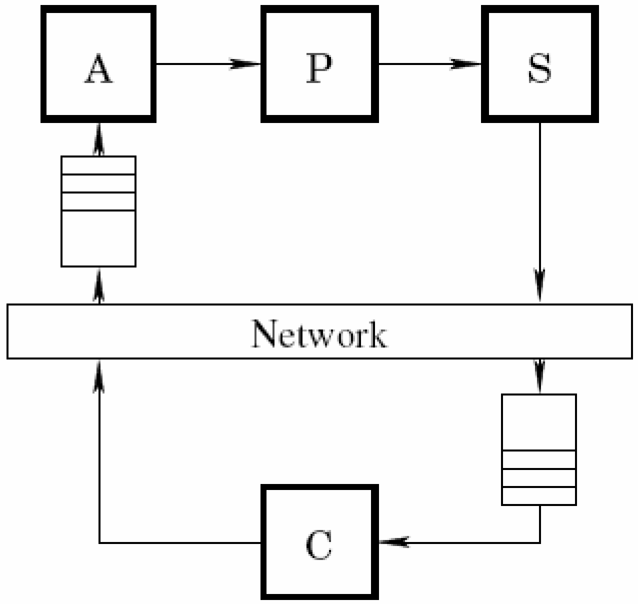
$$\bar{x}(kh) = \hat{x}(kh) + K[y(kh) - C\hat{x}(kh)]$$

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

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

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

Large delays and out-of-order delivery



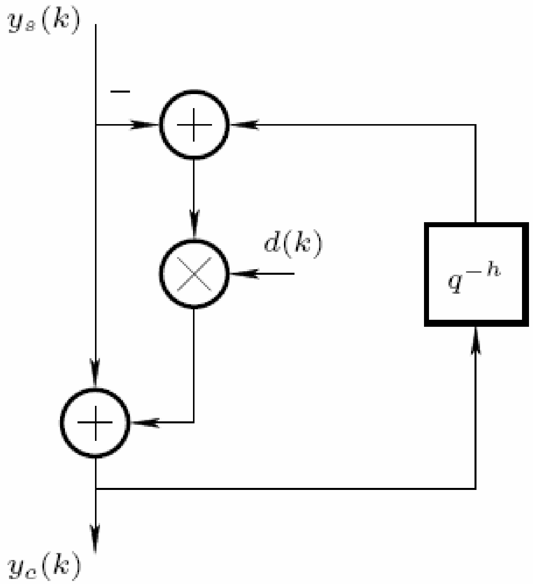
$\tau(kh) \geq h$: Large known delays can be treated as before by extending the estimator state (one dim per extra sampling period delay)

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

Packet loss

Channel between sensor node and control node modelled through stochastic binary variable $d(k)$:

$$d(k) = \begin{cases} 1, & \text{lost packet } k \\ 0, & \text{no loss} \end{cases}$$



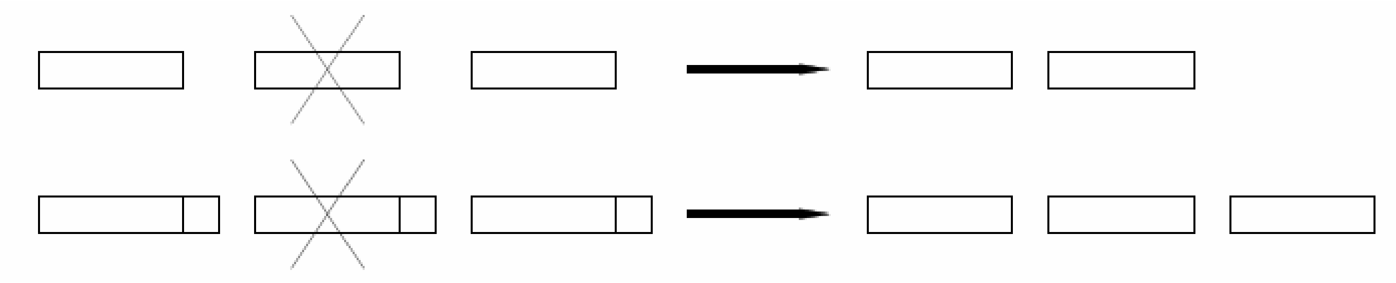
Modify traditional observer; simplest case:

$$\hat{x}(k+1) = \Phi\hat{x}(k) + \Gamma u(k) + \begin{cases} K[y(k) - C\hat{x}(k)], & d(k) = 0 \\ 0, & d(k) = 1 \end{cases}$$

- Can be hard to handle packet loss: when decide that $d(k) = 1$?
  - E.g., TCP uses TimeOut variable to decide when a packet is lost
- It can be better to drop data, than use old information for control

Bit errors and outages

- **Bit errors** are due to rapid variations in the physical channel
- Unlikely in wired systems, but important in wireless systems
- Compensation through forward error correction (coding)



- **Outages** are sudden events when connection is lost
- A severe problem in most wireless systems

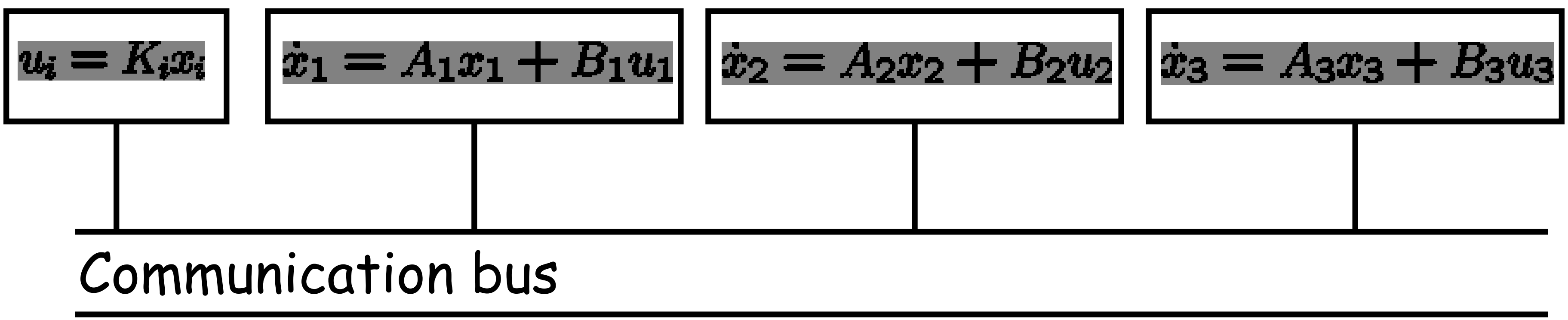
Integrated design of control and communication systems

- Up to here, communication has been considered as a disturbance or model imperfection affecting control
- What about jointly design control and communication, along the proposal in Mitter's lecture?

- Let's illustrate with an example

Example: Stabilization of networked systems

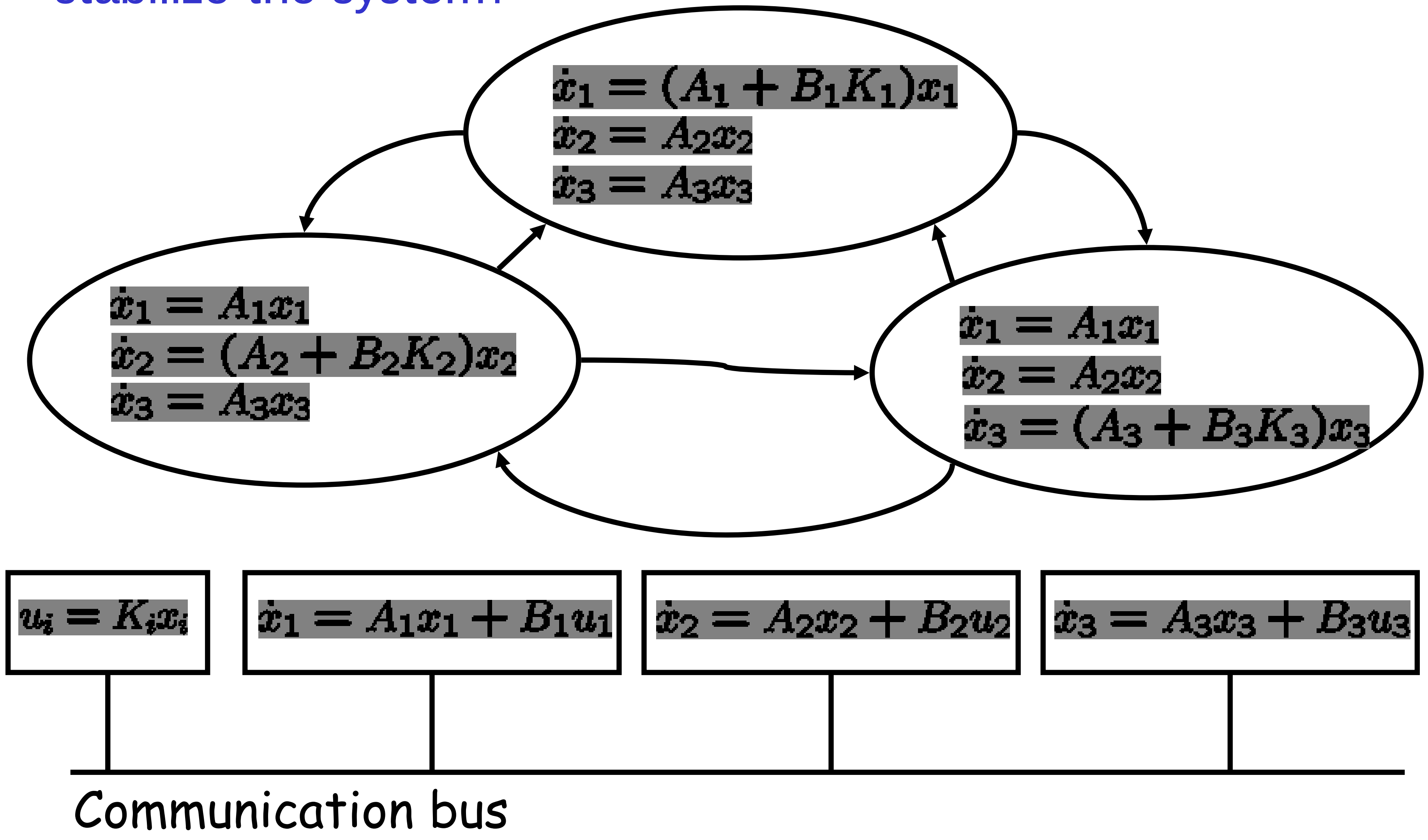
- Consider joint state feedback stabilization of a set plants, when only one plant can utilize the bus at a time:



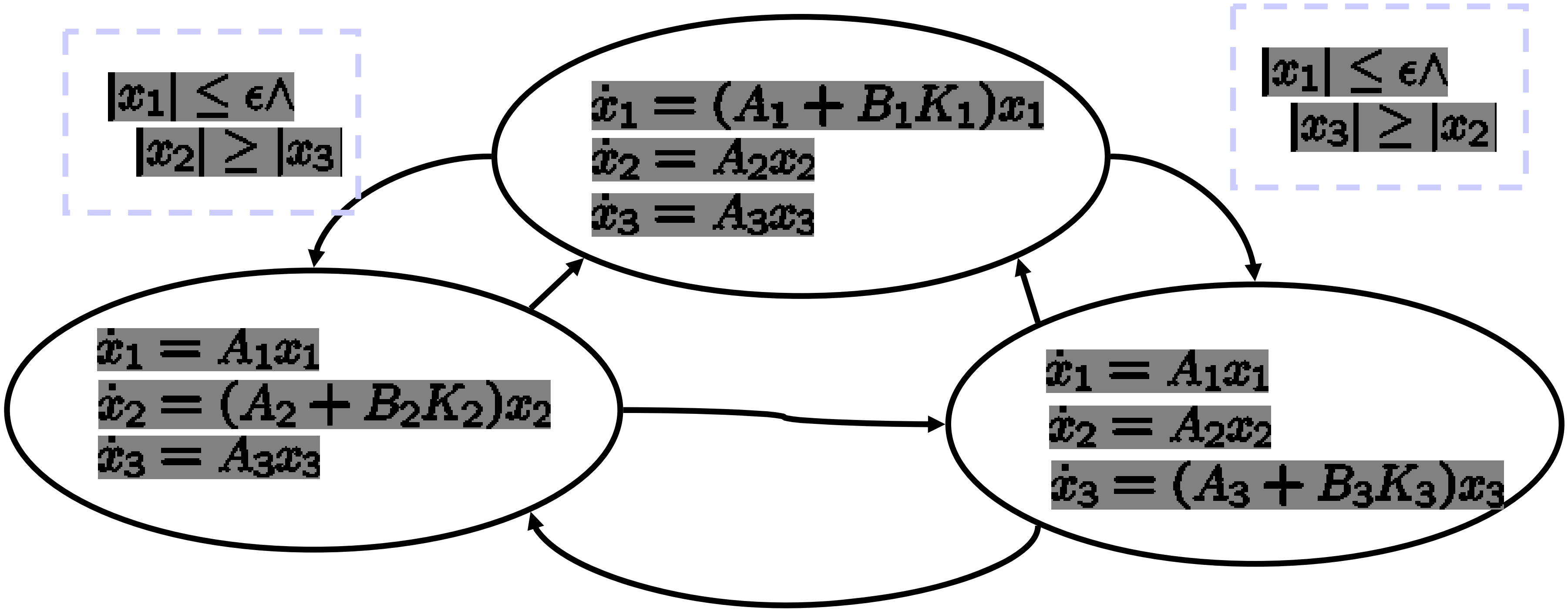
- What control and communication policy should be adopted?

Hybrid system representation

- How choose the guard conditions of the hybrid automaton to stabilize the system?



“Largest state first”-policy

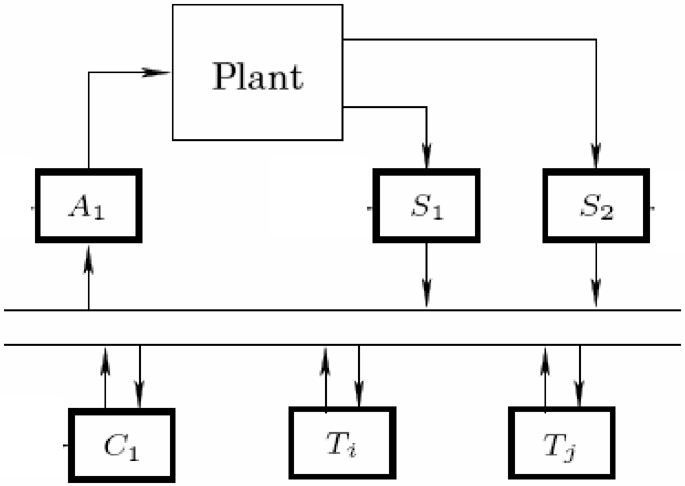


Theorem [Hristu-V. and Kumar]

For scalar unstable systems:

$$|x_i| \to \epsilon \text{ if and only if } -\sum_{i=1}^{3} \frac{A_i}{B_i K_i} < 1.$$

Summary



- Communication and networking important in growing number of control applications
- Communication delays, quantizers, losses, errors and outages can be viewed as constraints imposed on the control system
- Can in many cases be suitably modelled as hybrid systems
- Design methodologies exist for certain classes of constraints, but much more remains to be done
- Desirable to jointly design control and communication system
  - Control algorithms need to adapt to changing network conditions
  - Communication protocols should be aware of control needs
  - But, other network applications set competing restrictions

References

- D. Hristu-Varsakelis and W. S. Levine, Ed.'s, Handbook of Networked and Embedded Control Systems, Birkhäuser, 2005
- L. G. Bushnell, Ed., Special Issue on Networks and Control, IEEE Control Systems Magazine, Feb, 2001
- B. Lincoln, "Dynamic programming and time-varying delay systems," PhD thesis, Lund University, 2003
- K. J. Åström and B. Wittenmark, Computer-Controlled Systems, 3rd edition, Prentice Hall, 1997
- 2E1245 Hybrid and Embedded Control Systems, http://www.s3.kth.se/control/kurser/2E1245

http://www.s3.kth.se/~kallej

Outline

- Lecture I: Control under communication constraints
  - Motivating applications
  - Communication constraints
  - Compensation for delay and loss
  - Integrated design of control and communication
  - References
- **Lecture II: Hybrid control of communication systems**
  - **Packet-switched networks**
  - **Hybrid model of congestion control**
  - **References**

Traffic control in packet-switched communication network

Objective is to

- Give each user suitable service
- Utilize network resources efficiently

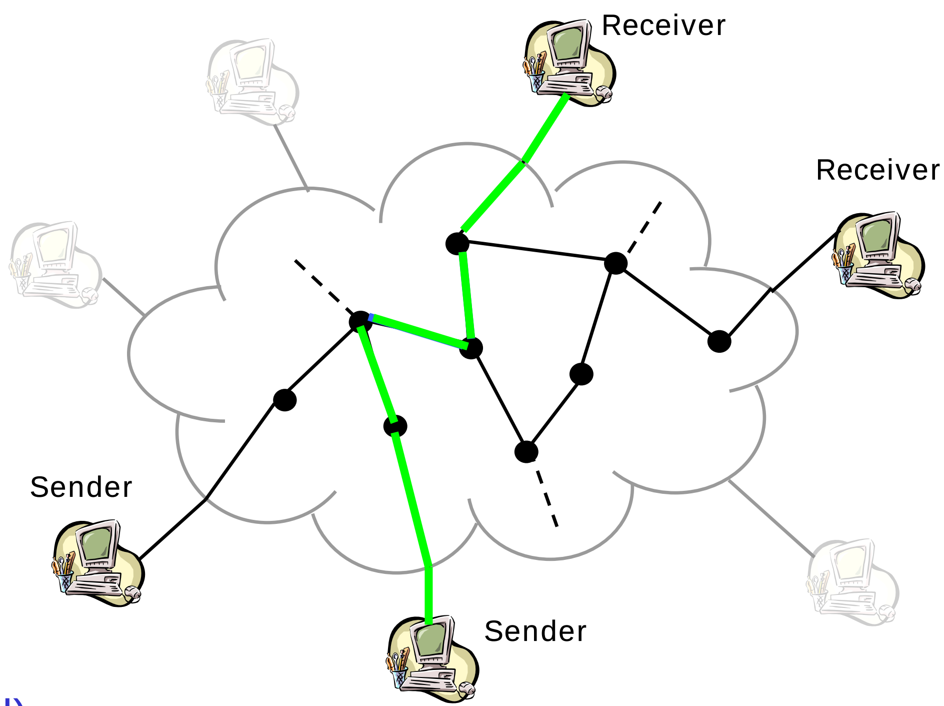
Obtained through two control mechanisms:

Spatial control

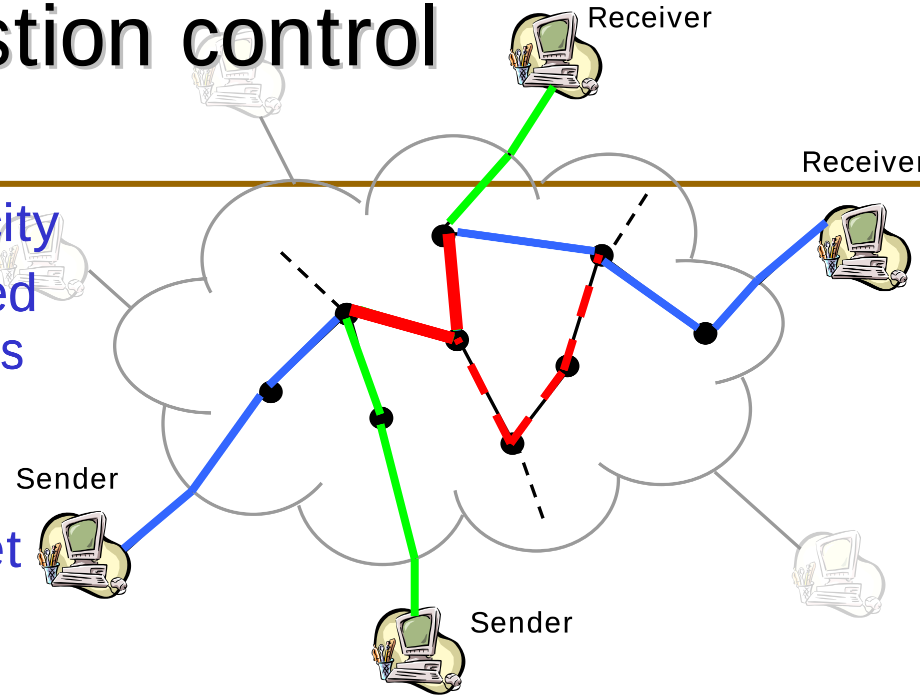
- route traffic short way through the network
- receiver address in header of each packet
- shortest-distance matrix in each router
- updated on a slow time scale

Temporal control

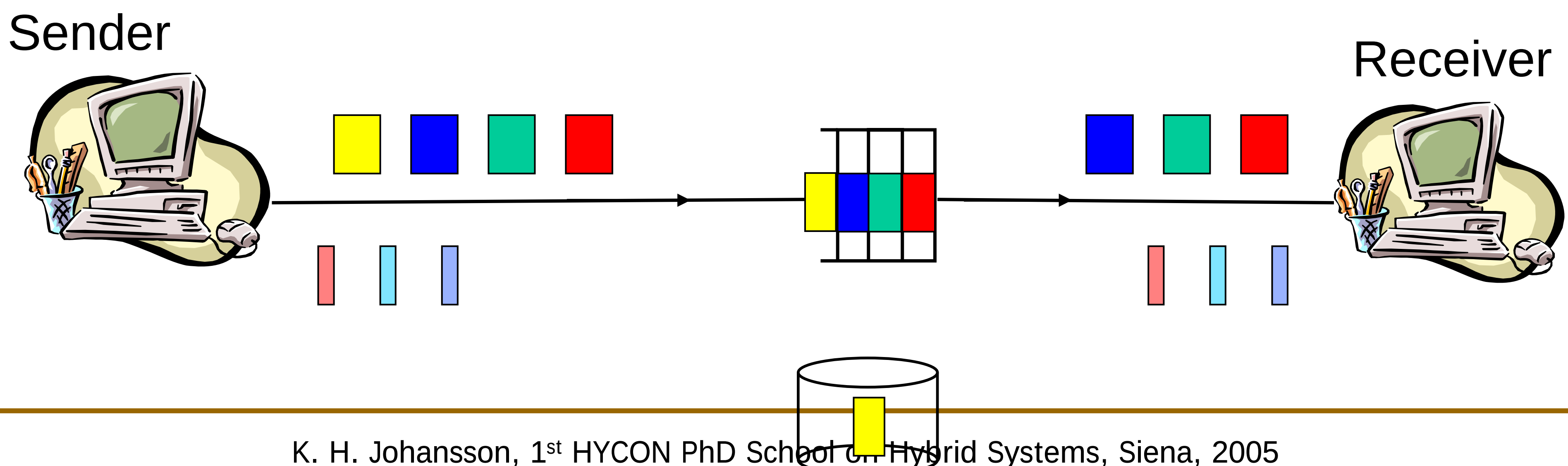
- adjust sending rate to available bandwidth
- base on info available in sender (end-to-end)
- implicit bandwidth estimate through ack's
- updated on a faster time scale



Temporal congestion control

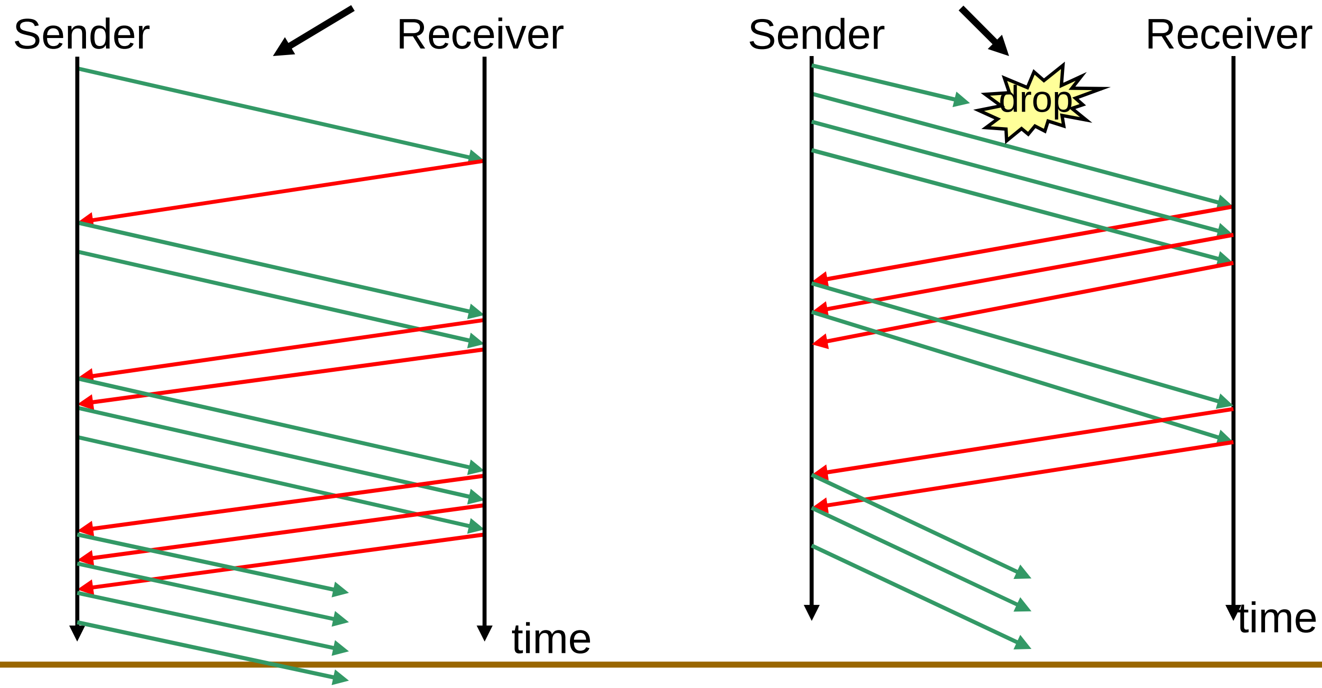


- Each network link has a limited capacity
- Variations in traffic is primarily handled by temporary storage in router buffers
- If a buffer gets full, it simply throws away incoming packets
- Hence, congestion leads to lost packet
- Acknowledgements (ack's) indicate sender, who can take action

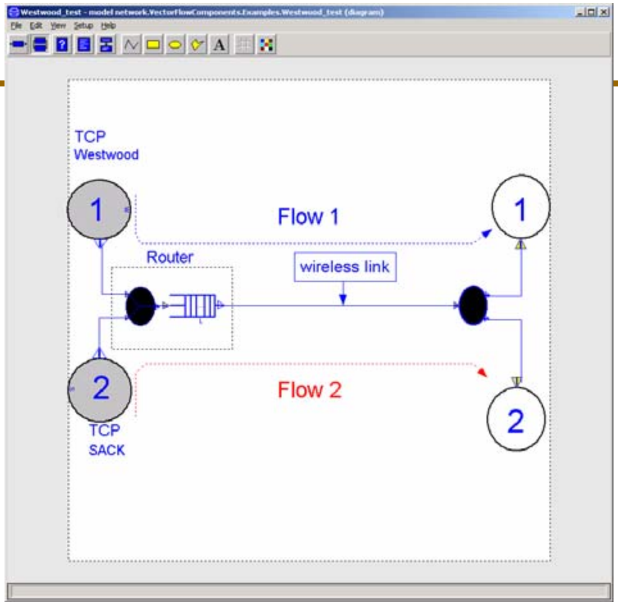


Transmission control protocol (TCP)

- TCP implements a congestion controller that regulates the sending rate
- Control variable is the congestion window w, which represents number of outstanding (not-yet-acknowledged) packets
- Control is based on implicit feedback information from ack's
- TCP follows <u>additive increase</u> <u>multiplicative decrease</u> (AIMD) strategy



TCP congestion avoidance

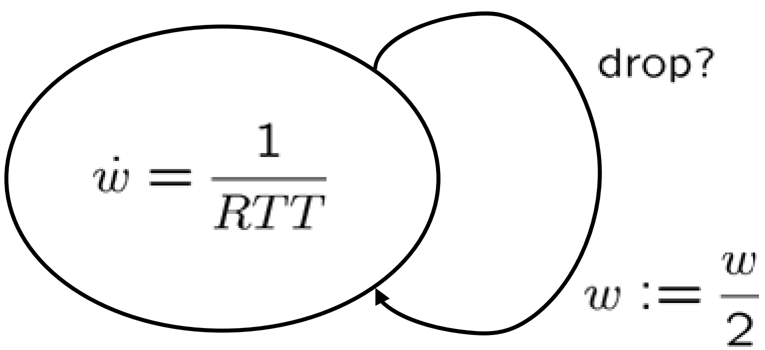


Window w is updated each round-trip time RTT

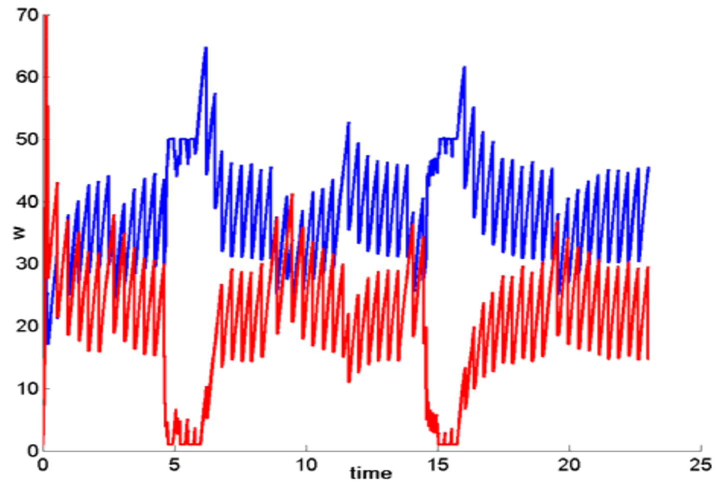
If no drops occur, then $w := w + 1$

If drop occurs, then $w := w/2$

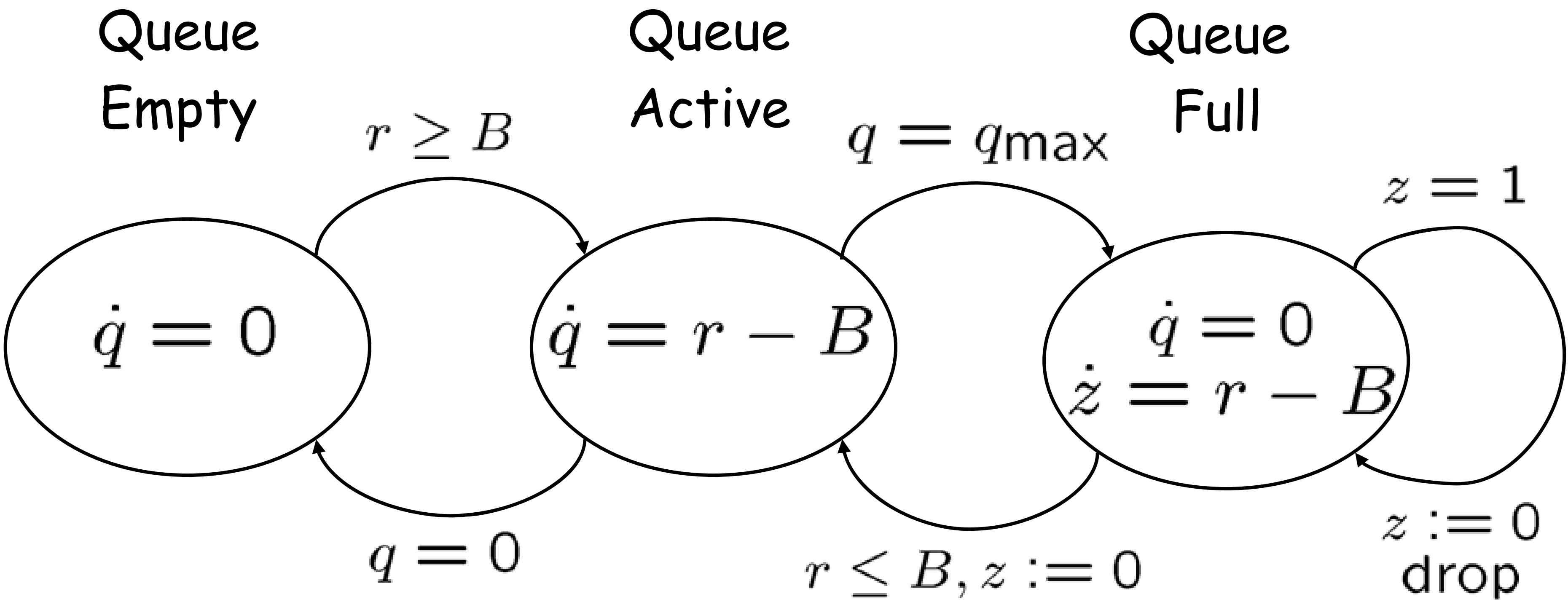
Hybrid system is obtained by interpreting w as a continuous-time real variable:

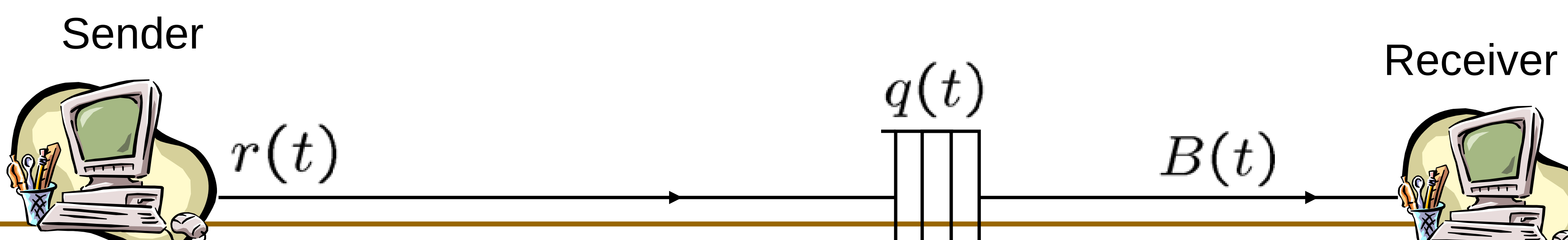


Typical windows evolution:

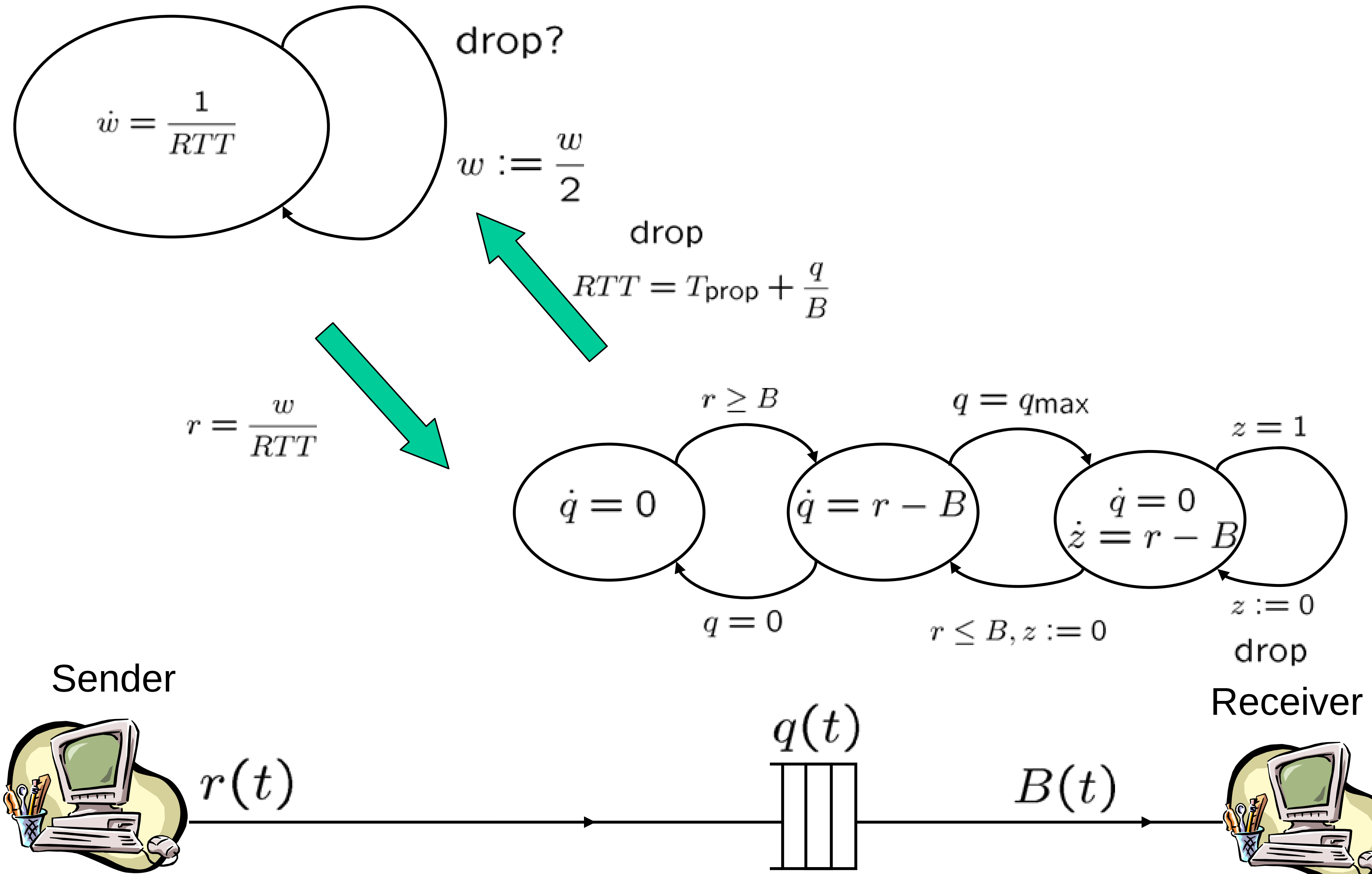


Hybrid dynamics of a queue

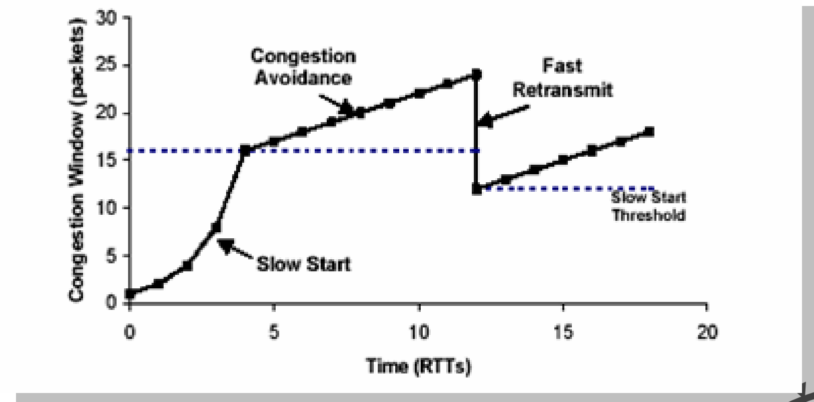


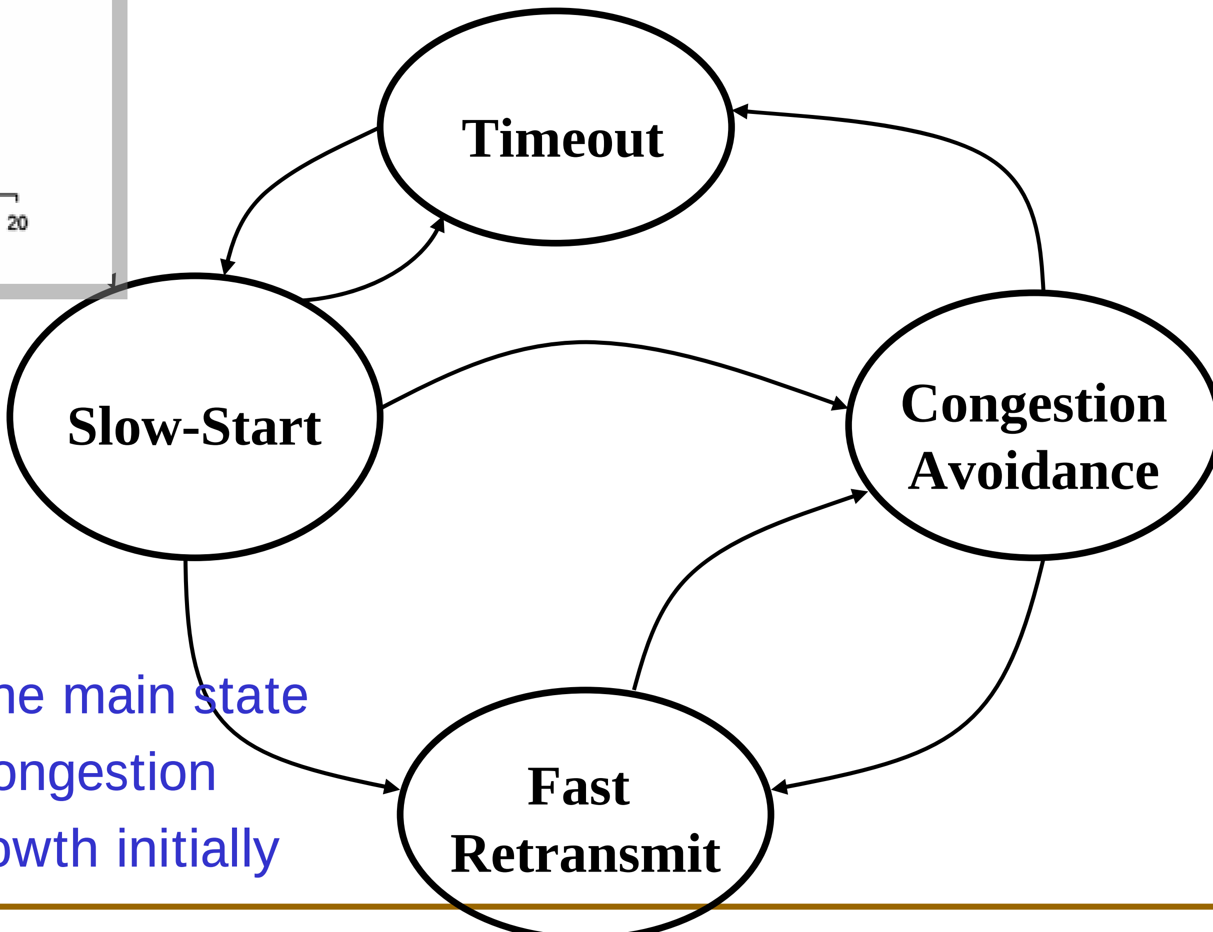


Hybrid model of TCP over single link



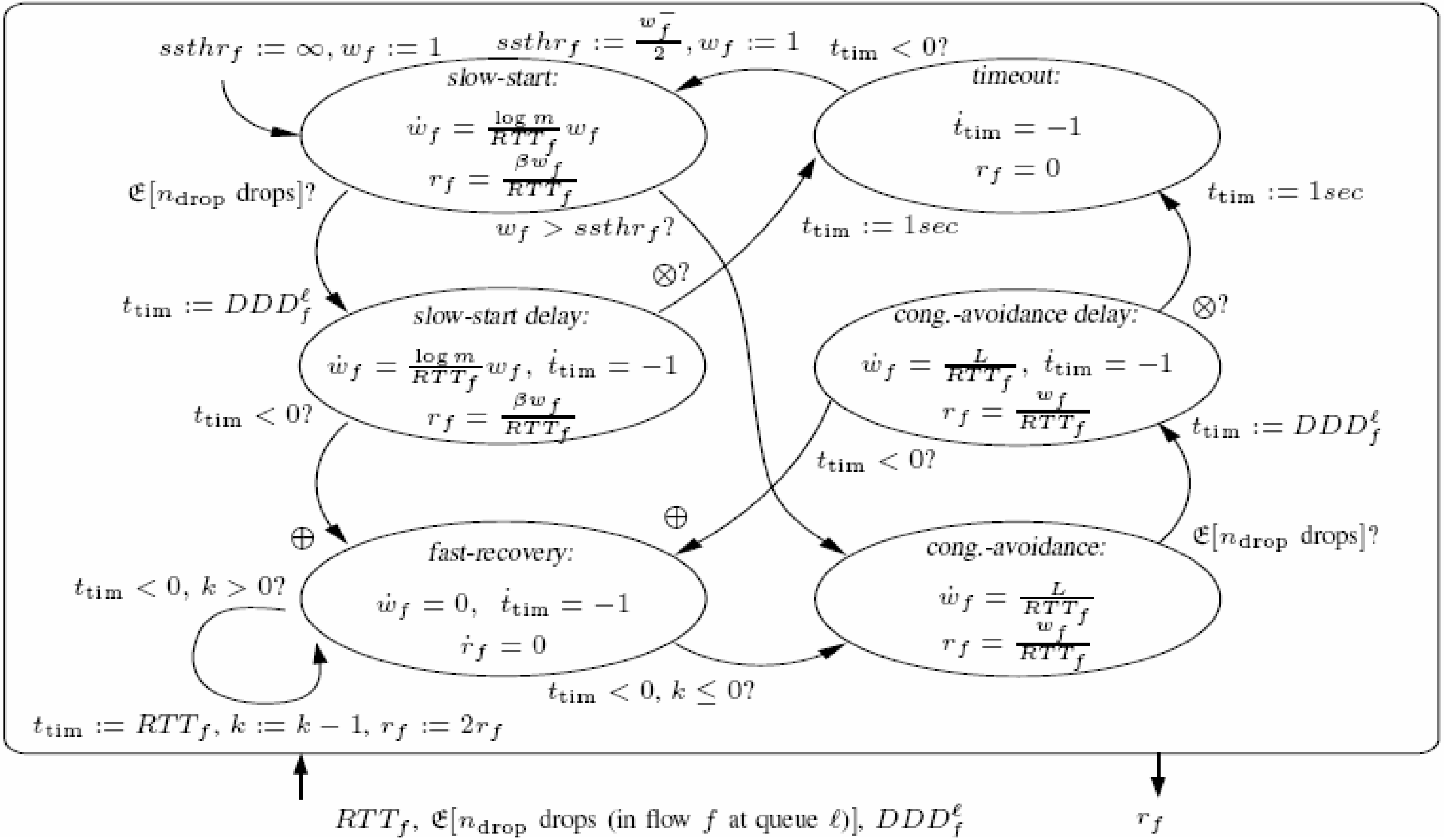
The discrete states of TCP





- Congestion avoidance is the main state
- Timeout handles severe congestion
- Slow-Start gives faster growth initially

Hybrid model of TCP



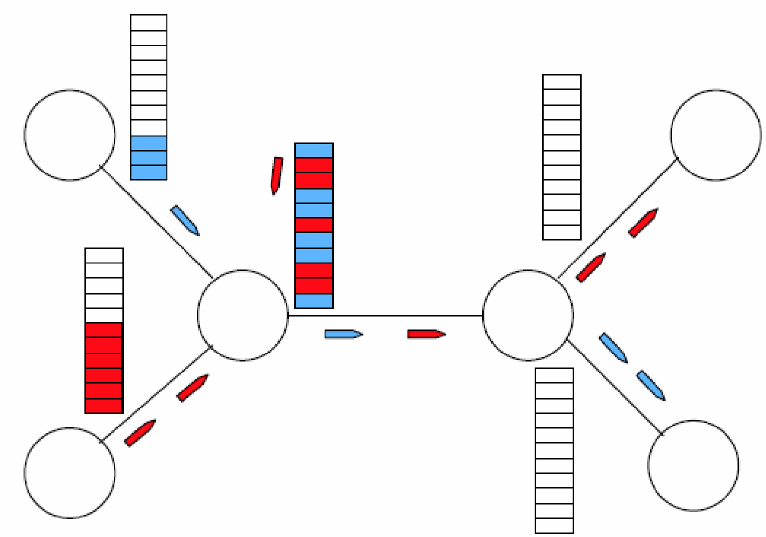
Alternative models of network traffic: Packet models and fluid models

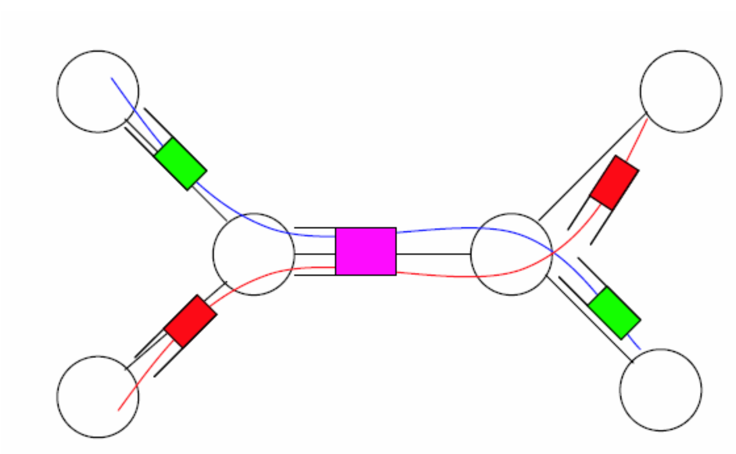
Packet models

- Model each individual packet (event-driven)
- Accurate but computationally heavy

Fluid models

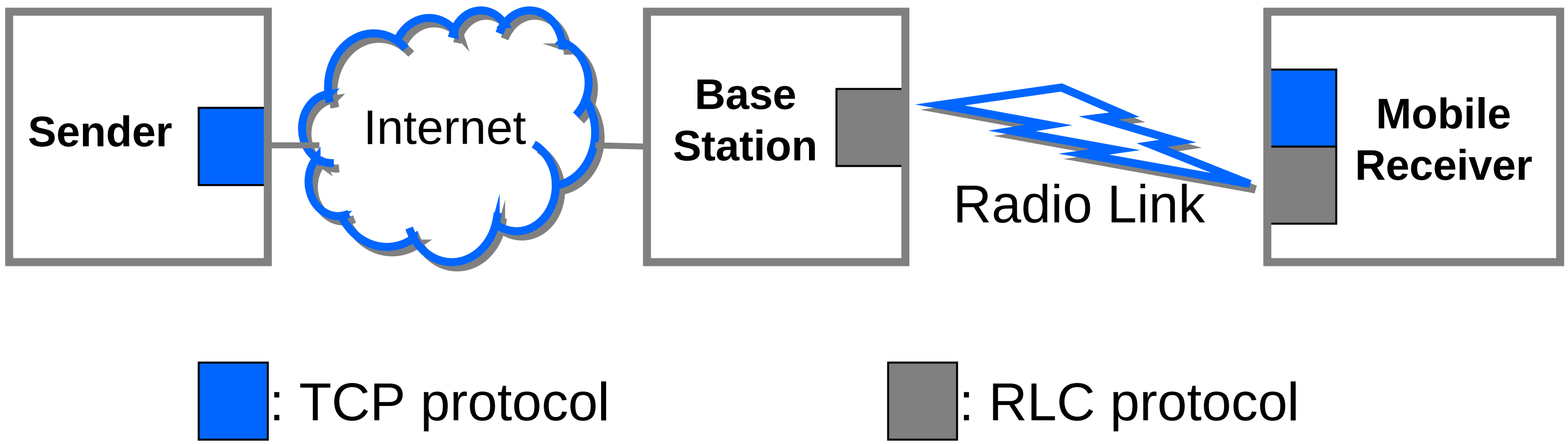
- Averaged fluid quantities (time-driven)
- Capture only steady-state and slow behaviors





- Hybrid model combines features of these traditional network models

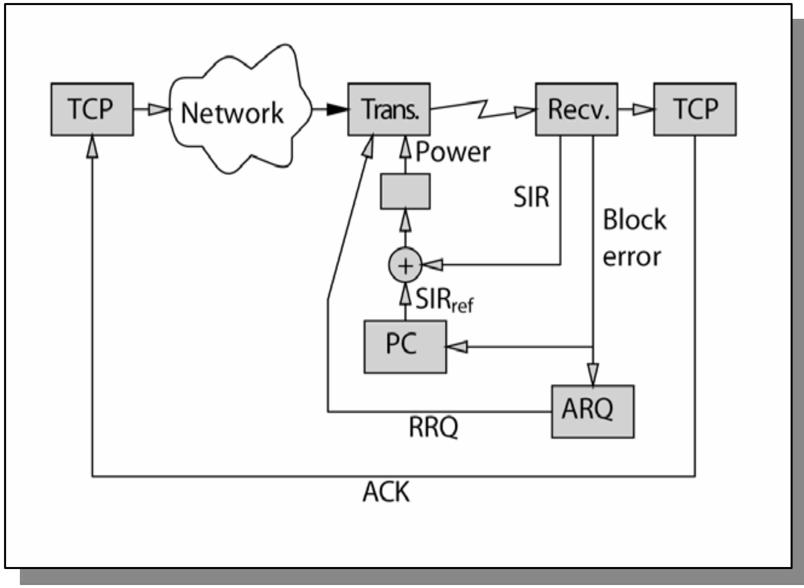
TCP over wireless links

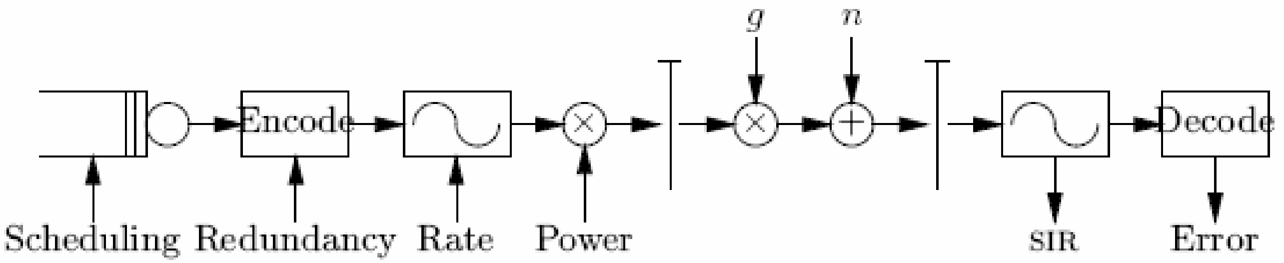


- Integration of Internet and cellular networks hard due to radio link variations
- When used over wireless links, TCP cannot ensure a high link utilization
- Packet drops, bandwidth and delay variations in radio link erroneously indicate network congestion to TCP
- How do radio links affect TCP throughput?
- Can we make the radio link and the cellular system “TCP friendly”?

A hybrid cascade control problem

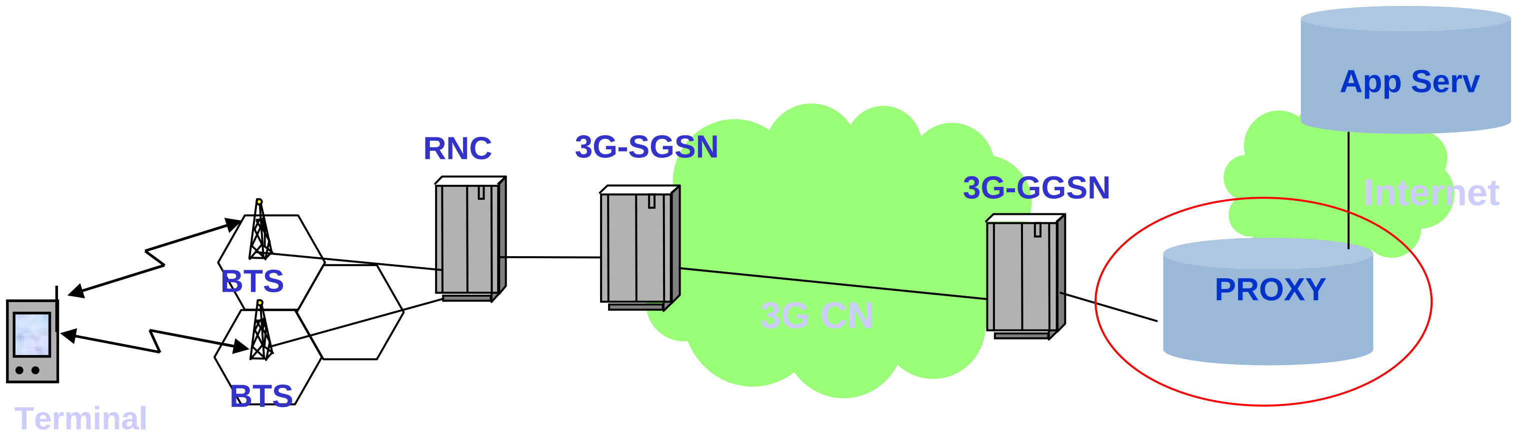
- Radio link transforms losses into random delays
- Key dynamics from cascaded feedback control loops
  - Inner and outer power controls
  - Link-layer retransmission
  - TCP
- Increased probability of spurious timeout gives reduced TCP throughput
- Adjust link layer properties to optimize TCP throughput





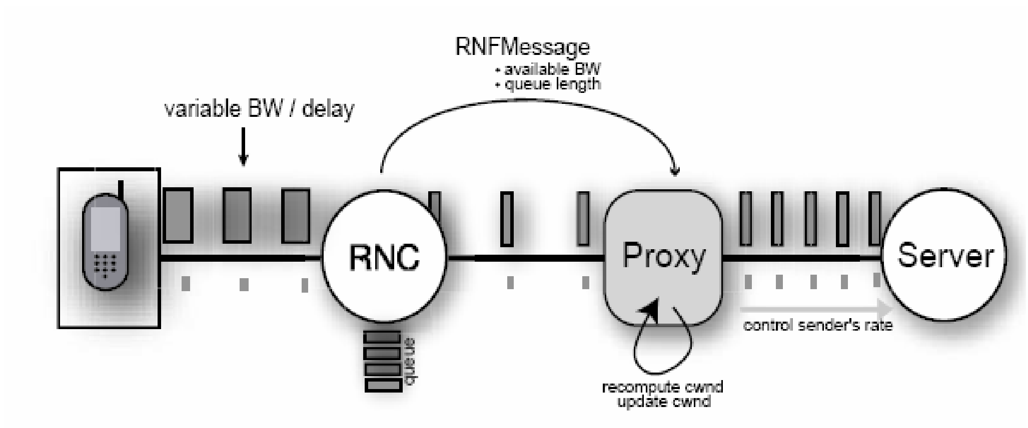
New feedback protocols for wireless Internet

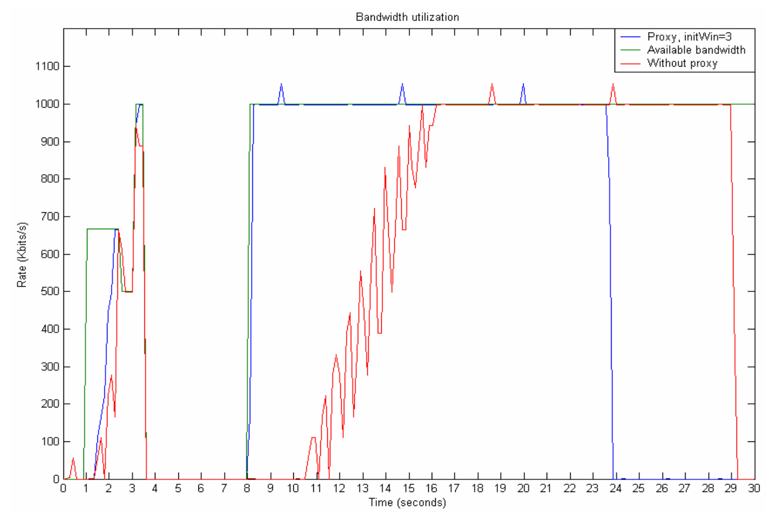
- Improved TCP throughput through new radio network feedback protocol
- Proxy between cellular system and Internet adapt sending rate to radio bandwidth variations obtained from radio network controller (RNC)



New feedback protocols for wireless Internet

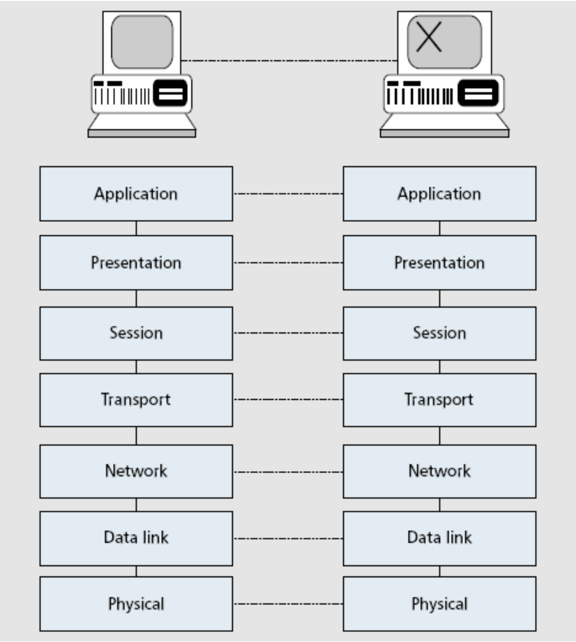
- Hybrid controller in proxy regulates sending rate based on
  - Events generated by radio bandwidth changes obtained from RNC
  - Sampled measurements of queue length in RNC
- Improved time-to-serve-user and utilization compared to traditional end-to-end TCP





Challenges in network traffic control

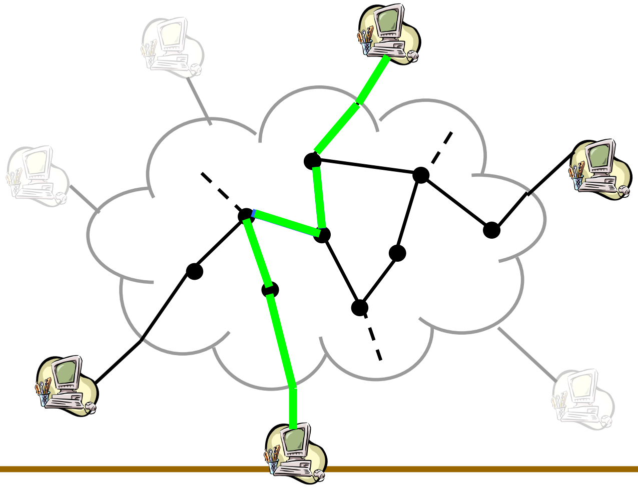
- Deployment
  - Implementation in end computers
- Distributed control
  - Communication constraints
  - Implicit state information
- Complex interacting dynamics
  - Network, protocol and user dynamics
  - Large and varying time delays
  - Wired and wireless links
  - Packet loss
- No clear optimality objective
  - Network throughput
  - User throughput
  - Response time
  - Fairness



Summary

- Hybrid model of congestion control in packet-switched networks
- Combine event-driven packet models with time-driven fluid models
- Accurate on time-scale of the round-trip time
- Enables analysis and efficient simulations of congestion control

- Interactions between wireless links and TCP lead to performance loss
- Hybrid controller gives improved user experience and network utilization



References

- V. Jacobson, "Congestion avoidance and control," in Proc. of SIGCOMM, 1988, pp. 314–329
- J. Walrand and P. Varaiya, High-performance communication networks, Morgan Kaufmann, 2nd edition, 2000
- J. Hespanha, S. Bohacek, K. Obraczka, and J. Lee, "Hybrid Modeling of TCP Congestion Control". In M. D. Di Benedetto, A. Sangiovanni-Vincentelli, Hybrid Systems: Computation and Control, number 2034 in Lect. Notes in Comput. Science, 2001
- N. Möller, C. Fischione, K. H. Johansson, F. Santucci, and F. Graziosi, "Modelling and control of IP transport in cellular radio links", IFAC World Congress, 2005
- N. Möller, I. Cabrera Molero, K. H. Johansson, J. Petersson, R. Skog, and Å. Arvidsson, "Using radio network feedback to improve TCP performance over cellular networks", IEEE CDC-ECC, 2005

http://www.s3.kth.se/~kallej