Electronic Systems Design
Synthesis Verification Testing Power Communication

Design of Networked Control System

Davide Quaglia,
Riccardo Muradore

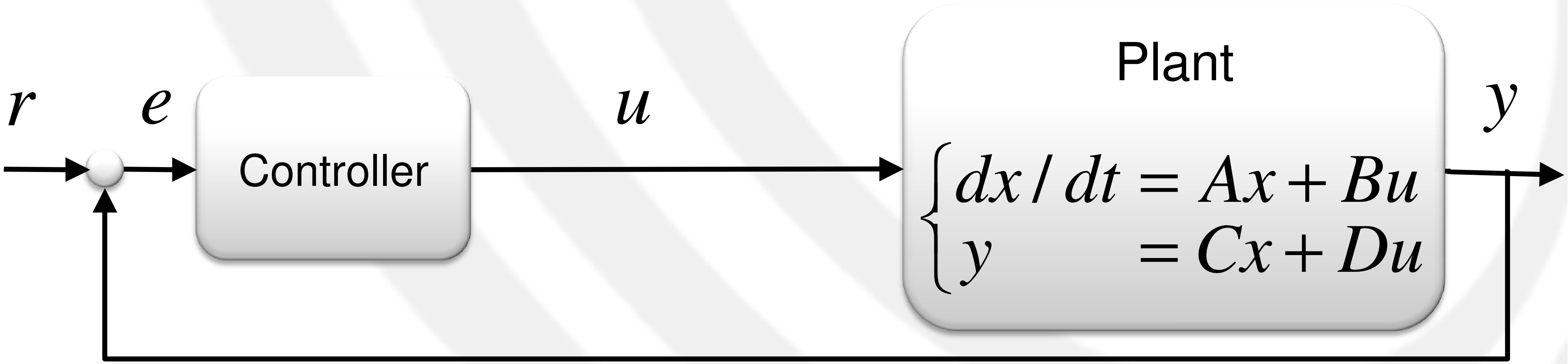
Outline

- Definition
- Applications
- Control problems…
- … and some design solutions
  - Differentiated services
  - Transmission power adaptation
- Simulation problems
- Relationship between NES and NCS

DEFINITION

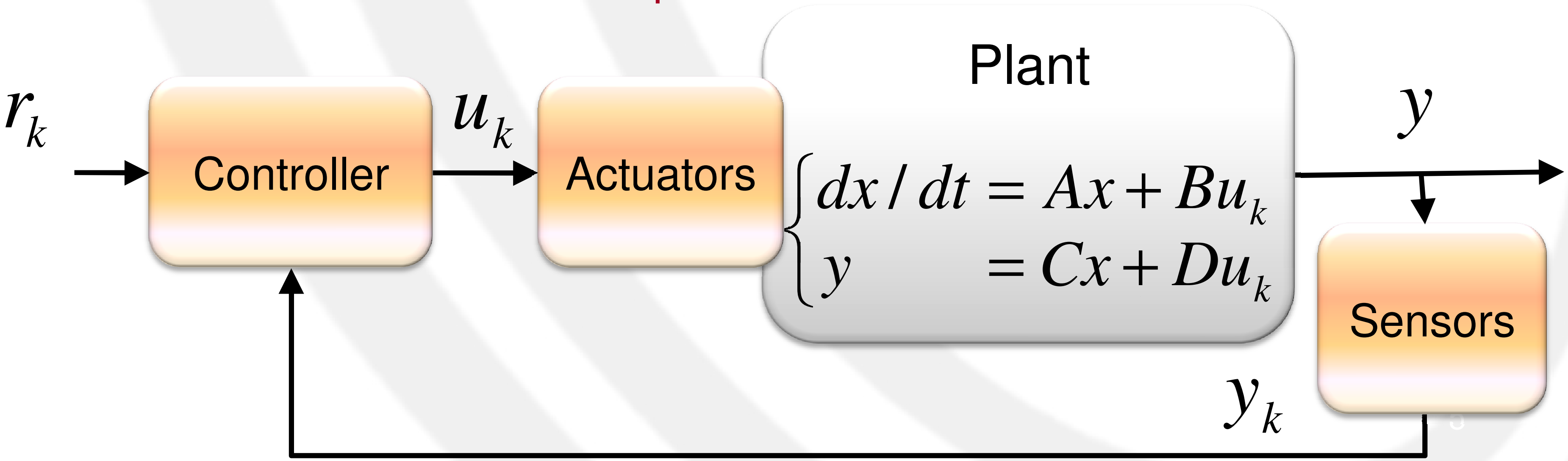
Automation control system

- According to Control Theory, an Automation Control System consists of
  - System to be controlled (Plant)
  - Controller



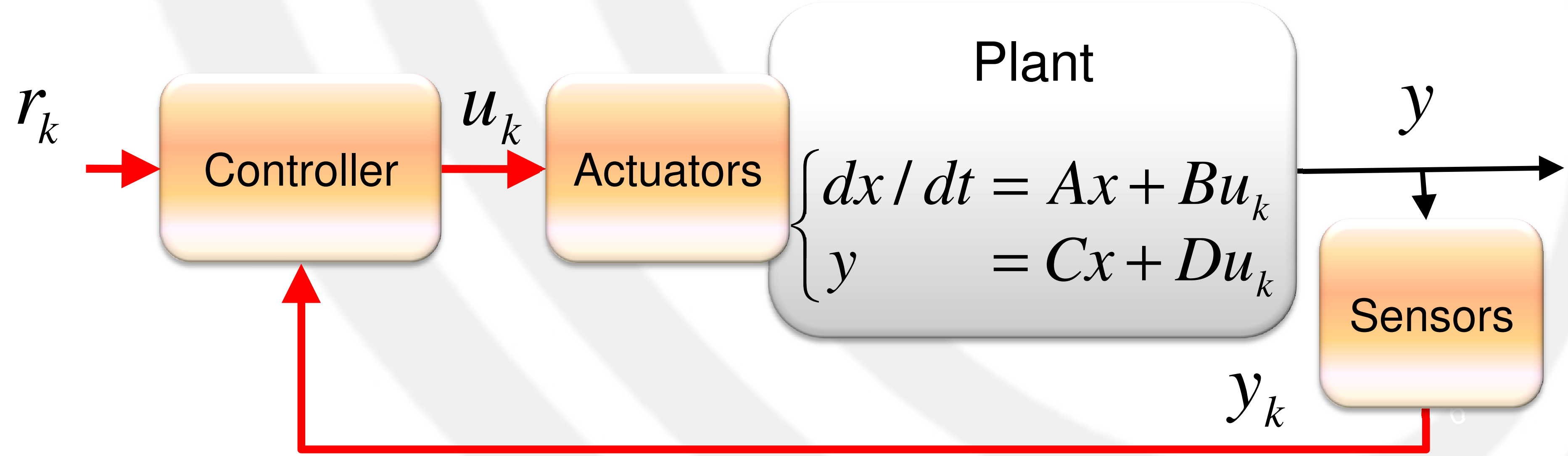
Architecture of a control system

- The Plant is the **given** physical system
- The blocks built by the designer are:
  - Controller = SW program implementing the control strategy (it computes also e_k)
  - Sensors to read information from the plant
  - Actuators to act on the plant



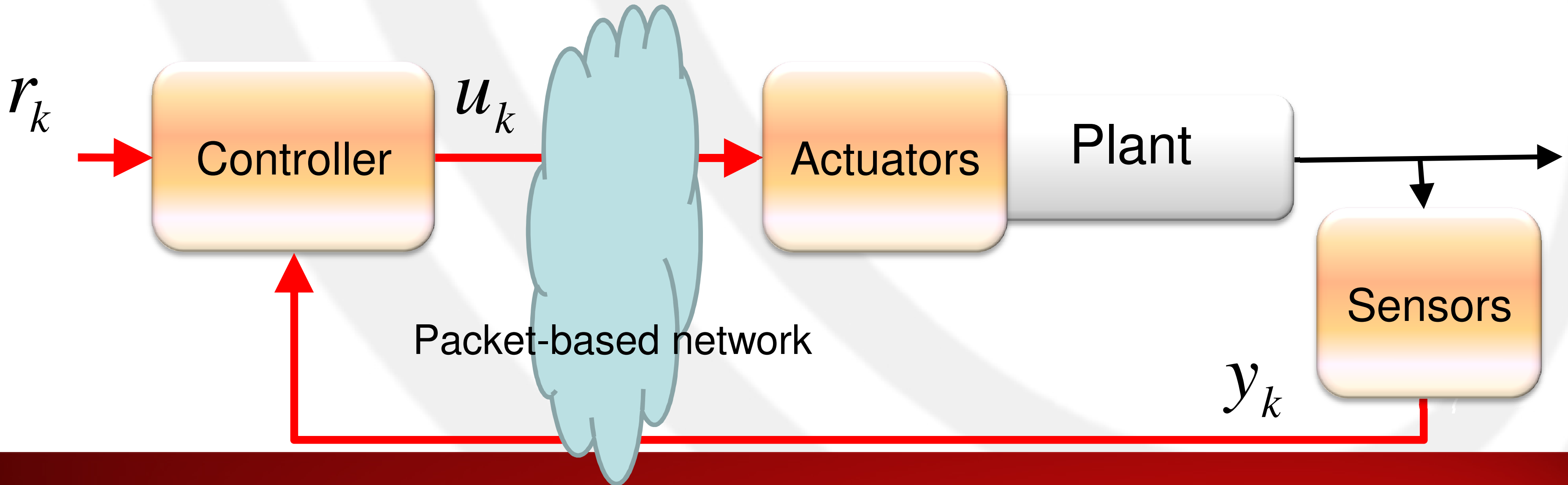
Cyber-Physical System

- Controller, actuators and sensors are digital blocks evolving according to discrete events (cyber)
- The plant follows physical (continuous time) laws
- The red connections move digital information

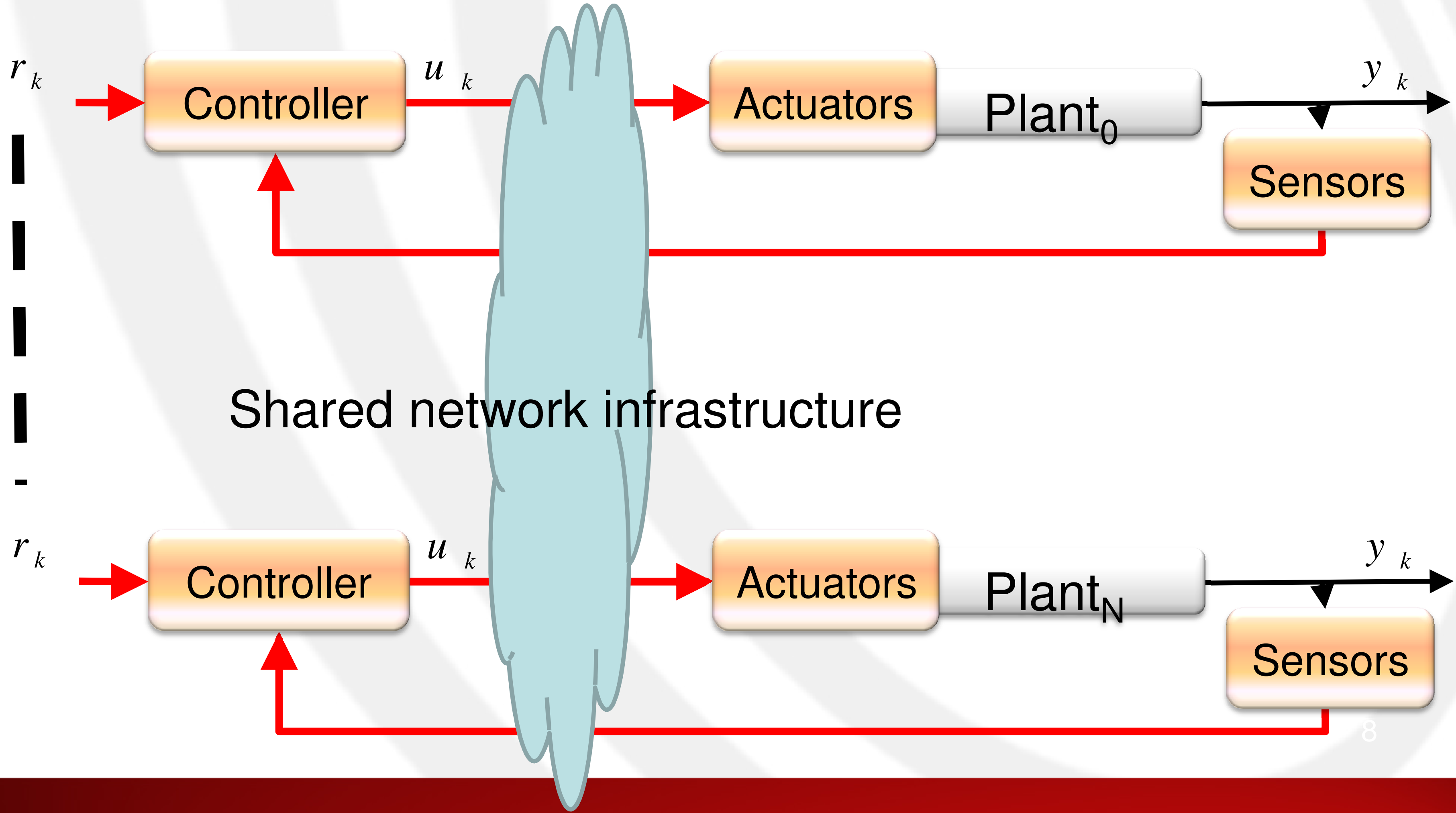


Networked Control System

- A packet-based network delivers both commands (forward) and measurements (backward)
  - Scalability
  - Cost efficiency



Scalability

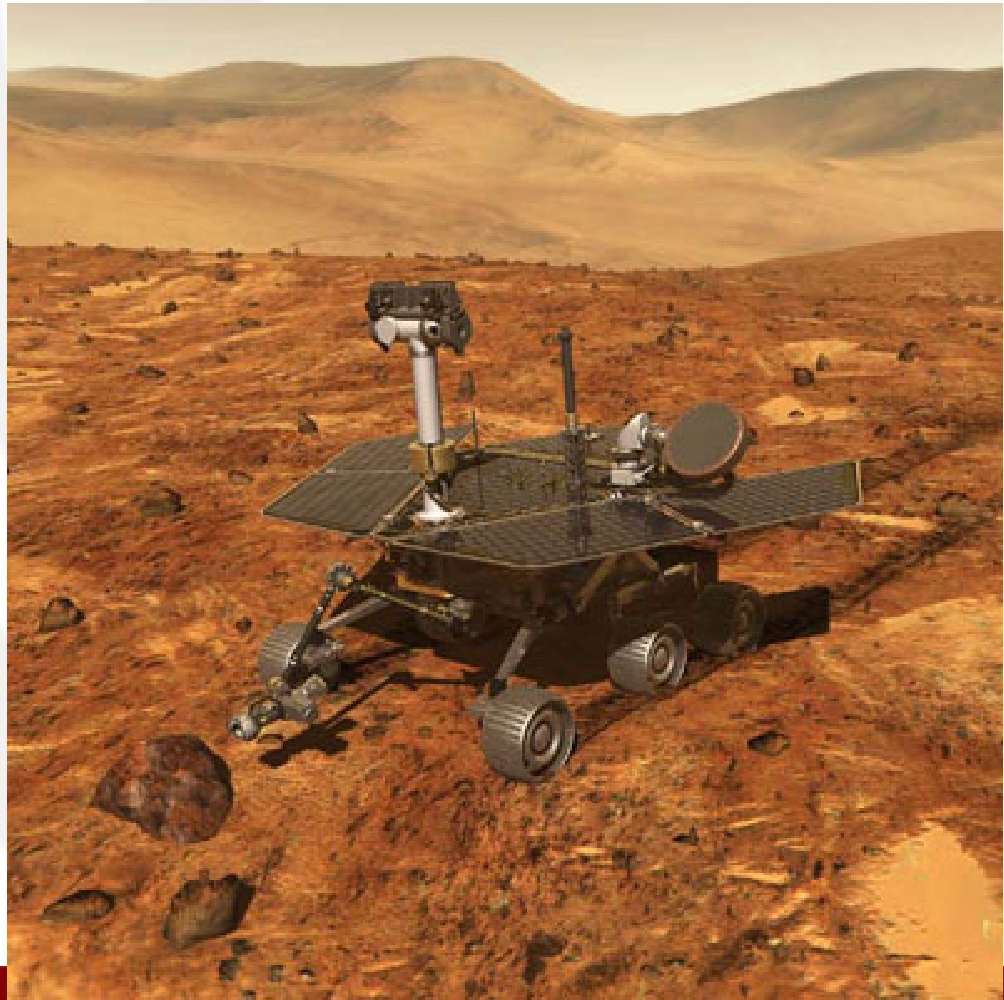


Cost efficiency

- Single network infrastructure for the growing needs of the factory
- Well-known re-used protocols and equipments
  - Ethernet
  - CAN
  - Wifi (incredible !)
  - TCP/IP

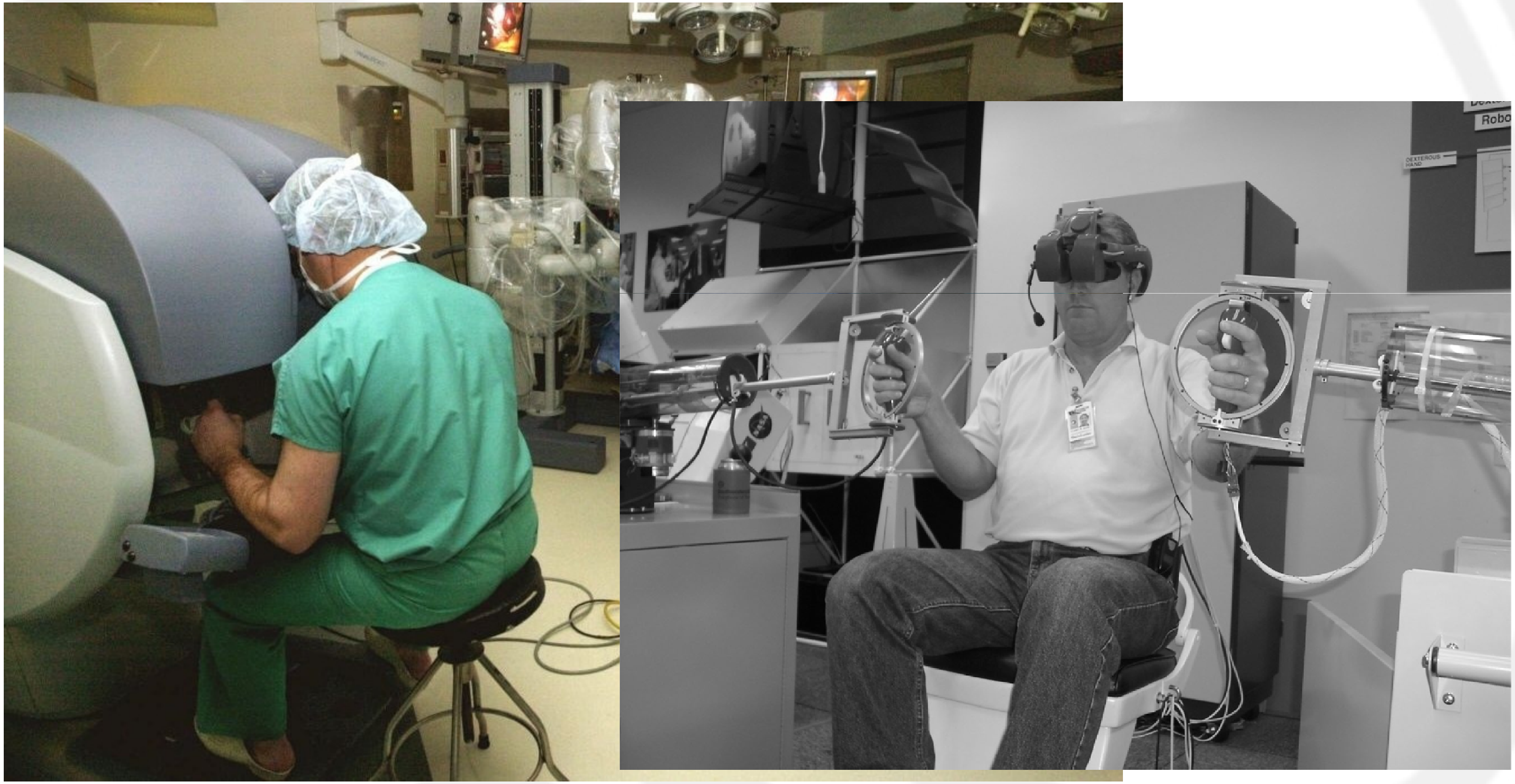
APPLICATIONS

Space exploration

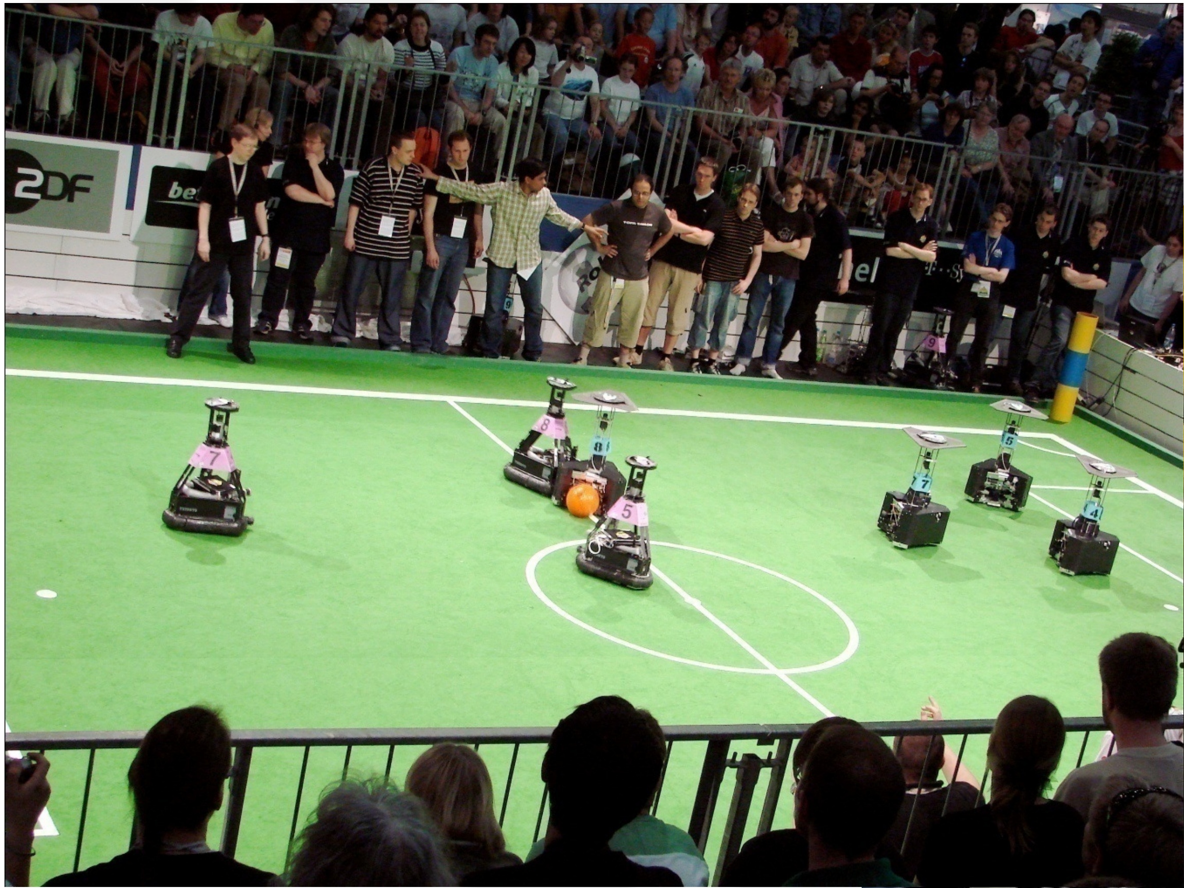


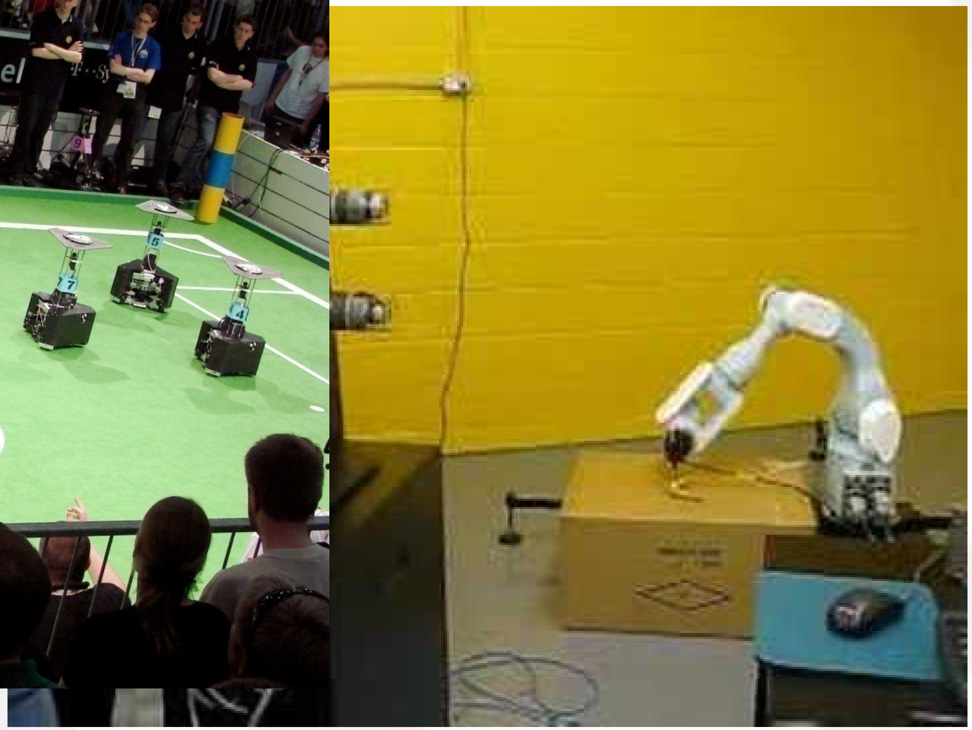
Underwater exploration

Teleoperation



Robot coordination





CONTROL PROBLEMS

The network introduces new problems in the control loop

- Transmission delay
- Packet losses
- Bit errors

Transmission delay

- Def: total time between the generation of command/measurement and its use at actuator/controller side
- Contributes to the delay:
  - Packet encoding time
  - Propagation delay
  - Channel arbitration time
  - Re-transmission time
  - Processing time by the intermediate systems (switches, access points, routers, coordinators)

Delay components

- Packet encoding time depends on packet size and speed of network interface
  - Constant for a given system/application
- Propagation delay depends on signal speed and transmission range
  - Constant for wired networks
  - Variable for wireless networks (e.g., acoustic waves)

Delay components (2)

- Channel arbitration time is the time to get the use of the channel
  – Constant for TDMA policy
  – Variable for CSMA
- Re-transmission time: the network interface waits for ack and it may retry several time before success
  – Variable and depending on the traffic level and channel quality

Delay components (3)

- Processing time by the intermediate systems
  - CPU time (constant)
  - Waiting time in queues (variable and depending on the traffic level)
  - The higher is the number of traversed intermediate systems, the higher is the delay!

Impact of delay on plant control

- The delay value determines the loop delay and should be compatible with the control application
  - Requirements on reaction time, settling time
- Delay variation alters the interval between packets (sampling frequency) and loop delay
  - Assumptions on sampling frequency and loop delay used in the control design are not satisfied at run-time

Packet losses

- Def: some packets do not arrive at destination (actuators and controller)
- Causes:
  – Channel failure (not an exception in wireless)
  – Queue overflow due to high traffic
  – Timeout of the receiver (if a sample is too much delayed then it is useless)
  – Bit errors detected (but not corrected)

Impact of packet loss on plant control

- The control loop is temporary broken:
  – Commands are not applied
  – Measurements are not considered by the controller

Bit errors

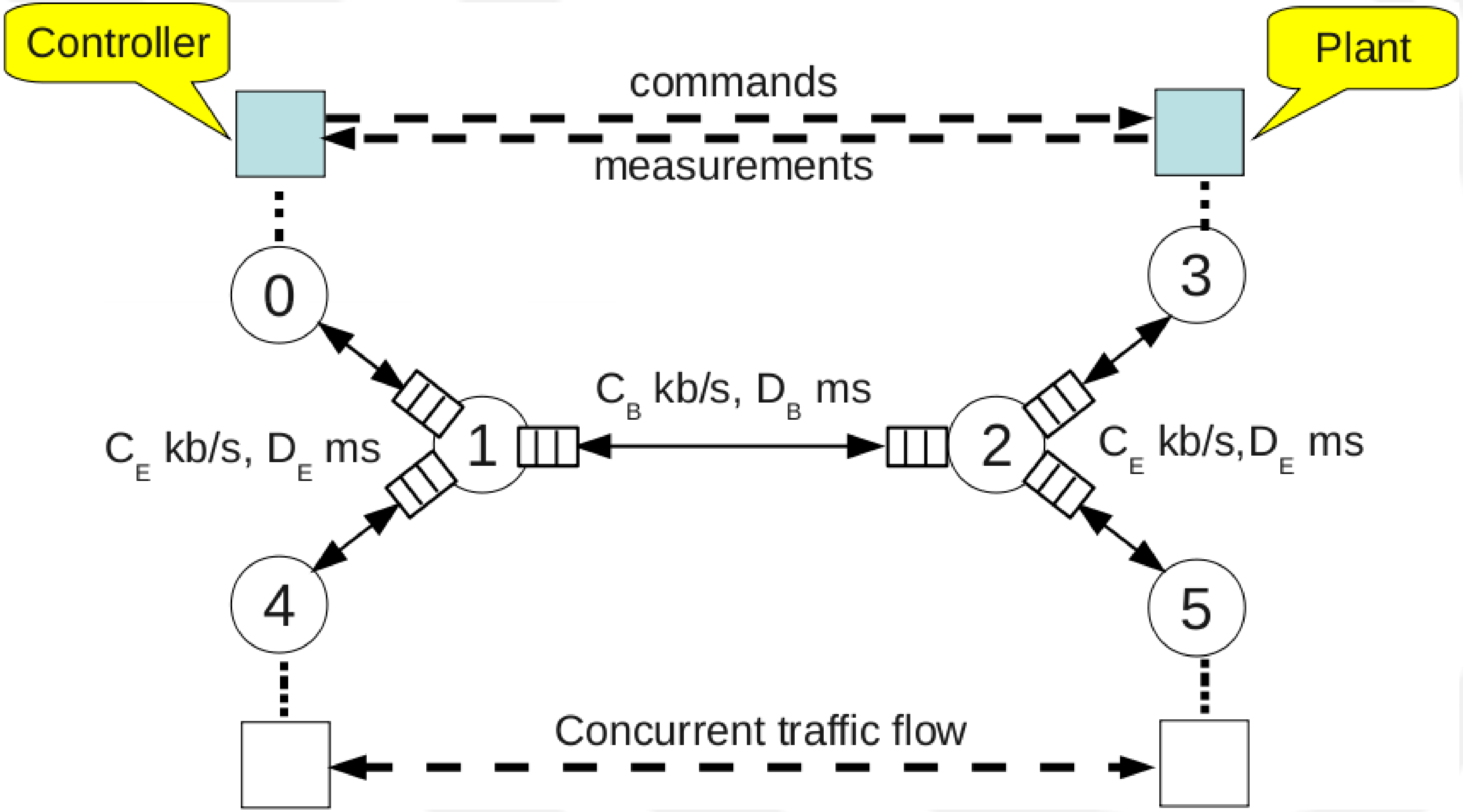
- Def: one or more bits in the packet are flipped and this event is not detected by error check
- Causes:
  - Channel failure
  - Interference from other signal sources
  - Signal weakness due to distance and obstacles

Impact of bit errors on plant control

- Command/measurement is altered
  - Let's imagine a position value with the most significant bit altered by a bit error!
- Weak SW blocks may crash in presence of un-expected values

SOLUTION 1: DIFFERENTIATED SERVICES

Network scenario



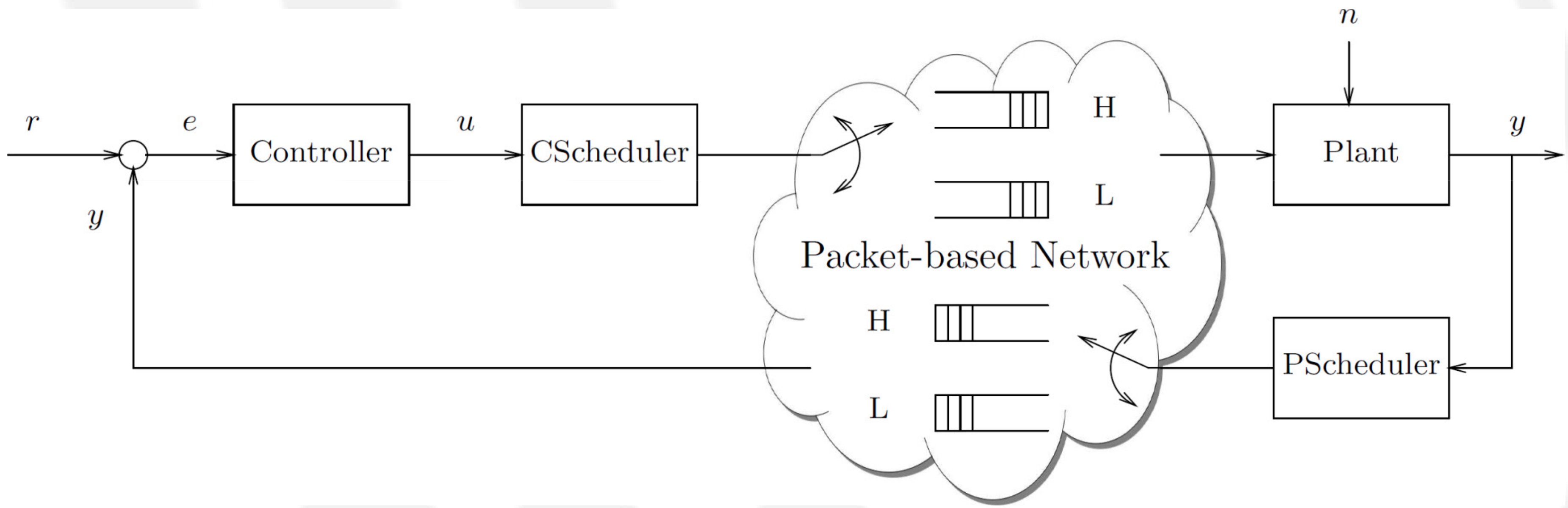
Network scenario (2)

- Example of a typical bottleneck topology in which peripheral nodes are connected through high-capacity low-delay links to a backbone link with less capacity and higher delay
- Between Node 0 and Node 3: NCS traffic (commands and measurements)
- Between Node 4 and Node 5: concurrent traffic
- Node 1 and 2 are switching nodes with input queues

Network scenario (3)

- Since the backbone capacity is shared among different traffic flows, queue level may vary inside nodes and congestions may happen leading to:
  - transmission delays
  - packet drops
- Key Observation:
  - Transmission performance depends on the design of:
    - nodes and channels
    - communication protocols
    - service differentiation
  - The perfomance of a NCS can be related not only to the controller design technique (as usual) but also to the design of the transmission strategy

Differentiated services model (DiffServ)



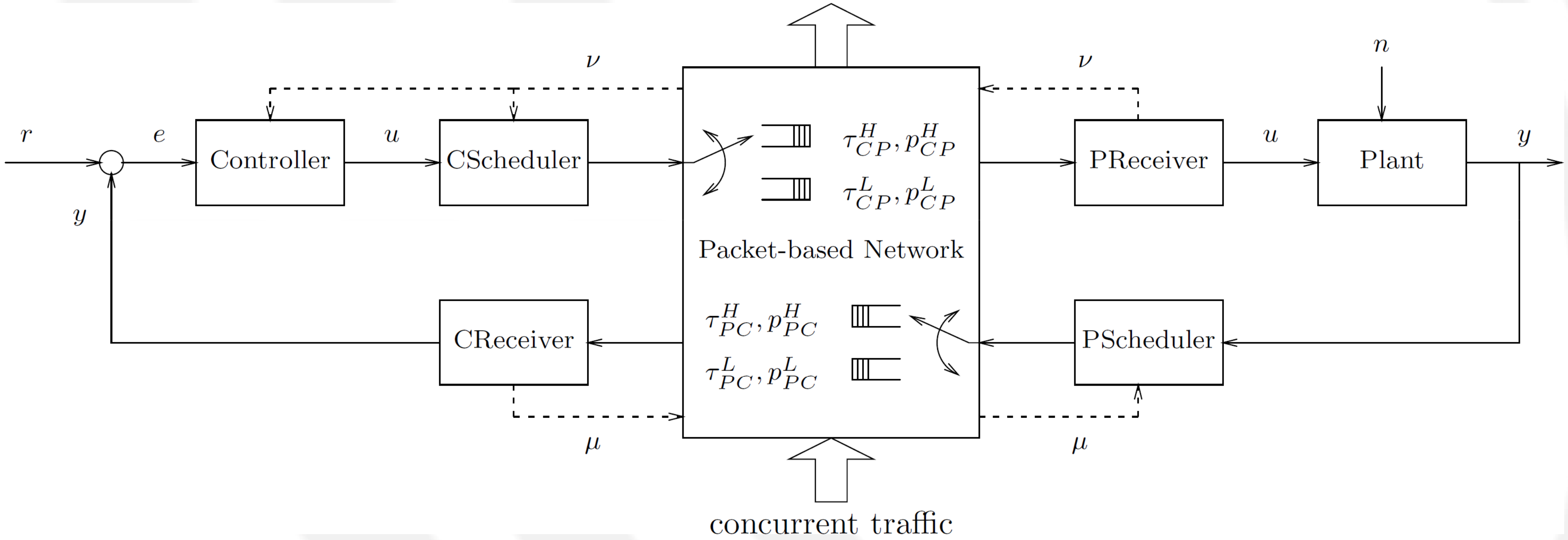
Differentiated services model (2)

- DiffServ is a standard technique to introduce Quality-of-Service (QoS) guarantees in IP networks.
- At each intermediate system there are 2 queues for 2 different forwarding priorities (virtual wires):
  - H queue for high-priority packets (H policy)
  - L queue for low-priority (best effort) packets (L policy)
- Schedulers assign priorities to packets by setting an appropriate field in their header
- Only a fraction of the total bandwidth should be devoted to the H policy otherwise differentiation becomes useless

Solution outline

- General Goal
  - Improve the performance of a Networked Control System by using the network resources in a smarter way
- Specific problem to be solved
  - Improve the control performance by optimally distributing packets between H and L policy
- Strategy for the solution
  - Mark the current packet as L or H according to the importance of the packet and the time-varying statistics of the network

Proposed architecture



Proposed architecture (2)

- Plant: continuous-time system
- Controller: discrete-time system with sample time Ts
- CScheduler (PScheduler): scheduler at the controller(plant)-side that decides the policy for the command (measurement) packets
- τ^{H}_{CP}, τ^{L}_{CP}, p^{H}_{CP}, p^{L}_{CP} and τ^{H}_{PC}, τ^{L}_{PC}, p^{H}_{PC}, p^{L}_{PC} : time-varying transmission delays (τ) and packet loss rates (p)
- CReceiver: receiver at the controller-side that computes the estimations on delay and PLR to be sent to the plant-side
- PReceiver: receiver at the plant-side that computes the estimations on delay and PLR to be sent to the controller-side

Network assumptions

- Let τ^H, τ^L and p^H, p^L be the transmission delays and packet loss rates for the H queue and the L queue, respectively.
- τ^H, τ^L are time-varying values and their estimation is computed at run time by comparing the time stamp within the packet payload and the arrival time (assuming synchronized nodes)
- p^H, p^L are time-varying values and their estimation is computed at run time by counting the arrived and lost packets.
- The following relationship holds
  - $\tau^H \leq \tau^L$
  - $p^H \leq p^L$

Network assumptions (2)

- The packets sent in each queue arrive in the proper order (this means that a packet can be overtaken only by packets belonging to a different queue)
- The delay values τ^H, τ^L and the packet loss rate values p^H, p^L are different in the controller-to-plant and plant-to-controller paths
- The delay values τ^H, τ^L are smaller than a sampling interval

Schedulers

- They choose the policy π_k for the *k*-th packet
- CScheduler: scheduler at the controller side → commands
- PScheduler: scheduler at the plant side → measurements

Algorithm for the CScheduler

- To choose the policy π_k for the k-th packet we go through the following steps:
  - compute the estimated plant output for the successful reception (using H and L policies) and for the lost packet case
    - we assume to hold the previous command whenever the current command does not arrive, i.e. ^u(k) = u(k-1)
  - compute the displacement between the estimated plant outputs
  - compare the displacement with a used-defined threshold to choose the policy (π_k = H or π_k = L)
- CScheduler: scheduler at the controller side → commands
- PScheduler: scheduler at the plant side → measurements

Algorithm for the CScheduler (2)

- Network condition is considered by weigthing the estimation of plant behaviour through packet loss statistics used as *a-posteriori* probabilities

$$
\begin{aligned}
\hat{y}^H(k) &= (1-\hat{p}^H(k))\hat{y}^H_{get}(k) + \hat{p}^H(k)\hat{y}_{lost}(k) \\
\hat{y}^L(k) &= (1-\hat{p}^L(k))\hat{y}^L_{get}(k) + \hat{p}^L(k)\hat{y}_{lost}(k)
\end{aligned}
$$

The displacement between estimated outputs is:

$$\hat{e}(k) = \hat{y}^L(k) - \hat{y}^H(k)$$

Algorithm for the CScheduler (3)

- Plant state is considered by observing measurements and estimating evolution by recording the current transmission strategy

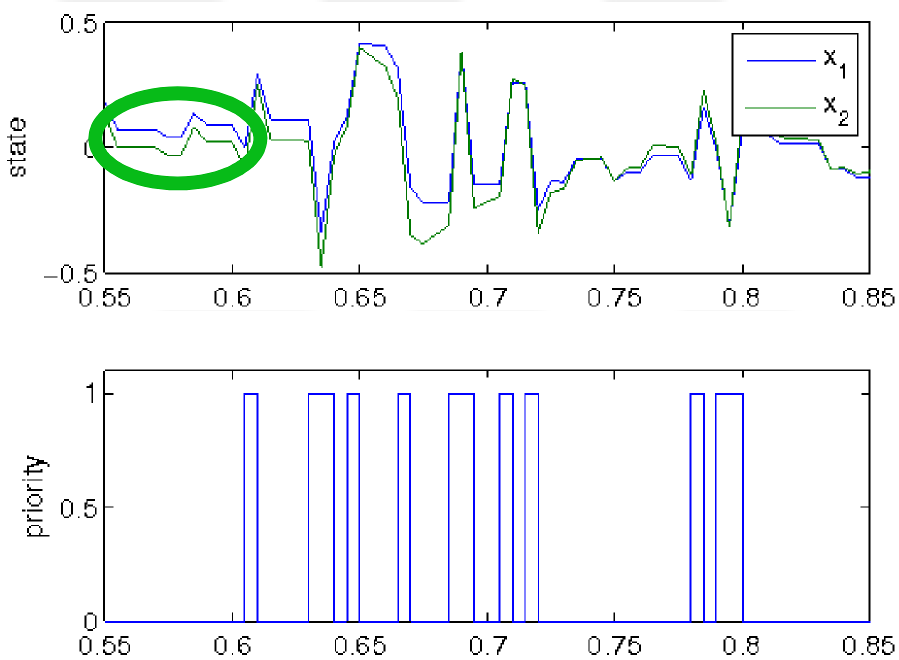
```
if |ê(k)| > E
    then π_k = H
         x̂(k+1|π_k) = x̂^H_get(k+1)   % next state
    else π_k = L
         x̂(k+1|π_k) = x̂^L_get(k+1)   % next state
```

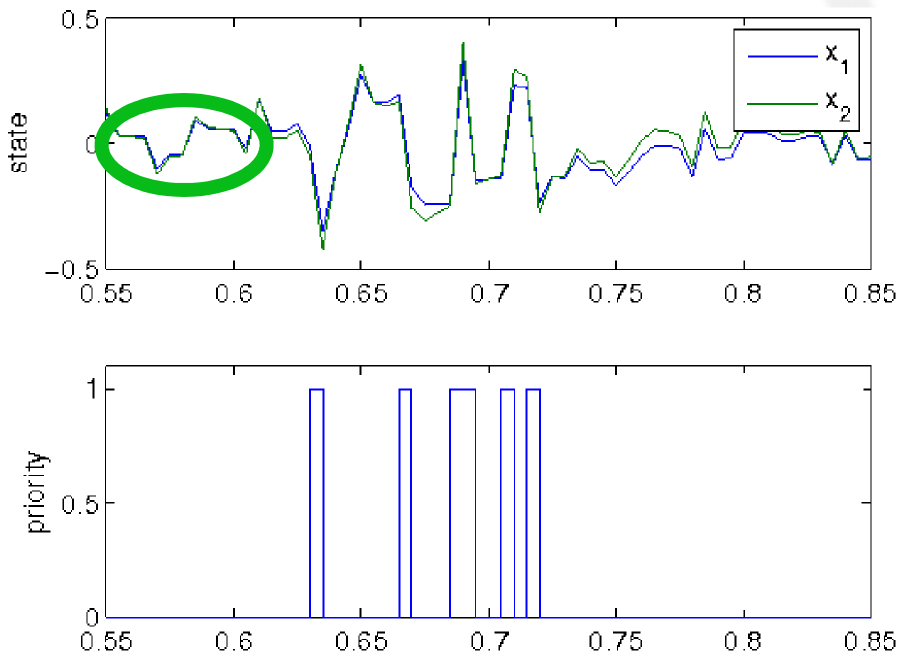
$$
\begin{aligned}
&\texttt{if } |\hat{e}(k)| > E \\
&\quad \texttt{then } \pi_k = H \\
&\qquad \hat{x}(k+1|\pi_k) = \hat{x}^H_{get}(k+1) \quad \texttt{\% next state} \\
&\quad \texttt{else } \pi_k = L \\
&\qquad \hat{x}(k+1|\pi_k) = \hat{x}^L_{get}(k+1) \quad \texttt{\% next state}
\end{aligned}
$$

Example

- Control goal: try to keep plant state at zero
- Two different intervals in the network with different values of packet loss rate in the low-priority class

Example

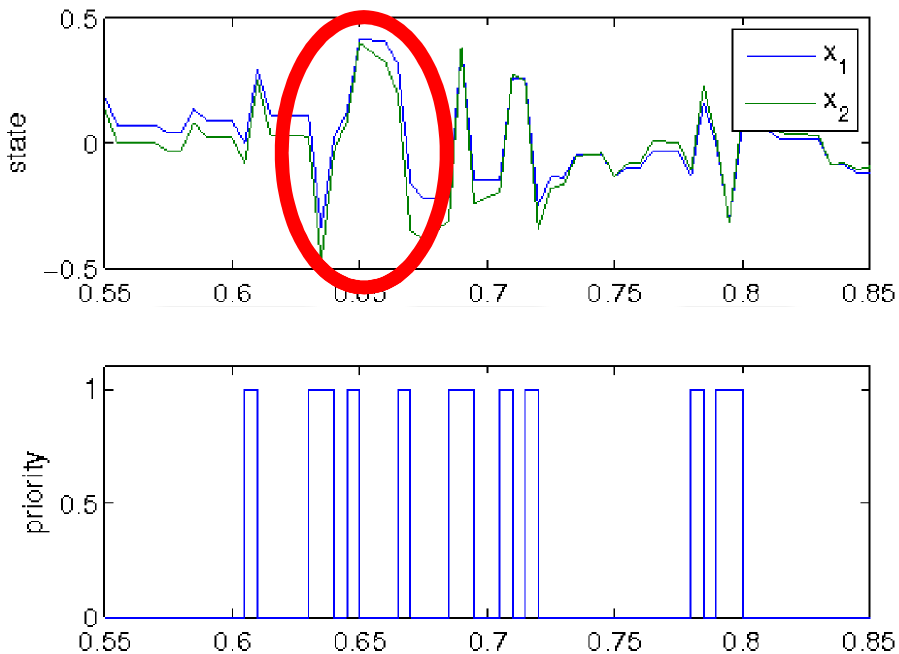


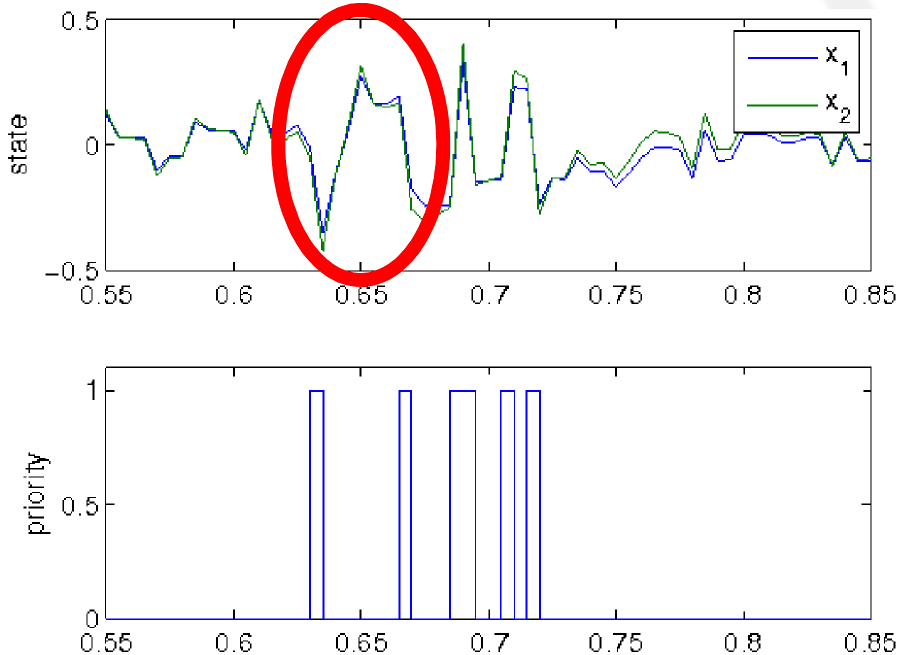


Packet loss rate
- H service: 10%
- L service: 50%

Packet loss rate
- H service: 10%
- L service: 35%

Example





Packet loss rate
- H service: 10%
- L service: 50%

Packet loss rate
- H service: 10%
- L service: 35%

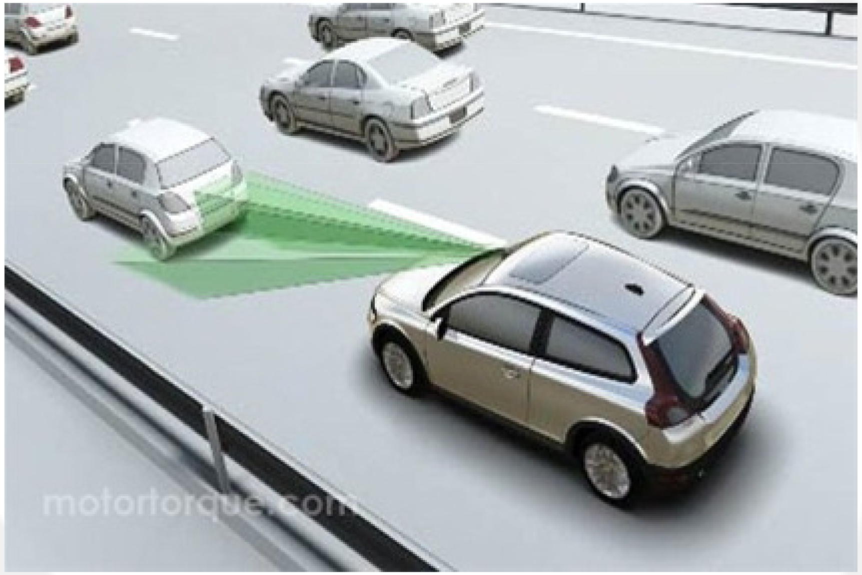
Advantages

- High priority packets are used when
  - Important data have to be sent
  - Low priority service is bad due to network problems
- High-priority class is not wasted
  - More controller-plant pairs can share the same channel since statistically they may not have to send important packets at the same time

SOLUTION 2: DESIGN OF TRANSMISSION POLICY IN A FORMATION CONTROL SCENARIO

Formation control

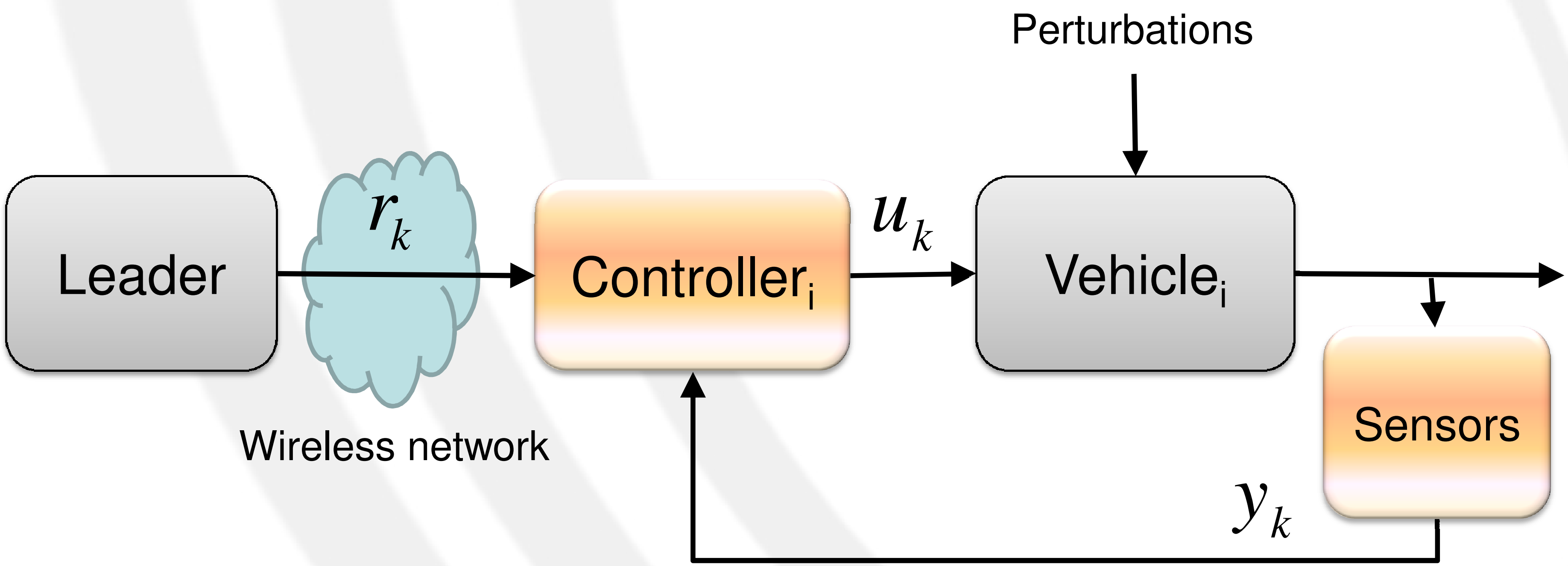
- Autonomous vehicles should adapt their trajectory and speed to keep relative distances with respect to each other
  - The formation leader chooses the trajectory
  - Presence of spatial constraints (e.g., a street) and obstacles should be taken into account



Formation control and NCS

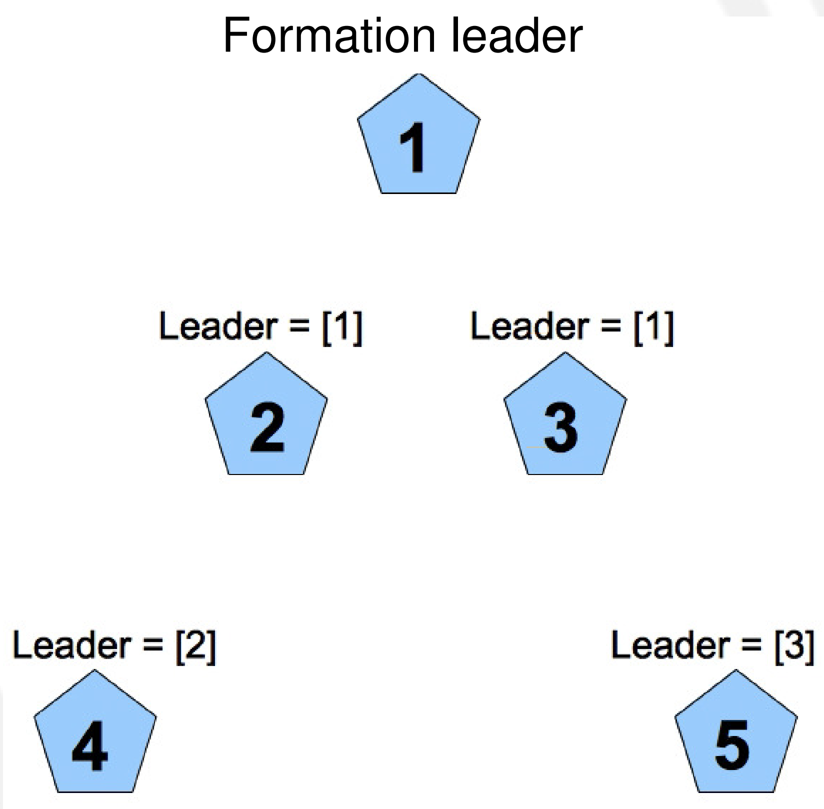
- Each vehicle receives position and speed of neighbours through wireless messages (reference signal), considers its own position and speed (measurements) and changes trajectory and speed accordingly (commands).
- Each vehicle can be considered a NCS
  - Plant: its dynamic and cinematic behavior
  - Controller and Plant are directly connected
  - Reference: the position of the leader received through the network
  - Perturbation: its position and speed may change due to wind, water flow, obstacles.

Formation control and NCS



A simplified but complete scenario

- Each vehicle
  - has only one leader
  - broadcasts its position and speed so that followers can know them
  - receives all packets but keeps only the ones from its leader
  - changes its trajectory and speed according to the speed/position of its leader



Open problems

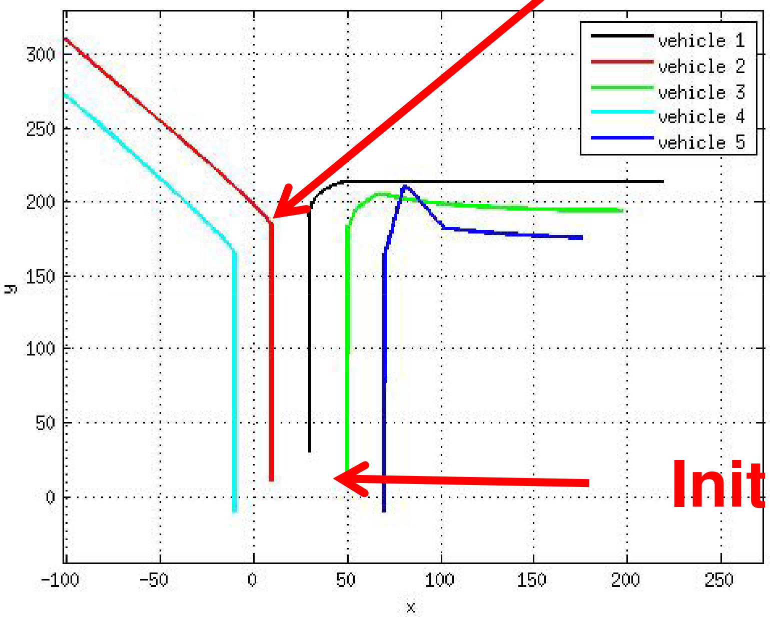
- Messages may not arrive to the followers
  - Collisions
  - Out-of-range transmission
- If the position of the leader is not heard then the vehicle cannot react in time
  - Collisions (vehicles not packets!)
  - Loss of vehicles
- Reaction delay depends on the timely reception of reference packets
  - Channel access
  - Propagation delay as a function of distance (relevant in case of acoustic wave transmission of underwater vehicles)

Design space dimensions

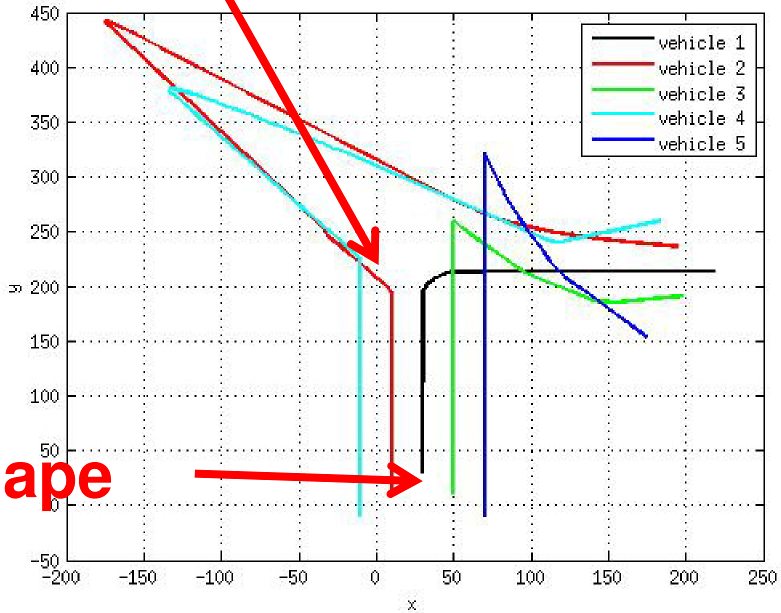
- Controller: it takes the position/speed errors and decides the speed
  - Traditional control design approach
- Network: many parameters can be controlled
  - Transmission power
  - Channel access policy (TDMA vs. CSMA)
  - Packet priority
  - Packet redundancy

Transmission power

Perturbation



Always minimum power

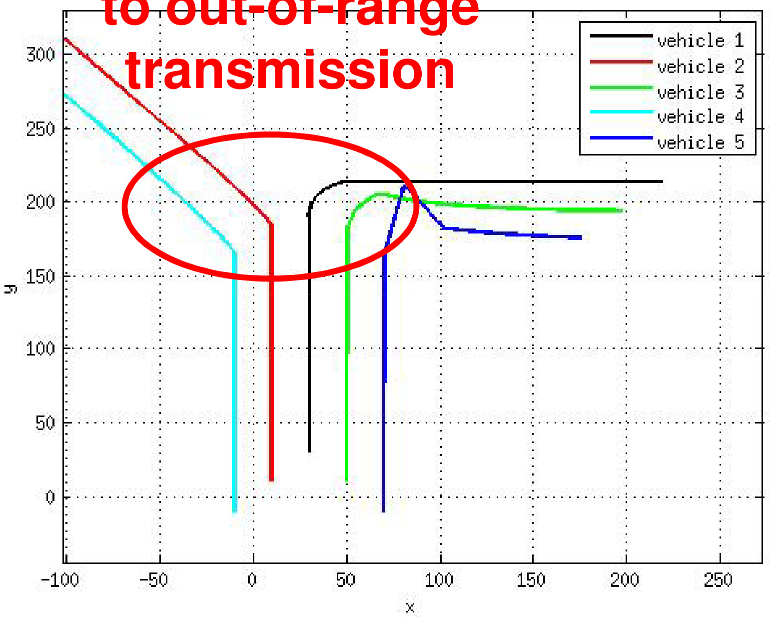


Always maximum power

Initial shape

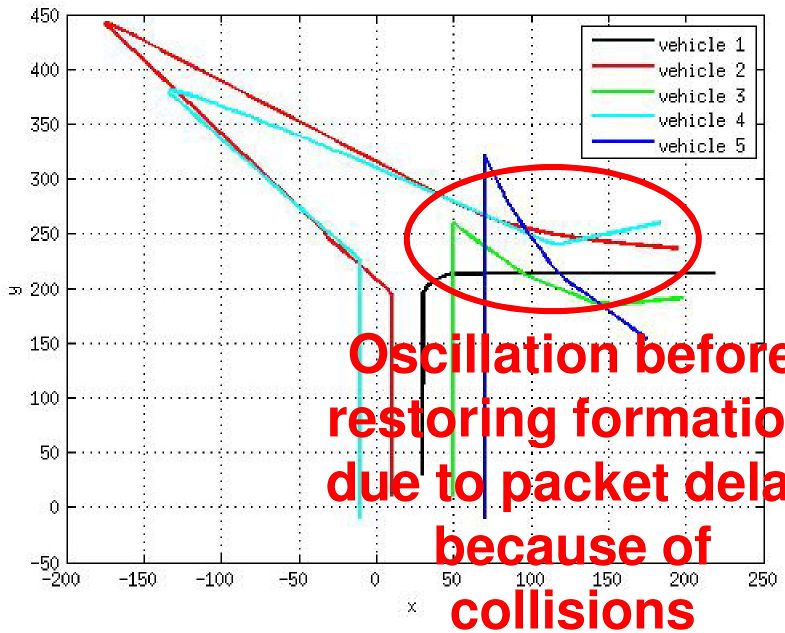
Transmission power

Loss of vehicles due to out-of-range transmission



Always minimum power

Oscillation before restoring formation due to packet delay because of collisions



Always maximum power

Power adaptation is desired !!!

Transmission power adaptation

- Goal: adjust the transmission power to reach the followers (no more!) avoiding to disturb others
- Strategy: use the information received by followers to estimate their distance and adjust TX power accordingly
  - not used for speed control
  - used to change the transmission power according to a given *signal loss law*

Signal loss law

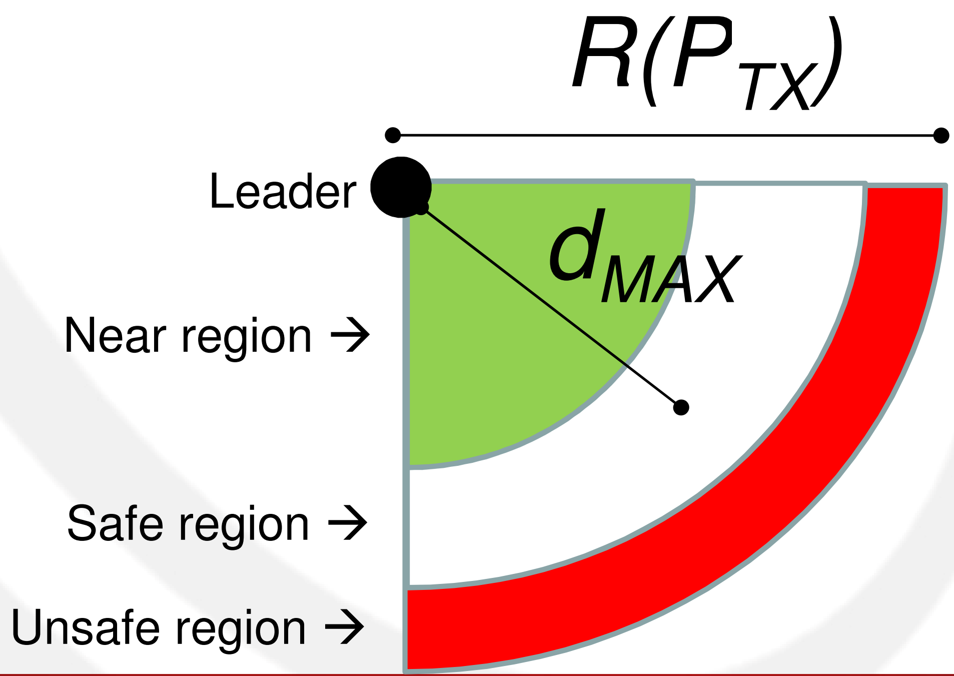
- Let us assume that the signal power decreases according to

$$P_{RX} = \frac{1}{d^{\alpha}} P_{TX}$$

- If $P_{RX}<P_{min}$ then the packet is not received
- Let $R(P_{TX})$ the valid transmission range in which $P_{RX} \geq P_{min}$

Power adaptation algorithm

- At each sample time:
  - hear position messages from the followers
  - let d_{MAX} be the maximum distance among all the followers
  - adjust P_{TX} so that d_{MAX} falls in the *Safe Region*

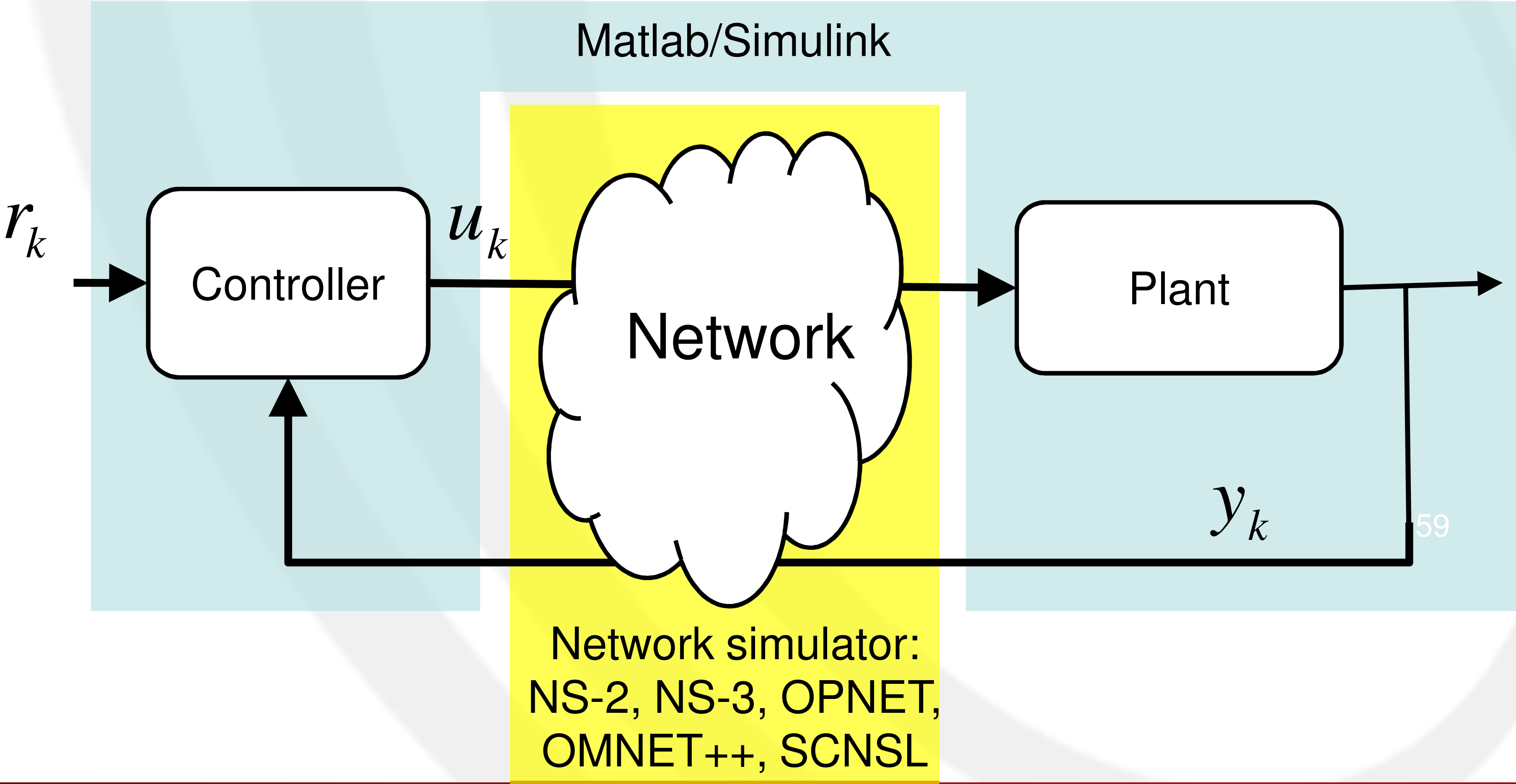


SIMULATION ISSUES FOR NCS

Simulation of communications

- Matlab/Simulink
  - Just injection of delay and packet losses on a point-to-point link
- Network simulator
  - Description of a full topology
  - Effect of interaction with other packet sources
    - Collision
    - Hidden node

Co-simulation

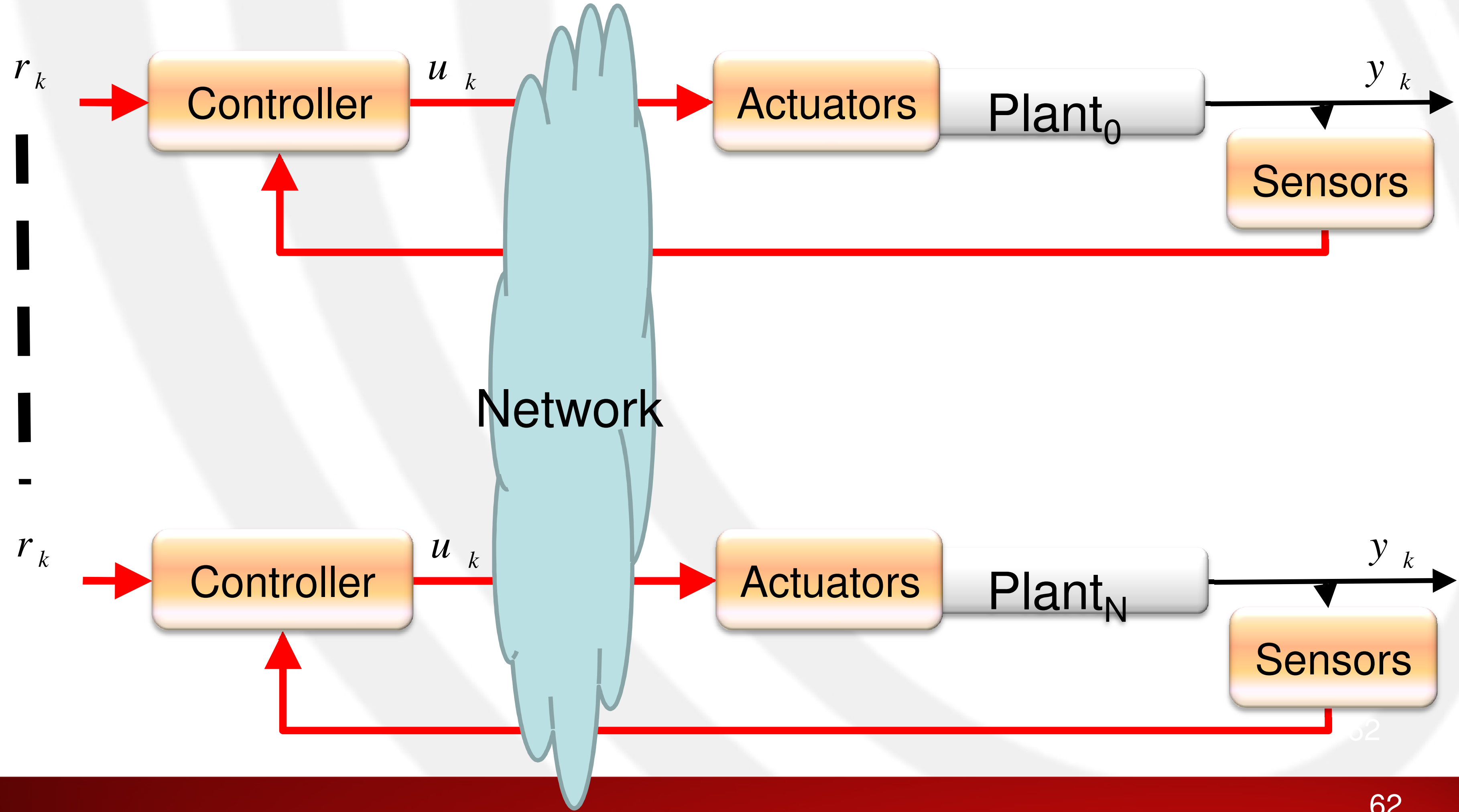


Co-simulation issues

- How to connect different tools?
  - Socket
  - Shared memory
- How to synchronize simulation threads?
  - Only one tool execution at each time
  - Parallel execution with synch points
- How to represent external entities inside the model?

RELATIONSHIP BETWEEN NCS DESIGN AND NES DESIGN

Set of networked control systems



Distributed application of networked embedded systems