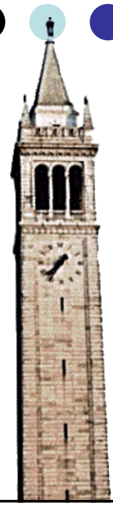

Introduction to Embedded Systems

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UC Berkeley

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Lecture 20: Control Area Network and FlexRay

Today's Cars

- *X-by-wire* vs. conventional mechanical and hydraulic systems
- Basics: power locks/door/window/engine start
- Sensors/Actuators: tire, powertrain, video, radar, and photoelectrics, etc.
- Control/Safety: ABS, EBD/CBC, EBA/BAS/BA, ASR/TCS/TRC, ESP/DSC/VSC, etc.
- Entertainment System
- Auto-Park
- DARPA's Urban Challenge

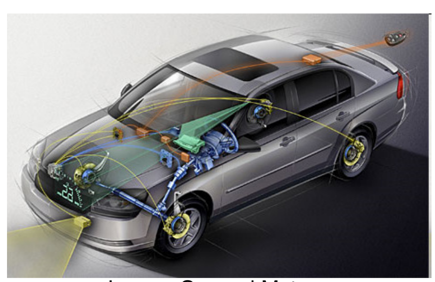


Image: General Motors

Today's Cars

- Number of Electronic Control Units (ECUs) in a car:
  - Low end: 30 ~ 50 (doors, roof, etc)
  - High end: 70~100
- Lines of code: ~100 million (Future: 200~300 million)
- The radio and navigation system in the current S-class Mercedes-Benz requires over 20 million lines of code alone and that the car contains nearly as many ECUs as the new Airbus A380 (excluding the plane's in-flight entertainment system).
- Cost of electronics/software: 35% ~ 40% in premium cars (for hybrid it is even higher!)

- How can we ensure timely and reliable communication via the "wires"?

[http://www.spectrum.ieee.org/feb09/7649]

CAN bus

CAN = Controller Area Network

- Publicly available communications standard [1]
  http://www.semiconductors.bosch.de/pdf/can2spec.pdf

Serial data bus developed by Bosch in the 80s

- Support for broadcast and multicast comm
- Low cost
- Deterministic resolution of the contention
- Priority-based arbitration
- Automotive standard but used also in automation, factory control, avionics and medical equipment
- Simple, 2 differential (copper) wire connection
- Speed of up to 1Mb/s
- Error detection and signalling

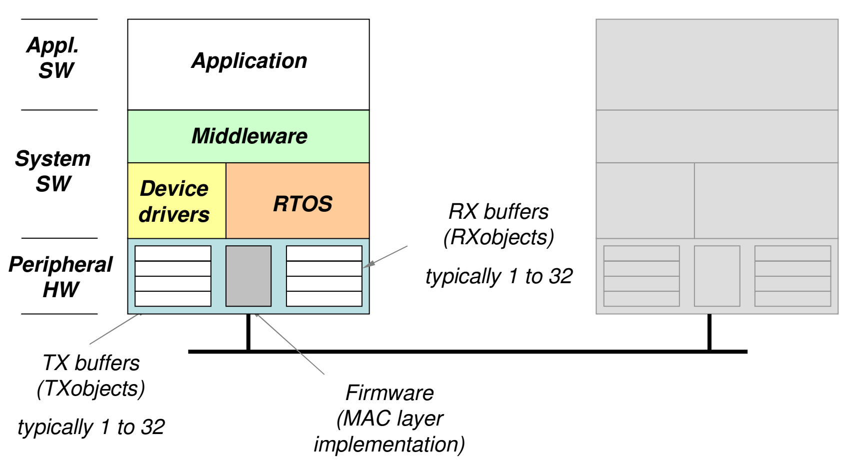
CAN bus

Purpose of this Lesson

- Introduction to a widely-used communication protocol standard in the automotive industry
- Develop time analysis for real-time messages
- Understand how firmware can affect the time determinism and spoil the priority assignment

CAN bus

A CAN-based system



CAN bus

CAN standard (MAC protocol)

- Fixed format messages with limited size
- CAN communication does not require node (or system) addresses (configuration information)
  - Flexibility – a node can be added at any time
  - Message delivery and routing – the content is identified by an IDENTIFIER field defining the message content
  - Multicast – all messages are received by all nodes that can filter messages based on their IDs
  - Data Consistency – A message is accepted by all nodes or by no node

CAN bus

Frame types

DATA FRAME

- Carries regular data

REMOTE FRAME

- Used to request the transmission of a DATA FRAME with the same ID

ERROR FRAME

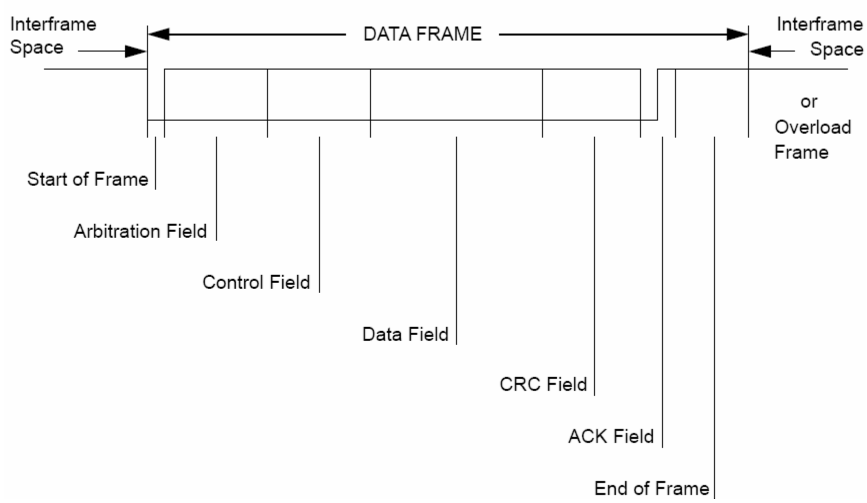
- Transmitted by any unit detecting a bus error

OVERLOAD FRAME

- Used to force a time interval in between frame transmissions

CAN bus

DATA FRAME



CAN bus

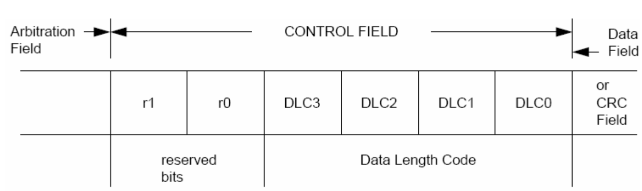
DATA FRAME

Start of frame – 1 dominant bit. A frame can only start when the bus is IDLE. All stations synchronize to the leading edge of the SOF bit

Identifier – 11 (or 29 in version 2.0) bits. In order from most significant to least significant. The 7 most significant bits cannot be all recessive (all 1s)

RTR – remote transmission request, dominant for REQUEST frames, recessive for DATA frames

CONTROL – (see figure) maximum data length is 8 (bytes) other values are not used



CAN bus

DATA FRAME (conitinued)

Data – 0 to 8 bytes of data

CRC – 15 CRC bits plus one CRC delimiter bit (recessive)

ACK – two bits (SLOT + DELIMITER) all stations receiving the message correctly (CRC check) set the SLOT to dominant (the transmitter transmits a recessive). The DELIMITER is recessive

END OF FRAME – seven recessive bits

Bit stuffing

any sequence of 5 bits of the same type requires the addition of an opposite type bit by the TRANSMITTER (and removal from the receiver)

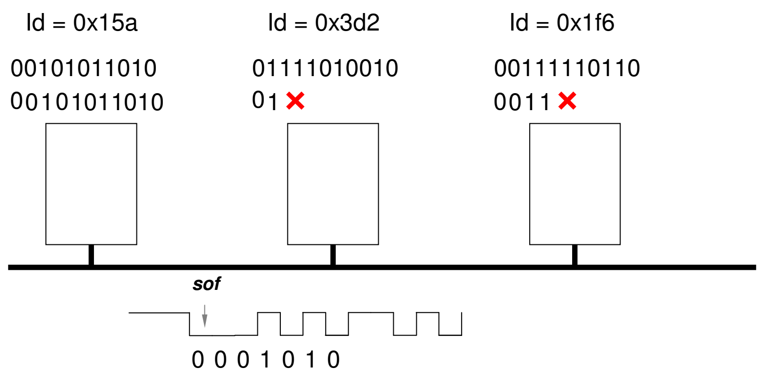
CAN bus

Arbitration

All nodes are synchronized on the SOF bit

The bus behaves as a wired-AND

An example …



CAN bus

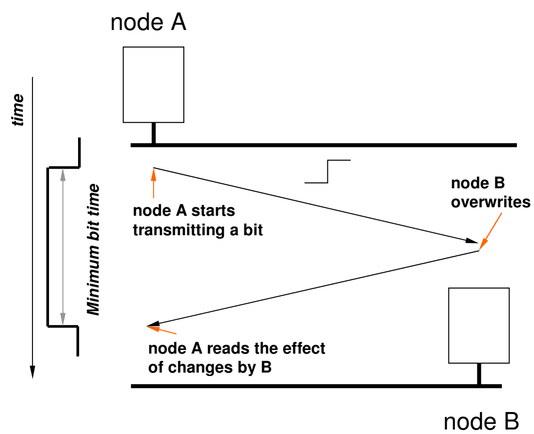
A sender must wait longer than that maximum propagation latency before sending the next bit.

Why?

CAN bus

The type of arbitration implies that the bit time is at least twice the propagation latency on the bus

This defines a relation between the maximum bus length and the transmission speed. The available values are



Bit rate	Bus length
1 Mbit/s	25 m
800 kbit/s	50 m
500 kbit/s	**100 m**
250 kbit/s	250 m
125 kbit/s	500 m
50 kbit/s	1000 m
20 kbit/s	2500 m
10 kbit/s	5000 m

CAN bus

Error and fault containment

There are 5 types of error

BIT ERROR

- The sender monitors the bus. If the value found on the bus is different from the one that is sent, then a BIT ERROR is detected

STUFF ERROR

- Detected if 6 consecutive bits of the same type are found

CRC ERROR

- Detected by the receiver if the received CRC field does not match the computed value

FORM ERROR

- Detected when a fixed format field contains unexpected values

ACKNOWLEDGEMENT ERROR

- Detected by the transmitter if a dominant value is not found in the ack slot

CAN bus

A station detecting an error transmits an ERROR FLAG.

For BIT, STUFF, FORM, ACKNOWLEDGEMENT errors, it is sent in the immediately following bit.

For CRC it is sent after the ACK DELIMITER

CAN bus

Fault containment

Each node can be in 3 states:

- Error active
- Error passive: limited error signalling and transmission features
- Bus off: cannot influence the bus

Each node has two counters:

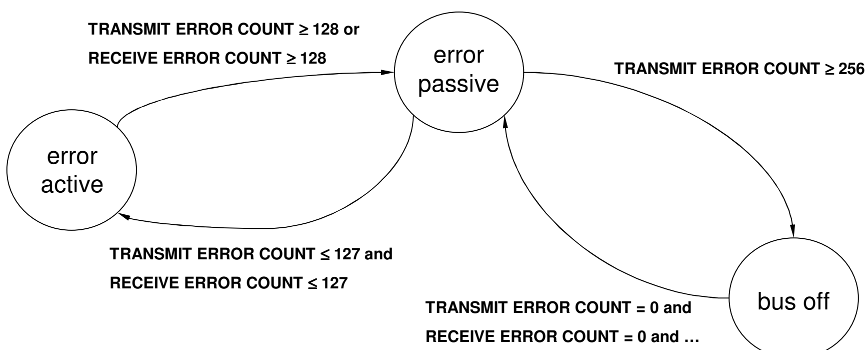
- TRANSMIT ERROR COUNT:
  - increased – (list) by 8 when the transmitter detects an error …
  - decreased – by 1 after the successful transmission of a message (unless it is 0)
- RECEIVE ERROR COUNT:
  - increased – (list) by 1 when the node detects an error, by 8 if it detects a dominant bit as the first bit after sending an error flag …
  - decreased – (if between 1 and 127 by 1, if >127 set back to a value between 119 and 127) after successful reception of a message

CAN bus

Fault containment

Each node can be in 3 states:

- Error active
- Error passive: limited error signalling and transmission features
- Bus off: cannot influence the bus

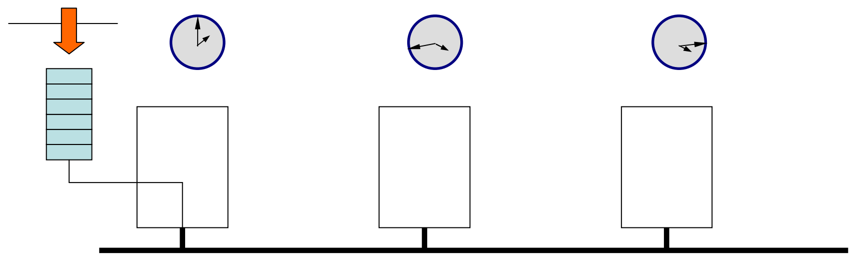


CAN bus

Timing Analysis (and inversions) – Ideal behavior

Assumption 3: periodic messages, but no assumption on the message phases

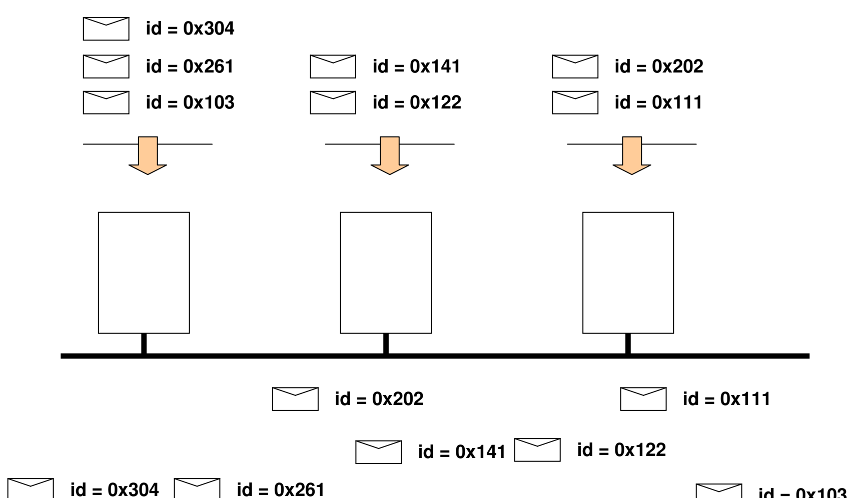
Assumption 1: nodes are not synchronized, nor any assumption on local clocks is used by the MW and driver levels



Assumption 2: messages are always transmitted by nodes based on their priority (ID) – ideal priority queue of messages

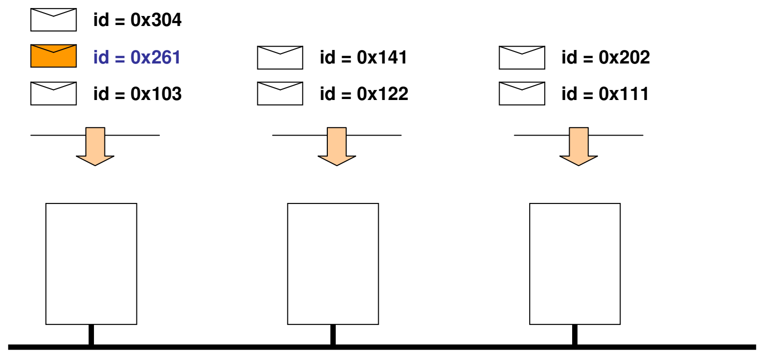
CAN bus

Timing Analysis (and inversions) – Ideal behavior



CAN bus

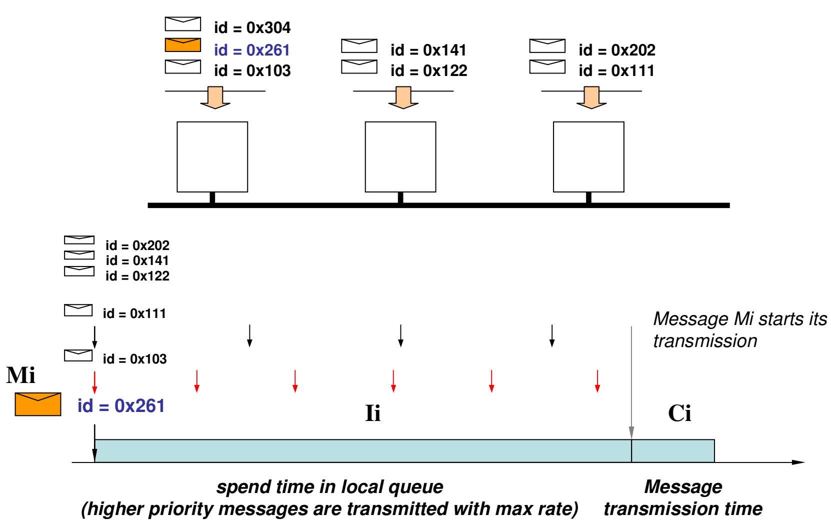
Timing Analysis – worst case latency – Ideal behavior



Critical instant theorem: for a preemptive priority based scheduled resource, the worst case response time of an object occurs when it is released together with all other higher priority objects and they are released with their highest rate

CAN bus

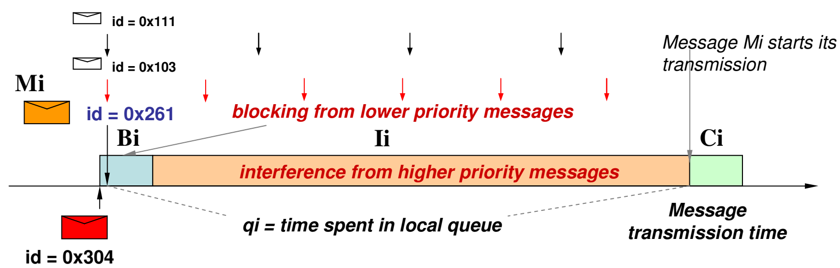
Timing Analysis – worst case latency – Ideal behavior



CAN bus

Timing Analysis – worst case latency – Ideal behavior [2]

The transmission of a message cannot be preempted



$$q_i = B_i + I_i \qquad I_i = \sum_{j \in hp(i)} I_{i,j}$$

$$w_i = q_i + C_i \qquad I_{i,j} = \left\lceil \frac{q_i}{T_j} \right\rceil C_j$$

$$q_i = B_i + \sum_{j \in hp(i)} \left\lceil \frac{q_i}{T_j} \right\rceil C_j$$

Fixed point formula: solved iteratively by setting qi(0)=0 until the minimum solution is found

CAN bus

An example (Ci computed for maximum size, bus speed 500 kb/s)

Message	ID	Ti	ECU								
msg1	100	10	ECU1	msg24	123	12.5	ECU3	msg47	146	1000	ECU4
msg2	101	10	ECU1	msg25	124	100	ECU4	msg48	147	1000	ECU3
msg3	102	6.25	ECU2	*msg26*	*125*	*20*	*ECU4*	msg49	148	1000	ECU4
msg4	103	12.5	ECU3	msg27	126	25	ECU2	msg50	149	10	ECU9
msg5	104	10	ECU4	msg28	127	30	ECU7	msg51	150	1000	ECU4
msg6	105	12.5	ECU2	msg29	128	10	ECU8	msg52	151	1000	ECU6
msg7	106	5000	ECU4	msg30	129	20	ECU8	msg53	152	1000	ECU4
msg8	107	100	ECU4	msg31	130	50	ECU3	msg54	153	1000	ECU3
msg9	108	100	ECU1	msg32	131	50	ECU5	msg55	154	1000	ECU1
msg10	109	100	ECU1	msg33	132	50	ECU1	msg56	155	1000	ECU10
msg11	110	20	ECU1	msg34	133	500	ECU9	msg57	156	1000	ECU7
msg12	111	12.5	ECU3	msg35	134	100	ECU3	msg58	157	1000	ECU11
msg13	112	12.5	ECU2	msg36	135	100	ECU4	msg59	158	1000	ECU12
msg14	113	25	ECU2	msg37	136	100	ECU3	msg60	159	1000	ECU5
msg15	114	25	ECU3	msg38	137	100	ECU3	msg61	160	1000	ECU13
msg16	115	25	ECU3	msg39	138	250	ECU4	msg62	161	1000	ECU9
msg17	116	20	ECU1	msg40	139	250	ECU3	msg63	162	1000	ECU2
msg18	117	25	ECU5	msg41	140	250	ECU3	msg64	163	1000	ECU4
msg19	118	20	ECU1	msg42	141	500	ECU3	msg65	164	1000	ECU4
msg20	119	30	ECU4	msg43	142	500	ECU2	msg66	165	50	ECU1
msg21	120	10	ECU1	msg44	143	500	ECU3	msg67	166	50	ECU1
msg22	121	20	ECU1	msg45	144	500	ECU6	msg68	167	100	ECU5
msg23	122	12.5	ECU6	msg46	145	1000	ECU4	msg69	168	10	ECU9

CAN bus

In reality, this analysis can give optimistic results!

A number of issues need to be considered …

- Priority enqueuing in the sw layers
- Availability of TxObjects at the adapter
- Possibility of preempting (aborting) a transmission attempt
- Finite copy time between the queue and the TxObjects
- The adapter may not transmit messages in the TxObjects by priority

CAN bus

In reality, this analysis can give optimistic results!

A number of issues need to be considered …

- …
- Availability of TxObjects at the adapter
- Finite copy time between the queue and the TxObjects

Adapters typically only have a limited number of TXObjects or RxObjects available

CAN bus

A number of issues need to be considered …

  – …
  – Availability of TxObjects at the adapter

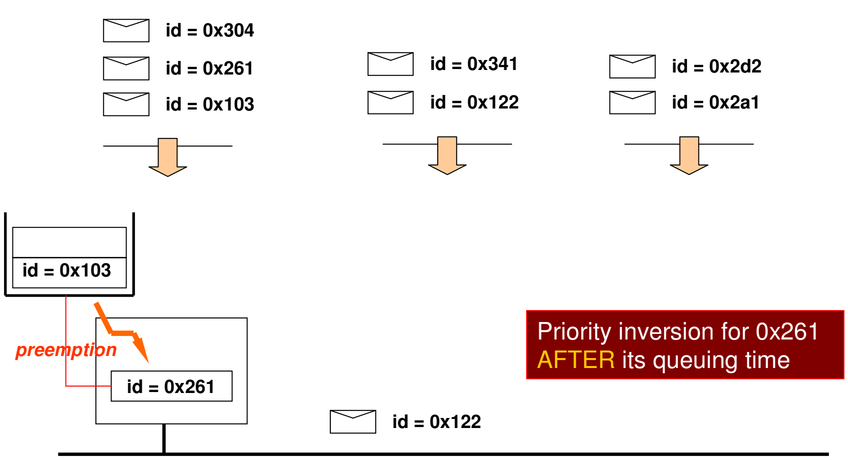
- Let's check the controller specifications!

Model	Type	Buffer Type	Priority and Abort
Microchip MCP2515	Standalone controller	2 RX - 3 TX	lowest message ID, abort signal
ATMEL AT89C51CC03 AT90CAN32/64	8 bit MCU w. CAN controller	15 TX/RX msg. objects	lowest message ID, abort signal
FUJITSU MB90385/90387 90V495	16 bit MCU w. CAN controller	8 TX/RX msg. objects	lowest buffer num. abort signal
FUJITSU 90390	16 bit micro w. CAN controller	16 TX/RX msg. objects	lowest buffer num. abort signal
Intel 87C196 (82527)	16 bit MCU w. CAN controller	14 TX/RX + 1 RX msg. objects	lowest buffer num. abort possible (?)
INFINEON XC161CJ/167 (82C900)	16 bit MCU w. CAN controller	32 TX/RX msg. objects (2 buses)	lowest buffer num., abort possible (?)
PHILIPS 8xC592 (SJA1000)	8 bit MCU w. CAN controller	one TX buffer	abort signal

CAN bus

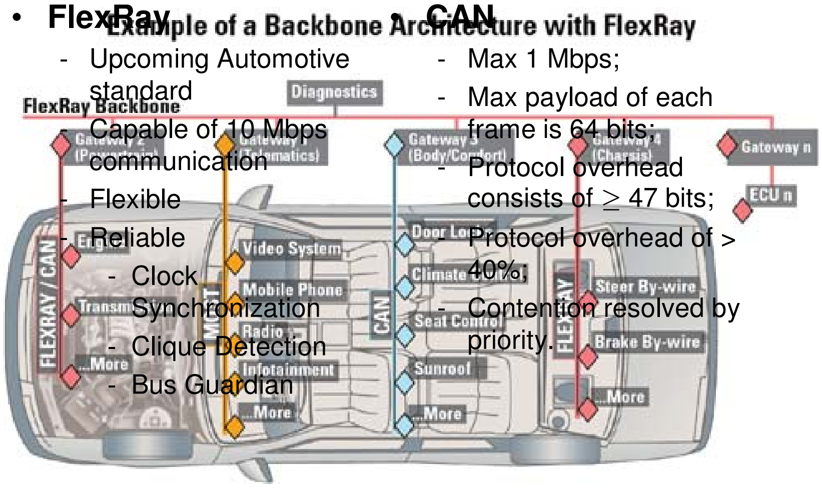
What happens if only one TxObject is available?

  – Assuming preempatbility of TxObject



FlexRay vs. CAN

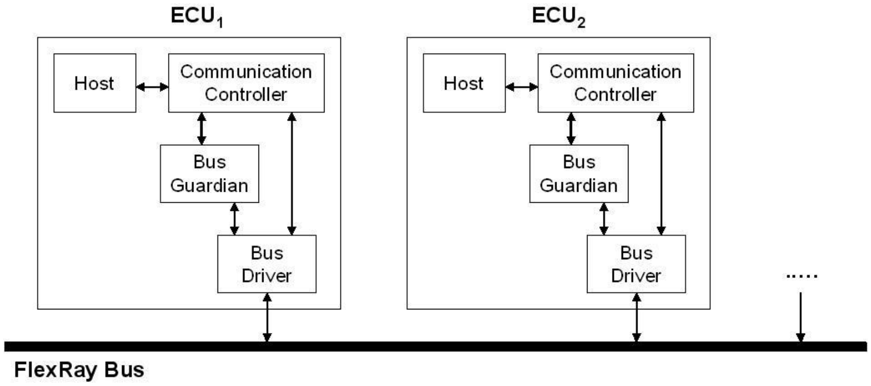
- **FlexRay**
  - Upcoming Automotive standard
  - Capable of 10 Mbps communication
  - Flexible
  - Reliable
    - Clock Synchronization
    - Clique Detection
    - Bus Guardian
- **CAN**
  - Max 1 Mbps;
  - Max payload of each frame is 64 bits;
  - Protocol overhead consists of $\geq$ 47 bits;
  - Protocol overhead of > 40%;
  - Contention resolved by priority.



FlexRay

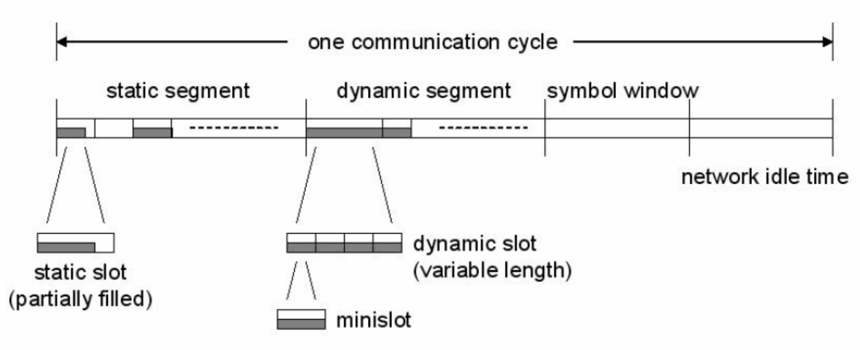
- Being developed by a consortium of automotive makers and 1-tier suppliers.
- Successor to CAN, higher bit rate, more ECUs, and more reliable
  – FlexRay: max 10 Mbps
  – CAN: max 1 Mbps (but protocol itself has over 40% overhead)
- Allow both *time-triggered* and *event-triggered* communication
- Good clock synchronization (distributive) with built-in fault tolerance

FlexRay

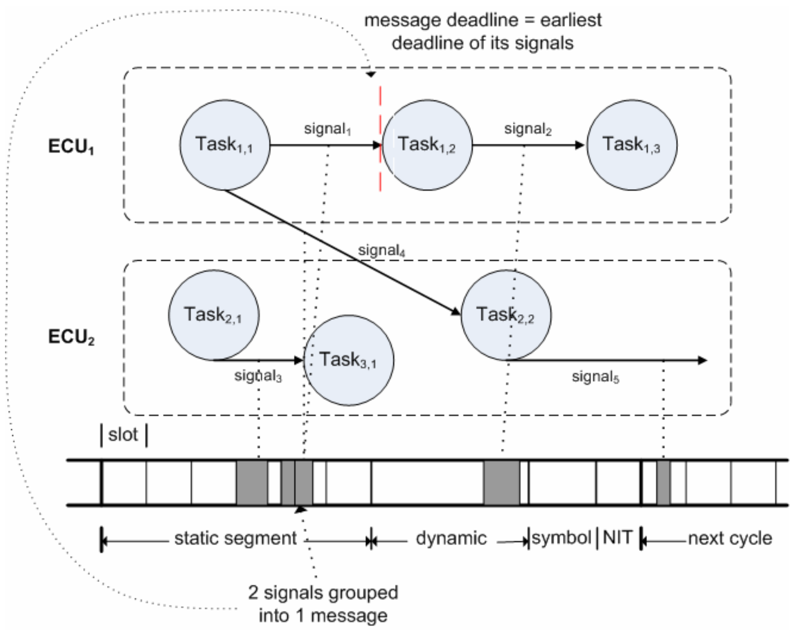


FlexRay Specification v2.1

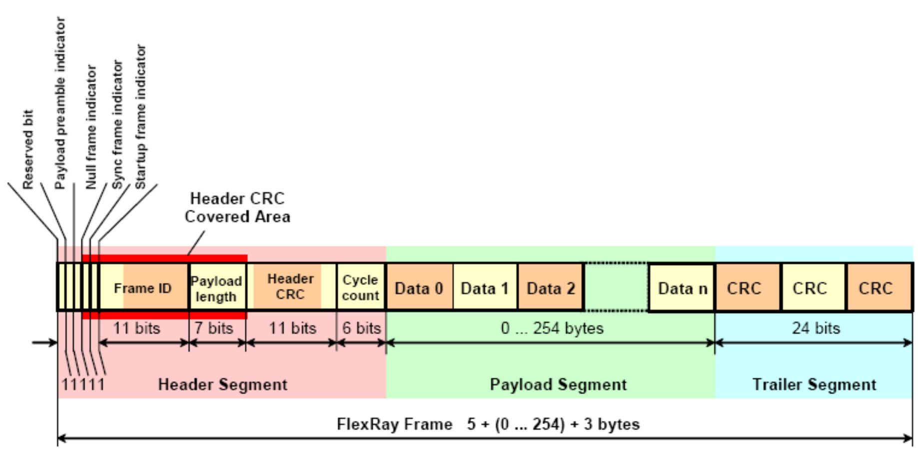
FlexRay



FlexRay Specification v2.1



Frame Format



Issues in FlexRay

- The current specification instructs the ECUs to drop a message if it is corrupted.
- Acknowledgment-Retransmission mechanism (similar to the one in CAN) is missing
- Timing analysis in the dynamic segment is difficult
- Static/Dynamic ratio has to be determined at design time (what ratio is good?)

CAN bus

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[3] A. Meschi M. Di Natale M. Spuri Priority Inversion at the Network Adapter when Scheduling Messages with Earliest Deadline Techniques , Euromicro Conference on Real-time systems, L'Aquila, Italy 1996.

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