Lecture 16: Real-Time Networks and Networked Control Systems

[These slides]

- Background
- Real-Time Networks
- Protocol Stack
- Network Examples
  - CAN
  - TTP
- Networked Control Systems

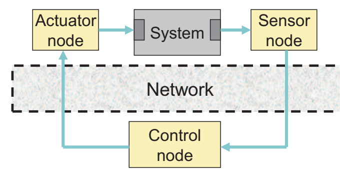
These slides are partly based on material from Luis Almeida, Universidade do Porto, Portugal

Background

Distributed architectures are pervasive in many application fields:
- Industrial automation
- Transportation systems (airplanes, cars, trucks, trains, …)
- Multimedia systems (remote surveillance, industrial monitoring, video on demand, …)

In many cases with **critical timeliness** and **safety** requirements

Increasingly common that control loops are closed over networks (= **networked control**)



Background

Motivations for distributed architectures:
- Processing closer to data source /sink
  - "Intelligent" sensors and actuators
- Dependability
  - Error-containment within nodes
- Composability
  - System composition by integrating subsystems
- Scalability
  - Easy addition of new nodes with new or replicated functionality
- Maintainability
  - Modularity and easy node replacement
  - Simplification of the cabling

Background

Today there are many different networks with real-time capabilities aiming at different application domains, e.g.

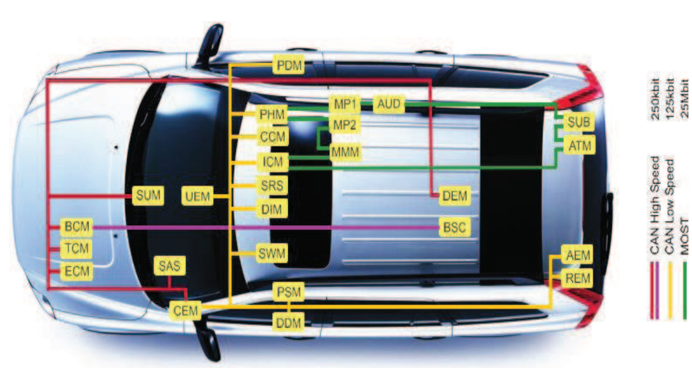
- ATINC629, SwiftNet, SAFEbus – avionics
- WorldFIP, TCN – trains
- CAN, TT-CAN, FlexRay – cars
- ProfiBus, WorldFIP, P-Net, DeviceNet, Ethernet – automation
- Firewire, USB – multimedia

VW Phaeton

- 11,136 electrical parts
- 61 ECUs (Electronic Controller Units == CPUs)
- Optical bus for high bandwidth infotainment data
- 35 ECUs connected by 3 CAN-busses sharing
  - 2500 signals
  - In 250 CAN messages

The VW Phaeton
Adapted from (Loehold, WFCS2004)

Volvo XC 90 network topology



Contents

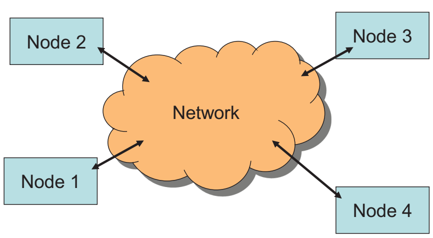
- Background
- **Real-Time Networks**
- Protocol Stack
- Network Examples
  - CAN
  - TTP
- Networked Control Systems

Service requirements

Typical service requirements in real-time networks:
- Efficient transmission of **short data** (few bytes)
- **Periodic** transmission (control, monitoring) with **short periods** (ms), **low latency**, and **small jitter**
- Fast transmission (ms) of **aperiodic requests** (alarms, commands, …)
- Transmission of **non-real-time data** (configuration information, log data, …)
- Multicasting as well as unicasting (peer to peer)

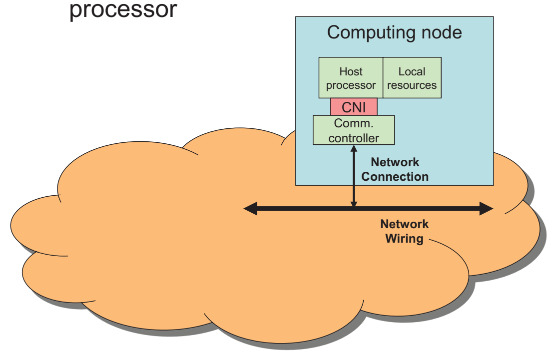
The Network in a Distributed System

- The network is a fundamental component in a distributed system supporting all the interactions among the nodes
- Hence, it is also a critical resource since loss of communication results in the loss of all global system services



Network Interfaces

- The network extends up to the **Communication Network Interface (CNI)** that is the interface between the communication systems and the node host processor



Messages & Transactions

- Interactions are supported by **message passing**
- A message is a **unit of information** that should be transferred at a given time from a sender to one or more receivers
- Contains both the **data** and the **control information** that is relevant for the proper transmission of the data (e.g., sender, destination, checksum, …)
- A network **transaction** is the sequence of actions within the communication systems required to transfer the message
- Might include messages containing only control information, i.e., **control messages**
- Some networks automatically break large messages into smaller packets (**fragmentation/reassembly**)
- A **packet** is the smallest unit of information that is transmitted
- The **data efficiency** of the network is the ratio between the the time to transmit **effective data** bits and the total duration of the transaction

Timing Figures

- Typical figures concerning the temporal behaviour of the network:
  - **Network induced delay** – extra delay caused by the transmission of data over the network. Some applications, e.g., control, are very sensitive to this
  - **Delay jitter** – variations in the network induced delay. Some applications, e.g., multimedia streaming, are very sensitive to this, but not so sensitive to the delay.
  - **Buffer requirements** – when the instantaneous transmission from a node is larger than the capacity of the network to dispatch, the traffic must be stored in buffers. Too small buffers lead to packet losses
  - **Packet loss probability** – packet losses can in addition to the above also be caused by unreliable network media. One example of this is wireless networks.

Timing Figures, cont

- **Throughput (bandwidth)** – amount of data, or packets, that the network dispatches per unit of time (bit/s and packet/s)
- **Arrival/Departure rate** – rate at which data arrives at/from the network
- **Burstiness** – measure of the traffic submitted to the network in a short interval of time. Bursts may have a negative impact on the real-time performance of the network and impose high buffering requirements. **Traffic shaping** can be used to control the characteristics of the traffic generated by a node.

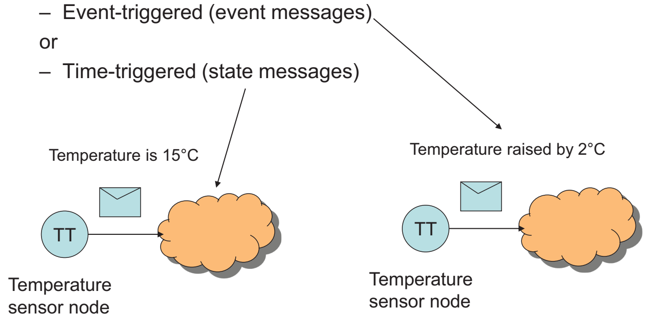
Real-Time Messages

- Real-time messages can have **event** or **state semantics**
- **Events** are perceived changes in the the system state. All events are significant for the state consistency across sender and receiver.
- **Event messages** must be queued at the receiver and removed upon reading. **Correct order** in delivery must be enforced.
- **State messages** (containing state data) can be read many times and overwrite the values of the previous message concerning the same real-time entity

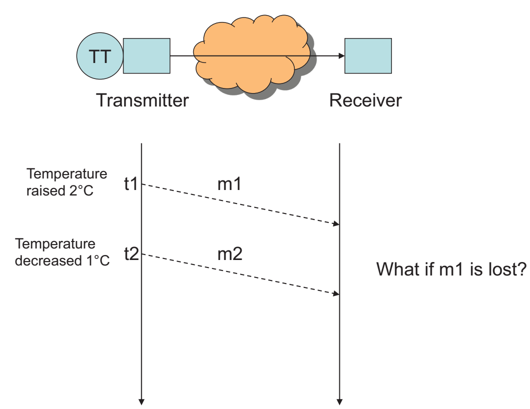
Event or Time Triggering

- According to the type of message (event or state) conveyed by the network, it can be
  - Event-triggered (event messages)

  or
  - Time-triggered (state messages)



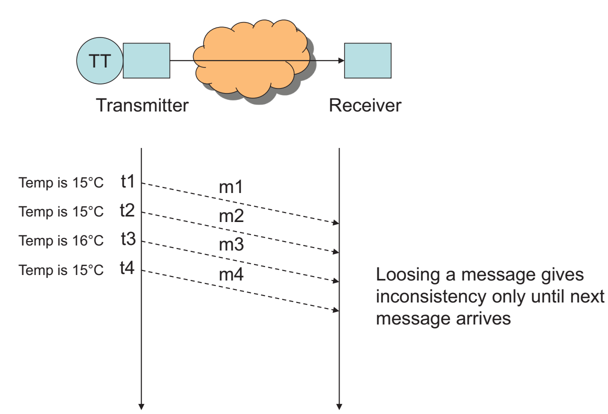
Event-Triggered Network



Time-triggered Network

- There is a notion of **network time**
  - All clocks are globally synchronized
- Transactions carrying **state data** are triggered at **predefined time instants**
- Receivers have a **periodic refresh** of the system state
- The submitted communictaion load is well determined

Time-Triggered Network



Event vs Time Triggering

Time-triggered networks:

- Are more deterministic
  - Transmission instants are predefined
  - Fault-tolerance mechanisms are easier to design
- Are less flexible in reacting to errors
  - Retransmissions are often not possible because the traffic schedule is fixed
  - A lost message is not recovered until the next period of the message stream
- Are less flexible with respect to changes
  - Everything must be known a priori and very little can be changed dynamically (cp. static cyclic CPU scheduling)
- The communication protocols are often quite complex

Event vs Time Triggering

Event-Triggered Networks:

- Low level of determinism
  - Events can occur at any time
- More complex fault-tolerance schemes
- Very flexible with respect to errors
  - Retransmissions can be carried out immediately
- The communication protocols are normally quite simple

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- Real-Time Networks
- **Protocol Stack**
- Network Examples
  - CAN
  - TTP
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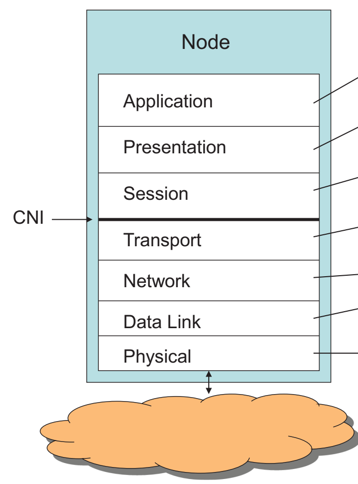
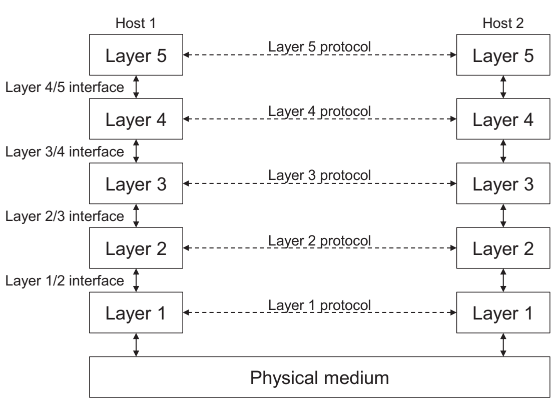
The OSI Protocol Stack



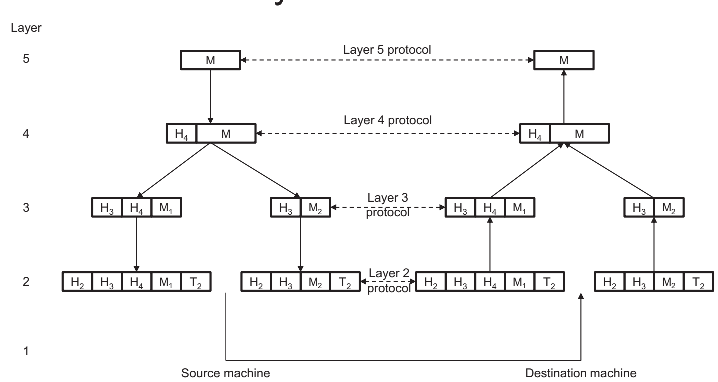
The OSI Reference Model

- Common services for a class of apps. (FTP, HTTP, ...)
- Data semantics (conversion, compression, encryption, …)
- Remote actions (name services, directory, billing, ...)
- End-to-end comm. control, e.g., (TCP, UDP)
- Routing, logical addressing
- Physical addressing, medium access control
- Topology, medium, bit-encoding

Protocol Stack



Layer Interfaces



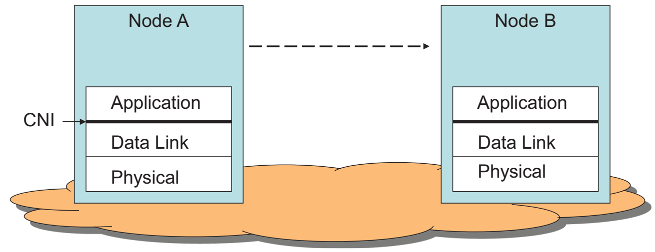
Very large computing and communication **overhead** for short real-time data traffic!!

Real-Time Protocol Stack

- The end-to-end communication delay must be bounded
  - All services at all layers must be time-bounded
  - Requires appropriate time-bounded protocols
- The 7 OSI layers impose a considerable overhead…
- Many real-time networks
  - are dedicated to a well-defined application (no need for presentation)
  - use single network domain (no need for routing)
  - use short messages (no need to fragment/reassemble)

Collapsed OSI Model

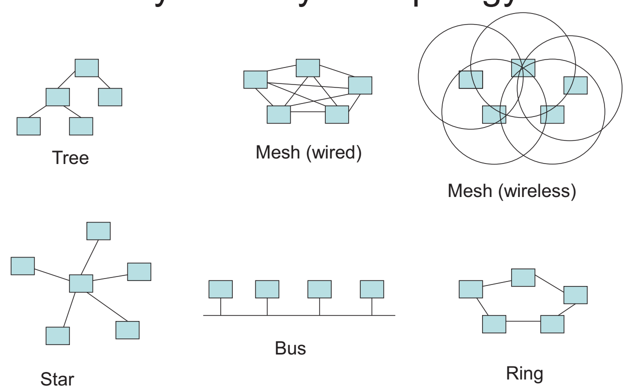
- Application accesses the Data Link directly
- Other layers may be present but are not fully stacked
- In industrial automation these networks are called **fieldbuses**



Physical Layer

- **Interconnection topology**
- **Physical medium**
- Coding of digital information
- Transmission rate
- Maximum interconnection length
- Max. number of nodes
- Immuniy to EMI (Electro-magnetic interference)
- ….

Physical Layer: Topology



Physical Layer: Medium

- Copper wiring
  - Cheaper cables and interfaces (+), suffers EMI(-)
- Optical fibres
  - Immune to EMI, wide bandwidth, low attenuation (+), expensive cables and interfaces (-)
- Wireless – Radio Frequency (RF)
  - Mobility, flexibility (+), very susceptible to EMI (-), multi-path fading (-), attenuation (-), open medium (+/-)
- Wireless – Infra-red light (IR)
  - Mobility, flexibility (+), line-of-sight (-), open medium (+/-)

Data Link Layer

Issues related to:

- Addressing
- Logical Link Control (LLC)
  - Transmission error control
- Medium Access Control (MAC)
  - for shared media

Data Link Layer: Addressing

- Direct addressing
  - The sender and receiver(s) are explicitly identified in every transaction, using physical address (MAC addresses in Ethernet)
- Indirect (source) addressing
  - The message contents are explicitly identified (e.g. temperature of sensor X). Receivers that need the message retrieve it from the network (as in CAN)
- Indirect (time-based) addressing
  - The message is identified by the time instant at which it is transmitted (as in TTP – Time Triggered Protocol)

Data Link Layer: LLC

- Logical Link Control (LLC)
  - Deals with the information transfer at this level
  - Upper sub-layer of the data link layer
  - Typical services are:
    - **Send with immediate acknowledge**
      Sender waits for acknowledge from receiver
    - **Send without acknowledge**
      No synchronization between data and receiver
    - **Connection-oriented services**
      A connection must be established between parts before any communication may take place

Data Link Layer: Transmission Error Control

Part of the LLC

Specifies error detection and action upon this. Typical actions are
- **Forward error correction** (FEC)
  - Error correcting codes (more related to the physical layer)
- **Automatic Repeat reQuest** (ARQ)
  - The receiver triggers a repeat request upon error
- **Positive Acknowledgement and Retry** (PAR)
  - The sender resends if ACK is not received

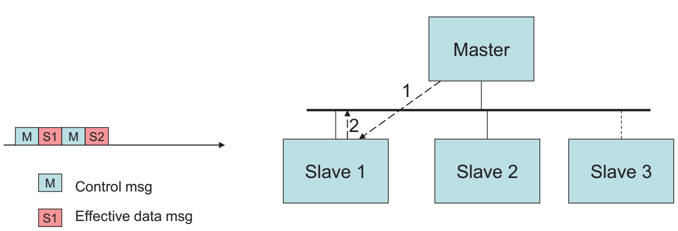
From a real-time perspective, ARQ and PAR may induce longer delivery delays as well as extra communication load

Data Link Layer: MAC

Medium Access Control (MAC)
- Lower sub-layer of the data link layer
- Determines the order of the network access by contending nodes and, thus, the network access delay
- Is of **paramount importance for the real-time behavior** of networks that use a shared medium

MAC: Master-Slave

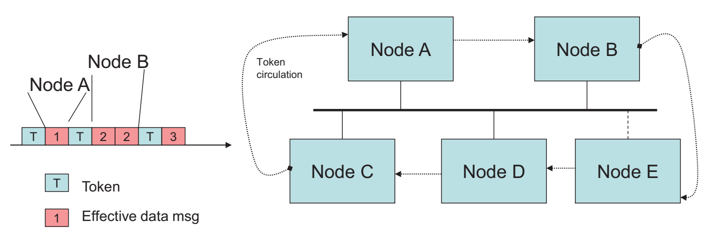
- Access is granted by the Master node
- Nodes synchronized with the master
- Requires one control message per data message



- Ex. WorldFIP, Ethernet Powerlink, Bluetooth (within piconets)

MAC: Token Passing

- Access is granted by the possession of a token
- Order of access enforced by token circulation
- Real-time operation requires bounded token holding time

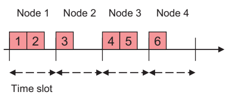


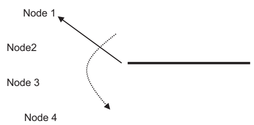
- Ex. FDDI, PROFIBUS

MAC: TDMA

Time-Division Multiple Access

- Access granted in a dedicated time-slot
- Time slots are pre-defined in a cyclic framework
- Requires global clock syncronization
- High data efficiency
- Typically uses static table-based scheduling





- Ex. TTP/C, TT-CAN, PROFINET

MAC: CSMA

Carrier-Sense Multiple Access:

- Set of protocols based on sensing bus inactivity before transmitting (asynchronous bus access)
- There may be collisions
- Upon collision, nodes back off and retry later, according to some specific rule (this rule determines to a large extent the real-time features of the protocols)

MAC: CSMA/CD

Carrier-Sense Multiple Access with Collision Detection

- Used in shared Ethernet (hub instead of switch)
- Collisions are destructive and are detected within collision window
- Upon collision, the retry interval is random and the randomization window is doubled for each retry until 1024 slots
- Non-deterministic (e.g., chained collisions)
- Not suitable for a real-time network. However,
  - The physical Ethernet layer is often used in real-time networks.
  - It is possible to get real-time performance on an Ethernet network, if the access to the medium is scheduled in some way, i.e., collisions are avoided

MAC: CSMA/BA

Carrier-Sense Multiple Access with Bit-Wise Arbitration

- Bit-wise arbitration with non-destructive collisions
- Upon collision, highest priority node is unaffected. Nodes with lower priorities retry right after.
- Determinsitic
- E.g. CAN
- Sometimes also called CSMA/CR (Collision Resolution) or CSMA/CA (Collision Arbitration), although the latter really is something else

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- **Network Examples**
  - **CAN**
  - **TTP**
- Networked Control Systems

CAN

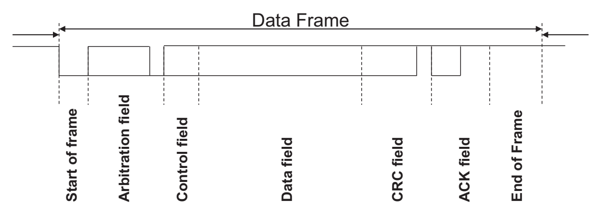
- Controller Area Network
- Created by Bosch for use in the automotive industry
- Used in most European cars today
- Adopted by GM as an in-house standard
- Expanded to industrial automation
- Defines physical and data link layer
- Multi-master, broadcast, serial bus
- Transmision rate from 5 kbit/s to 1 Mbit/s
- Small sized messages – 0-8 bytes
- Relatively high overhead (47 bits + stuff bits)
- On transmission, nodes synchronize on bit level

CAN

- CAN is like Ethernet …
  - Everybody with a message to send waits until the bus is quiet, then starts transmitting, and if a node detects a collision it backs off and retries later
- … but more deterministic
  - A CAN bus has a special electrical property that allows it to handle collisions better

The CAN Protocol

- Messages are called frames
- A frame is tagged by an identifier
  - Indicates the contents of the frame (used for addressing)
  - Used in the arbitration for prioritizing frames (the frame with the lowest identifier is selected to send in case of collision)
- The CAN physical layer behaves as a wired AND, i.e., if any node sends a logical 0, then all nodes receive 0 bit.



Bit Stuffing

- CAN frames are **bit stuffed**
  - If 5 bits in a row are the same sign then the protocol inserts a bit of the opposite sign
  - Used to ensure enough edges to maintain synchronization
  - Used to distinguish data frames from special error handling frames

The CAN Protocol, cont

- All nodes receive all frames
- The handling of the CAN bus communication within a node is done by a special CAN controller (card/chip)
- The CAN controller throws away frames not needed by the node using ID filtering hardware
- Messages that are waiting to be sent are queued in a priority sorted list in the CAN controller

The Basic Protocol

- Frames start by sending the identifier field **most significant bit first**
- When sending the identifier the frame is in **arbitration**
  - Other frames may be sent too
  - Need to find the highest priority frame
- If a node sends a 1 (recessive bit) but reads back a 0 (dominant bit) then it gives up and backs off
  - There must be a higher priority frame being sent
- Restarts sending the same frame when the bus is idle again

Arbitration

Frame 1	1344	1
Frame 2	1306	1
Frame 3	1498	1
Bus		1

Arbitration

Frame 1	1344	10
Frame 2	1306	10
Frame 3	1498	10
Bus		10

Arbitration

Frame 1	1344	101
Frame 2	1306	101
Frame 3	1498	101
Bus		101

Arbitration

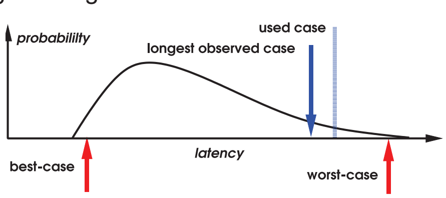
Frame 1	1344	1010
Frame 2	1306	1010
~~**Frame 3**~~	~~1498~~	~~1011~~
Bus		1010

Arbitration

~~**Frame 1**~~	~~1344~~	~~10101~~
Frame 2	1306	10100011010
~~**Frame 3**~~	~~1498~~	~~1011~~
Bus		10100011010
	1306	

CAN and hard real-time

- Need to know the worst-case frame latencies (end-to-end delay)
- Through testing



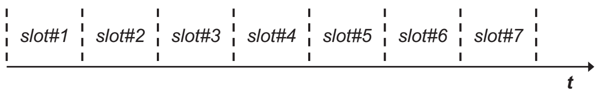
- Through analysis
  - Fixed priority scheduling theory can be applied
  - Bus = shared resource, cp. CPU
  - Frame = job (invocation of a task)

TTP – Time Triggered Protocol

- Not just a network, more of an architecture
- Shared broadcast bus, 2-25 Mbit/s
- Popular in car industry for safety-critical applications, e.g., X-by-wire
- Design goals
  - Fault-tolerance
  - Messages latencies that are easy to calculate and have no jitter

TTP – Time Triggered Protocol

- Mostly periodic messages
- Replicated broadcast communication channels
- Replicated nodes are grouped into FTUs – Fault Tolerant Units
- Access to the network through TDMA (statically allocated)



- More deterministic than CAN (cp. static scheduling vs dynamic scheduling)

TTP Design

- Message transport with predictable low latency: simple protocol with known WCET & minimal overhead
- Fault tolerance: allow node and network failures without loss of functionality
- High precision clock synchronization
- Off-line network traffic scheduling
- TTP info
  - TTTech (www.tttech.com)
  - TTP Froum (www.ttpforum.org)

FlexRay

- TTP competitor
- Developed by European car manufacturers
- Combines time-driven and event-driven communication
- Event-driven communication allowed in special slots in the TDMA structure
- Similar extensions are also possible in TTP

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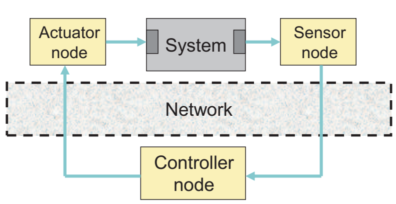
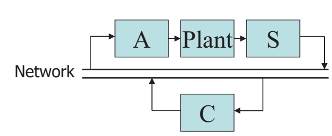
Networked Control Systems



- Networked Control System
  - wired or wireless

Networked Control Structures

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



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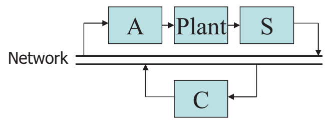

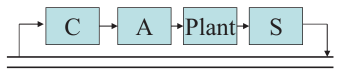

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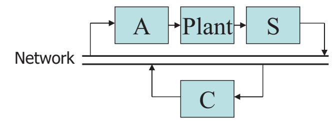

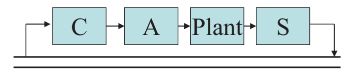

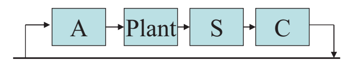

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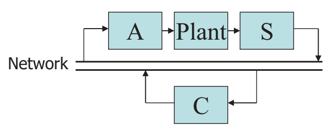

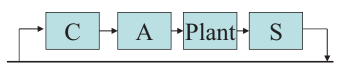

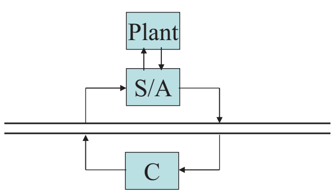

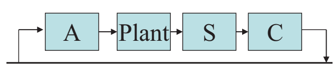

Networked Control Loop Timing

- Networked embedded control implies temporal non-determinism
  - network communication
  - real-time scheduling
- Degraded control performance due to
  - sampling interval jitter
  - non-negligible input-output latencies with jitter
  - lost samples
- However
  - Most control loops are fairly robust towards temporal non-determinism

Networked Control Loop Timing

- Networked embedded control implies temporal non-determinism
  - network communication
  - real-time scheduling
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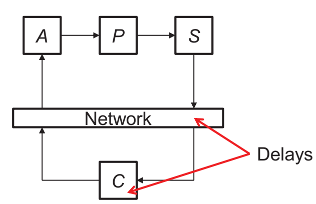
- However
  - Most control loops are fairly robust towards temporal non-determinism

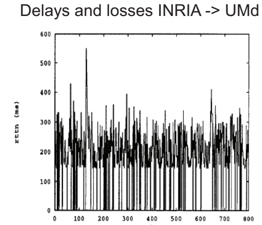
- network interface processing delay
- queuing delay
- transmission delay
- propagation delay
- link layer resend delay
- transport layer ACK delay
- ….

Control under network delay

- Delays in communication due to buffering, propagation delays, collisions/resends, …
- Delays can be fixed or varying, known (measurable) or unknown



Delays and losses INRIA -> UMd



[Bolot, 1993]

Clocks and Time Stamps

- The controller must know when the data was sampled/sent in order to compensate for varying network latencies
- Approaches:
  - Global clock
    - clock synchronization
    - complexity overhead
  - Local clocks
    - associate time-stamps with data packets
    - absolute or relative
    - OK if the data always comes from the same sensor node
    - A problem if the source node of the data changes

Compensate for Input-Output Delays

Sampled model with varying delay τ_k

$$x(k+1) = \Phi x(k) + \Gamma_0(\tau_k)u(k) + \Gamma_1(\tau_k)\mathrm{u}(\mathrm{k}-1)$$

- Design the feedback

$$u(k) = -L\begin{pmatrix} \hat{x}(k) \\ u(k-1) \end{pmatrix}$$

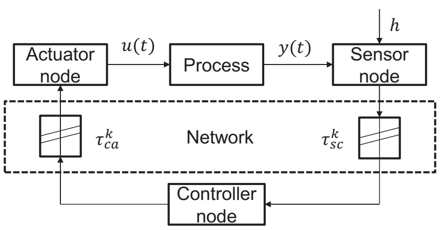
Or, let the feedback be dependent on the actual delay

based on the average (expected) input-output delay

- Modify the observer to take into account current delay τ_k

$$\hat{x}(k+1) = \Phi\hat{x}(k) + \Gamma_0(\tau_k)u(k) + \Gamma_1(\tau_k)\mathrm{u}(\mathrm{k}-1) + \mathrm{K}(\mathrm{y}(\mathrm{k}) - \mathrm{C}\hat{x}(k))$$

Compensate for Network Delays

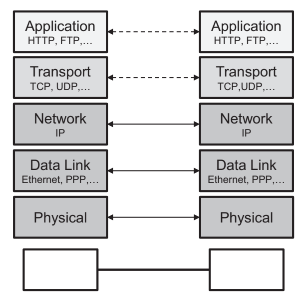


Only part of the current loop delay (τ_{sc}) can now be measured!

- Time-varying state feedback L_k based on $\tau_{sc}^k + \mathbb{E}\{\tau_{ca}\}$
- Let the actuator node record the total delay
- The total delay is communicated back to the controller
- Make the observer time-varying as before

Cross-Layer Design

- Control applications can often adapt to varying network conditions
- Network information needed at application layer -> cross-layer designs
- Specially important if full OSI or IP protocol stacks are used



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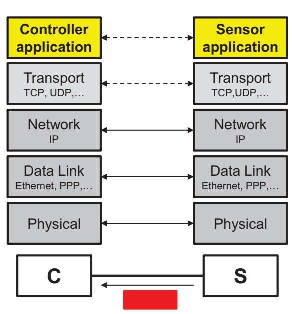

Sensor to Controller:
- when collision happens
- resample rather than resend old data

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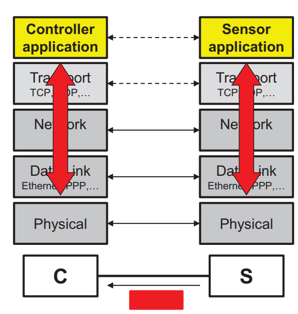

Sensor to Controller:
- when collision happens
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General Conclusions

- Real-time communication increasingly important in several fields
- The traditional OSI/IP stacks are not well suited for real-time networks
- Collapsed OSI stack (physical, data link, application) better for real-time networks
- Networked control systems increasingly common
- Problems with delays, jitter and lost packets if non-real time networks are used
- Can partly be compensated for by control methods
- In wireless systems the problems become worse