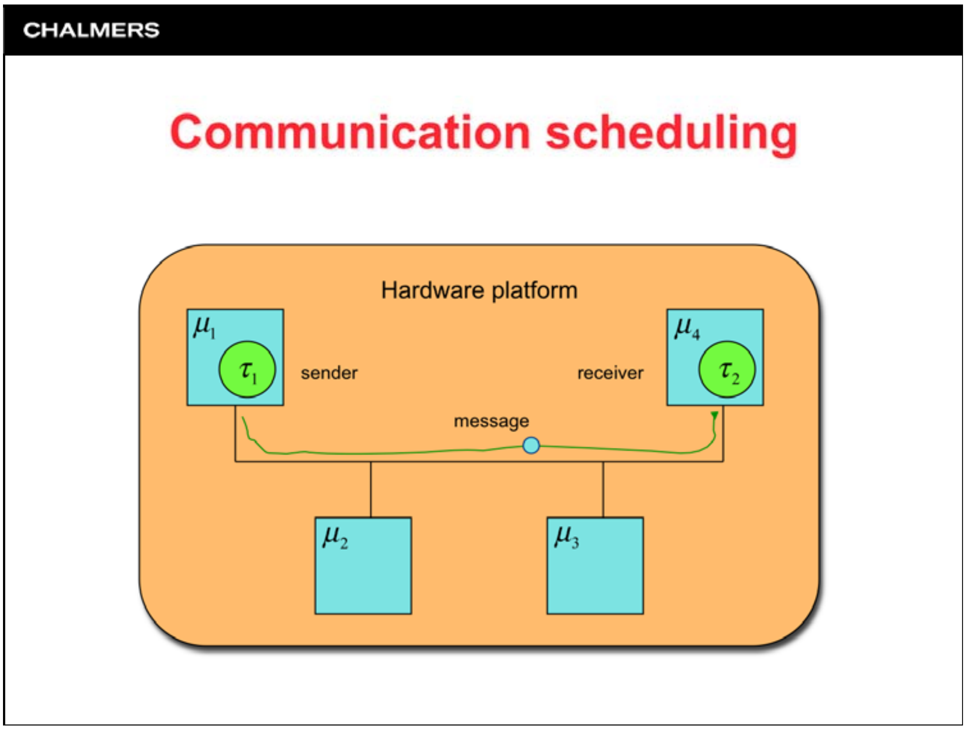
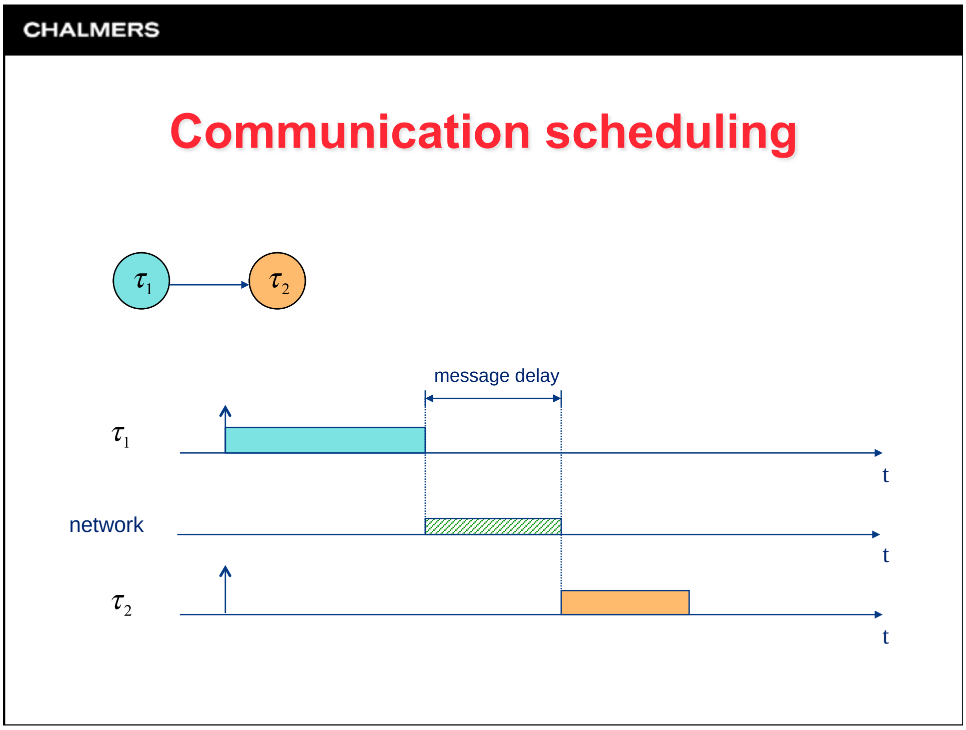

CHALMERS
Communication scheduling
Hardware platform
μ_1
τ_1
sender
μ_4
τ_2
receiver
message
μ_2
μ_3


CHALMERS
Communication scheduling
τ_1
τ_2
message delay
τ_1
t
network
t
τ_2
t

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Communication scheduling

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.

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Communication scheduling

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)
  - Waiting for a contention-free transmission (Ethernet)
  - Waiting for network priority negotiation (CAN)
  - Waiting for removal from priority queue (EDD-D, Switched Ethernet)

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Communication scheduling

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)

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

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

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Communication scheduling

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.

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Communication scheduling

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

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Communication scheduling

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

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Communication scheduling

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:
  - Sender and receiver have to synchronize their network medium access at run-time.

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Communication scheduling

Asynchronous communication

- Implementation:
  - Network controller chips administrate message transmission (example: CAN, Ethernet)
  - Interrupt handler notifies the receiver
  - Large variations (”jitter”) in message arrival time can occur
  - Message jitter gives rise to release jitter at receiving task (which may negatively affect schedulability)
- Techniques for minimizing release jitter:
  - Explicit arrival times (offsets) for receiving tasks
  - Maintained message periodicity in multi-hop networks

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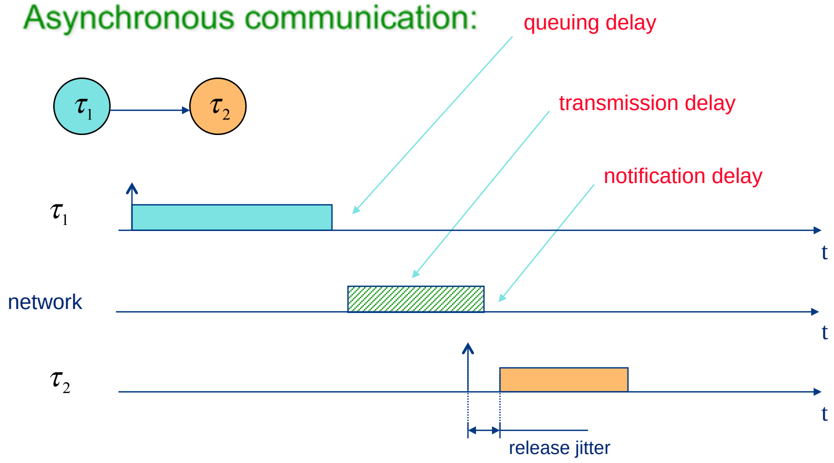
Communication scheduling

Asynchronous communication:



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Communication scheduling

Synchronous communication

- Implementation:
  – Dedicated time slot in a TDMA network
  – Global off-line scheduling necessary
- Techniques for minimizing release jitter
  – Suitable arrival times (offsets) for receiving tasks
  – Use an off-line scheduling algorithm with jitter minimization as the scheduling objective

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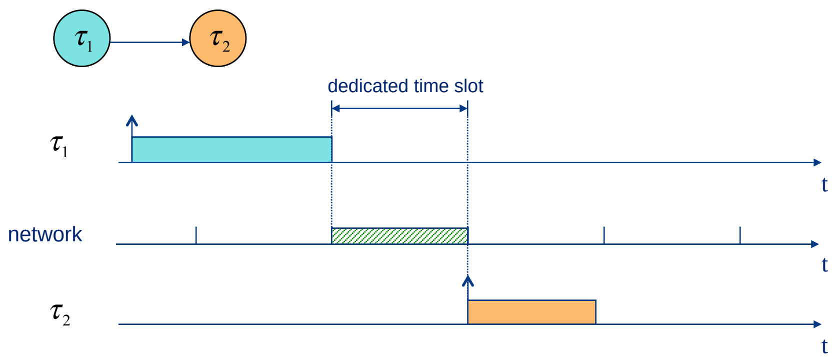
Communication scheduling

Synchronous communication:



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Communication scheduling

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

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Communication scheduling

How is the message transferred onto the medium?

- Contention-free communication:
  - Processors need not contend for medium access at run-time
  - Examples: TTP/C, FlexRay, Switched Ethernet
- Token-based communication:
  - Each processor using the medium gets one chance to send its messages, based on a predetermined order
  - Examples: FDDI, Token Ring (IEEE 802.5)
- Collision-based communication:
  - Processors may have to contend for the medium at run-time
  - Examples: Ethernet (IEEE 802.3), CAN

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Communication scheduling

Contention-free protocols:

- 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)
  - 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 delay bounds
  - EDD-D, Switched Ethernet, Network Calculus

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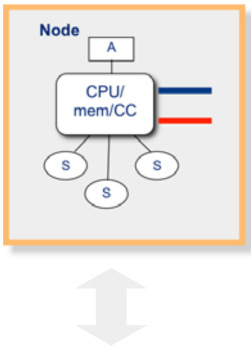
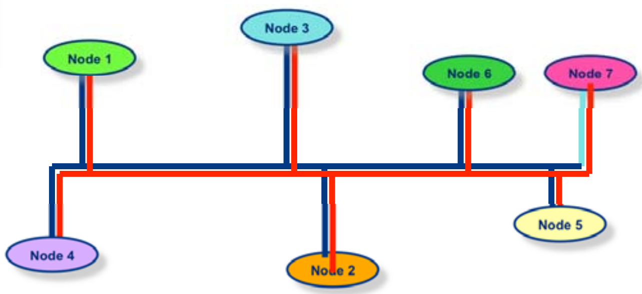
The TTCAN protocol

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



A second controller is required to implement the redundant bus



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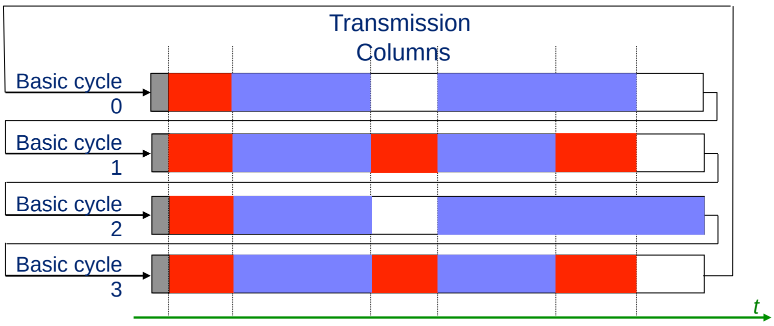
The TTCAN protocol

- "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)

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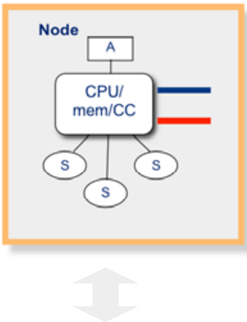
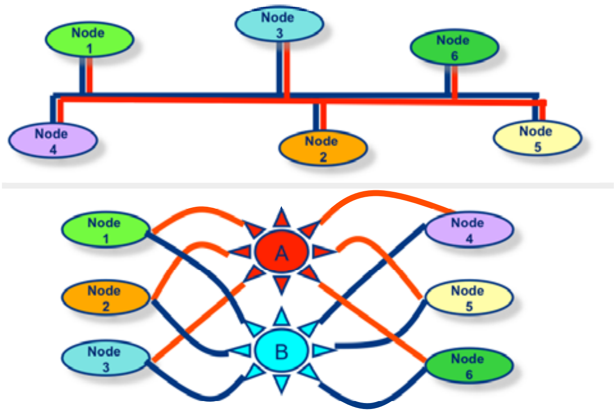
The TTP/C protocol

- 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.

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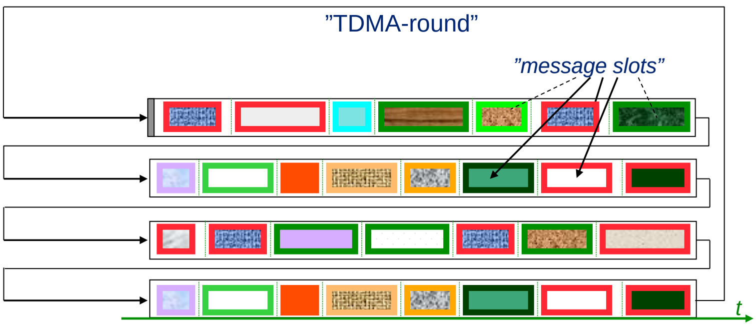
The TTP/C protocol

All communication is statically scheduled
Guaranteed service



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

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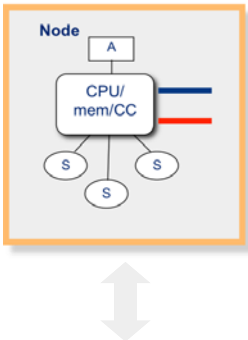
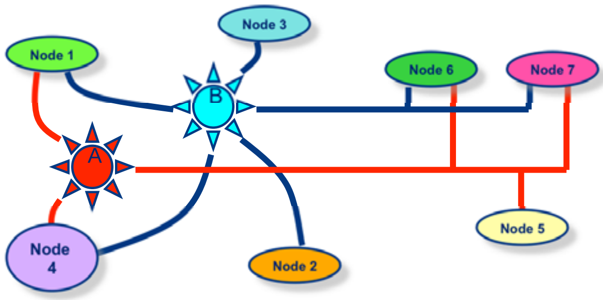
The FlexRay protocol

- 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

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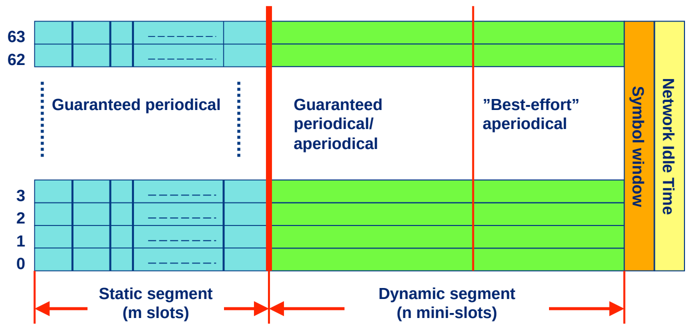
The FlexRay protocol

"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.

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Communication scheduling

Token-based protocols:

- Utilize a token for the arbitration of message transmissions on a shared medium
  - The processor is only allowed to transmit its messages when it possesses the token
- Examples:
  - Timed-Token Protocol
  - Token Bus (IEEE 802.4)
  - Token Ring (IEEE 802.5)

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Communication scheduling

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

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Communication scheduling

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.

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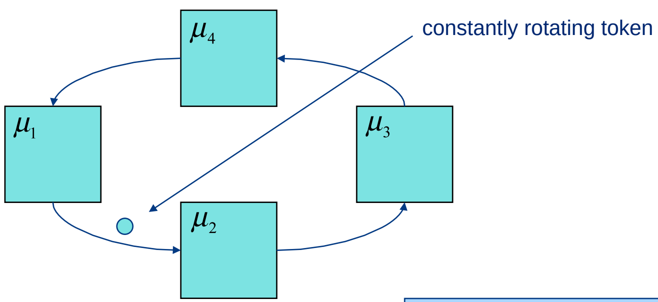
Communication scheduling

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

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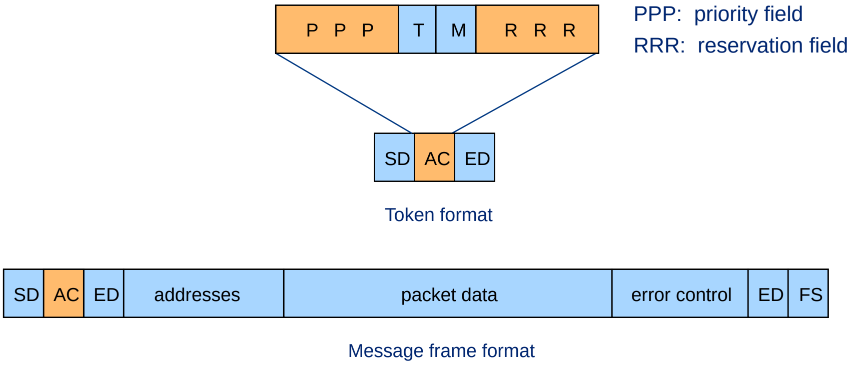
Communication scheduling

Token Ring message frame format:



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Communication scheduling

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.

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Communication scheduling

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.

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Communication scheduling

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

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Communication scheduling

Ethernet-based protocols:

- Senders attempt to send a complete message
- Utilize collision-detect techniques to recognize the need for re-transmission
- Examples:
  - VTCSMA (Zhao & Ramamritham, 1987)
  - Window Protocol (Zhao, Stankovic & Ramamritham, 1990)

Since the queuing delay in general cannot be bounded, these protocols do not give any guarantees for meeting imposed message deadlines!

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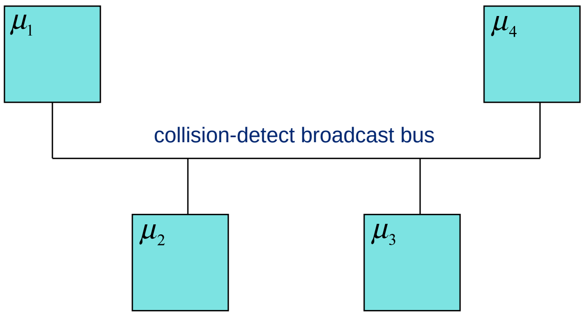
Communication scheduling

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



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Communication scheduling

Controller Area Network:

- Senders transmit a message header (with an identifier)
- Collision-detect mechanism is used to determine what sender will be allowed to send the entire message

Message queuing delay can be bounded with appropriate identifier assignment, and it could therefore be possible to meet imposed message deadlines!

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Communication scheduling

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'.

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Communication scheduling

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.

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Communication scheduling

CAN real-time protocols:

- Protocol #1: (Tindell et al., 1994)
  - The rate-monotonic (RM) 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 Zuberi and Shin (RTAS'95)