Real-Time Networks and Distributed Systems

- Topics
  - Distributed Real-Time Systems
    - Bus-based multi-processor systems
  - Real Time Networks
    - RT busses e.g. CAN, TTP, TTCAN
  - Analysis of Distributed RT Systems
    - Message Transmission Analysis
    - Response Time Analysis

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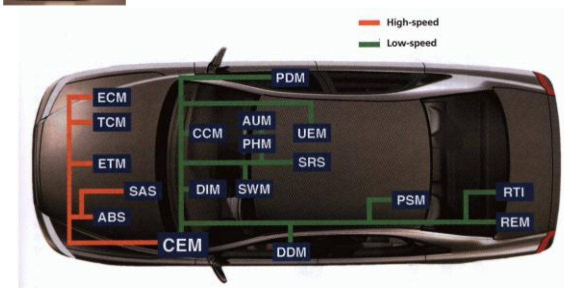
A Distributed Real-Time System



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Why Distributed Systems ?

- Physically distributed applications - (close to physical equipment, e.g. engine control)
- Modularity (components developed in isolation)
- Scalability (just add another node in the network)
  - Some new cars contain > 3 miles of wire
  - Clearly inappropriate to connect all pairs of communicating entities with their own wires
  - Which needs O(n*n) wires
- Fault tolerance (errors only propagate within sub-part of system)

Challenge

- build complex distributed systems and maintain high reliability *at low cost*!

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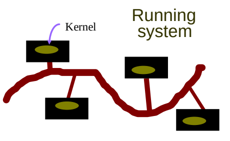
Dsign of Distributed RTS

Tasks
- Execution time
- Period
- Deadlines
- Dependences

⇑

Functional Design

⇒ allocation/ scheduling ⇒



3 aspects:
- off-line allocation
- run-time scheduling
- á priori schedulability analysis

The core for the development of real time systems

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RT-Networking: Basic Problem

Bounded latency: A → B

- Competing traffic
- Guarantees
  - Hard-RT: Absolute G.
  - Soft-RT: Probabilistic G.
- Other issues
  - Reliability
    - F. detection & recovery
  - Resource Utilisation

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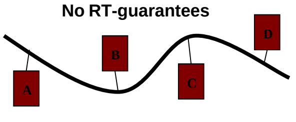
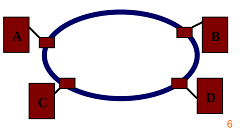
RT-Networking: Solutions

CSMA/CD
(*Carrier Sense Multiple Access/Collision Detection*)
Ethernet
Collisions
back-off
Stochastic behaviour
No RT-guarantees

Token-ring
Physical or logical ring
Circulating token
No collisions
RT-guarantees possible





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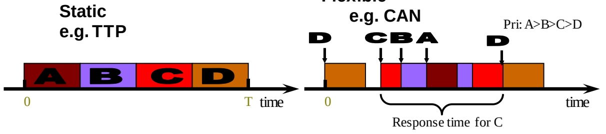
RT-Networking: Solutions

Time triggered
- **TDMA**
  (*Time Division Multiple Access, e.g. GSM*)
- **Pre-Scheduled**
  - **Predictable**
  - **Testable**
- **Static**
- **e.g. TTP**

Event triggered
- **CSMA/CR (Collision Resolution)**
  (*Carrier Sense Multiple Access / Collision Resolution*)
- **Priority driven**
  - **Dynamic Scheduling**
- **Flexible**
  - **e.g. CAN**

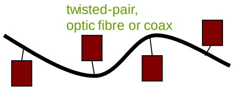


More examples

- Time triggered:
  - **SAFEbus - airplanes, eg. Boeing**
  - **TTA - cars, eg. Audi, Volkswagen**
  - **FlexRay - cars, eg. BMW, DaimlerChrysler**
- Event triggered
  - **CAN - cars, eg. Volvo, Saab, VW, Ford, GM**
  - **Byteflight - cars, BMW**
  - **LIN – a cheaper and simple bus protocol**
- Mixtures
  - **Time-Triggered CAN (TTCAN)**
  - **TTA extended with events**

CAN: Controller Area Network

- Initiated in the late 70's to connect a number of processors over a cheaper shared serial bus
- From Bosch (mid 80ies) for automotive applications
- De facto standard for invehicle comm.
  (100 million CAN nodes sold 2000, 300 million sold 2004)
- Cost ~$3 / node
  - $1 for CAN interface
  - $1 for the transceiver
  - $1 for connectors and additional board area
- Controllers available
  (from Phillips, Intel, NEC, Siemens, etc.)
- Shared broadcast bus (one sender/many receivers) (CSMA/CR)
  - **CAN permits everyone on the bus to talk**
- Medium speed:
  - **Max: 1Mbit/sec; typically used from 35 Kbit/sec up to 500Kbit/sec**
- Highly robust (error mechanisms to overcome disturbance on the bus) and
- Real-time guarantees can be made about CAN performanc



CAN is Synchronous

- Fundamental requirement: Everyone on the bus sees the current bit before the next bit is sent
  - This is going to permit a very clever arbitration scheme (later)
  - Ethernet does NOT have this requirement →This is one reason Ethernet bandwidth can be much higher than CAN
- Time per bit:
  - Speed of electrical signal propagation 0.1-0.2 m/ns
  - 40 Kbps CAN bus → 25000 ns per bit
    - A bit can travel 2500 m (max bus length 1000~1250 m)
  - 1 Mbps CAN bus → 1000 ns per bit
    - A bit can travel 100 m (max bus length 40~50 m)
- Bandwidth
  - 1 Mbps up to 40~50 m
  - 0.5 Mbps upto 80~100 m
  - 40 Kbps up to ~1000 m
  - 5 Kbps up to ~10,000 m

More on CAN

- Message based with payload size 0-8 bytes
  - Not for bulk data transfer!
  - But perfect for many embedded control applications
- CAN interfaces are usually pretty smart
  - Interrupt only after an entire message is received
  - Filter out unwanted messages in HW – zero CPU load

CAN Addressing

- CAN bus can have an arbitrary number of nodes
  - **Nodes do not have proper addresses**
  - **Rather, each message has an 11-bit "field identifier"**
    - In extended mode, identifiers are 29 bits
  - **Everyone interested in a message type listens for it**
    - Works like this: "I'm sending a temperature sensor reading"
    - Not like this: "I'm sending a message to node 8"
- Designer should allocate the message identifiers to the stations (different nodes send different messages!)
- Each node has a queue for messages ordered by priorities/identifiers

CAN Message Types

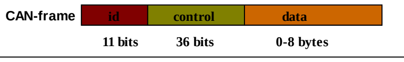
- **Data frame:**
  - **Frame containing data for transmission**
- **Remote frame:**
  - **Frame requesting the transmission of a specific identifier**
- **Error frame:**
  - **Frame transmitted by any node detecting an error**
- **Overload frame:**
  - **Frame to inject a delay between data and/or remote frames if a receiver is not ready**

Controller Area Network (CAN)

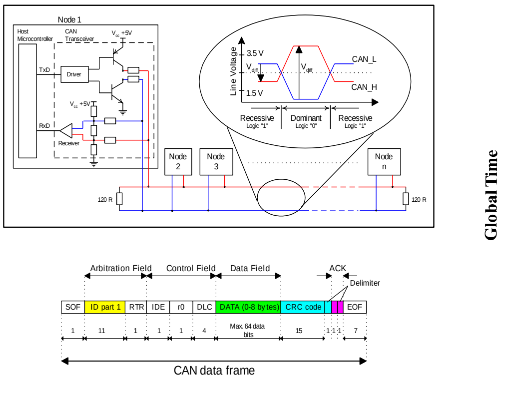
Frame layout:

SOF, Start Of Frame	Identifier	RTR, Remote Trans-mission Request	Control	Data	CRC, Cyclic Redun-dancy Check	CRC DEL, CRC Delimiter	ACK, Acknow-ledge	ACK DEL, Acknow-ledge Delimiter	EOF, End Of Frame	IFS, Inter Frame Space
1 bit	11 bitar	1 bit	6 bitar	0–8 bytes	15 bitar	1 bit	1 bit	1 bit	7 bitar	3–, min 3 bitar

- Small sized frames (messages)
  - **0 to 8 bytes**
  - **Very different from mainstream computing messaging**
- Relatively high overhead
  - **A frame size of more than 100 bits to send just 64 bits**

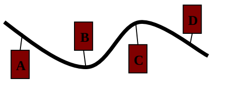


Controller Area Network (CAN)



The CAN Arbitration Mechanism

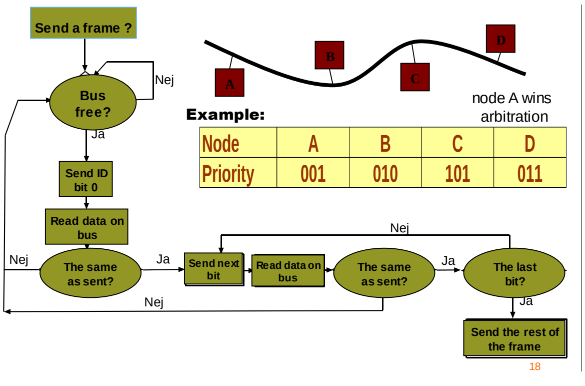
- Shared broadcast bus
- Bus behaves like a large AND-gate
  - if all nodes sends 1 the bus becomes 1, otherwise 0.
- A frame is tagged by an *identifier*
  - **indicates contents of frame**
  - **also used for arbitration as "priority"**
- Bit-wise arbitration
  - **Each message has unique priority ⇒ node with message with lowest id wins arbitration**
  - **Lowest id = highest priority!**
- The CAN bus is a priority-based scheduled resource



Details on CAN

- When the bus is busy, the stations wait (listening all time)
- As soon as the bus is idle, all stations who want to send enter the arbitration phase (run the arbitration algorithm)
  - **Transmit the highest priority message, from the most significant bit to the least significant one**
  - **0 is the highest priority!!**
    - **0: dominant bit (in fact, sending 0 by "high voltage")**
    - **1: recessieve bit**
  - **It behaves like an AND-gate**
  - **Send and monitor:**
    - **Send a 1, but monitor a 0: a collision**
    - **the protocol says: nodes sending 0's win, the others back off (monitor and send)**
    - **This means: the highest priority message wins, to be transmitted**
    - **E.g. 100, 101, 111 on three stations, 100 will be sent**

The CAN Arbitration Mechanism



Example:

Node	A	B	C	D
Priority	001	010	101	011

"Idiot" Node

- **What happens if a CAN node goes crazy/haywire and transmits too many high priority frames?**
  - This can make the bus useless
  - Assumed not to happen
- **Schemes for protecting against this have been developed but are not commonly deployed**
  - Most likely this happens very rarely
  - CAN bus is usually managed by hardware

Error handling

- Several types of errors:
  - Checksum error, acknowledge error, bit error, ...
- When error is detected by node it sends an error frame
  - starting with 6 dominant bits (000000) in a row
  - tells other nodes that error occurred
  - other nodes then also send error frames
  - Arbitration restarts when bus is idle
- In effect, error frames are used to resync protocol engine

Transmission Errors

- CAN has a mechanism to protect against broken hardware: *error counters*
- The CAN controller in a node counts failed frames and successful frames
  - When errors exceed a threshold, the controller gets disconnected
- ERROR-counter **EC**
  - **EC:= EC+1** when an error is signalled
  - **EC:= EC-1** when a frame is correctly received
  - **EC > K** ⇒ the node shuts-off itself (is fail-silent)

Details on CAN

- After the priority transmitted (the arbitration is finished), the rest of the message is transmitted
- A message contains: 0-8 bytes for data and 47bits OH
  - Priority/identity: 11bits
  - Data field: 0-8 bytes long
  - CRC field (checksum, parity bits etc: checking the message has not been corrupted, and other "housekeeping" bits)
  - Out of the 47, 34 bits are bitstuffed
- 000000 and 111111 are reserved as "marker" to signal all stations on the bus
  - So "bitstuffing" is needed: whenever 00000 or 11111 appears in a bitstream, an extra bit of the opposite sign should be added
  - E.g. 1111 1000 0111 1000 0111 1 should be
    1111 1000 0011 1110 0000 1111 10

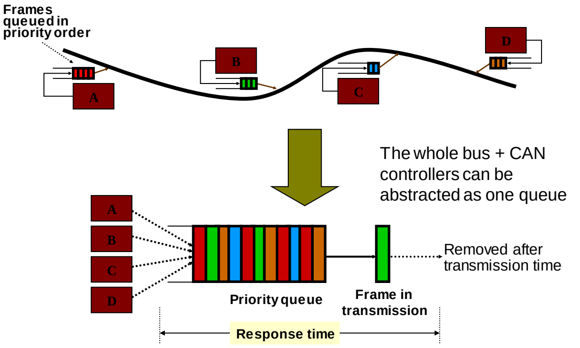
More details on CAN

- The total number before bitstuffing: 8n+47
- After bitstuffing: $8n+47+\lfloor(34+8n-1)/4\rfloor$
  - Max: 64+47+24=135 bits
  - E.g. 1Mbit/sec, 1 bit needs 1 micro seconds
  - The max transmission time for one message= 135 micro sec

CAN Message Scheduling

- **Network scheduling is usually non-preemptive**
  - Non-preemptive scheduling means high-priority sender must wait while low-priority sends
  - Short message length keeps this delay small

The CAN-bus Abstraction



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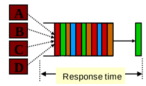
Transmission Delay Calculation for CAN



Set of messages = $\mathcal{M}$ (queued on different nodes)

$M_j = < T_j, C_j >$ $(M_j \in \mathcal{M})$

T_j = period (time between queuing)

C_j = transmission time

B_j = blocking time (waiting for low priority message, bus non-preemptive)

Worst-case waiting/queuing time (before transmission):

$q_i = B_i + \Sigma_{j \in hp(i)} \lceil q_i / T_j \rceil C_j$

hp(i) = frames with priority higher than P_i

Worst-case Response time (delay before delivered):

$R_i = C_i + q_i$

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Transmission delay analysis

- C_i = (number of bits) X (time to transmit 1 bit)
- B_i = MAX $_{\forall k \in lp(i)}$ (Ci) <= time to transmit 135 bits
- **Worst case: $B_i = C_i =$ 135 micro sec**
  (for 1MB/sec CAN)

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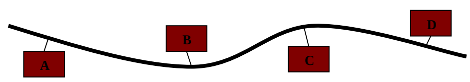
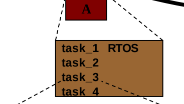
End of Story?



- Unfortunately not!
  - **Non-periodic queuing times causes jitter**
  - **No global time reference**
  - **Transmission errors (recovery + retransmission)**

Queuing causes jitter




```
task_3() {
  while(1) {
    read_sensor();
    if(...)
       // do some work
    else
       // do some other work
    send_CAN(mAtoB, prio);
    // some more work
    sleep_until_next_period();
}
```

- Task_3 on node A executes with certain period
- Message mAtoB gets same period as task_3
- Shortest time before send: BCET = $C_{3\ min}$ for task_3
- Longest time before send: task_3's worst case response time = R_3
- $R_3 - C_{3\ min}$ = jitter for message mAtoB

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Adding Jitter to the Analysis

New equation for worst-case Transmission Delay:

$R_i = J_i + q_i + C_i$

$q_i = B_i + \Sigma_{j \in hp(i)} \lceil (q_i + J_j) / T_j \rceil C_j$

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Transmission Errors

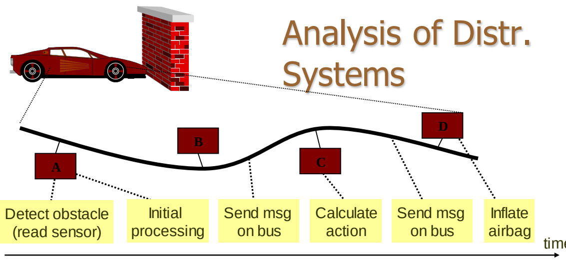
- Max number of errors must be bounded
- Fault hypothesis ⇒
  - Error function E(t) = max time required for error signalling and recovery in any time interval of length t

New equation for worst-case transmission delay:

$$R_i = J_i + q_i + C_i$$

$$q_i = B_i + E(q_i) + \Sigma_{j \in hp(i)} \lceil (q_i+J_j)/T_j \rceil C_j$$

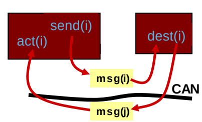
Analysis of Distr. Systems



- System wide (end-to-end) timing requirements
  - control closed over the entire system
  - includes sensors, CPUs, controllers, busses, actuators, OS, ...
- *Holistic analysis* can be applied!

Holistic Scheduling Problem

- When tasks on a node can both send and receive messages we have a *holistic scheduling problem*
- The equations giving the worst case time for tasks depends on messages arriving at the node
- We cannot apply the processor scheduling analysis before we get values from the bus scheduling analysis



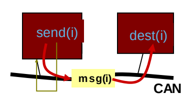
- Similarly: We cannot apply the bus scheduling analysis before we get values from the processor scheduling analysis
- Solution: *Holistic Analysis*

Distributed Systems

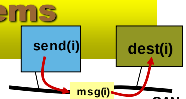
- Tasks on CPUs are exchanging msgs over CAN
- Tasks are queuing messages
  - **Completion times will vary =>**
  - **Jitter (variations in release times) will be inherited**
- Message m(i), queued by a task *send(i):*

  ⇒ $J_{m(i)} = R_{send(i)} - C_{send(i)}$
- Task *dest(i)* is activated by a message m(i):

  ⇒ $J_{dest(i)} = R_{m(i)} - C_{m(i)}$



Distributed Systems



- Example:

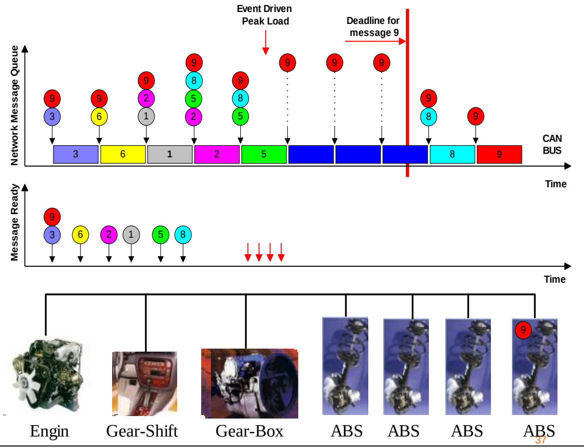
Node A:
- $R_{send(i)} = C_{send(i)} + \Sigma_{j \in hp(send(i))} \lceil (R_{send(i)} + J_j)/T_j \rceil C_j$
- $J_{m(i)} = R_{send(i)} - C_{send(i)}$

CAN:
- $R_{m(i)} = q_{m(i)} + J_{m(i)} + C_{m(i)}$
- $q_{m(i)} = B_{m(i)} + \Sigma_{j \in hp(m(i))} \lceil (q_{m(i)} + J_{m(j)}) / T_{m(j)} \rceil C_{m(j)}$

Node B:
- $J_{dest(i)} = R_{m(i)} - C_{m(i)}$
- $R_{dest(i)} = w_{dest(i)} + J_{dest(i)}$
- $w_{dest(i)} = C_{dest(i)} + \Sigma_{j \in hp(dest(i))} \lceil (w_{dest(i)} + J_j)/T_j \rceil C_j$

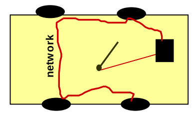
$C_{m(i)} = B_{m(i)}$ = 135 micro sec

Problem with CAN: some of the message may never get a chance for transmission

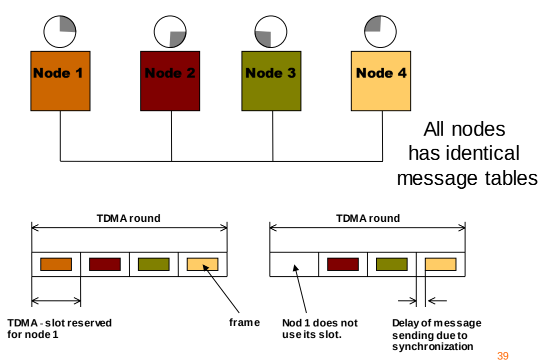


Other Solutions: e.g.TTP - the Time Triggered Protocol

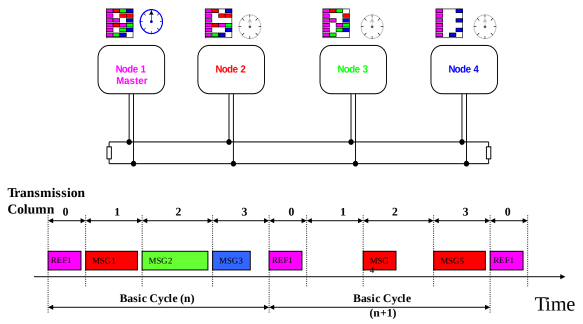
- Intended for X-by-wire applications
  Example: Break-by-wire in car
- A lot of features built in into the bus protocol
  (which must be added on top of the CAN bus)
- Conceptually similar to
  static cyclic scheduling



TTP - Time Triggered (TDMA)



TTCAN: an example of TTP



TTP - CAN: a comparison

TTP

- **Time triggered**
- **Overallocation of aperiodic messages**
- **No jitter**
- **Ultra-reliable systems**
- **Includes distributed system functionality**
  - **Clock-synchronization**
  - **Fault-handling**
  - **Membership protocol**
- **Capacity 10 Mb/sec**

CAN

- **Event triggered**
- **No message sending if not neccessary**
- **Jitter due to varying system loads**
- **Priority driven**
- **RT-Network**
- **Some functionality added on top**
- **Capacity: 1Mb/sec**

Trends for RT networks in Automotives

- Today CAN dominates
- Time-triggered seems to be the future for X-by-wire: TTP e.g. FlexRay, TTCAN
- Future cars will include many different and parallel buses:
  - **CAN for comfort**
  - **TT for X-by-wire**
  - **MOST (Media Oriented Systems Transport) for multimedia**
  - **etc.**