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CAN SCHEDULABILITY ANALYSIS REFUTED, REVISTED AND REVIEWED

Presented by

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Presented by
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OUTLINE

- Objective
- Introduction
- Response Time Analysis
- Priority Assignment Policies
- Implications of Flawed Analysis
- Conclusion

OBJECTIVE

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  - Flaws in the analysis of CAN messages.

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  - Optimality of priority assignment policies
  - Impact on commercial CAN systems designed and developed using flawed schedulability analysis

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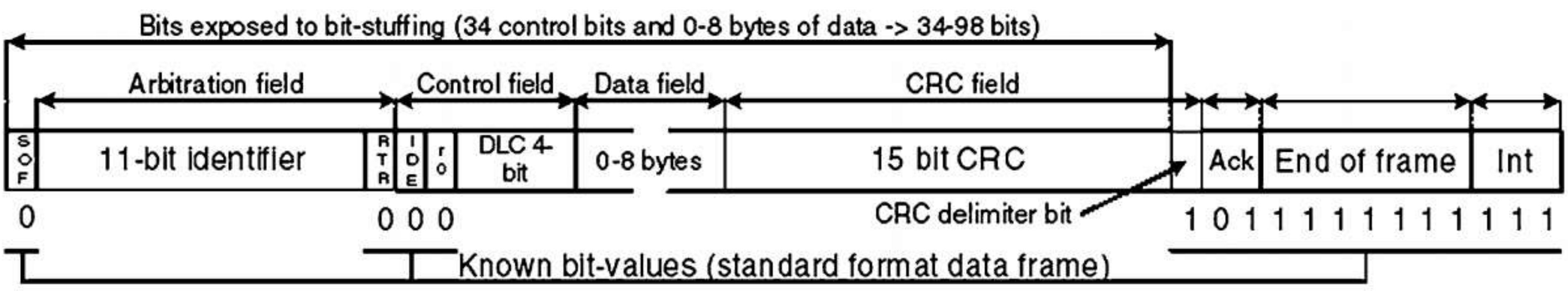

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$$C_m = \left(g + 8s_m + 13 + \left\lfloor \frac{g + 8s_m - 1}{4} \right\rfloor \right) \tau_{\text{bit}}$$

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- This analysis provided a method of calculating the worst-case response times of all CAN messages

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- Tindell’s work has been cited more than 200 times.

Flaws in Tindells work

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- The Tindells CAN Analysis has some flaws
- It may result in computed worst-case response times for messages that are optimistic, i.e. less than the response times that may actually occur.

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Message	Priority	Period	Deadline	TX time
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- Hence the system is deemed to be schedulable

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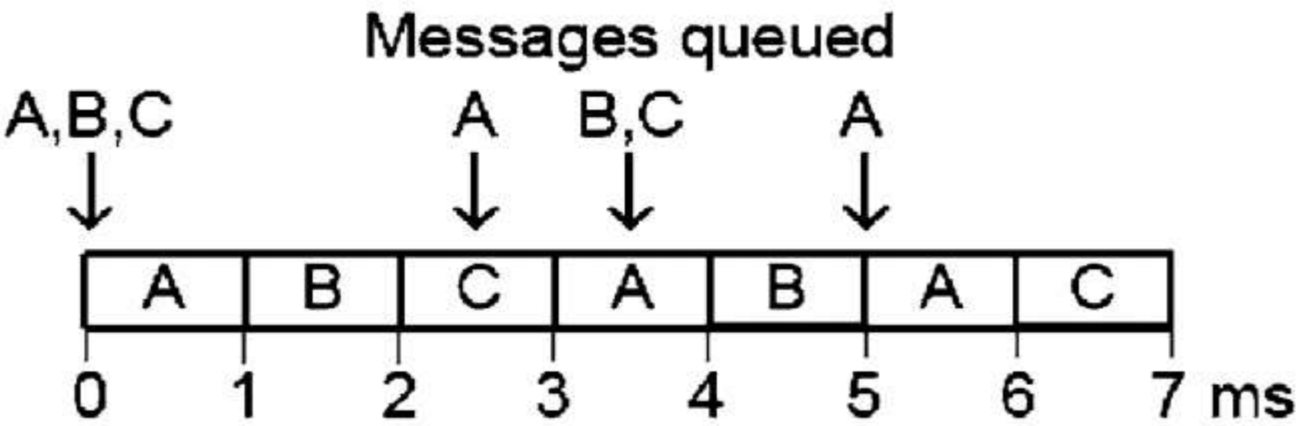

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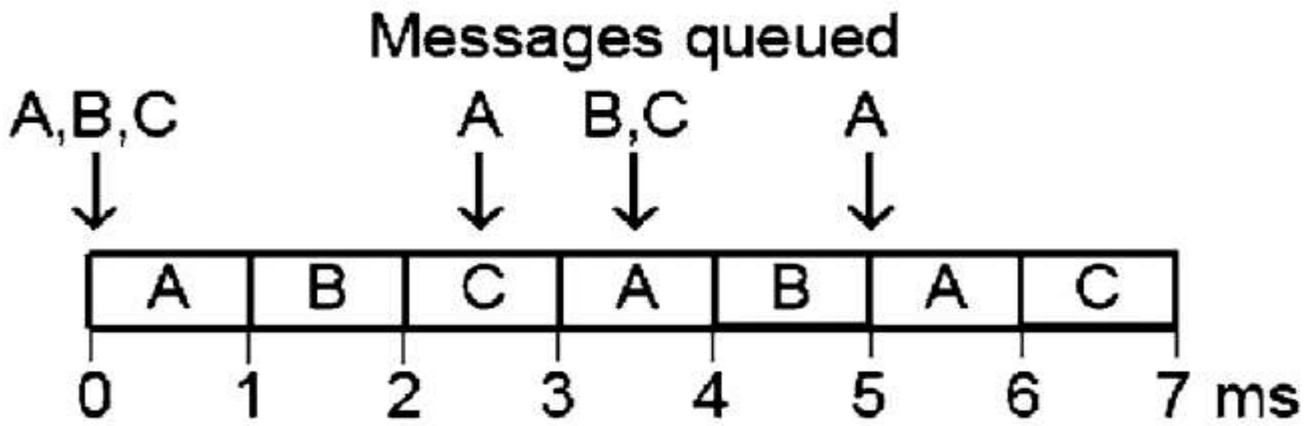

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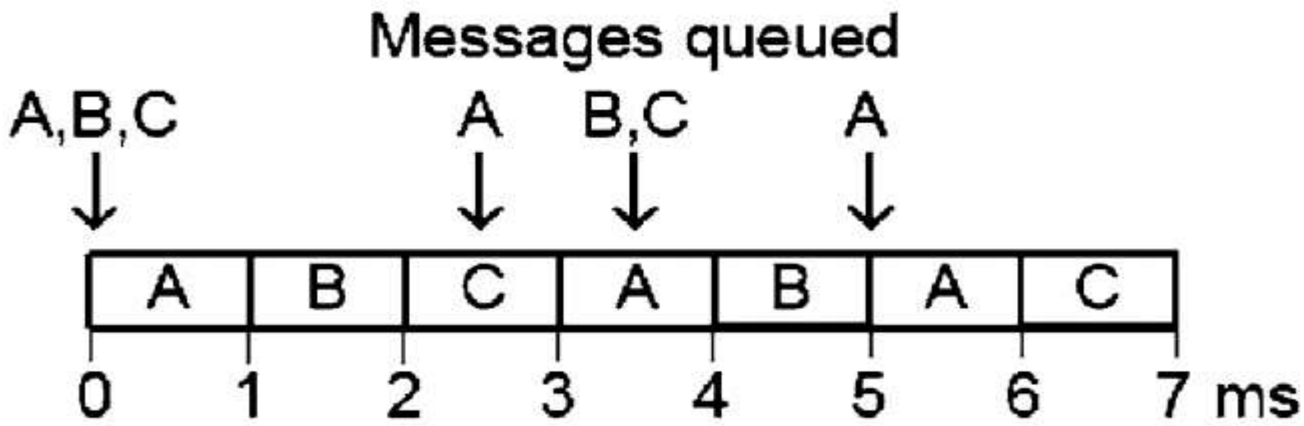

- Worst-case response time of C = 3ms according to Tindells Analysis
- However due to higher priority interference the actual worst-case response time for message C is 3.5 ms, which is greater than its deadline of 3.25 ms.

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  - Schedulable $R_m <= D_m$

Response Time Analysis

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$$B_m = \max_{k \in lp(m)} (C_k)$$

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  - It is a contiguous interval of time during which any message of priority lower than m is unable to start transmission and win arbitration.
  - It ends at the earliest time t^e when the bus becomes idle, ready for the next round of transmission and arbitration, yet there are no messages of priority m or higher waiting to be transmitted that were queued strictly before time t^e

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- Critical Instant: where the maximal busy period begins and message m is queued simultaneously with all higher priority messages

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- The worst case queuing delay is given by

$$w_m = B_m + \sum_{\forall k \in hp(m)} \left\lceil \frac{w_m + J_k + \tau_{\mathrm{bit}}}{T_k} \right\rceil C_k$$

- The worst-case response time of the first Instance of the message in the busy period is given by: $J_m + w_m^{n+1} + C_m$
- The flaw in this analysis is that, given the constraint $D_m \leq T_m$, it implicitly assumes that if message m is schedulable, then the priority level-m busy period will end at or before T_m.

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$$t_m^{n+1} = B_m + \sum_{\forall k \in hep(m)} \left\lceil \frac{t_m^n + J_k}{T_k} \right\rceil C_k$$

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- If $t_m \leq T_m - J_m$, then the busy period ends at or before the second instance of message m is queued.

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- If $t_m \leq T_m - J_m$, then the busy period ends at or before the second instance of message m is queued.
- If $t_m > T_m - J_m$, then the existing analysis may give an optimistic worst-case response time, depending on whether the first, or a subsequent instance of message m has the longest response time.

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- The number of instances Q_m, of message m that become ready for transmission before the end of the busy period is given by

$$Q_m = \left\lceil \frac{t_m + J_m}{T_m} \right\rceil$$

- To determine the worst-case response time of message m, it is necessary to calculate the response time of each of the Q_m instances
- The maximum of these values then gives the worst-case response time.

RTA CONTD…

- The longest time from the start of the busy period to instance q beginning successful transmission is given by

$$w_m^{n+1}(q) = B_m + qC_m + \sum_{\forall k \in hp(m)} \left\lceil \frac{w_m^n + J_k + \tau_{\text{bit}}}{T_k} \right\rceil C_k$$

- The event initiating instance q of the message occurs at time $qT_m - J_m$ so

$$R_m(q) = J_m + w_m(q) - qT_m + C_m$$

RTA CONTD…

- The worst-case response time of message m is therefore

$$R_m = \max_{q=0..Q_m-1} (R_m(q))$$

- If $D_m > T_m$ then CAN controller hardware may need to be capable of buffering more than one instance of a message
- N_m the number of instances of each message that need to be buffered is bounded by

$$N_m = \left\lceil \frac{R_m}{T_m} \right\rceil$$

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a value of $t_3^0 = C_3 = 1$, the recurrence relation given by Eq. (8) iterates as follows: $t_3^1 = 3$, $t_3^2 = 4$, $t_3^3 = 6$, $t_3^4 = 7$, converging as $t_3^5 = t_3^4 = 7$. The length of the busy period is therefore 7.0 ms, and the number of instances of message C that need to be examined is given by Eq. (10):

$$Q_3 = \left\lceil \frac{7.0}{3.5} \right\rceil = 2$$

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$$w_m^{n+1}(q) = B_m + qC_m + \sum_{\forall k \in hp(m)} \left\lceil \frac{w_m^n + J_k + \tau_{\text{bit}}}{T_k} \right\rceil C_k$$

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Calculation of the response time of the first instance proceeds using Eq. (11): $w_3^0(0) = 0$, $w_3^1(0) = 2$, converging as $w_3^2(0) = w_3^1(0) = 2$. Using Eq. (12), we have $R_3(0) = 3$, the same response time calculated by the existing analysis.

Moving on to the second instance, $w_3^0(1) = w_3(0) + C_m = 3$, $w_3^1(1) = 4$, $w_3^2(1) = 5$, $w_3^3(1) = 6$. At this point computation would normally stop as the response time, given by $J_3 + w_3(q) - qT_3 + C_3$, has reached 3.5 ms which is greater than the message deadline. However, if we continue iterating, assuming a longer deadline, then the recurrence relation converges on $w_3^4(1) = w_3^3(1) = 6$ and hence $R_3(1) = 3.5$ ms. The worst-case response time of message C is in fact 3.5 ms, as previously illustrated

RTA CONTD…

- Sufficient Schedulability Tests
- The schedulability tests given in this section are only applicable given the constraint that message deadlines do not exceed their periods.
- Assuming that this first instance completes transmission before its deadline and hence before the end of its period, then we have two possibilities to consider.
  - Busy period ends before the next instance of message m is queued
  - Busy period continues beyond the time at which the next instance of message m is queued

CONTD…

- $s_{m,q}$ and $s_{m,q+1}$, at which two arbitrary but consecutive instances q and q+1, of message m start transmission.
- An upper bound on the length of the time interval $[s_{m,q}, s_{m,q+1})$ can be found by making the potentially pessimistic assumption that all higher priority messages are queued just as instance q starts transmission

$$w_m^{n+1} = C_m + \sum_{\forall k \in hp(m)} \left\lceil \frac{w_m^n + J_k + \tau_{\text{bit}}}{T_k} \right\rceil C_k$$

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- Given the assumption that the first q instances in the busy period are schedulable, and the constraint that $D_m \leq T_m$, then the start (and end) of transmission of the qth instance must happen before the end of its period, and hence before the (q+1)th instance is queued.
- The queuing delay for the (q+1)th instance, as measured from the time at which it is queued to the start of its transmission, is less than the length of the interval $[s_{m,q}, s_{m,q+1})$.

CONTD…

- Intuitively, the second and subsequence instances of message m in the busy period are subject to blocking, of at most C_m, due to the previous instance of the same message.

$$w_m^{n+1} = \max(B_m, C_m) + \sum_{\forall k \in hp(m)} \left\lceil \frac{w_m^n + J_k + \tau_{\text{bit}}}{T_k} \right\rceil C_k$$

- An instance of message m can be subject to blocking; either of B_m, due to non-preemptive transmission of lower priority messages; or of Cm, due to the non-pre-emptive transmission of the previous instance of message m itself.

CONTD…

- Further Simplifying

$$w_m^{n+1} = B^{\mathrm{MAX}} + \sum_{\forall k \in hp(m)} \left\lceil \frac{w_m^n + J_k + \tau_{\mathrm{bit}}}{T_k} \right\rceil C_k$$

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- The worst-case impact of a single bit error is to cause transmission of an additional 31 bits of error recovery overhead plus re-transmission of the affected message.
- Only errors affecting message m or higher priority messages can delay message m from being successfully transmitted

$$E_m(t) = \left(31\tau_{\text{bit}} + \max_{k \in hep(m)} (C_k)\right) F(t)$$

CONTD…

- Busy Period

- Worst Case Response Time

CONTD...

- Busy Period

$$t_m^{n+1} = E_m\left(t_m^n\right) + B_m + \sum_{\forall k \in hep(m)} \left\lceil \frac{t_m^n + J_k}{T_k} \right\rceil C_k$$

- Worst Case Response Time

CONTD…

- Busy Period

$$t_m^{n+1} = E_m\left(t_m^n\right) + B_m + \sum_{\forall k \in hep(m)} \left\lceil \frac{t_m^n + J_k}{T_k} \right\rceil C_k$$

- Worst Case Response Time

$$w_m^{n+1}(q) = E_m\left(w_m^n + C_m\right) + B_m + qC_m + \sum_{\forall k \in hp(m)} \left\lceil \frac{w_m^n + J_k + \tau_{\text{bit}}}{T_k} \right\rceil C_k$$

CONCLUSIONS FROM DISCUSSION

- Any message from the lowest priority to the 3rd highest priority in a set of 3 or more messages can be given an optimistic response time and therefore a faulty guarantee by the existing analysis
- The above statement is true even for low utilization levels.
- If the existing analysis showed that every message was schedulable in the presence of any reasonable error model, with $F(t) \geq 1$, then, despite the flaw in the existing analysis, every message is actually guaranteed to be schedulable when no errors are present.

CONTD…

- The omission of a single maximum length message of arbitrary priority provides sufficient reduction in interference/blocking to ensure that the flaw in the existing analysis cannot lead to any of the remaining messages missing their deadlines.
- If $B_m \geq C_m$, then the first instance of message m is guaranteed to have a response time at least as long as subsequent ones.

Priority Assignment Policies

PRIORITY ASSIGNMENT POLICIES

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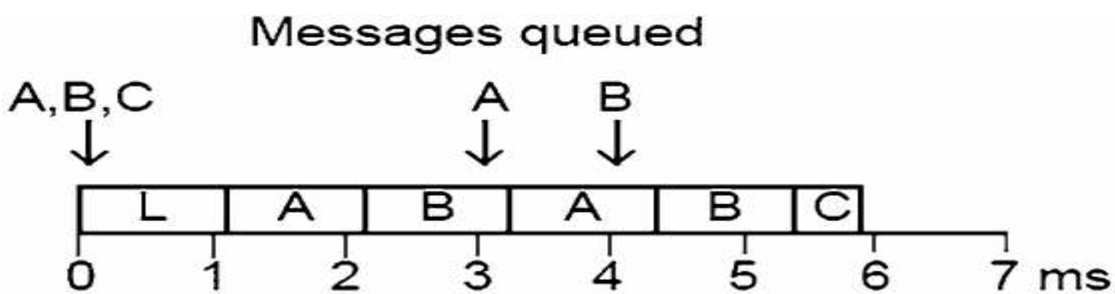
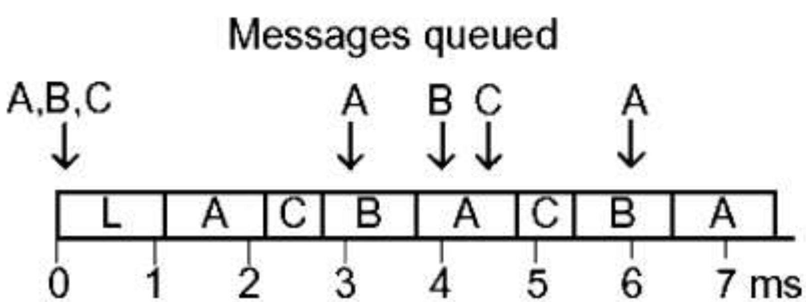


CONTD…

- If we use the priority ordering A, C, B then the worst-case response times of the messages are: RA=2.16 ms, RC=2.68 ms and RB=3.76 ms



OPTIMAL PRIORITY ASSIGNMENT

```
Optimal Priority Assignment Algorithm

for each priority level, lowest first
{
   for each unassigned message m
   {
       if m is schedulable at this priority
       {
           assign m this priority
           break (continue outer loop)
       }
   }
    return unschedulable
}
return schedulable
```

CONCLUSION

1. The existing analysis can provide optimistic worst-case response times for messages from the 3rd highest priority to the lowest priority.
2. The existing analysis can lead to broken guarantees and hence deadline misses in systems with low bus utilisation.
3. Where an error model has been considered, the flaw in the existing analysis is not sufficient to lead to CAN configurations that will result in missed deadlines when no errors are present on the bus. The desired robustness to errors may not however be achieved.
4. The omission of a single maximum length diagnostic message, accounted for by the existing analysis, reduces interference/blocking enough to ensure that the deadlines of all the remaining messages are met during normal operation.
5. Despite its flaws, the existing analysis gives the correct response time for any message where there is at least one lower priority message with the same or longer transmission time/message length.