EECS 571 Principles of Real-Time Embedded Systems
Lecture Note #18:

Controller Area Network (CAN)

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Non-Preemptive Scheduling of Messages on CAN

- The Controller Area Network (CAN) protocol: contention-based multi-master network (up to 1 Mbps) with high schedulable utilization and reliability, prioitized bus access, and good reconfigurability.
- Scheduling messages on CAN
  - Workload characteristics.
  - MTS algorithm.

Real-Time Control Systems

- Main devices are controllers (CPUs), sensors, and actuators (drives).
- Detect events and respond to them.
- Real-world events are aperiodic in nature
- But if they occur frequently enough, can use periodic polling of sensors, e.g., servo control of drives.
- But if event occurs *sporadically*, periodic polling is a waste of bandwidth, e.g., temperature-too-high event.
- For such events, *smart sensors* are appropriate. So, ∃ two requirements to meet:
  - Fast response to sporadic messages.
  - Efficient handling of both periodic and sporadic messages.
- CAN satisfies both requirements.

The CAN Protocol

- Contention-based multimaster bus with a special bus acquisition algorithm.
- Wired-OR (or wired-AND) bus.
- Each message has an *identifier* (ID) – reflects message priority.
- When bus becomes free, each node transmits (bit-by-bit) the ID of its highest-priority message.
- After writing each bit, each node reads the bus.
- If bit read different from bit written, node drops out of contention.
- In the end, only one winner which transmits its message.
- Two CAN message formats: *standard* (11-bit ID) and *extended* (29-bit ID).
- This algorithm implemented in low-cost bus interface chip.

CAN Message Format

SOF	Identifier	Control	Data	CRC	Ack	EOF

SOF: Start of Frame
CRC: Cyclic Redundancy Code
EOF: End of Frame

ID field: Serves two purposes:

- Controls bus arbitration.
- Describes the meaning of the data (message routing).

Routing:

- Suppose ID is %xxxxxx10110.
- All nodes desirous of receiving this message, will set *filters* in their interface chips.

Advantages of CAN

- Global bus arbitration despite being distributed.
- Fast bus access to highest priority message.
- Prioritized bus access.
- Minimal priority inversion.
- Easily implemented bus acquisition algorithm – cheap interface chips.
- Reconfiguration flexibility – nodes can be easily added or removed.

Workload Characteristics and Message Scheduling

Hard periodics: Commonly found in servo control of drives. Deadline may be less than the period.

Hard sporadics: Used for notification of events. Each has a *minimum interarrival time* (MIT).

Non-real-time aperiodics: Examples include diagnostic information, device status, device setup, etc.

Message scheduling:

- For CAN: message scheduling = design of ID.
- Non-preemptive scheduling under release-time and deadline constraints is NP-hard $\Rightarrow$ *Mixed Traffic Scheduler* (MTS) based on ED.

Fixed-Priority Scheduling on CAN

- CAN nodes send messages as follows:
  - Node assigns an ID to a message and transfers the message (with ID) to bus interface chip.
  - Chip will contend for the bus autonomously.
  - Once message transferred to chip, its ID will remain fixed unless processor changes it.
- Fixed-priority scheduling is a natural choice.
  - Use *deadline monotonic* scheduling.
  - Each message has a fixed priority according to the tightness of its deadline.
  - This fixed priority forms the message ID. It also uniquely identifies message for reception purposes.
- But to get greater utilizations, try dynamic scheduling . . .

Earliest-Deadline Scheduling on CAN

- Design of ID:

  - *Deadline* is logical inverse of message deadline.
  - *Uniqueness* (unique code assigned to each node) distinguishes messages with same deadlines.
  - *Priority* is a 1-bit field: 1 for real-time messages, 0 otherwise.
- Problem: absolute deadlines keep increasing.
- One solution: *slack time* (time to deadline). But,

  P1. Slack time changes with every clock tick, so must be updated before each arbitration round $\Rightarrow$ too time-consuming.

  P2. Messages in typical workloads may have a wide range of laxities – but not enough bits in ID.
- P2 makes ED impractical for CAN:
  - Laxities can range from 100's of microseconds (high-speed drives) to several seconds (temperature readings) $\Rightarrow$ need $\sim$20 bits (μs granularity).
  - Can use CAN extended format, but this wastes 20–30% bandwidth.

MTS

- MTS gives high utilization (like ED) while using 11-bit IDs (like DM).
- Observation: 11 bits are too many for DM — a few bits will remain unused.
- Use these bits to enhance schedulability by using ED.

MTS – Solution to **P1**: Time Epochs

- Use actual deadlines (instead of slack time), but express them relative to a periodically increasing reference called the *start of epoch* (SOE).

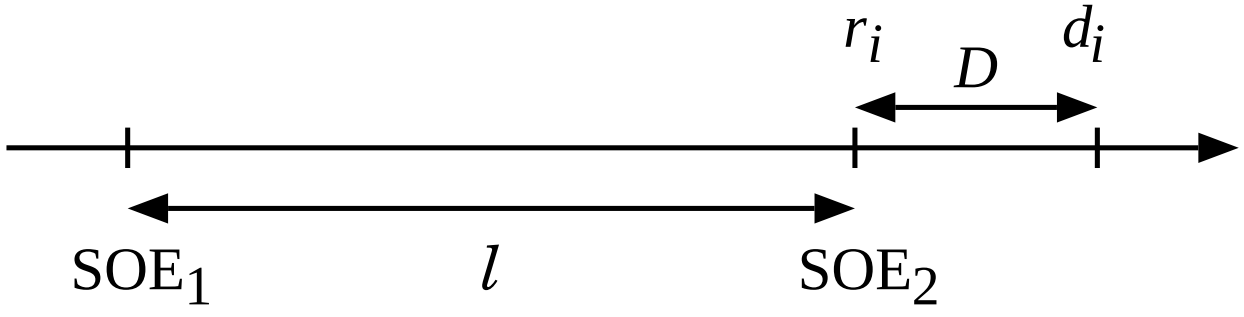
  $\Rightarrow$ Deadline values stay fixed for duration of epoch.
- A periodic process wakes up every ℓ seconds (length of epoch) and updates IDs.
- Deadline field for message i

  = logical inverse of $(d_i - \text{SOE})$

  = logical inverse of $(d_i - \lfloor \frac{t}{\ell} \rfloor \cdot \ell)$

  - o if want x% of CPU time spent on updates, $\ell = \frac{n}{xM \times 10^6}$.
- Disadvantage: need more bits in deadline field:

  $m = \log_2(\ell + D)$, where D is the largest $(d - r)$.



MTS – Solution to **P2**

- Define two classes of messages:

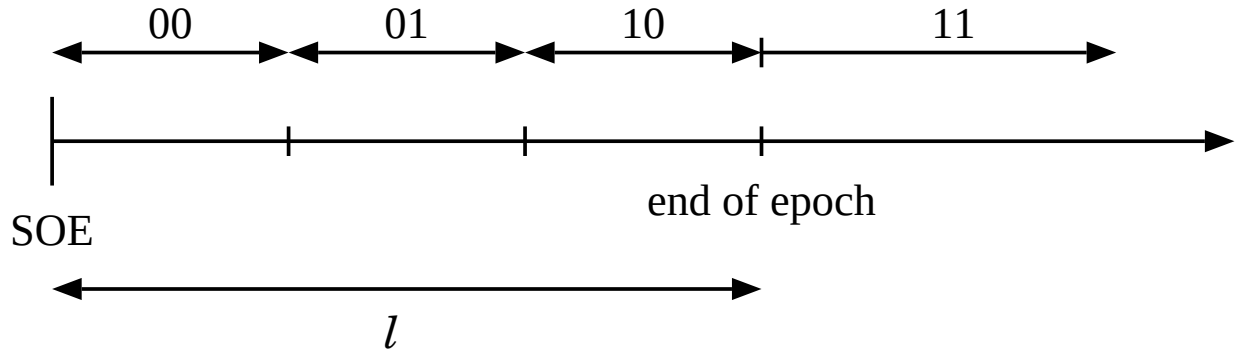
  High-speed: The tightest deadline messages in the workload.

  Low-speed: The remaining messages.
- *Goal*: improve schedulability of high-speed messages since they tend to use several times more BW than low-speed messages.
- Use ED for high-speed and DM for low-speed messages.
- High-speed messages:

  - MSB is 1.
  - *Uniqueness* field is 5 bits (32 high-speed messages).
  - remaining 5 bits not enough to encode the deadlines (relative to the latest SOE) . . .

MTS – Solution to **P2**: Quantized Deadlines

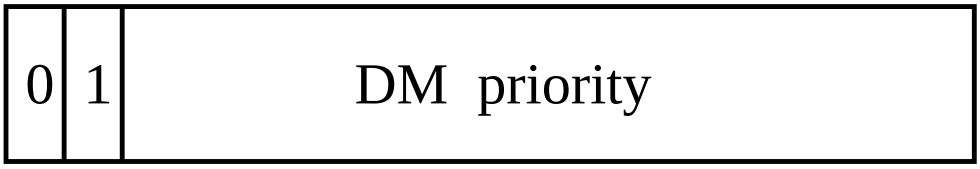
- Quantize time into *regions*.
- Encode deadlines according to which region they fall in.



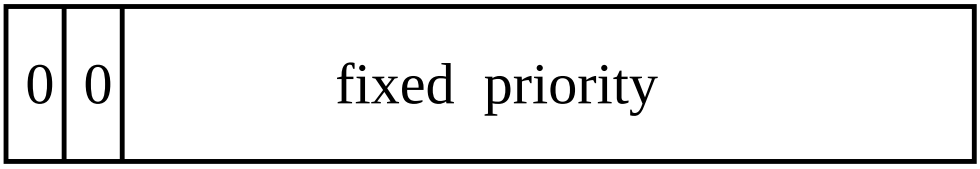
- Length of a region is $l_r = \frac{\ell}{2^m - 1}$, where m is the length of the deadline field (5 in this case).
- What if two deadlines fall in same region (and quantize to same value)?
  - Use DM-priority of a message as its uniqueness code.
  - This makes MTS a hierarchical scheduler.

MTS – Low-Speed and Non-Real-Time Messages

- Use DM scheduling for low-speed messages.
- Use fixed-priority for non-real-time messages; priorities assigned arbitrarily.



(Low-speed)



(Non-real-time)

- So MTS allows:
  - 32 high-speed messages (periodic or sporadic).
  - 512 low-speed messages (periodic or sporadic).
  - 512 non-real-time messages.

Schedulability Conditions – ED and DM

- Non-preemptive ED (Zheng and Shin '94; modified for relative phase offsets):

  1. $\sum_{j=1}^{n} C_j/T_j \leq 1$.

  2. $\forall t \in S,\ \sum_{i=1}^{n} \lceil (t - d_i - \phi_i)/T_i \rceil^+ C_i + C_p \leq t$, where $S = \cup_{i=1}^{n} S_i,\ S_i = \{d_i + nT_i :\ n = 0, 1, \cdots, \lfloor (t_{max} - d_i - \phi_i)/T_i \rfloor\}$, and $t_{max} = \max\{d_1, \cdots, d_n, (C_p + \sum_{i=1}^{n}(1 - d_i/T_i)C_i)/(1 - \sum_{i=1}^{n} C_i/T_i)\}$.

     - T_i, C_i, d_i are the period, length, and deadline of message i.
     - C_p is the length of the longest possible packet.
     - $\lceil x \rceil^+ = n$ if $n - 1 \leq x < n,\ n = 1, 2, ...$, and $\lceil x \rceil^+ = 0$ for $x < 0$.

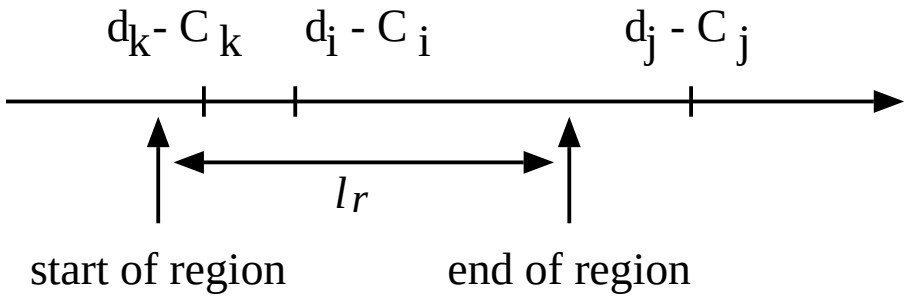
- Non-preemptive DM. Message i schedulable if

  $\exists t \in S,\ \sum_{j=1}^{i-1} \lceil (t - \phi_j)/T_j \rceil C_j + C_p \leq t$,
  where $S =$ {set of all release times of messages $0, 1, \cdots, i-1$ through time $d_i - C_i$} $\cup \{d_i - C_i\}$, and ϕ_j are the *relative* phase offsets.

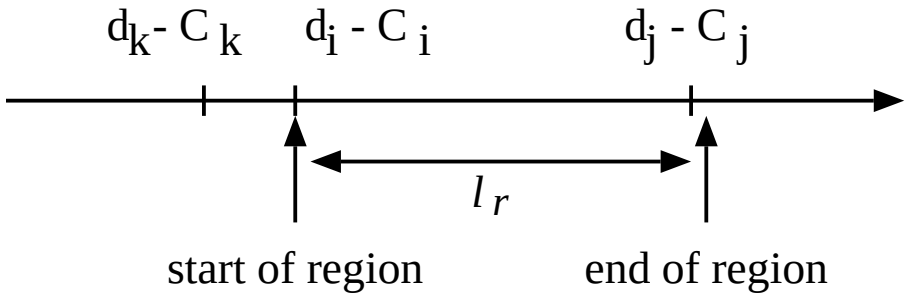
Schedulability Conditions – MTS

- **High-speed** messages – worst-case situation created when
  1. worst possible traffic congestion.
     - release all messages at same time.
  2. worst possible deadline encoding.
     - maximize number of messages which get priority over message i.
     - occurs when deadline-to-start of i coincides with the start of a region.

(a)



(b)



Schedulability Conditions – MTS

- Message invocations j will have priority over i if:
  1. $(d_i - C_i) > (d_j - C_j)$, or
  2.(a) $(d_i - C_i) < (d_j - C_j) \leq (d_i - C_i + l_r)$, and
  (b) DM priority of j is greater than that of i, and
  (c) j is released before $d_i - C_i$.
- So a high-speed message is schedulable if its first invocation i satisfies the condition:

  $\exists t \in S$,
  $\sum$(lengths of all "qualified" j released before t) $+ C_p \leq t$,
  where $S =$ {set of release times of each j} $\cup \{d_i - C_i\}$,
  C_p is the size of a longest possible packet.
- **Low-speed** messages – just check DM schedulability for each low-speed message.
  - Since high-speed messages have shorter deadlines than low-speed ones, they will automatically have higher DM priority (which is exactly what we want).

Simulation

- Let ED* be an ideal (imaginary) scheduling policy:
  - Works same as ED (no quantization), but . . .
  - Requires only an 11-bit ID.
- We expect MTS's performance to be
  - Better than that of DM.
  - Close to that of ED*.

Simulation Workload Model

Consider an industrial drill with attached robot arm.

High-speed periodics: Needed for servo control of high-speed drives.

- Two messages per drive (feedback and command).

  $r_1 = t_0$, $r_2 = t_0 + 0.5c$, $d_1 = d_2 = 0.4c$.

High-speed sporadics: Needed for contact sensors in robotic grippers.

- Assume that deadline of contact sensor message is one-fourth of drive cycle time.

High-speed messages				
Type	*Class*	*Period/MIT*	*Deadline*	*# of mssg.*
Fingers	Periodic	125.0μs (8 kHz)	50.0μs	4
Joints	Periodic	166.7μs (6 kHz)	66.6μs*	6*
Carriage	Periodic	250.0μs (4 kHz)	100.0μs	2
Drill	Periodic	500.0μs (2 kHz)	200.0μs	2
Sensors	Sporadic	2s	30.0μs*	2*

Low-speed messages: Examples: servo control of low-speed drives (periodic) and smart temperature monitoring sensor (sporadic).

Low-speed messages			
Class	*Period* (ms)	*Deadline* (ms)	*MIT*
Periodic	20.0	8.0	—
Sporadic	—	5.0	5s

Simulation Workload Model (cont'd)

Message sizes: Standard CAN format has 47 framing bits.

- Servo control typically needs 32-bit command and feedback values. So periodic messages are 79 bits long. (Use for C_p as well).
- Sporadic messages only notify of an event; so the ID is enough – 0 data bytes needed.

Length of epoch: $M = 10$ MIPS, $n = 1000$ instructions, $x = 5\%$.

$$\ell = \frac{1000}{(0.05)(20 \times 10^6)} = 1\text{ms}$$

Length of region:

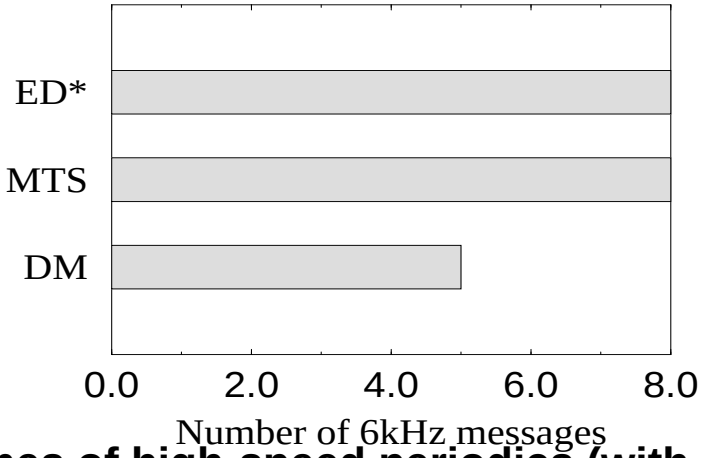
$$l_r = \frac{\ell}{2^m - 1} = \frac{1\text{ms}}{2^5 - 1} = 32.3\mu\text{s}$$

- Use this workload to evaluate MTS on 10 Mb/s CAN.

Simulation Results

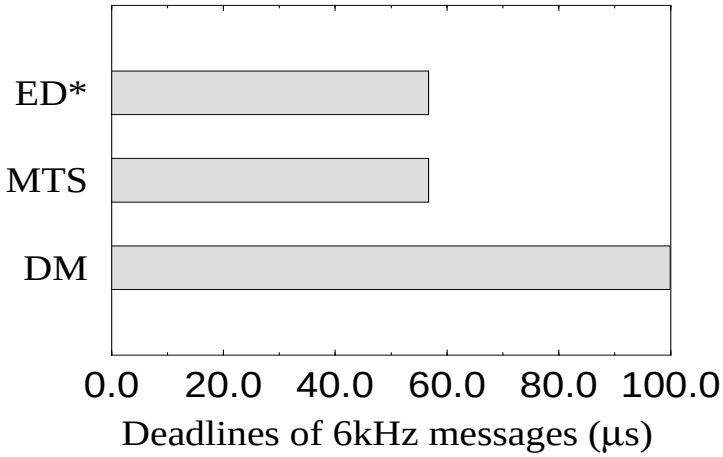
Vary number of high-speed periodics (6kHz messages):

DM can handle only 5 ($U = 58.5\%$); MTS and ED* can handle 8 each ($U = 72.7\%$).



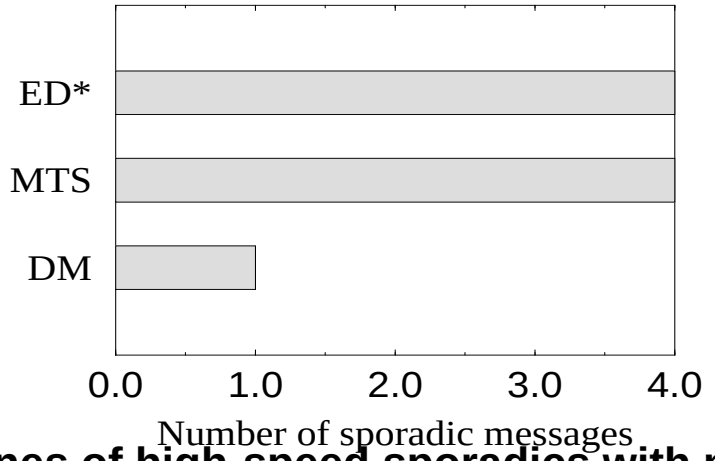
Vary deadlines of high-speed periodics (with six 6kHz messages and

DM fails at 99.9μs or less; MTS and ED* can handle even 56.8μs (min. possible).

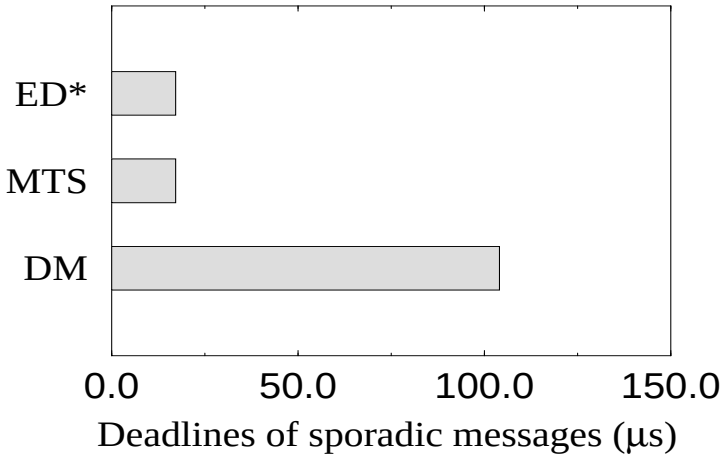


Simulation Results (cont'd)

Vary number of high-speed sporadics with $U = 63.2\%$:
DM can handle only 1 sporadic message; MTS and ED* can handle 4 each.



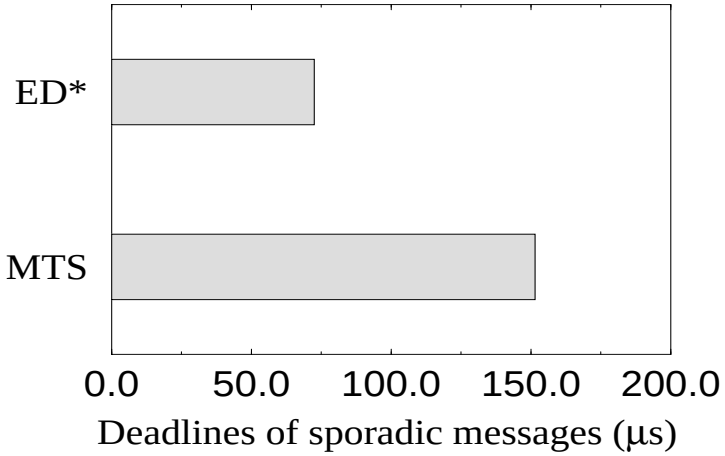
Vary deadlines of high-speed sporadics with number fixed at 2:
DM fails at 104.1μs or less; MTS and ED* can handle even 17.3μs (min. possible).



Simulation Results (cont'd)

Vary deadlines of high-speed sporadics (cont'd): To better compare MTS and ED*, increase load. Use 10 6kHz messages ($U = 82.2\%$).

MTS fails at 151.5μs or less; ED* fails at 72.5μs or less;



Low-speed messages: Even 10% of the bandwidth is enough to accommodate about a hundred low-speed messages. Thus, the schedulability of low-speed messages is not a problem. Our simulations showed no real difference between DM, MTS, or ED* in scheduling low-speed messages for a fixed load of high-speed messages.