Real-Time Communications and Internet of Things

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Random Access

- no access control; requires low medium utilization

\[ \text{probability that a slot is not taken by others: } (1 - p)^{n-1} \]

\[ \text{probability to send successfully: } p \cdot (1 - p)^{n-1} \]

the maximum probability with respect to \( p \) happens when

\[ \frac{d}{dp}(p \cdot (1 - p)^{n-1}) = 0, \text{ i.e., } p = \frac{1}{n}. \]
Random Access

- no access control; requires low medium utilization

- improved variant: slotted random access

Station 1
Station 2
Station 3

access conflict

Station 1
Station 2
Station 3

What is the optimal sending rate \( p \) in case of \( n \) stations?

- probability that a slot is not taken by others: \( (1 - p)^{n-1} \)

- probability to send successfully: \( p \cdot (1 - p)^{n-1} \)

- the maximum probability with respect to \( p \) happens when \( \frac{d}{dp} \left( p \cdot (1 - p)^{n-1} \right) = 0 \), i.e., \( p = \frac{1}{n} \).
Random Access

- no access control; requires low medium utilization

- improved variant: slotted random access

- What is the optimal sending rate $p$ in case of $n$ stations?
  - probability that a slot is not taken by others: $(1 - p)^{n-1}$
  - probability to send successfully: $p \cdot (1 - p)^{n-1}$
  - the maximum probability with respect to $p$ happens when $d(p \cdot (1 - p)^{n-1})/dp = 0$, i.e., $p = 1/n$. 
TDMA (Time Division Multiple Access)

- Communication in statically allocated time slots
- Synchronization among all nodes necessary:
  - periodic repetition of communication frame or
  - master node sends out a synchronization frame
- Examples: TTP, static portion of FlexRay, satellite networks
CSMA/CD

- CSMA/CD (Carrier Sense Multiple Access / Collision Detection)
- Try to avoid and detect collisions:
  - before starting to transmit, check whether the channel is idle
  - if a collision is detected (several nodes started almost simultaneously), wait for some time (backoff timer)
  - repeated collisions result in increasing backoff times
- Examples: Ethernet, IEEE 802.3
- Stochastic behavior, and problematic in general for real-time systems without any treatments
CSMA/CA

- **Carrier Sense Multiple Access / Collision Avoidance**
- **Operation:**
  - reserve $s$ slots for $n$ nodes; note: slots are normally idle they are (short) time intervals, not signals; if slot is used it becomes a slice.
  - nodes keep track of global communication state by sensing
  - nodes start transmitting a message only during the assigned slot
  - If $s = n$, no collisions; if $s < n$, statistical collision avoidance
- **Examples:** 802.11, part of FlexRay
CSMA/CR

- Carrier Sense Multiple Access / Collision Resolution
- Operation:
  - Before any message transmission, there is a global arbitration
  - Each node (or each message type) is assigned a unique identification number
  - All nodes wishing to transmit compete by transmitting a binary signal based on their identification value
  - A node drops out the competition if it detects a dominant state while transmitting a passive state
  - Thus, the node with the lowest identification value wins
- Example: CAN Bus
Outline

Analysis of TDMA

CAN (Controller Area Network)

Flexray

Summary of Other Busses
Recall: TDMA Resource in Real-Time Calculus

- Consider a real-time system consisting of \( n \) applications that are executed on a resource with bandwidth \( B \) that controls resource access using a TDMA (Time Division Multiple Access) policy.
- Analogously, we could consider a distributed system with \( n \) communicating nodes, that communicate via a shared bus with bandwidth \( B \), with a bus arbitrator that implements a TDMA policy.
- TDMA policy: In every TDMA cycle of length \( \bar{c} \), one single resource slot of length \( s_i \) is assigned to application \( i \).
TDMA Resource

\[ \beta^u_{TDMA}(\Delta) = B \min \left\{ s_i, \Delta - \left\lfloor \frac{\Delta}{\bar{c}} \right\rfloor (\bar{c} - s_i) \right\} \]

\[ \beta^l_{TDMA}(\Delta) = B \max \left\{ s_i, \Delta - \left\lceil \frac{\Delta}{\bar{c}} \right\rceil (\bar{c} - s_i) \right\} \]
Arrival Curve Served by TDMA

\[ D = \sup_{t \geq 0} \{ \inf \{ \tau \geq 0 : R(t) \leq R'(t + \tau) \} \} \]

\[ = \sup_{ \Delta \geq 0} \{ \inf \{ \tau \geq 0 : \alpha^u(\Delta) \leq \beta^l(\Delta + \tau) \} \} \]
Why is TDMA interesting?

- Integrated Modular Avionics (IMA) exactly partitions the functions by using a *flexible* TDMA, and uses fixed-priority preemptive scheduling within each partition.
- Partitions are scheduled according Time Division Multiple Access (TDMA).
- Execution times, number of partitions windows and offsets are defined in the Major Cycle.

Outline

Analysis of TDMA

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Summary of Other Busses
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 80’s) for automotive applications
- De facto standard for in-vehicle communications.
- Fair cost
- Shared broadcast bus (one sender/many receivers) (CSMA/CR)
- CAN bus is a twisted wire
- 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 performance
Bit Transmission on CAN

- Fundamental requirement: Everyone on the bus sees the current bit before the next bit is sent
  - This permits a very clever arbitration scheme (later)

- Global time is assumed and maintained

- Bits per second (depending on the length of CAN bus):
  - 1 Mbps CAN bus \(\rightarrow\) 1 micro sec per bit: a bit can travel 100 m per 1000ns (thus max bus length 40~50 m)
  - 40 Kbps CAN bus \(\rightarrow\) 25000 ns per bit: A bit can travel 2500 m per 25000 ns (thus max bus length 1000~1250 m)

- Bandwidth
  - 1 Mbps up to 40~50 m (normal)
  - 0.5 Mbps upto 80~100 m
  - 40 Kbps up to \~1000 m
  - 5 Kbps up to \~10,000 m (maximum)
CAN Frame

- Small sized frames (messages): 0 to 8 bytes:
  - perfect for many embedded control applications
- Relatively high overhead: a frame size of more than 100 bits to send 64 data bits
  - do not use this for bulk data transfer
- Interrupt only after an entire message is received
CAN Addressing

- CAN bus can have an arbitrary number of nodes
  - Nodes do not have proper addresses
  - Each message has an 11-bit “field identifier”
  - Everyone interested in a message type listens to it
  - Works like this: “I’m passing a ball”
  - Not like this: “I’m passing a ball to Reus”

- 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
The CAN Arbitration Mechanism

- Shared broadcast bus
- Bus behaves like a large AND-gate - if all nodes send 1 the bus becomes 1, otherwise 0.
  - 0: dominant bit (in fact, sending 0 by high voltage)
  - 1: recessive bit
- A frame is tagged by an identifier
  - indicates contents of frame
  - most importantly, it is used for arbitration as priority
- Bit-wise arbitration
  - Each message has unique priority \( \rightarrow \) node with message with lowest id wins arbitration
- Lowest id = highest priority!
- The CAN bus is a fixed-priority-based scheduled resource
- 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
CAN Message Scheduling and Analysis

- Each frame should be non-preemptive
- This is a non-preemptive fixed-priority scheduling
- The maximum bits per frame is 135 bits (by considering all the overheads and bitstuffing)
- This results in a maximum blocking time due to a frame of 135 bits in CAN
- For a CAN with 1Mbit/s, the blocking time is up to 135 $\mu$s

**Theorem**

A system $T$ of periodic, independent, preemptable, and constrained-deadline message-passing tasks is schedulable on a CAN bus if

$$\forall \tau_i \in T \ \exists t \text{ with } 0 < t \leq D_i \text{ and } B_i + C_i + \sum_{j=1}^{i-1} \left\lceil \frac{t}{T_j} \right\rceil C_j \leq t,$$

where the higher-priority message types have lower indexes and $B_i$ is the blocking time of message type $i$. 

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Summary of Other Busses
Flexray

- Developed by the FlexRay consortium (BMW, Ford, Bosch, DaimlerChrysler, ...)
- Meets requirements with transfer rates $\gg$ CAN standard
  - High data rate can be achieved:
    - initially targeted for $\sim 10$Mbit/sec;
- Design allows much higher data rates
- Improved error tolerance and time-determinism
- Flexible TDMA protocol
- Cycle subdivided into a static and a dynamic segment.
  - Static segment is based on a fixed allocation of time slots to nodes.
  - Dynamic segment for transmission of ad-hoc communication with variable bandwidth requirements.
Flexray

- Use of two independent channels to eliminate single-point failures and to allow flexibility of different channel configurations
- Bandwidth in the dynamic segment is used only when it is actually needed.

http://www.ixxat.de/introduction_flexray_de.html?markierung=flexray
FlexRay Message Cycle
Static Segment

TDMA messages, most likely used for critical messages

- All static slots are the same length
- All static slots are repeated in order every communication cycle
- All static slot times are expended in cycle whether used or not
Dynamic Segment

- Each minislot is an opportunity to send a message
- If message isn’t sent, minislot elapses unused (short idle period)
- All nodes watch whether a message is sent so they can count minislots

transmission may only start within the first $p_{LatestTx}$ minislots of the dynamic segment
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Summary of Other Busses
Other Busses

- IEEE 488: Designed for laboratory equipment.
- LIN: low cost bus for interfacing sensors/actuators in the automotive domain
- MOST: Multimedia bus for the automotive domain (not a field bus)
- MAP: bus designed for car factories.
- Process Field Bus (Profibus): used in smart buildings
- The European Installation Bus (EIB): bus designed for smart buildings; CSMA/CA; low data rate. Upgrade: KNX-Bus
- Attempts to use Ethernet. Timing predictability an issue.
Wireless Communication: Examples

- IEEE 802.11 a/b/g/n
- UMTS; HSPA; LTE
- Bluetooth
- WirelessHART
- ZigBee
Summary

- Communication in embedded systems
- Timing analysis
  - TDMA
  - CAN bus
- Flexray architecture