A Practical Message ID Assignment Policy for Controller Area Network that Maximizes Extensibility

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Outline

- Motivation: Automotive System Design
- Controller Area Network (CAN) Protocol
- Problem Statement

- Measuring Extensibility

- ID-Assignment for Max. Extensibility

- Evaluation: Case Study
  (Multiple System Upgrades)
System & Responsibilities

- many ECUs with dedicated functionality; developed by Tier1-suppliers
- data-exchange between ECUs via network (CAN, LIN, FlexRay, Ethernet)
- network-design & system integration by OEM

Incremental System Design & System-Upgrade

- new functions added later (e.g. next generation version of car)
- new functions = new ECUs → new CAN messages for data-exchange
- new CAN messages must be integrated into existing CAN configuration
  - assign IDs to new CAN messages, without changing IDs of existing messages (i.e. backwards compatibility)
  - ensure all messages meet their deadlines (i.e. schedulability)
  - ensure future CAN messages can also be added later (i.e. extensibility)
Controller Area Network (CAN)

- asynchronous, multi-master, broadcast, serial communications bus
- each message uniquely identified by its ID, which also determines priority during arbitration phase

<table>
<thead>
<tr>
<th>ID</th>
<th>payload</th>
</tr>
</thead>
</table>

payload: 0…8 bytes
ID: 11 or 29 bits

- once idle, priority-based bus arbitration; highest priority (i.e. lowest ID) wins
- non-preemptive transmission of message

- schedulability analysis (response time analysis)

\[
    R_m = J_m + w_m + C_m \\
    R_m \leq D_m \\
    C_{m}^{11} = (55 + 10 \cdot s_m) \cdot \tau_{bit} \\
    C_{m}^{29} = (80 + 10 \cdot s_m) \cdot \tau_{bit} \\
    \]

\[
    w_{m+1} = B + \sum_{\forall k \in h_{p}(m)} \frac{w_{m} + J_{k} + \tau_{bit}}{T_{k}} \cdot C_{k} \\
    B = \max \{C_{m}\} 
\]

Message specification:
- s: payload size
- T: period
- D: deadline
- ID-format (11 or 29 bit)
Problem Statement

Initial System (car platform)
- given a set of message (without IDs)
- assign IDs to messages, so all messages meet their deadline
- assign IDs, so that system is extensible (i.e. system upgrades are possible)

Upgrade System (car model, e.g. Audi A3, VW Golf 4)
- given a set of messages (with IDs), and a set of new messages (without IDs)
- assign IDs to new messages, so that all messages meet their deadlines
- assign IDs, so that system is backwards compatible (i.e. existing IDs are not changed)
- assign IDs, so that system is extensible (i.e. system upgrades are possible)

Prior Work
- Davis et al. “On priority assignment for controller area network when some message identifiers are fixed”, RTNS 2015
- extensibility remains an open issue
How to measure extensibility of a CAN configuration?
- assessment method

How to assign IDs to CAN messages, such that extensibility is maximized at each stage along an upgrade path, without prior knowledge of the upgrades?
- ID assignment policy
Measuring Extensibility of given ID Assignment
Extensibility

Engineer’s View

- How much additional payload data can be transmitted?
- How many additional messages can be transmitted?

“Extensibility is the ability to add new messages to the system, while meeting all deadlines, without changing the IDs of existing messages.”

Related Metrics in Literature (Robustness & Sensitivity)

- breakdown utilization (decrease baud rate until just schedulable)
- robustness (add extra interference until just schedulable)
- sensitivity (increase C or decrease D until just schedulable)

- are sensitive to priority ordering only, but not to ID assignment
Extensibility

Priority Ordering vs. ID Assignment

- Priority Ordering: relative difference of priorities (e.g. \( m_1 > m_2 \))
- ID Assignment: ID values

<table>
<thead>
<tr>
<th>Message</th>
<th>D [ms]</th>
<th>Priority-Ordering</th>
<th>ID (v1)</th>
<th>ID (v2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>10</td>
<td>High</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>m2</td>
<td>100</td>
<td>Medium</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>m3</td>
<td>1000</td>
<td>Low</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>m4</td>
<td>20</td>
<td>?</td>
<td>?</td>
<td>3</td>
</tr>
</tbody>
</table>

- ID (v1) and ID (v2) have same priority ordering, but different IDs
- ID (v2) is better than ID (v1) ... because this system is more extensible
Measuring Extensibility

Metric (engineer’s view)

\[
\text{ext}_{\text{payload}} = \frac{\text{added payload}}{\text{period}} \\
\text{ext}_{\text{messages}} = \frac{\text{added messages}}{\text{period}}
\]

Assessment Method

- adding N synthetic messages
- defined size, period, deadline
- ID → [Davis et al., RTNS 2015]

Algorithm 1: Extensibility Assessment

1. for each \( T \) do
2. \( D = T; \)
3. \( n_{\text{upper}} = 2032; \)
4. \( n_{\text{lower}} = 0; \)
5. repeat
6. \( n = (n_{\text{upper}} + n_{\text{lower}})/2; \)
7. \( \text{newMessages} = \text{generateMessages}(n, \text{pay}, T, D); \)
8. \( \text{priorityAssignment}(	ext{messages}, \text{newMessages}); \)
9. if \( \text{schedulable} == \text{true} \) then
10. \( n_{\text{lower}} = n; \)
11. else
12. \( n_{\text{upper}} = n; \)
13. end
14. until \( \text{schedulable} == \text{true} \) and \( (n_{\text{upper}} - n_{\text{lower}}) \leq 1; \)
15. \( \text{pay}_{\text{last}} = \text{addLastSmallMessage}(T, D); \)
16. \( \text{ext} = (n \cdot \text{pay} + \text{pay}_{\text{last}})/T; \)
17. end

Output: extensibility for each period

s = 8 byte
\( D = T \)
\( T = \{1,2,5,10,20,50,100,200,500,1000\} \text{ ms} \)
Extensibility Metric … Does it work?

- SAE benchmark
  - 17 messages
  - \( s = 1\ldots 6 \) bytes
  - \( T = 5\ldots 1000 \) ms
  - 44% utilization (250 kb/s)

- Different ID assignments
  - DM at lowest IDs
  - DM at highest IDs
  - DM at middle IDs
  - DM evenly spaces IDs
  - grouped by ECU
  - random

<table>
<thead>
<tr>
<th>Message</th>
<th>Format</th>
<th>Size [byte]</th>
<th>T [ms]</th>
<th>D [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>m01</td>
<td>Standard</td>
<td>1</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>m02</td>
<td>Standard</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>m03</td>
<td>Standard</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>m04</td>
<td>Standard</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>m05</td>
<td>Standard</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>m06</td>
<td>Standard</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>m07</td>
<td>Standard</td>
<td>6</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>m08</td>
<td>Standard</td>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>m09</td>
<td>Standard</td>
<td>2</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>m10</td>
<td>Standard</td>
<td>3</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>m11</td>
<td>Standard</td>
<td>1</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>m12</td>
<td>Standard</td>
<td>4</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>m13</td>
<td>Standard</td>
<td>1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>m14</td>
<td>Standard</td>
<td>1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>m15</td>
<td>Standard</td>
<td>3</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>m16</td>
<td>Standard</td>
<td>1</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>m17</td>
<td>Standard</td>
<td>1</td>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>
DM at lowest IDs

high priority
(low ID)

low priority
(high ID)

“OR syntax”
DM at highest IDs

- High priority (low ID)
- Low priority (high ID)
DM at middle IDs

low priority (high ID)

high priority (low ID)
DM evenly spaced IDs

![Graph showing payload bytes per ms vs. T [ms] for high and low priority (low ID) with DM evenly spaced IDs.](image)

![Graph showing messages vs. T [ms] for low priority (high ID) with DM evenly spaced IDs.](image)
by ECU / random

high priority (low ID)

low priority (high ID)
Extensibility Metric … Conclusion

- state-of-the-art metrics cannot measure extensibility

- proposed metric & assessment methods works well
- gives detailed insight “why” CAN configuration is extensible

<table>
<thead>
<tr>
<th>ID assignment</th>
<th>min baudrate [bits/sec]</th>
<th>interference [bit]</th>
<th>ΔC</th>
<th>ΔD</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM at lowest IDs</td>
<td>123k</td>
<td>715</td>
<td>2.139</td>
<td>0.428</td>
</tr>
<tr>
<td>DM at highest IDs</td>
<td>123k</td>
<td>715</td>
<td>2.139</td>
<td>0.428</td>
</tr>
<tr>
<td>DM at middle IDs</td>
<td>123k</td>
<td>715</td>
<td>2.139</td>
<td>0.428</td>
</tr>
<tr>
<td>DM evenly spaced IDs</td>
<td>123k</td>
<td>715</td>
<td>2.139</td>
<td>0.428</td>
</tr>
<tr>
<td>By ECU</td>
<td>227k</td>
<td>115</td>
<td>1.112</td>
<td>0.908</td>
</tr>
<tr>
<td>Random</td>
<td>241k</td>
<td>50</td>
<td>1.046</td>
<td>0.960</td>
</tr>
</tbody>
</table>
ID Assignment Policy
which Maximizes Extensibility
What influences Extensibility?

Insight … so far

- Priority ordering impacts schedulability and extensibility (tight deadline messages)

- “middle IDs” and “evenly spaced” offer good overall extensibility (free IDs across ID range)

Finding Limitations of Extensibility

- apply extensibility metric to “empty system” → max. extensibility
- different typical baud rates (125k, 250k, 500k, 1M) used in automotive
Extensibility Limitations

Limitations

- number of schedulable messages exceeds number of available IDs (500k + 1M, and long deadline)
- schedulability (for tight deadlines)

Schedulability

- few messages with tight deadline
- some messages with medium deadline
- many messages with long deadline
ID Assignment Policy for Max. Extensibility

**Policy**

- split ID range into several ID-bands
- each ID-band for dedicated deadline
- ID-bands order by DM
- width of ID-band derived from “max. number of schedulable messages per deadline”

- each message is put into ID-band according to its deadline (high to low priority)

- “Deadline monotonic, increasing Width, ID-Bands” (DWB)

---

Algorithm 2: DWB ID-Assignment

```plaintext
Input: oldMessages /* messages with fixed IDs */
Input: newMessages /* messages without ID yet */
1 /* Phase 1: ID-Bands */;
2 setup ID-bands according to DM and increasing width;
3 /* Phase 2: ID-Assignment */;
4 for each message in newMessages do
5     choose ID-band according to message's deadline;
6     assign smallest free ID inside ID-band to message
7 end
Output: ID-Assignment
```
“best” policies from previous experiments (extensibility metric)
Effectiveness of DWB

DWB policy outperforms both

![Graph showing payload-bytes per ms against T [ms] for different strategies: DM at middle IDs, DM even spacing, and DWB (adjusted).]
Evaluation of ID-Assignment Policy
(Multiple System Upgrades)
Evaluation of ID-Assignment Policy

Subsequent System Upgrades

- initial system: DWB
- upgrade #1: DWB or RPA
- upgrade #2: DWB or RPA

<table>
<thead>
<tr>
<th>System</th>
<th>Messages</th>
<th>Utilization [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>17</td>
<td>44</td>
</tr>
<tr>
<td>Upgrade #1</td>
<td>+7</td>
<td>60 (44+16)</td>
</tr>
<tr>
<td>Upgrade #2</td>
<td>+7</td>
<td>76 (60+16)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>Messages</th>
<th>Utilization [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>Upgrade #1</td>
<td>+22</td>
<td>40 (20+20)</td>
</tr>
<tr>
<td>Upgrade #2</td>
<td>+18</td>
<td>60 (40+20)</td>
</tr>
</tbody>
</table>

DWB: Deadline Width Band
RPA: Robust Priority Assignment
[Davis et al., RTNS 2015]

paper (SAE benchmark)

technical report appendix
Results: SAE Benchmark

initial (DWB)
Results: SAE Benchmark

upgrade #1 (DWB)
upgrade #2 (DWB)
Results: SAE Benchmark

upgrade #1 (RPA)
Results: SAE Benchmark

upgrade #2 (RPA)
Results: Larger Case Study

- 69 messages (technical report appendix)
Conclusion & Future Work

Conclusion

- Assessment method for measuring extensibility of CAN configurations provides insight into “why” and “how much” system is extensible
- ID-assignment policy which maximized extensibility (initial system & subsequent system upgrades)
  - “weakly optimal” → proof see paper
- provides upgrade path for “incremental system design” (automotive)

Future Work

- Extensible ID assignment, starting from arbitrary initial ID assignment
- setting ID-band width according to statistical data (from real systems)
- refinements (release jitter, offsets, CAN-FD)
Questions & Discussions
Setting Width of ID-Bands

- ID-band width = max. number of schedulable messages for each deadline
- works for 125 kb/s systems

- doesn’t work for 250 kb/s (or higher), due to limited number of IDs

Adjusting ID-Band Width

- width = max (for tight deadlines)
- width < max (for long deadlines) (logarithmic, “heuristic”)
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