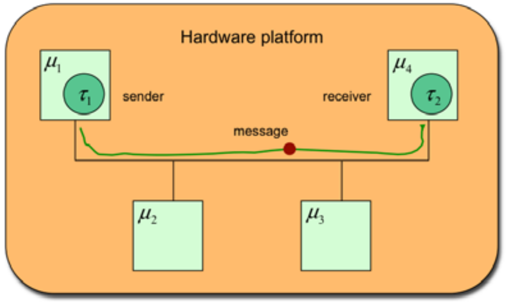
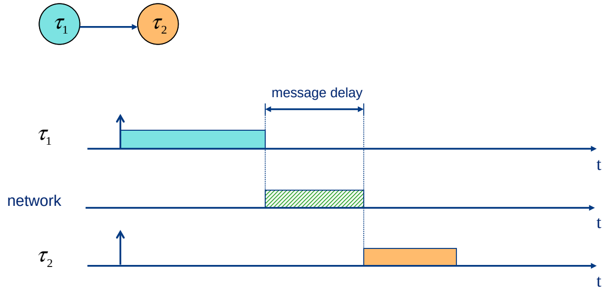
CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication



CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication



CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

Message delay:

- Message delays are caused by the following overheads:
  - Formatting (packetizing) the message
  - Queuing the message, while waiting for access to medium
  - Transmitting the message on the medium
  - Notifying the receiver of message arrival
  - Deformatting (depacketizing) the message

Formatting/deformatting overheads are typically included in the execution time of the sending/receiving task.

CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

Queuing delay:

- The queuing delay for a task is caused by:
  - Waiting for a corresponding time slot (TTP/C, FlexRay)
  - Waiting for a transmission token (Token Ring, FDDI)
  - Waiting for a contention-free transmission (Ethernet)
  - Waiting for network priority negotiation (CAN)
  - Waiting for removal from priority queue (Switched Ethernet, EDD-D)

CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

Transmission delay:

- The delay for transmitting the message is a function of:
  - Message length (bits)
  - Data rate (bits/s)

  and
  - Communication distance (m)
  - Signal propagation velocity (m/s)

$$t_{\text{frame}} = \frac{N_{\text{frame}}}{R}$$

$$t_{\text{prop}} = \frac{L}{v}$$

CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

How is the message transfer scheduled between tasks assigned to different processors?

- Integrated scheduling:
  - Scheduling of tasks and inter-task communication are regarded as comparable operations.
  - Requires compatible dispatching strategies.
- Separated scheduling:
  - Scheduling of tasks and inter-task communication are performed as separate steps.
  - Allows for different dispatching strategies.

CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

Integrated scheduling:

- Suitable for simple homogeneous systems with known assignment of tasks to processors
- Examples:
  - Time-driven task dispatching + TTP/C network protocol
  - Static-priority task dispatching + CAN protocol
  - Static-priority task dispatching + Token Ring network protocol

CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

Separated scheduling:

- Suitable for heterogeneous systems or when assignment of tasks to processors is not always known in advance
- Motivation:
  - Transmission delay is zero if communicating tasks are assigned to the same processor
  - Number of communication links that a message traverses may be a function of the assignment (depends on topology and routing strategy)
  - Different communication links may employ different message dispatching policies

CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

How is the message transfer synchronized between communicating tasks?

- Asynchronous communication:
  - Sending and reception of messages are performed as independent operations at run-time.
- Synchronous communication:
  - Sending and receiving tasks synchronize their network medium access at run-time.

CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

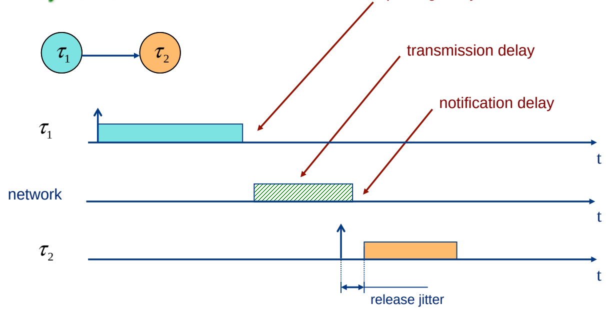
Asynchronous communication

- Implementation:
  - Network controller chip administrates message transmission and reception (example: CAN, Ethernet)
  - Interrupt handler notifies the receiver
- Release jitter:
  - Queuing delays (at sender or in multi-hop network switches) and notification delay cause variations in message arrival time
  - Arrival-time variations gives rise to release jitter at receiving task (which may negatively affect schedulability)
  - Release jitter is minimized by using offsets for receiving tasks, or by maintaining message periodicity in multi-hop networks

CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

Asynchronous communication:



CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

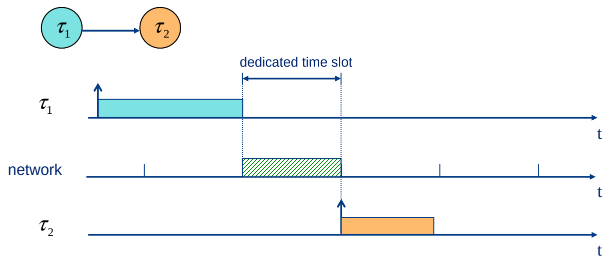
Synchronous communication

- Implementation:
  - Network controller chip makes sure message transmission and reception occurs within a dedicated time slot in a TDMA bus network
  - Off-line static scheduling is used for matching the time slot with the execution of sending and receiving tasks
  - Queuing and notification delays can be kept to a minimum by instructing the off-line scheduling algorithm to use jitter minimization as the scheduling objective

CHALMERS

Network communication

Synchronous communication:



CHALMERS

Network communication

How is the message transfer imposed with a deadline?

- As a separate schedulable entity:
  - Suitable deadline-assignment techniques must be used
  - Worst-case message delay must be known beforehand
- As part of the receiving task:
  - No explicit deadline needed for message transmission
  - May impose release jitter on the receiving task

CHALMERS

Network communication

How is the message transferred onto the medium?

- Contention-free communication:
  - Senders need not contend for medium access at run-time
  - Examples: TTP/C, FlexRay, Switched Ethernet
- Token-based communication:
  - Each sender using the medium gets one chance to send its messages, based on a predetermined order
  - Examples: Token Ring, FDDI
- Collision-based communication:
  - Senders may have to contend for the medium at run-time
  - Examples: Ethernet, CAN

CHALMERS

Network communication

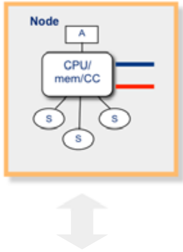
Contention-free communication:

- One or more dedicated time slots for each task/processor
  - Shared communication bus
  - Medium access is divided into communication cycles (normally related to task hyper periods to allow for integrated scheduling)
  - Dedicated time slots provide bounded message queuing delays
  - TTP/C, TTCAN ("exclusive mode"), FlexRay ("static segment")
- One sender only for each communication line
  - Point-to-point communication networks with link switches
  - Output and input buffers with deterministic queuing policies in switches provide bounded message queuing delays
  - Switched Ethernet, EDD-D, Network Calculus

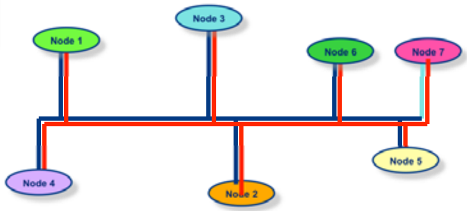
CHALMERS

The TTCAN protocol

- Based on the CAN protocol
- Bus topology
- Media: twisted pair
- 1Mbit/s



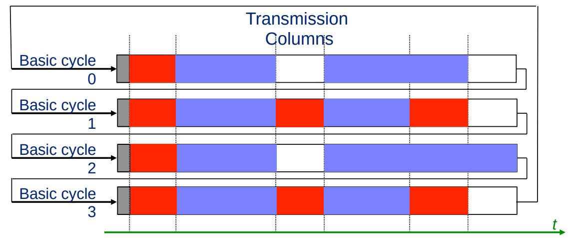
A second controller is required to implement the redundant bus



CHALMERS

The TTCAN protocol

- "Exclusive" – guaranteed service
- "Arbitration" – guaranteed service (high ID), best effort (low ID)
- "Reserved" – for future expansion…

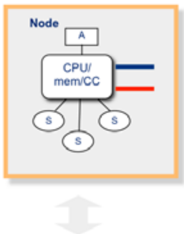


Time is global and measured in *network time units* (NTU's)

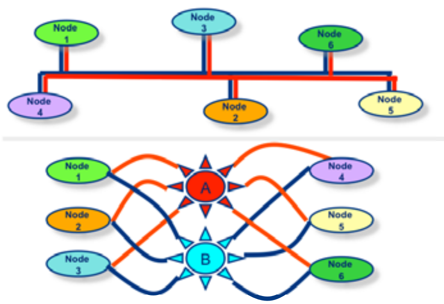
CHALMERS

The TTP/C protocol

- Double channels (one redundant). Bus topology or "star" (optical)
- Media: twisted pair, fibre
- 10 Mbit/s for each channel



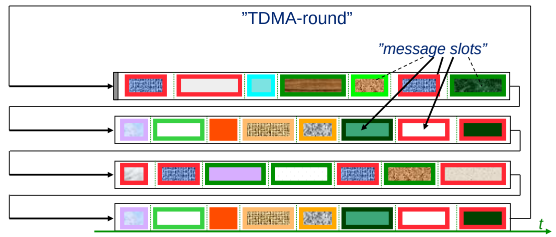
A network is built on either twin buses or twin stars.



CHALMERS

The TTP/C protocol

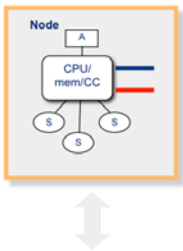
All communication is statically scheduled
Guaranteed service



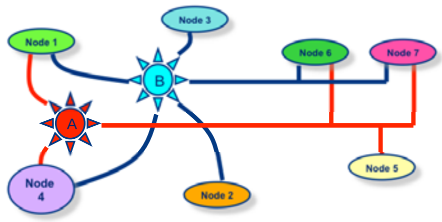
Non-periodic messages have to be fitted into static slots by the application

The FlexRay protocol

– Double channels, bus or star (even mixed).
– Media: twisted pair, fibre
– 10 Mbit/s for each channel



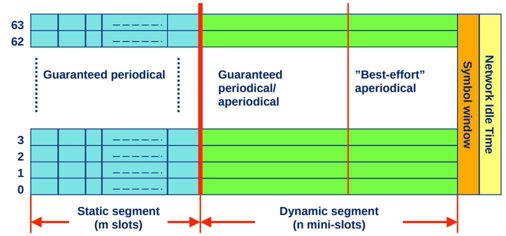
Redundant channel can be used for an alternative schedule



The FlexRay protocol

"Static segment" (compare w/ TTCAN "Exclusive")
– guaranteed service

"Dynamic segment" (compare w/ TTCAN "Arbitration")
– guaranteed service (high ID), "best effort" (low ID)



Max 64 nodes on a Flexray network.

Network communication

Token-based communication:

- Utilize a token for the arbitration of message transmissions on a shared medium
  - The sender is only allowed to transmit its messages when it possesses the token
  - Message priorities/quotas allows for bounded queuing delays
- Examples:
  - Timed-Token Protocol
  - Token Bus (IEEE 802.4)
  - Token Ring (IEEE 802.5)
  - FDDI (ANSI X3T9.5)

Token-based communication

Timed-Token Protocol: (Malcolm & Zhao, 1994)

- Concepts:
  - By token rotation (TR) we mean that the token has made a complete cycle among all the processor nodes.
  - The token cycle time is the real value of the time taken for TR.
  - The target token-rotation time (TTRT) is an expected value of the time taken for TR.
- Protocol:
  - Every time the token visits a processor node, it is allowed to transmit up to a pre-assigned quota of real-time messages.
  - At token reception, token cycle time is compared against TTRT:
    - if token is late, only real-time messages are transmitted
    - if token is early, non-real-time messages are also transmitted

CHALMERS
UNIVERSITY OF TECHNOLOGY

Token-based communication

Timed-Token Protocol:

A necessary feasibility test:

The deadline of each message transmission must be at least twice the TTRT.

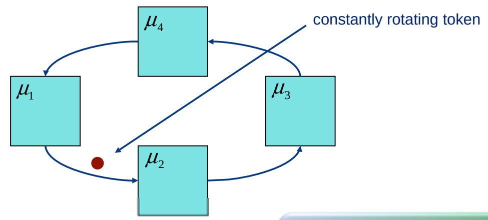
A sufficient feasibility test:

The accumulated transmission quotas should not exceed TTRT minus the overhead for token transmission time.

CHALMERS
UNIVERSITY OF TECHNOLOGY

Token-based communication

Token Ring: (IEEE 802.5)



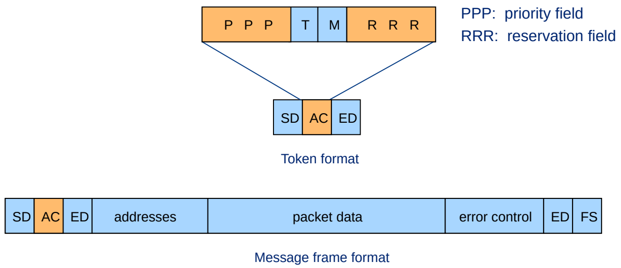
"token walk time": $W_T = (n-1)D_B + L + T_{prop}$

D_B : node delay
L : buffer delay
T_{prop} : ring propagation delay

CHALMERS
UNIVERSITY OF TECHNOLOGY

Token-based communication

Token Ring message frame format:



CHALMERS
UNIVERSITY OF TECHNOLOGY

Token-based communication

Token Ring protocol:

1. Each node examines RRR of a busy token as it passes and inserts the priority of its pending message only if it is greater than the priority currently in RRR.
2. A node does not grab a "free" token unless the priority of its pending message is at least as high as the priority in PPP. Then the token status is changed to "busy".
3. A transmitting node appends its pending message after the "busy" token and sets RRR appropriately.
4. A transmitting node waits until it receives back the "busy" token before releasing the next "free" token with PPP set to the (possibly) updated RRR.

CHALMERS
UNIVERSITY OF TECHNOLOGY

Token-based communication

Token Ring real-time protocol: (Sathaye & Strosnider, 1994)

The rate-monotonic (RM) scheduling algorithm can be adapted to the Token Ring protocol by assuming a non-preemptive dispatching model.

- Limitations:
  - Messages cannot be interrupted during transmission, which means that message scheduling is non-preemptive.
  - Message headers must be included in message size
  - Notion of highest priority might be outdated since the system is distributed
  - The number of priority bits (3) defined in IEEE 802.5 does not allow for an arbitrary number of priority levels.

CHALMERS
UNIVERSITY OF TECHNOLOGY

Token-based communication

Token Ring real-time protocol: (Sathaye & Strosnider, 1994)

A sufficient and necessary feasibility test:

$$\forall i : R_i = t_{sys} + b_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil e_j \leq D_i$$

t_{sys} : system overhead defined by the system
b_i : blocking time due to ongoing transmissions
e_j : "execution time" consisting of the following time components
- Capture token when node has highest-priority message pending
- Transmit message
- Transmit subsequent free token

CHALMERS
UNIVERSITY OF TECHNOLOGY

Network communication

Collision-based communication:

- Utilize collision-detect mechanism to determine validity of message transmissions on a shared medium
  - The sender tries to send messages independently of other senders' intention to do so
  - Attempts may be done at any time or when some specific network state occurs
- Examples:
  - Ethernet w/ multiple senders (IEEE 802.3)
  - CAN (SAE 1993)

CHALMERS
UNIVERSITY OF TECHNOLOGY

Collision-based communication

Ethernet protocols w/ multiple senders:

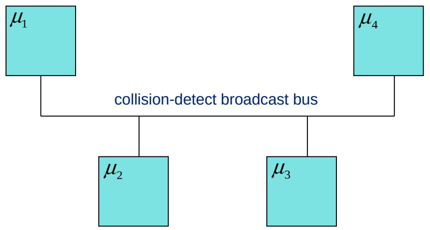
- Senders attempt to send a complete message
- If messages collide, all transmissions are aborted
- After collision, re-transmission is made after a random delay
- Protocol extensions for real-time systems:
  - VTCSMA (Zhao & Ramamritham, 1987)
  - Window Protocol (Zhao, Stankovic & Ramamritham, 1990)

Message queuing delay can in general not be bounded!
Therefore, these protocols do not give any guarantees for meeting imposed message deadlines!

CHALMERS
UNIVERSITY OF TECHNOLOGY

Collision-based communication

Controller Area Network (CAN): (Bosch 1991, SAE 1993)



CHALMERS
UNIVERSITY OF TECHNOLOGY

Collision-based communication

Controller Area Network (CAN):

- Senders transmit a message header (with an identifier)
- If messages collide, a hardware-supported protocol is used to determine what sender will be allowed to send the rest of the message; transmissions by other senders are aborted

Message queuing delay can be bounded with appropriate identifier assignment!
Therefore, this protocol makes it possible to meet imposed message deadlines!

CHALMERS
UNIVERSITY OF TECHNOLOGY

Collision-based communication

CAN message frame format: (short format)

SOF	11-bit identifier	control	0 - 8 bytes of message data	error control	Ack	EOF

11-bit identifier is used for two purposes:
- assign a priority to the message (low number ⇒ high priority)
- enable receiver to filter messages

Wired-AND:

Each node monitors the bus while transmitting.

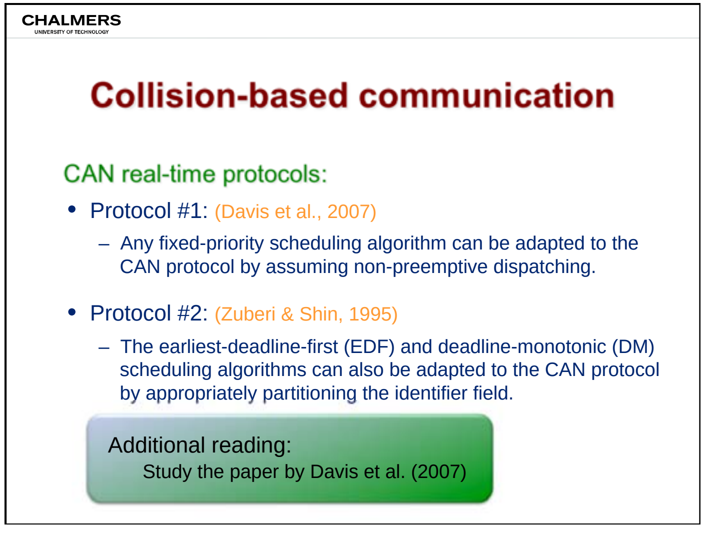
If multiple nodes are transmitting simultaneously and one node transmits a '0', then all nodes will see a '0'. If all nodes transmit a '1', then all nodes will see a '1'.

CHALMERS
UNIVERSITY OF TECHNOLOGY

Collision-based communication

CAN protocol: (binary countdown)

1. Each node with a pending message waits until bus is idle.
2. The node begins transmitting the highest-priority message pending on the node. Identifier is transmitted first, in the order of most-significant bit to least-significant bit.
3. If a node transmits a recessive bit ('1') but sees a dominant bit ('0') on the bus, then it stops transmitting since it is not transmitting the highest-priority message in the system.
4. The node that transmits the last bit of its identifier without detecting a bus inconsistency has the highest priority and can start transmitting the body of the message.


CHALMERS
Collision-based communication
CAN real-time protocols:
• Protocol #1: (Davis et al., 2007)
– Any fixed-priority scheduling algorithm can be adapted to the CAN protocol by assuming non-preemptive dispatching.
• Protocol #2: (Zuberi & Shin, 1995)
– The earliest-deadline-first (EDF) and deadline-monotonic (DM) scheduling algorithms can also be adapted to the CAN protocol by appropriately partitioning the identifier field.
Additional reading:
Study the paper by Davis et al. (2007)