Lecture 13: Real-Time Networks and Networked Control Systems

[These slides]

- Background
- Real-Time Networks
- Collapsed OSI Model
- Network Examples
  - CAN
  - TTP
- Wireless Control Systems

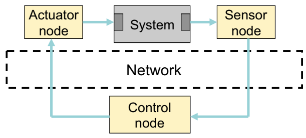
These slides are partly based on material from Luis Almeida, Universidade do Porto, Portugal

Background

Distributed architectures are pervasive in many applications:
- Industrial automation
- Transportation systems (planes, cars, trucks, trains, …)
- Multimedia systems (surveillance, 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 the 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 simple node replacement
  - Simplification of the cabling

Background

Different networks with real-time capabilities are aimed at different application domains, e.g.

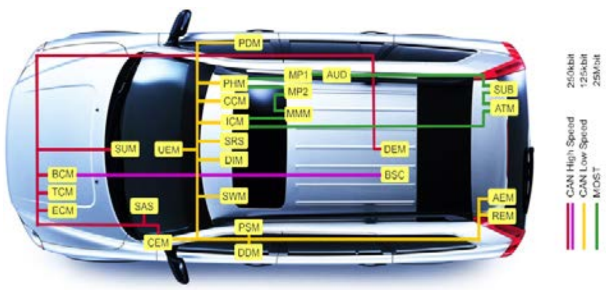
- ATINC629, SwiftNet, SAFEbus (avionics)
- WorldFIP, TCN (trains)
- CAN, TT-CAN, FlexRay, MOST (cars)
- ProfiBus, WorldFIP, P-Net, DeviceNet (automation)
- Firewire, USB (multimedia, …)

Example: VW Phaeton

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

The VW Phaeton
Adapted from (Loehold, WFCS2004)

Example: Volvo XC 90



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Requirements

Typical 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)

Messages and Packets

- 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 **data** and **control information** that is relevant for the proper transmission of the data (e.g., sender, destination, checksum, …)
- Some networks automatically break large messages into smaller packets (**fragmentation/reassembly**)
- A **packet** is the smallest unit of information that is transmitted

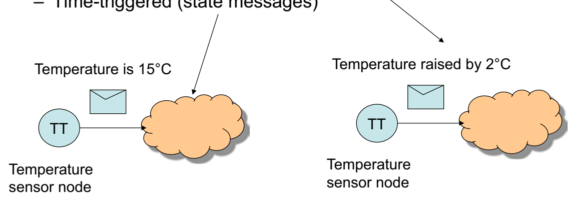
Real-Time Messages

- A real-time message is associated with a **deadline**
  - Soft or hard
- Real-time messages can have **event** or **state semantics:**
  - **Events** are perceived changes in 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.

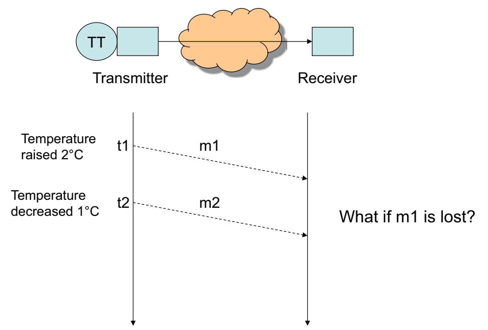
Event vs Time Triggered Messages

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

  or
  - Time-triggered (state messages)



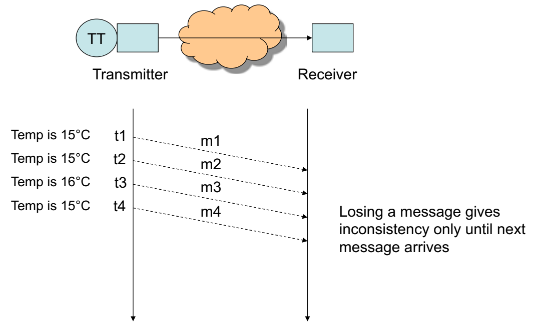
Event-Triggered Network



Time-Triggered Networks

- In time-triggered networks, 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 network load is predetermined

Time-Triggered Network



Event vs Time Triggered Networks

Time-triggered networks

- are more deterministic
  - All 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 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 at design time and very little can be changed dynamically (cp. static cyclic CPU scheduling)

Event vs Time Triggering

Event-Triggered Networks:

- Lower level of determinism
  - Events can occur at any time (flexible)
  - MAC protocol may be needed
  - Harder to give hard real-time guarantees
- More complex fault-tolerance schemes
- More flexible with respect to transmission errors
  - Retransmissions can be carried out immediately

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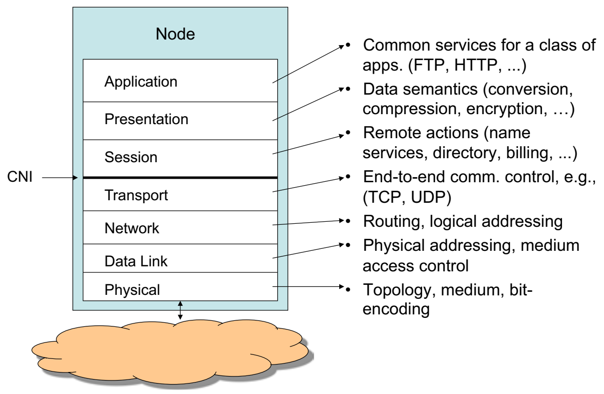
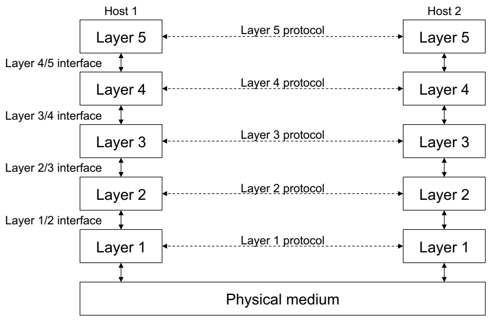
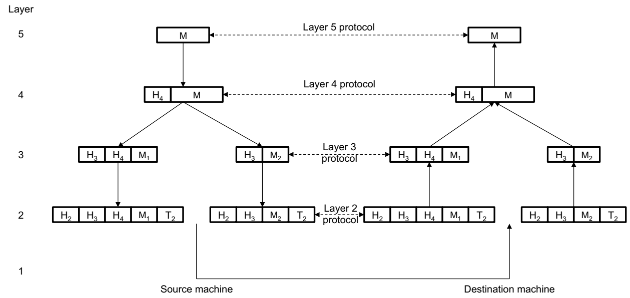
The OSI Model



Protocol Stack



Layer Interfaces



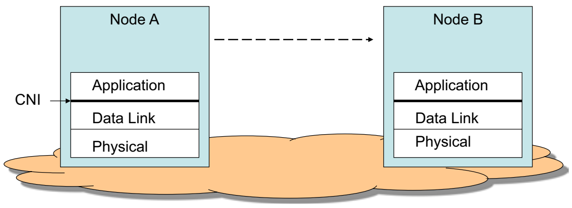
Very large computing and communication **overhead** for short real-time data traffic!

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 seven 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

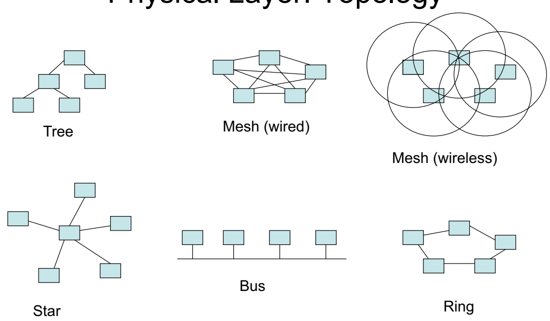
- Application accesses the Data Link directly
- Other layers may be present but are not fully stacked
- In industrial automation these networks are called **fieldbuses**



Physical Layer

- **Topology**
- **Medium**
- Coding of digital information
- …

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

- **Adressing**
- Logical Link Control (LLC)
  - Transmission error control
- **Medium Access Control (MAC)**
- ...

Data Link Layer: Addressing

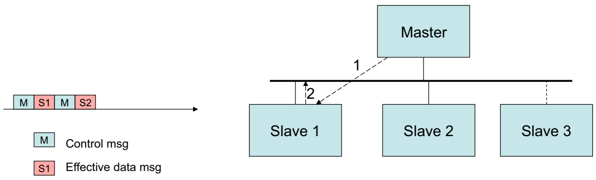
- Direct addressing
  - The sender and receiver(s) are explicitly identified in every transaction, using physical address (e.g., MAC addresses in Ethernet)
- Indirect (source) addressing
  - The message contents are explicitly identified (e.g. temperature of sensor X). Receivers that need the message retrieve it from the network (as in CAN – Controller Area Network)
- 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: MAC

Medium Access Control (MAC)
- Lowest 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

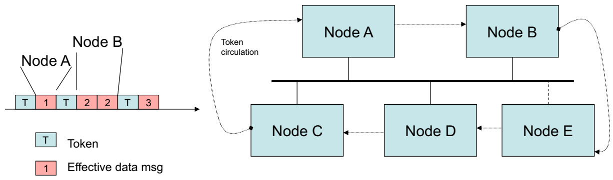
- Access is granted by the Master node
- Nodes synchronized with the master
- Requires one control message per data message



- 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

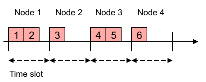


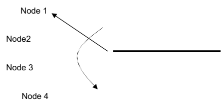
- Ex. FDDI, PROFIBUS

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, high determinism





- 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, the nodes back off and retry later, according to some specific rule

MAC: CSMA/CD

Carrier-Sense Multiple Access with Collision Detection

- Used in shared Ethernet, WiFi, ZigBee, ...
- Collisions are destructive
- Random, exponentially growing back-off times
- Non-deterministic
- Not suitable for real-time networks. However,
  - An Ethernet physical layer is often used in real-time networks.
  - Possible to get real-time performance on an Ethernet network, if access to the medium is scheduled in such a way that collisions are avoided

MAC: CSMA/BA

Carrier-Sense Multiple Access with Bit-Wise Arbitration

- Also called CSMA/CR (Collision Resolution) or (less accurately) CSMA/CA (Collision Arbitration)
- Bit-wise arbitration with non-destructive collisions
- Upon collision, the highest priority message is unaffected.
- Messages with lower priorities wait until end of transmission and then retry
- Deterministic worst-case behavior
- E.g. CAN

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  - **CAN**
  - **TTP**
- Wireless Control Systems

CAN – Controller Area Network

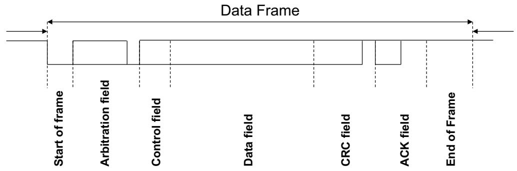
- Created by Bosch for use in the automotive industry
- Used in many European cars today
- Adopted by GM as an in-house standard
- Defines physical and data link layers
- Multi-master, broadcast, serial bus
- Transmision rate from 5 kbit/s to 1 Mbit/s
- Small sized messages: 0–8 bytes
- Relatively high overhead (47 bits + stuff bits)

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
  - The CAN bus has a special electrical property that allows it to handle collisions better

CAN Communication

- Messages are called frames
- A frame is tagged by an identifier
  - Indicates the contents of the frame (source addressing)
  - Used in the arbitration for prioritizing frames (frame with 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



CAN Communication

- 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

CAN Communication

- 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 filters out frames not needed by the node
- Messages that are waiting to be sent are queued in a priority sorted list in the CAN controller

CAN Arbitration

- Frames start by sending the identifier field's **most significant bit first**
- While 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
  - Means that a higher priority frame is being sent
  - Retries sending the frame when the bus is idle again

CAN Arbitration

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

CAN Arbitration

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

CAN Arbitration

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

CAN Arbitration

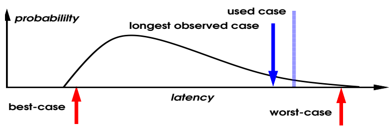
Frame 1	1344	1010
Frame 2	1306	1010
~~**Frame 3**~~	~~1498~~	~~1011~~
Bus		1010

CAN Arbitration

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

CAN and Hard Real-Time

- Need to bound the worst-case frame latency (end-to-end delay)
- Option 1: Testing



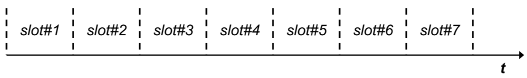
- Option 2: Analysis
  - Bus = shared resource (cp. CPU)
  - Frame = job (invocation of a task)
  - Fixed priority scheduling theory can be applied
    - Blocking factor from transmission of lower-priority frame

TTP – Time Triggered Protocol

- Not just a network, more of a communication architecture
- Shared broadcast bus, 2–25 Mbit/s
- Popular in car industry for safety-critical applications, e.g., drive-by-wire
- Features
  - Fault tolerance: allow node and network failures without loss of functionality
  - High precision clock synchronization
  - Predictable messages latencies, 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 (static scheduling)



- More deterministic than CAN

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

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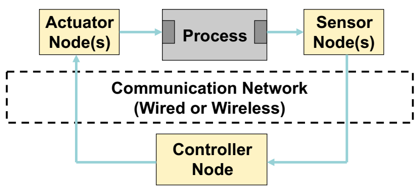
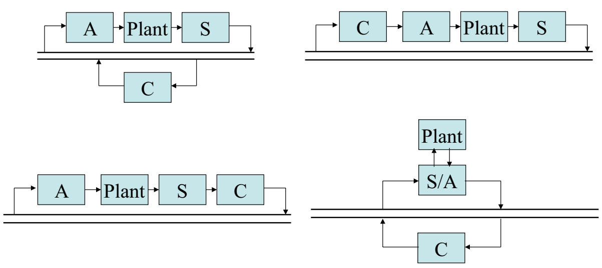
Networked Control Systems



- Hot research topic in the last 10 years

Networked SISO Control Structures



Several more options for MIMO controllers...

Networked Control Loop Timing

- Networked embedded control implies temporal non-determinism
  - network communication
  - real-time scheduling
- Degraded control performance due to
  - sampling jitter
  - control delay and control jitter
  - dropped packets (samples or controls)
- However
  - Most control loops are fairly robust towards temporal non-determinism

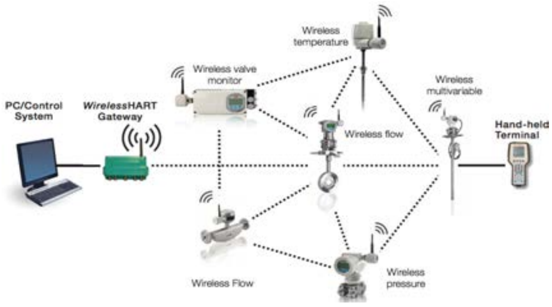
> - network interface processing delay
> - queuing delay
> - transmission delay
> - propagation delay
> - link layer resend delay
> - transport layer ACK delay
> - ….

Wireless Networked Control

Emerging technology. Potential advantages:

- Flexibility
  - Placement: moving parts, mobile units, outdoor, ...
  - Commissioning and maintenance
- Cost
  - Less cables, fewer connectors, less wear and tear
  - Reduced design and installation costs
- New applications

Example: Wireless Industrial Automation



[ABB product sheet for Wireless HART]

Example: Car Trains

[Volvo Cars Newsletter: "Fordonståg en möjlighet på vanliga motorvägar"]

Example: Control and Coordination of Mobile Robots

[RoboCup humanoid league]

Networks for Wireless Control

- ISM networks (licence free)
  - IEEE 802.11 (WLAN)
  - IEEE 802.15.1 (Bluetooth)
  - IEEE 802.15.4 (ZigBee)
- Mobile/cellular networks
  - GSM
  - 3G
  - 4G/LTE
  - Device to Device (D2D)

A Comparison

Market Name Standard	ZigBee® 802.15.4	--- GSM/GPRS CDMA/1xRTT	Wi-Fi™ 802.11b	Bluetooth™ 802.15.1
Application Focus	Monitoring & Control	Wide Area Voice & Data	Web, Email, Video	Cable Replacement
System Resources	4KB - 32KB	16MB+	1MB+	250KB+
Battery Life (days)	100 - 1,000+	1-7	.5 - 5	1 - 7
Network Size	Unlimited (2^{64})	1	32	7
Maximum Data Rate (KB/s)	20 - 250	64 - 128+	11,000+	720
Transmission Range (meters)	1 - 100+	1,000+	1 - 100	1 - 10+
Success Metrics	Reliability, Power, Cost	Reach, Quality	Speed, Flexibility	Cost, Convenience

[www.zigbee.org]

Protocols for Wireless Industrial Automation

Two protocols, both based on IEEE 802.15.4:

- Wireless Hart
  - Products since 2008 (ABB, Siemens, ...)
  - International standard (IEC 62591-1), 2010
- ISA 100 Wireless
  - Products since 2009 (Honeywell, GE, ...)
  - ANSI standard 2011
  - International standard (IEC 62734), 2014

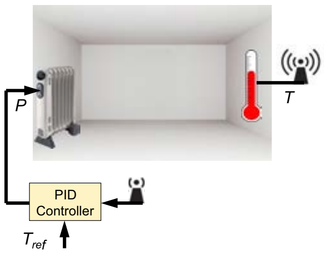
Challenges in Wireless Control

- Low data rates (implies slow sampling)
- **Dropped packets, long/variable control delays**
  - Radio channel affected by the environment, disturbing nodes
  - Routing in multi-hop networks give long delays
- No guarantees
  - Must ensure safe error handling and safe shut downs
- Security

Dropped Packets and Variable Delays

- Analyze and simulate the behavior in different possible scenarios
  - Average case
  - Worst case
- If needed, it is possible to design a controller that **compensates** for delays and lost packets

Example: Wireless Temperature Control



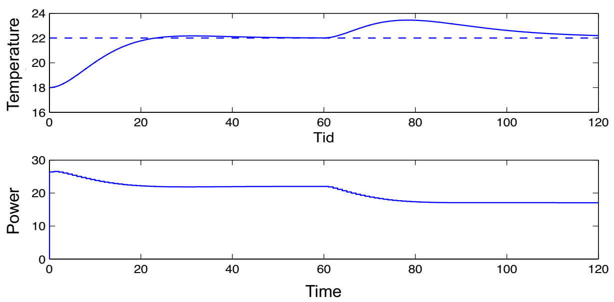
- Process model:

$$G_p(s) = (1 + 10s)^{-2}$$

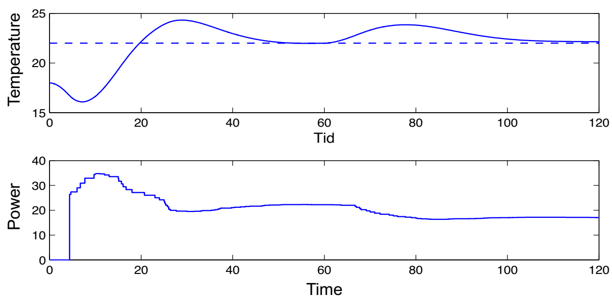
- PID controller, implemented with sampling interval $h = 1$

➔Simulation

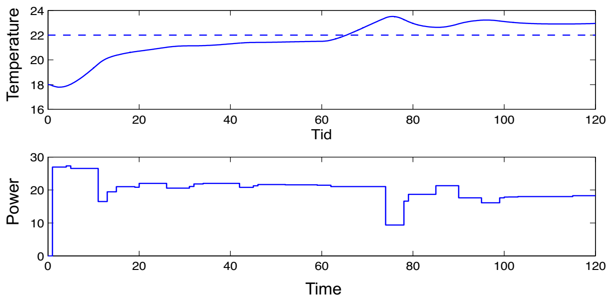
Simulation: Ideal behavior



Simulation: Behavior under varying control delay (τ = [1.0, 7.0] s)



Simulation: Behavior under dropped packets (p = 70%)

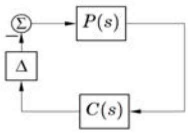


Some Analysis Tools from Recent Research

- The Jitter Margin (Y. Kao & B. Lincoln)
  - Stabilty analys (worst case)
- Jitterbug (B. Lincoln & A. Cervin)
  - Stochastic performance analysis (average case)
- TrueTime (A. Cervin *et al.*)
  - Simulation toolbox

The Jitter Margin

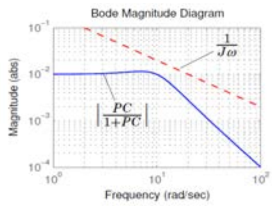
- Generalization of the well known *delay margin*
- How large *variable delay* (jitter) can a feedback loop tolerate and remain stable?
- Model:



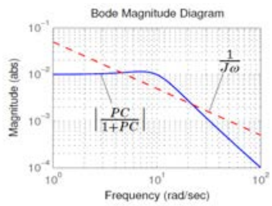
  - Linear process $P(s)$
  - Linear controller $C(s)$
  - Variable delay Δ = (0 … J)
    - Allowed to vary in *any way* within the interval

Jitter Margin

- Graphical test in Bode magnitude diagram:

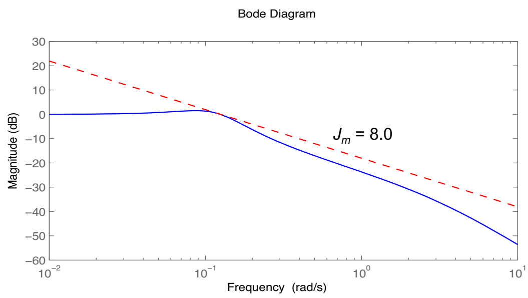


Stable



May be unstable

Jitter Margin for the Example



Conclusions from the Jitter Margin Example

- As long as the controller receives information that is at most 8 s old, the feedback loop will remain stable
- If this time is exceeded, the controller should switch off (time-out)

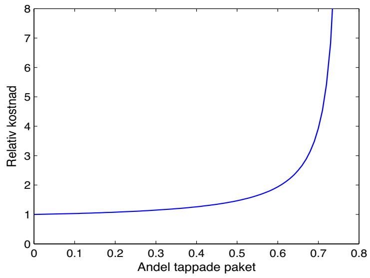
Jitterbug

- Matlab toolbox for calculation of average-case performance
- Delays are described using probability density functions
- LQG-type performance criterion
  - White noise disturbances
  - Quadratic cost function

$$V = \mathrm{E}\ x^T Q x$$

- V small <=> good performance
- $V = \infty$ <=> instability (in the mean-square sense)

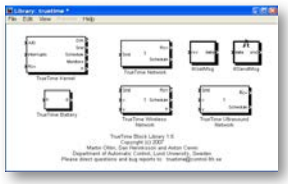
Jitterbug Analysis for the Example



Conclusions from the Jitterbug Example

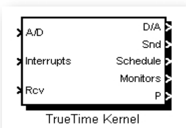
- The control loop can handle at most 75% dropped control packets
- The analysis assumes that packet drops are independent random events – realistic?

TrueTime



- A simulator for embedded control systems
- Matlab/Simulink-based
- Co-simulation of
  - Process dynamics
  - CPUs with RTOS
  - Wired and wireless networks
- Developed at Automatic Control LTH since 1999
  - Open source code

Modeling of CPUs

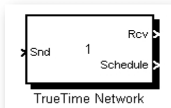


- Event-based RTOS
- User-defined code (tasks/ interrupt handlers)
  - C++ or Matlab code
- Advanced scheduling algorithms

```
function [exectime,data] = my_ctrl(segment,data)
switch segment,
  case 1,
     data.y = ttAnalogIn(1);
     data.u = calculate_output(data.x,data.y);
     exectime = 0.002;
  case 2,
     ttAnalogOut(1,data.u);
     data.x = update_state(data.x,data.y);
     exectime = 0.004;
   case 3,
     exectime = -1;
end
```

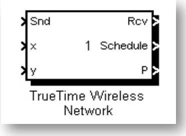
Modeling of Wired Networks

- Models the lowest layers (PHY, MAC)
- Support for common networks/protocols:
  - TDMA
  - FDMA
  - CSMA/CD (Shared Ethernet)
  - Switched Ethernet
  - CAN
  - Flexray
  - PROFINET IO

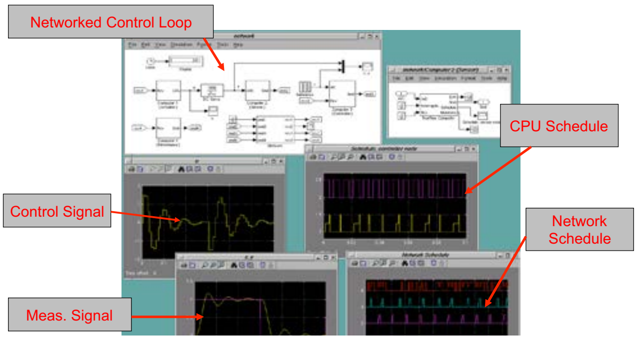


Modeling of Wireless Networks

- Two MAC protocols:
  - IEEE 802.11 (WLAN)
  - IEEE 802.15.4 (ZigBee)
    - (Wireless HART implemented by ABB Research)
- *x* and *y* inputs for node positions
- Radio models:
  - Exponential path loss (default)
  - User-defined models for multi-path propagation, fading, etc.



Example – Networked Control Loop



TrueTime – Demo

Conclusions

- Real-time communication increasingly important in several fields
- The traditional OSI model not well suited for real-time networks
- Collapsed OSI model (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 such as wireless networks are used
  - Some tools for control analysis and simulation exist
    - Jitter Margin, Jitterbug, TrueTime