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

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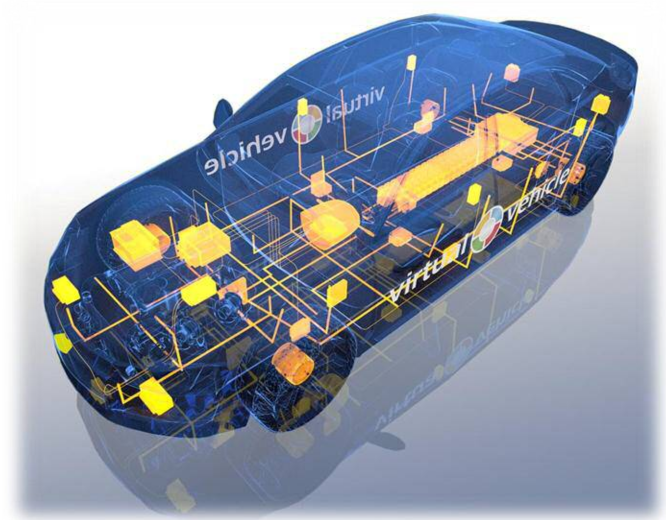
Outline

- Motivation: Automotive System Design
- Controller Area Network (CAN) Protocol
- Problem Statement
- Measuring Extensibility
- ID-Assignment for Max. Extensibility
- Evaluation: Case Study
  (Multiple System Upgrades)

Automotive System Design

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

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)

$$R_m = J_m + w_m + C_m$$

$$R_m \leq D_m$$

$$C_m^{11} = (55 + 10 \cdot s_m) \cdot \tau_{bit}$$

$$C_m^{29} = (80 + 10 \cdot s_m) \cdot \tau_{bit}$$

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

$$B = \max\{C_m\}$$

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

Research Questions & Contributions

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. m1 > m2)
- ID Assignment: ID values

Message	D [ms]	Priority-Ordering	ID (v1)	ID (v2)
m1	10	High	0	0
m2	100	Medium	1	10
m3	1000	Low	2	20
m4	20		?	3

- 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)

$$ext_{payload} = \frac{added\ payload}{period}$$

$$ext_{messages} = \frac{added\ messages}{period}$$

s = 8 byte
D = T
T = {1,2,5,10,20,50,100,200,500,1000} ms

Assessment Method

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

Algorithm 1: Extensibility Assessment

```
Input: messages              /* messages with fixed IDs */
Input: pay                   /* size of message payload */
Input: {T_1, ..., T_t}       /* set of pre-defined periods */
for each T do
    D = T;
    n_upper = 2032;
    n_lower = 0;
    repeat
        n = (n_upper + n_lower)/2;
        newMessages = generateMessages(n, pay, T, D);
        priorityAssignment(messages, newMessages);
        if schedulable == true then
            n_lower = n;
        else
            n_upper = n;
        end
    until schedulable == true and (n_upper − n_lower) ≤ 1;
    pay_last = addLastSmallMessage(T, D);
    ext = (n · pay + pay_last)/T;
end
Output: extensibility for each period
```

Extensibility Metric … Does it work?

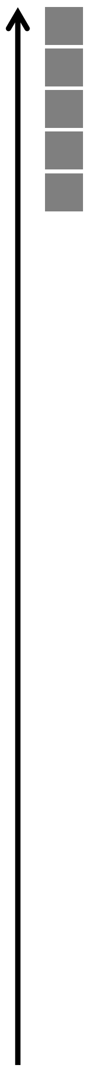
- SAE benchmark
  - 17 messages
  - s = 1…6 bytes
  - T = 5…1000 ms
  - 44% utilization (250 kb/s)

Message	Format	Size [byte]	T [ms]	D [ms]
m01	Standard	1	50	5
m02	Standard	2	5	5
m03	Standard	1	5	5
m04	Standard	2	5	5
m05	Standard	1	5	5
m06	Standard	2	5	5
m07	Standard	6	10	10
m08	Standard	1	10	10
m09	Standard	2	10	10
m10	Standard	3	10	10
m11	Standard	1	50	50
m12	Standard	4	100	100
m13	Standard	1	100	100
m14	Standard	1	100	100
m15	Standard	3	1000	1000
m16	Standard	1	1000	1000
m17	Standard	1	1000	1000

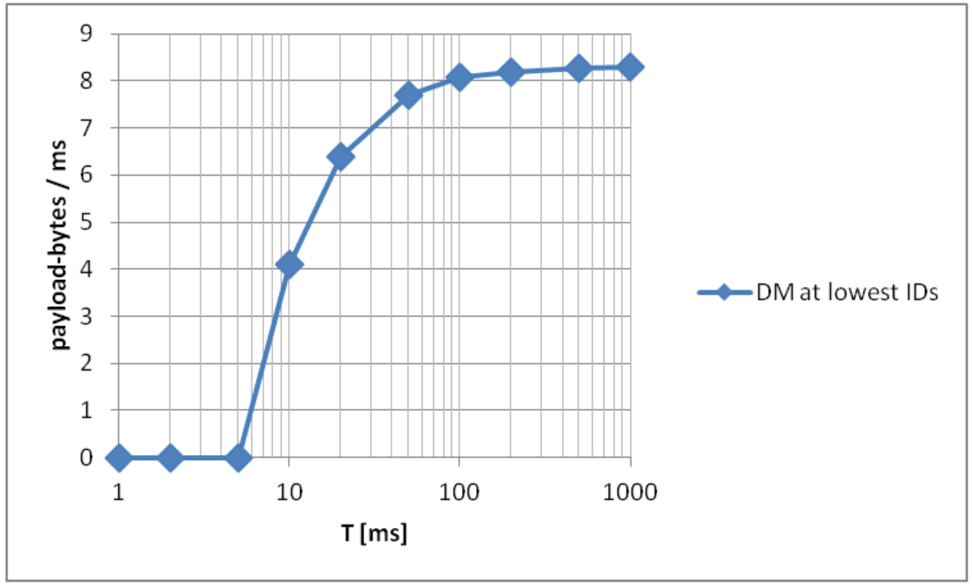
- Different ID assignments
  - DM at lowest IDs
  - DM at highest IDs
  - DM at middle IDs
  - DM evenly spaces IDs
  - grouped by ECU
  - random

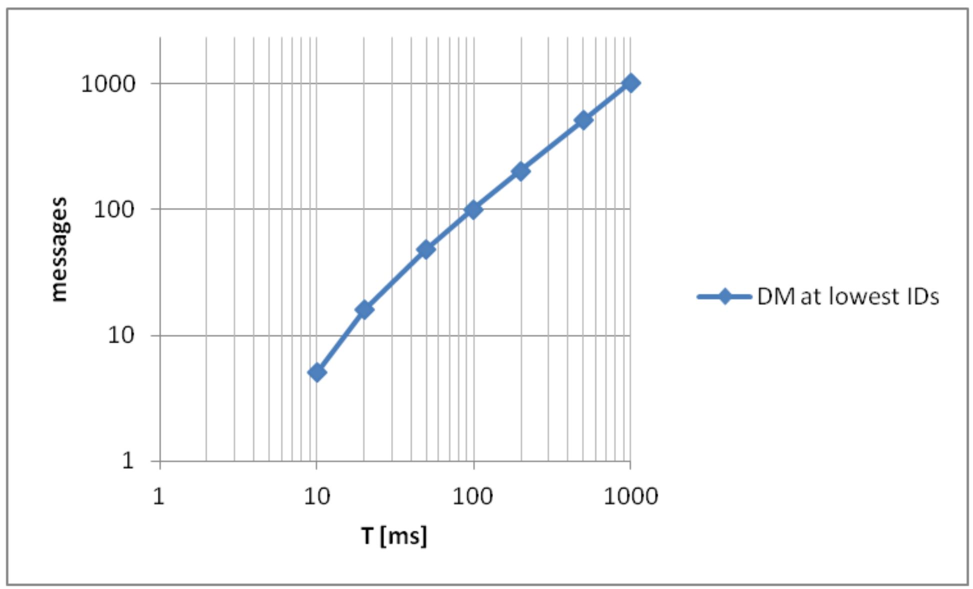
DM at lowest IDs

high priority
(low ID)



low priority
(high ID)



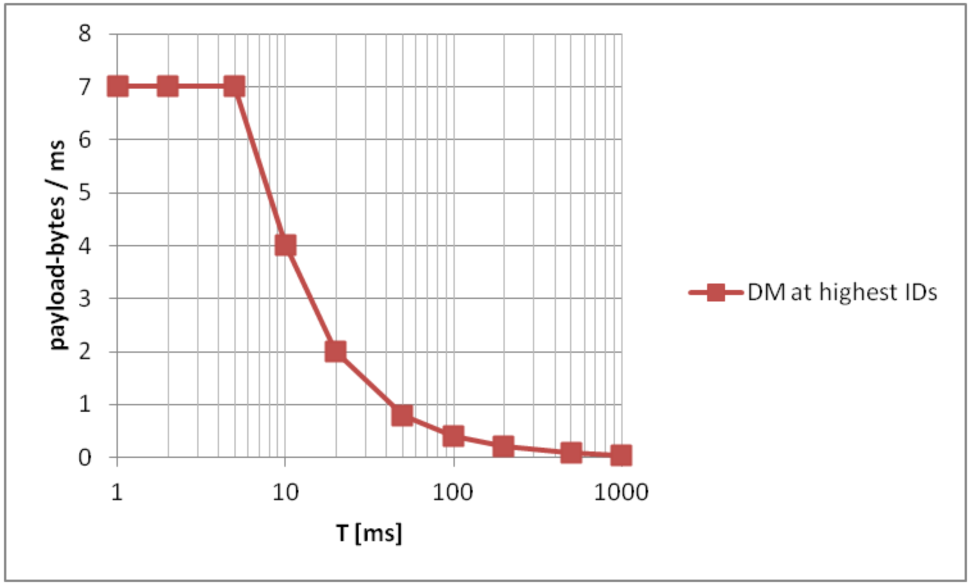


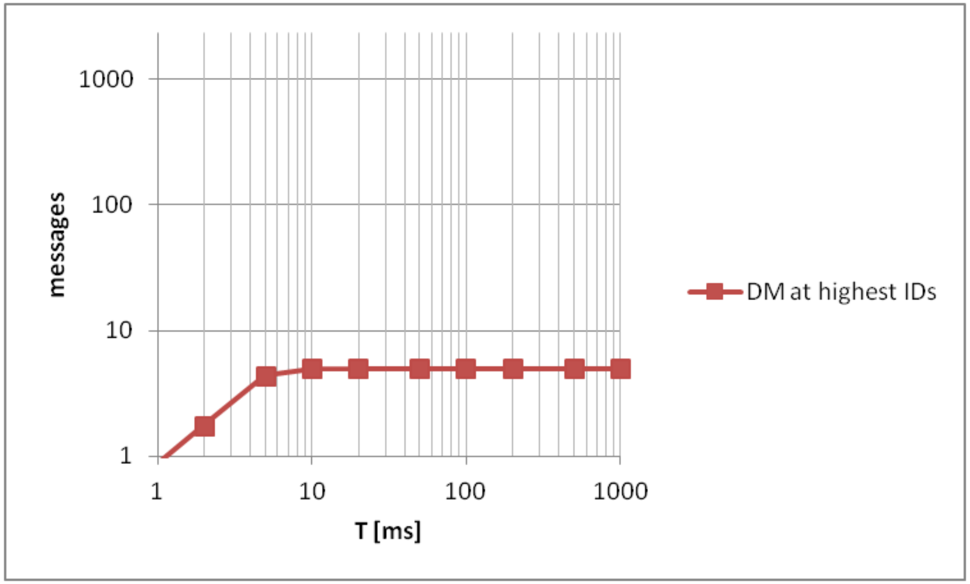
"OR syntax"

DM at highest IDs

high priority
(low ID)

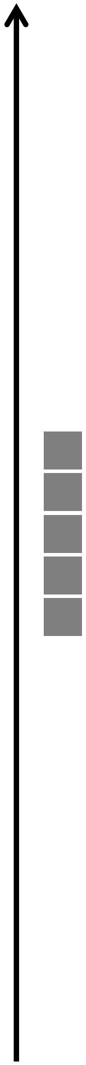
low priority
(high ID)



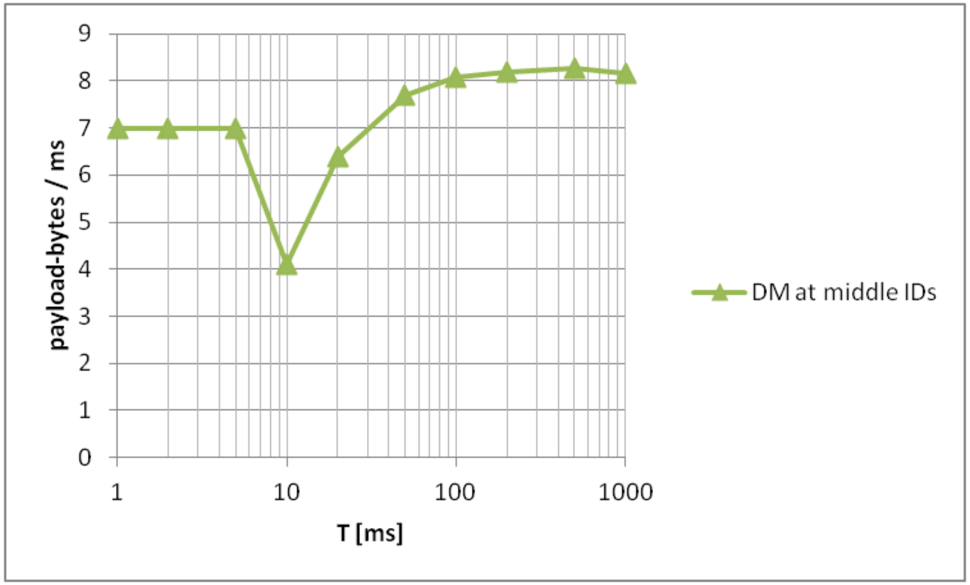


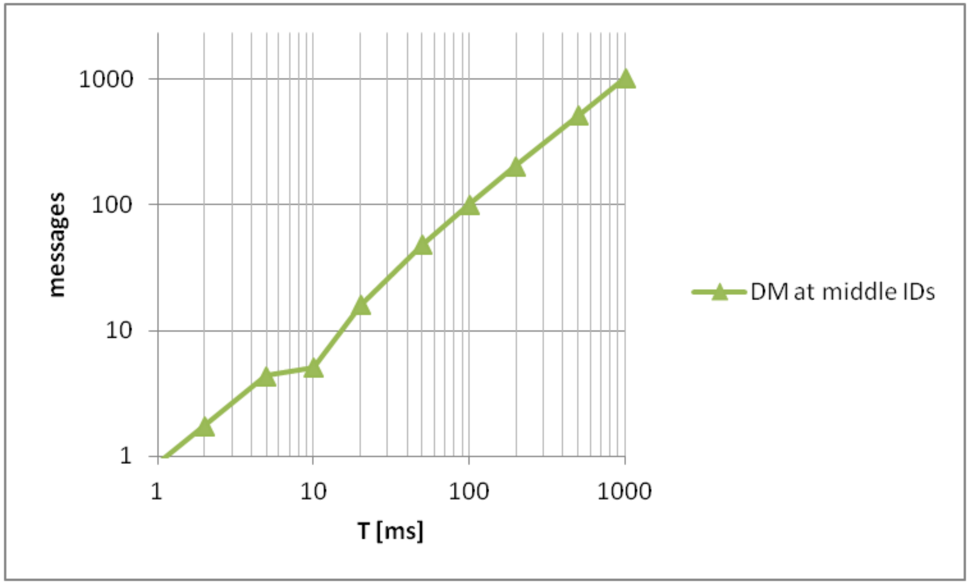
DM at middle IDs

high priority
(low ID)

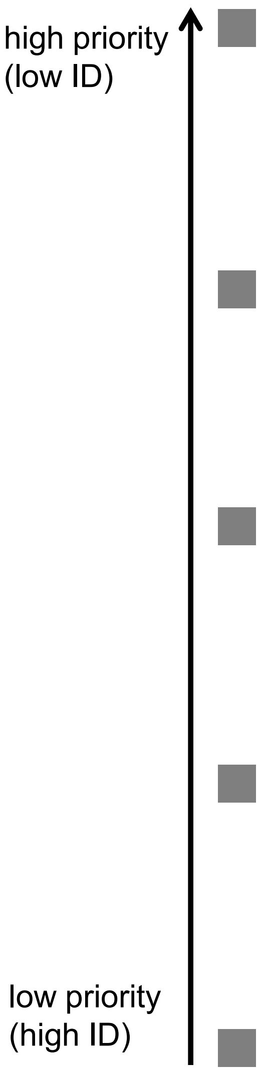


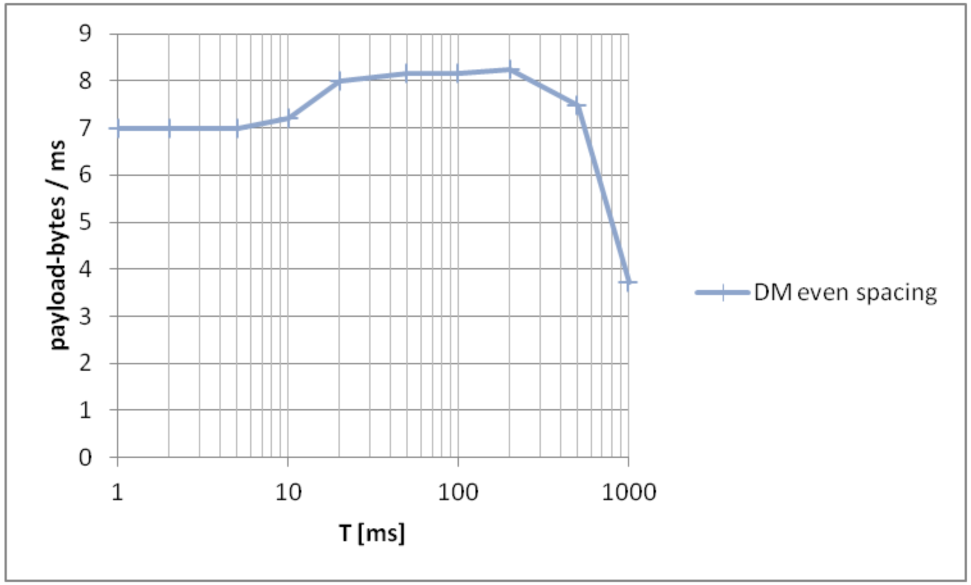
low priority
(high ID)

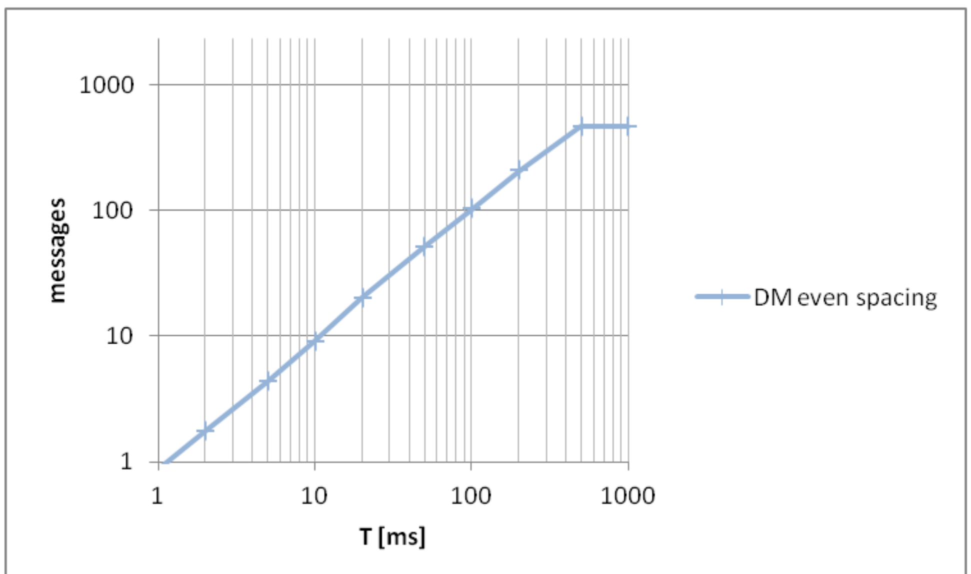




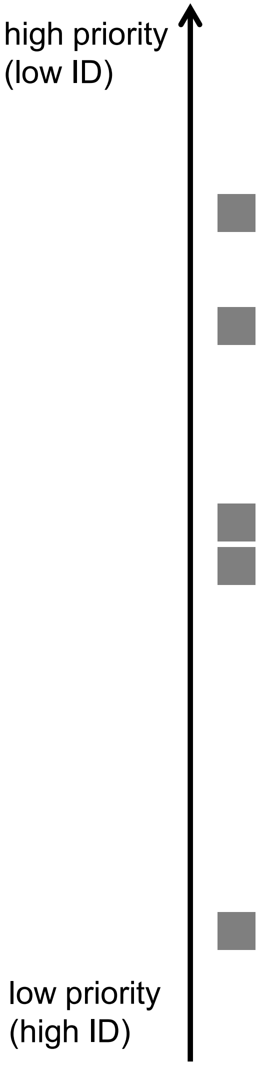
DM evenly spaced IDs

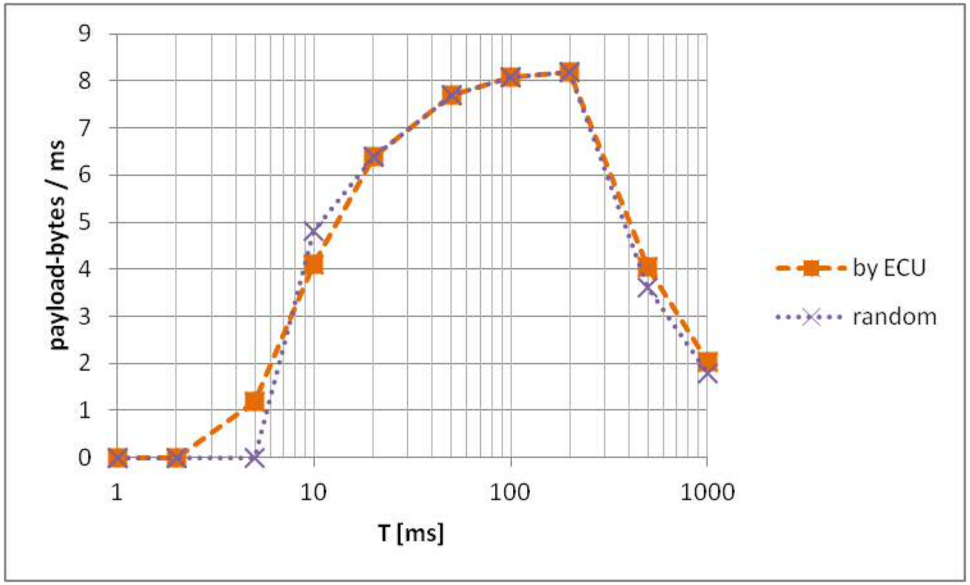


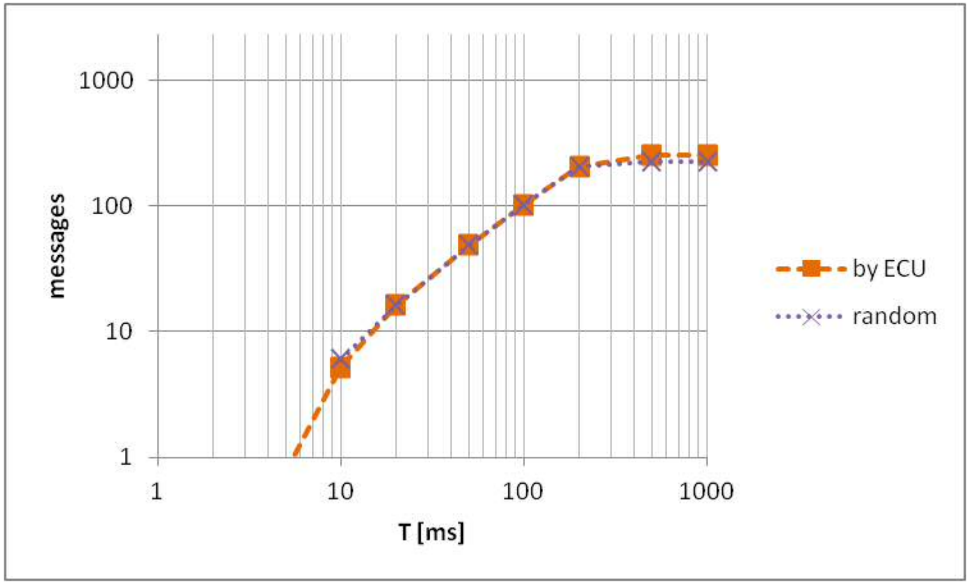




by ECU / random







Extensibility Metric … Conclusion

ID assignment	min baudrate [bits/sec]	interference [bit]	Δ_C	Δ_D
DM at lowest IDs	123k	715	2.139	0.428
DM at highest IDs	123k	715	2.139	0.428
DM at middle IDs	123k	715	2.139	0.428
DM evenly spaced IDs	123k	715	2.139	0.428
By ECU	227k	115	1.112	0.908
Random	241k	50	1.046	0.960

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

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

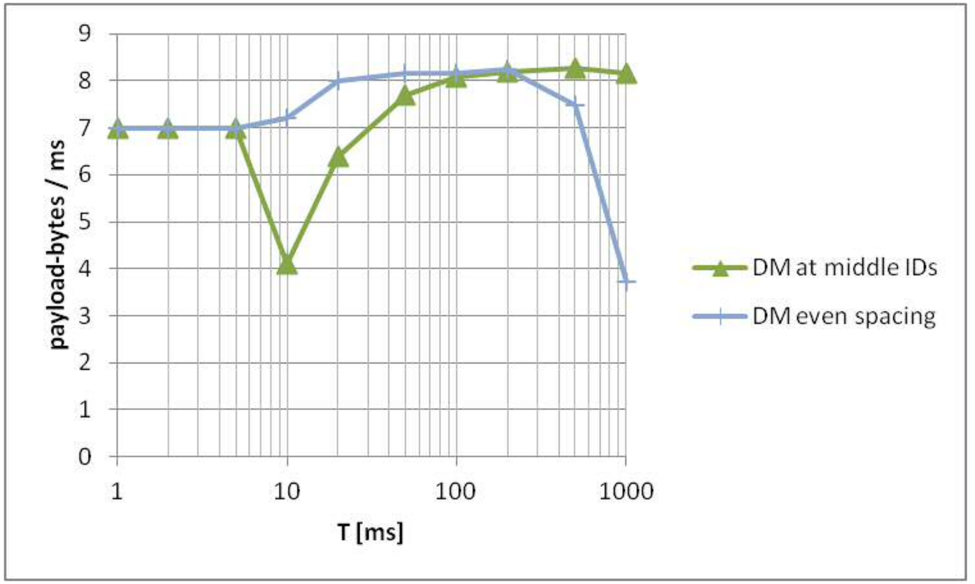
ID Assignment Policy which Maximizes Extensibility

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)



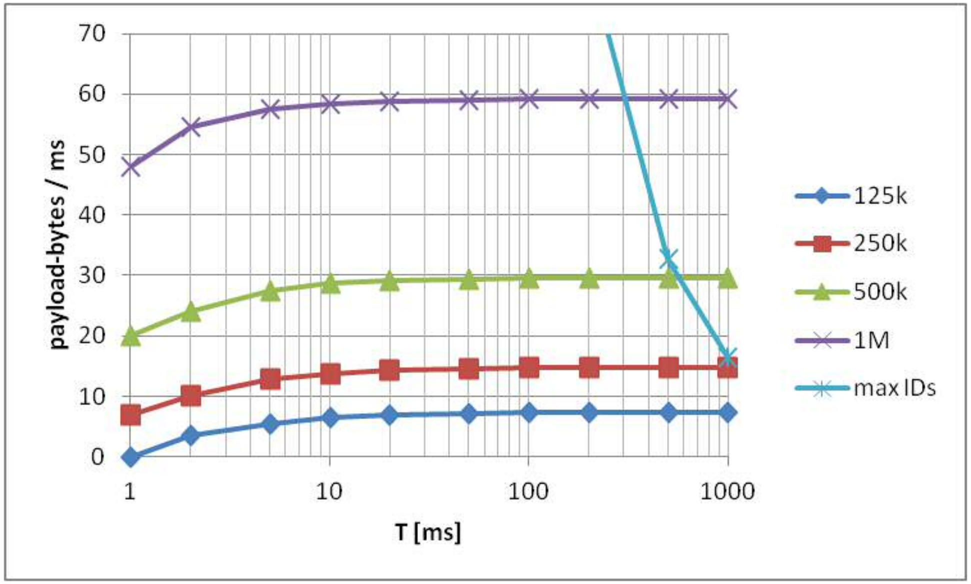
Finding Limitations of Extensibility

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

Extensibility Limitations

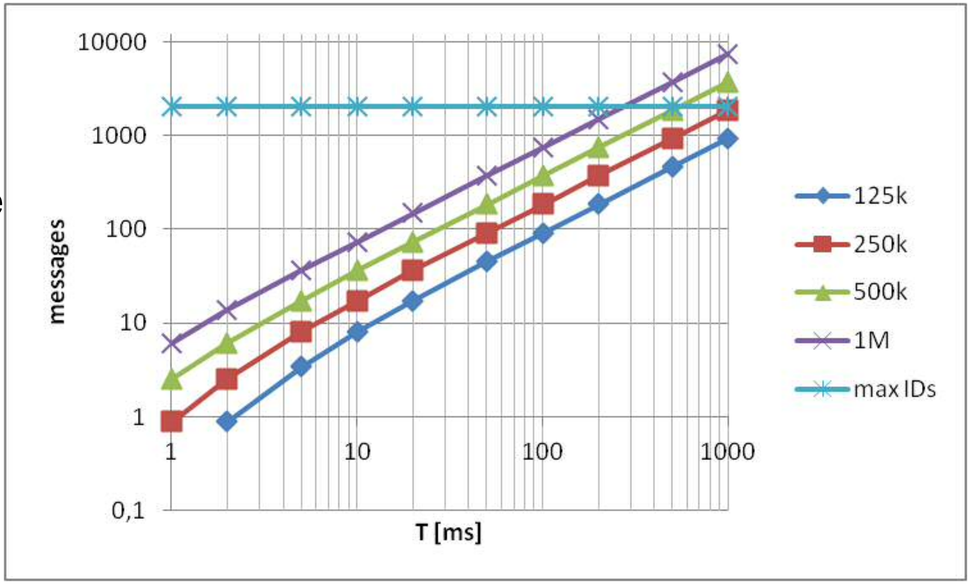
Limitations

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

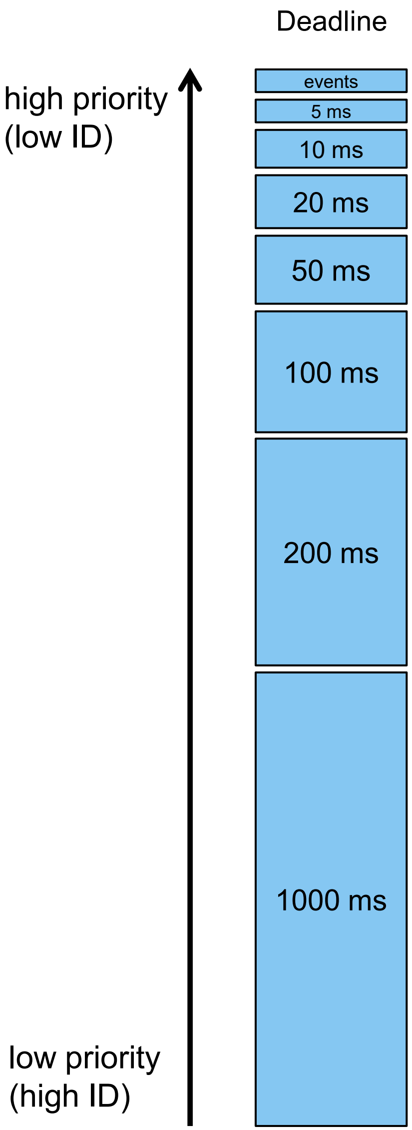


Schedulability

- 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"

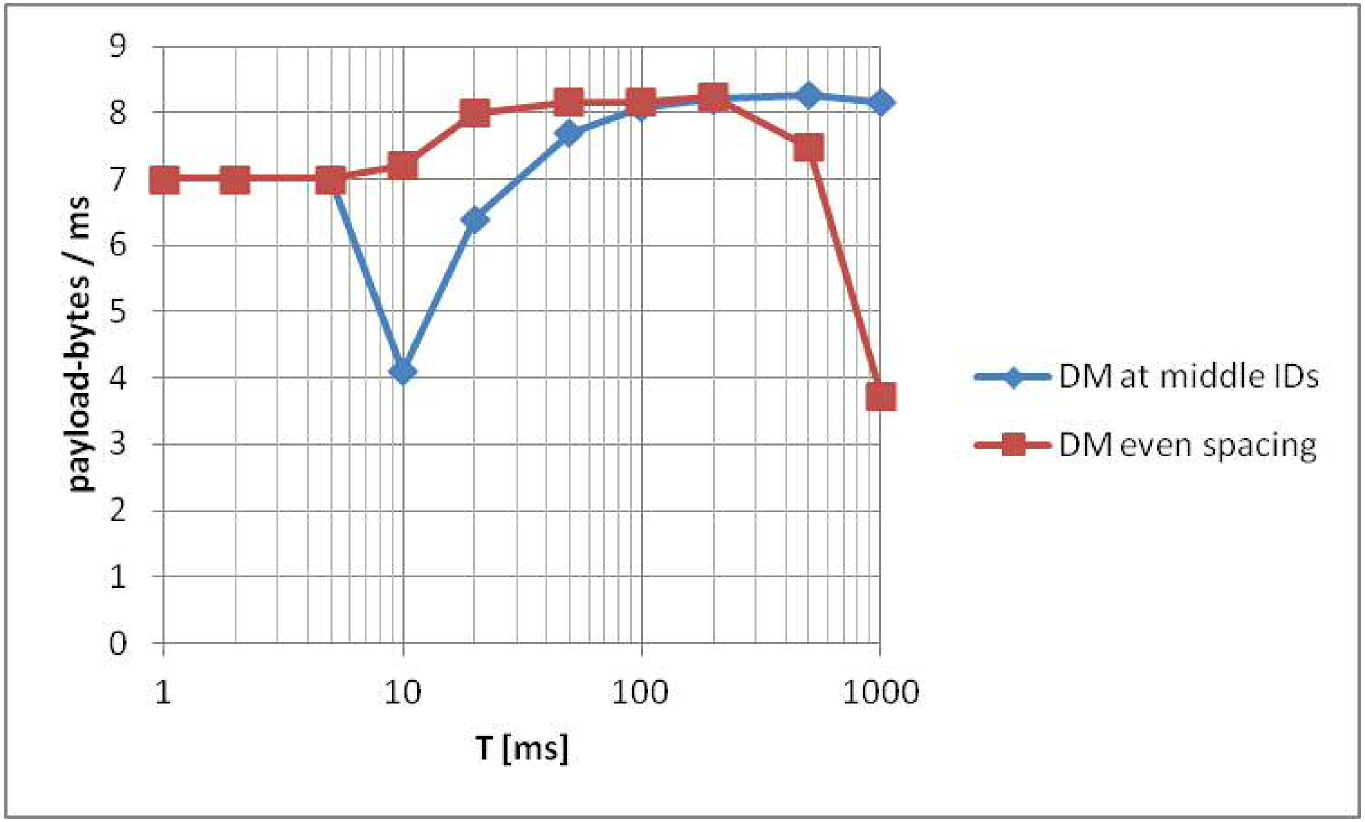
- each message is put into ID-band according to its deadline (high to low priority)

- "Deadline monotonic, increasing Width, ID-Bands" (DWB)

```
Algorithm 2: DWB ID-Assignment
Input: oldMessages              /* messages with fixed IDs */
Input: newMessages              /* messages without ID yet */
/** Phase 1: ID-Bands **/;
setup ID-bands according to DM and increasing width;
/** Phase 2: ID-Assignment **/;
for each message in newMessages do
    choose ID-band according to message's deadline;
    assign smallest free ID inside ID-band to message
end
Output: ID-Assignment
```

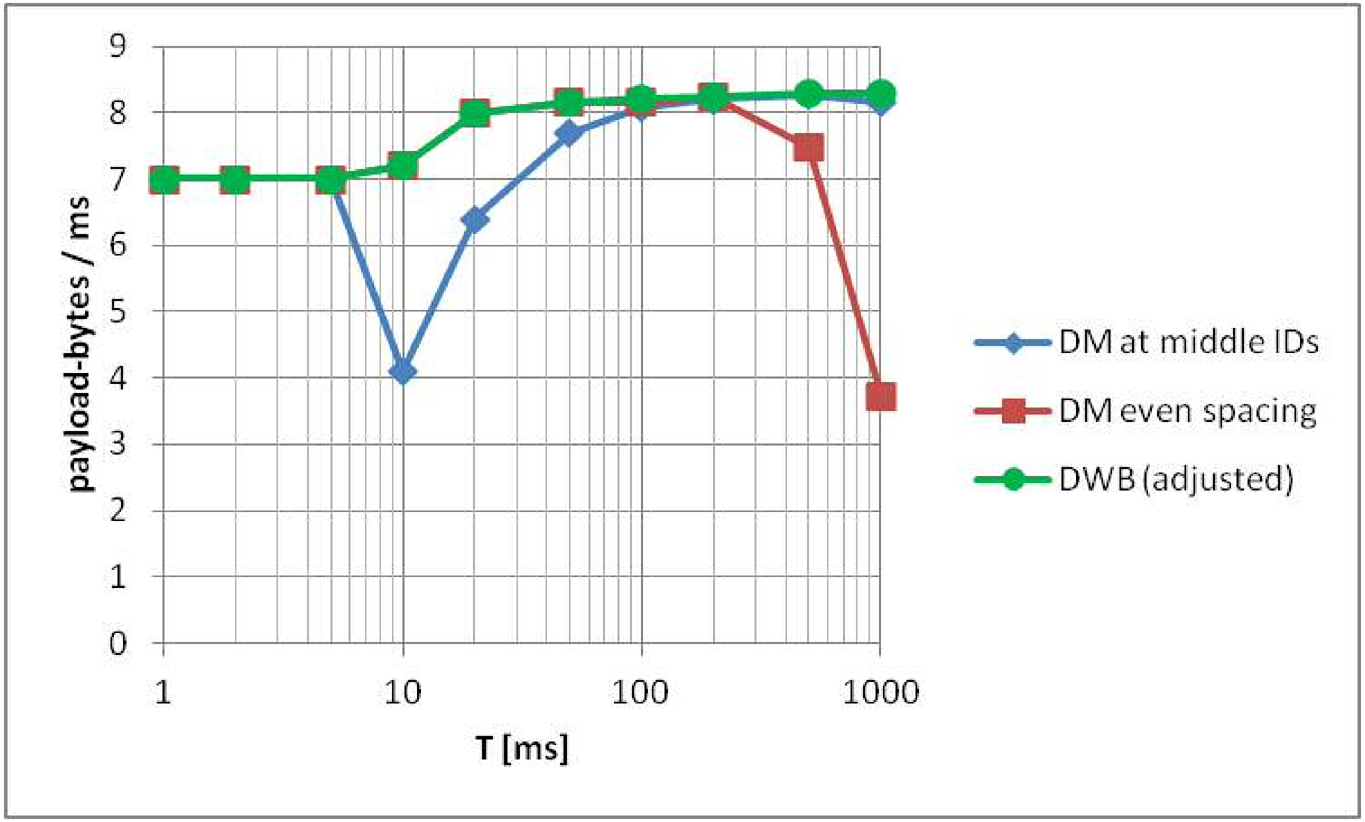
Effectiveness of DWB

"best" policies from previous experiments (extensibility metric)



Effectiveness of DWB

DWB policy outperforms both



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

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

System	Messages	Utilization [%]
Initial	17	44
Upgrade #1	+7	60 (44+16)
Upgrade #2	+7	76 (60+16)

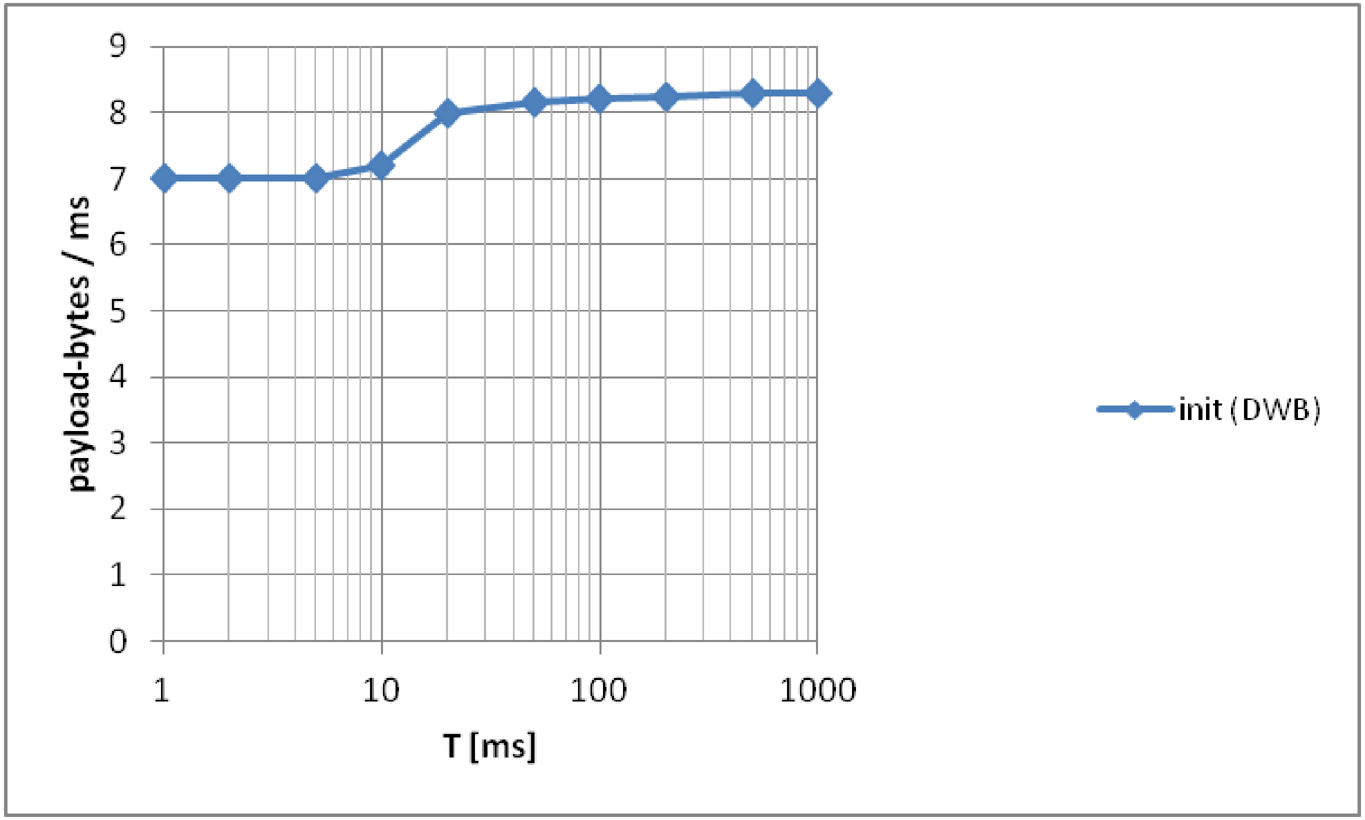
paper (SAE benchmark)

System	Messages	Utilization [%]
Initial	29	20
Upgrade #1	+22	40 (20+20)
Upgrade #2	+18	60 (40+20)

technical report appendix

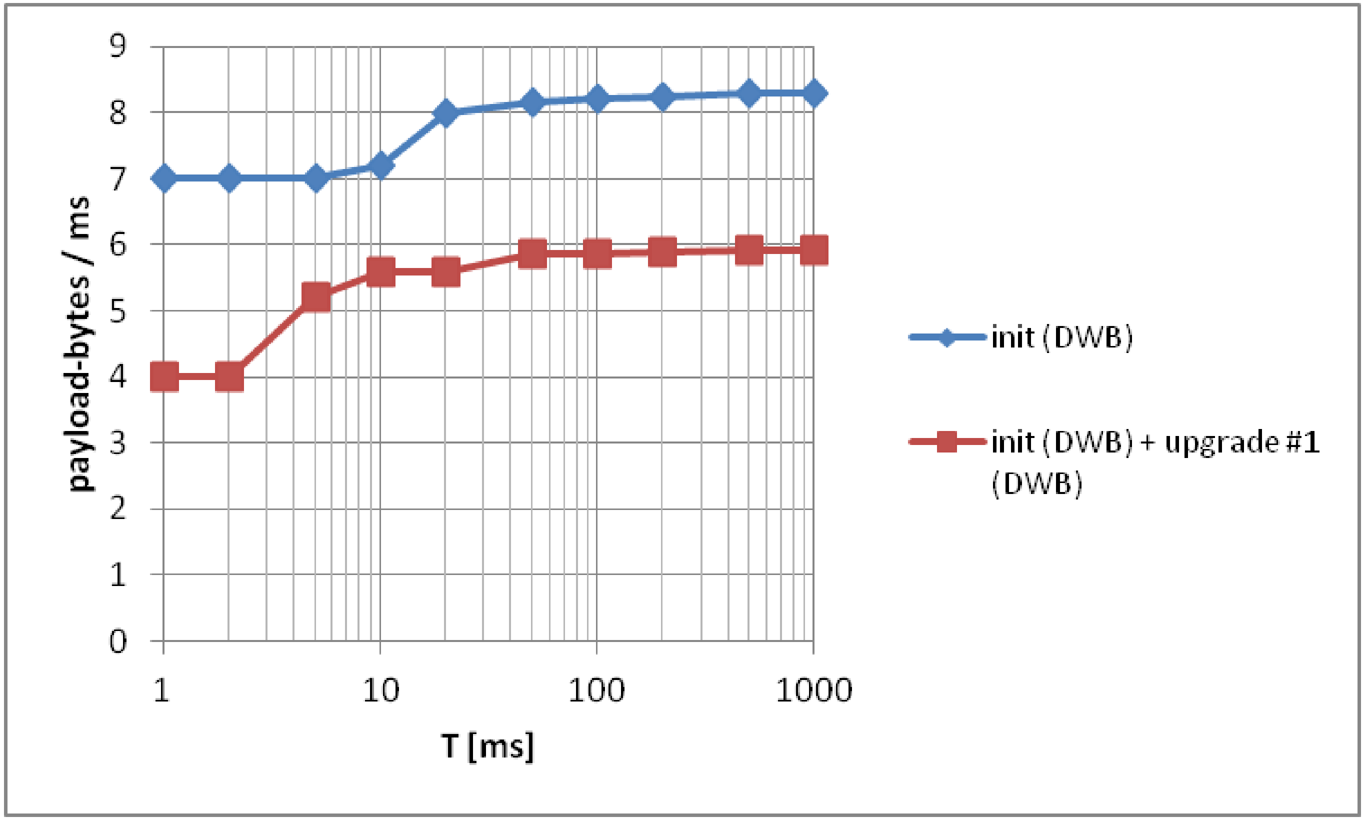
Results: SAE Benchmark

initial (DWB)



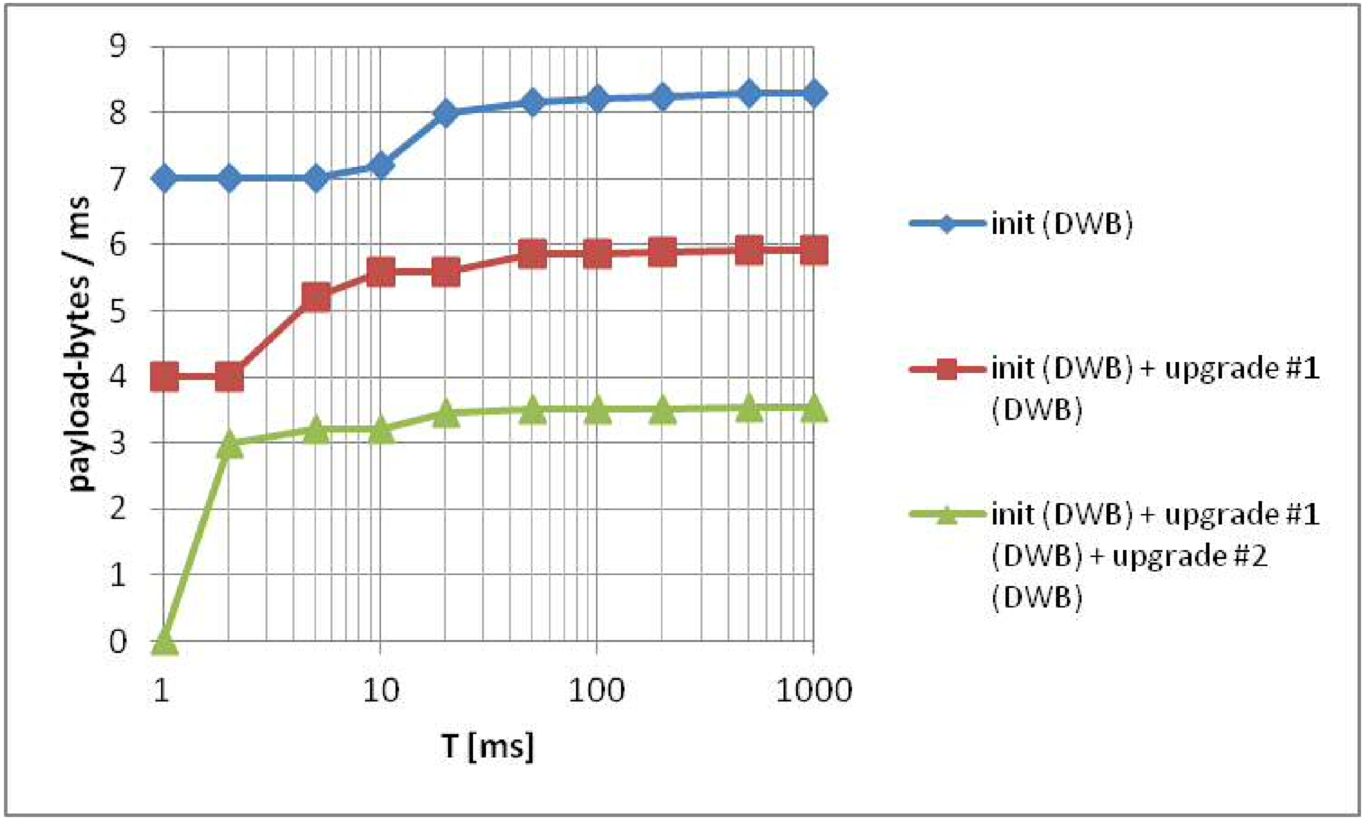
Results: SAE Benchmark

upgrade #1 (DWB)



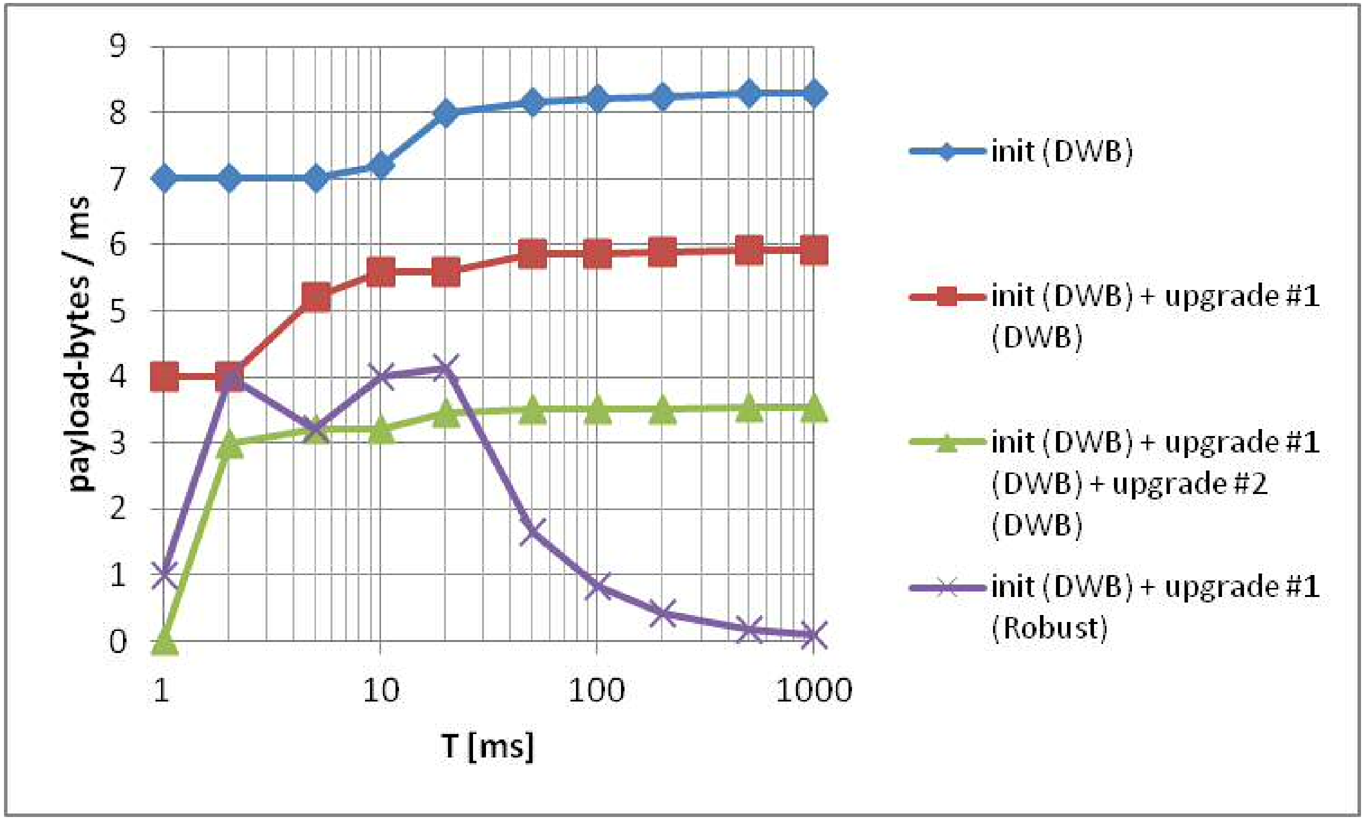
Results: SAE Benchmark

upgrade #2 (DWB)



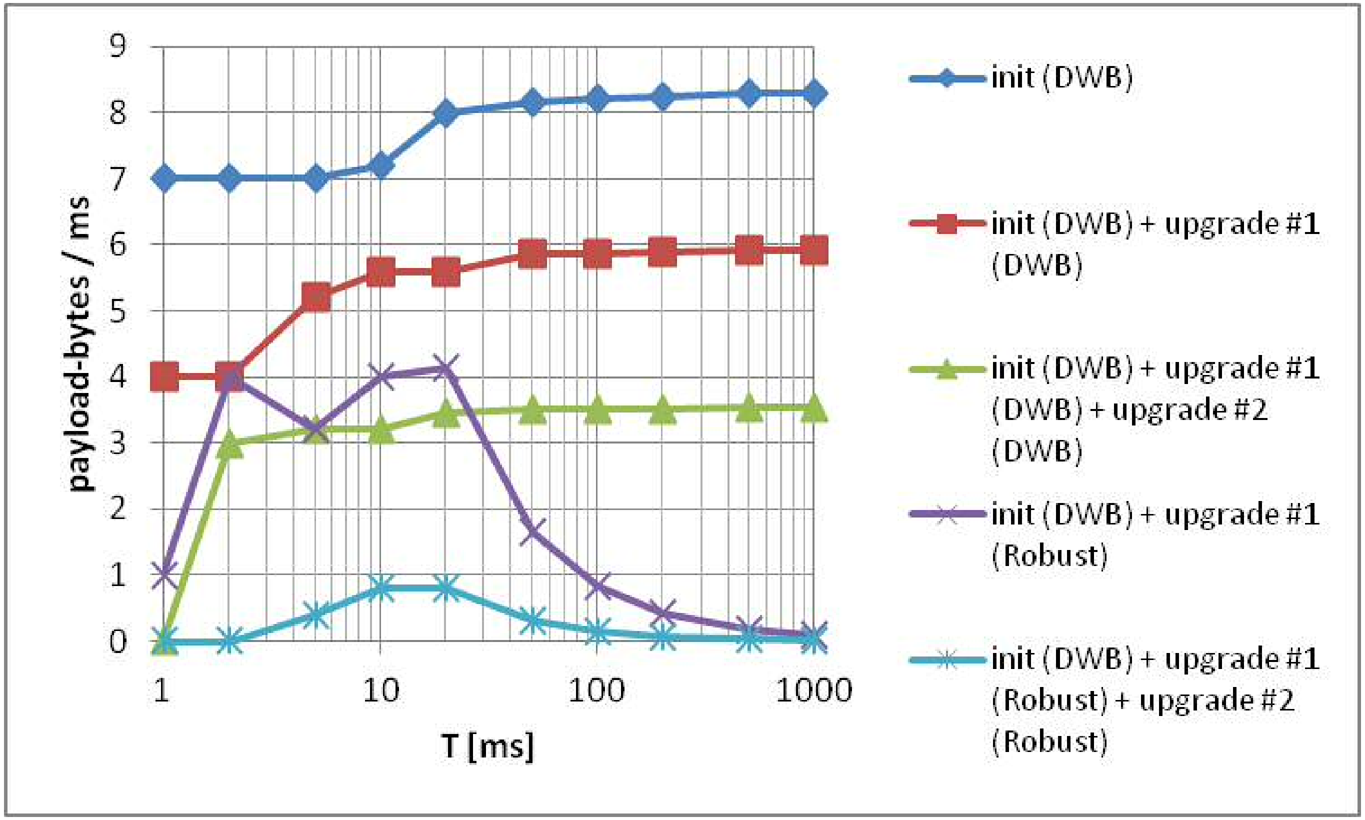
Results: SAE Benchmark

upgrade #1 (RPA)



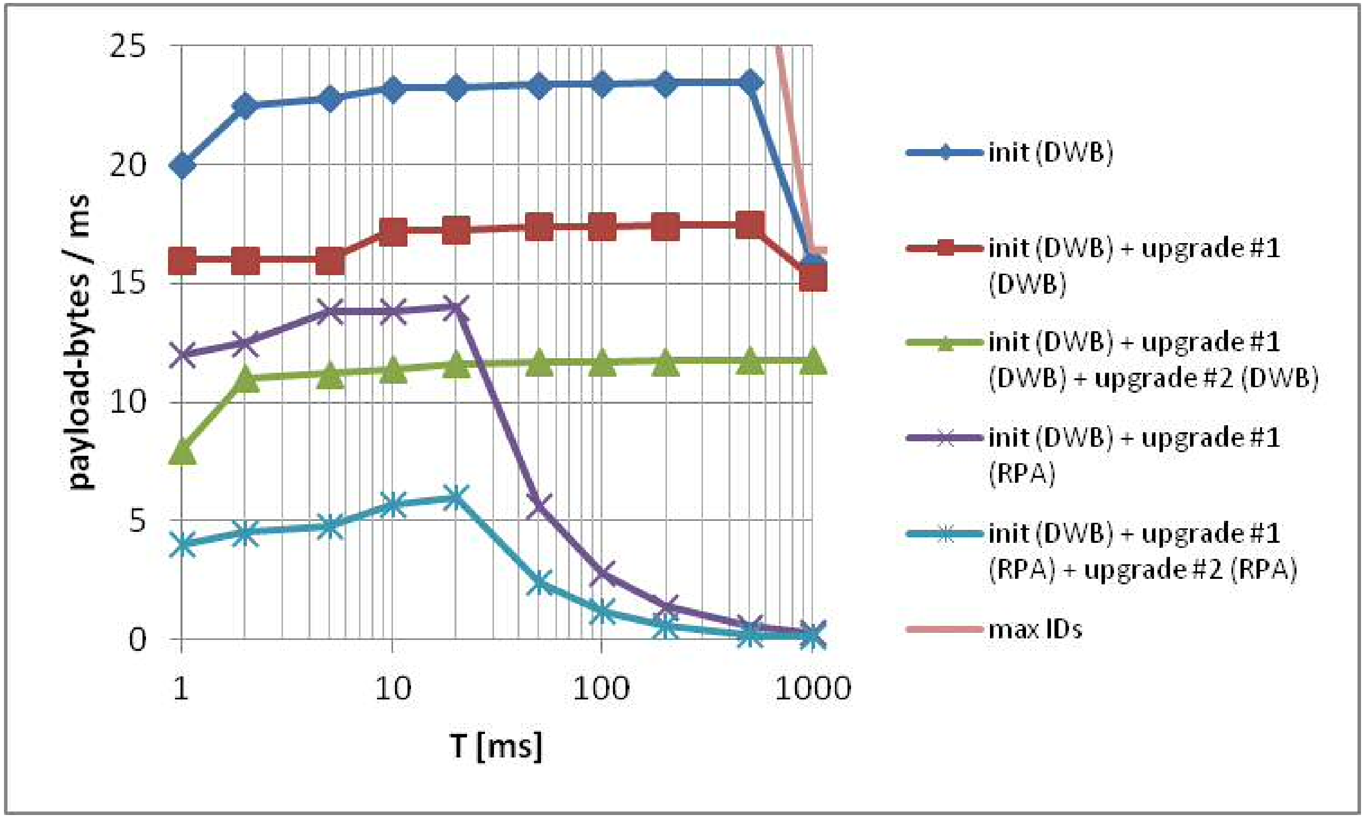
Results: SAE Benchmark

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)

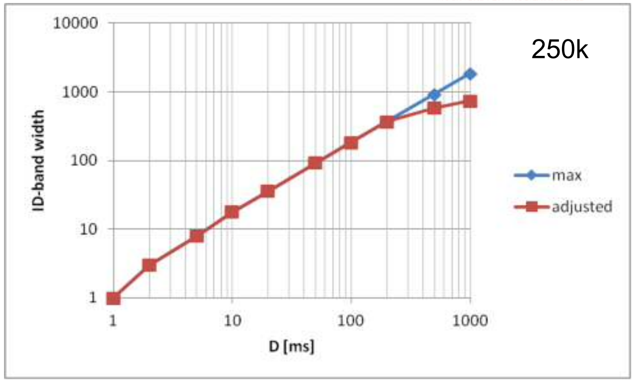
Questions & Discussions

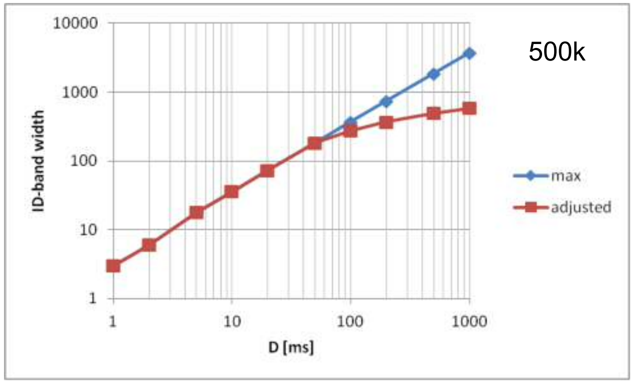
Setting Width of ID-Bands

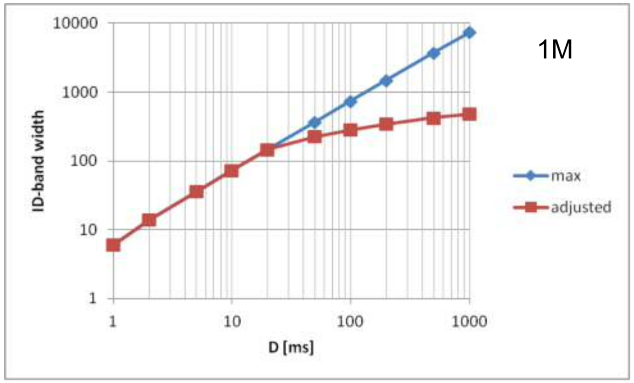
- ID-band width = max. number of schedulable messages for each deadline
- works for 125 kb/s systems
- doesn't work for 250 kb/s (or higher), due to limited number of IDs

Adjusting ID-Band Width

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







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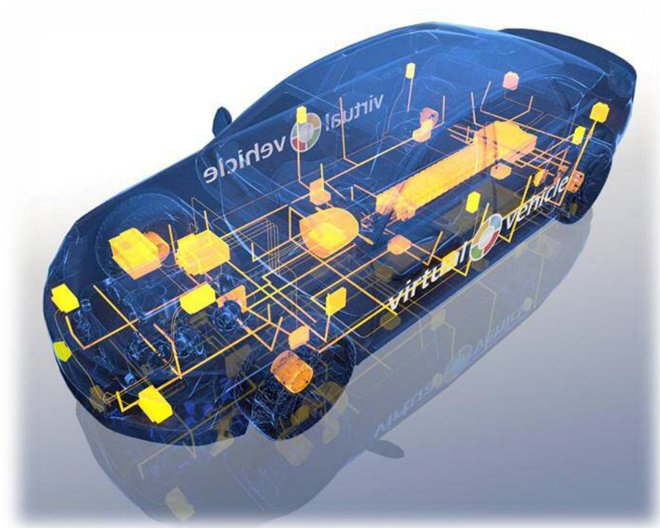

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