

Analysis and Optimization of Message Acceptance Filter Configurations for Controller Area Network (CAN)

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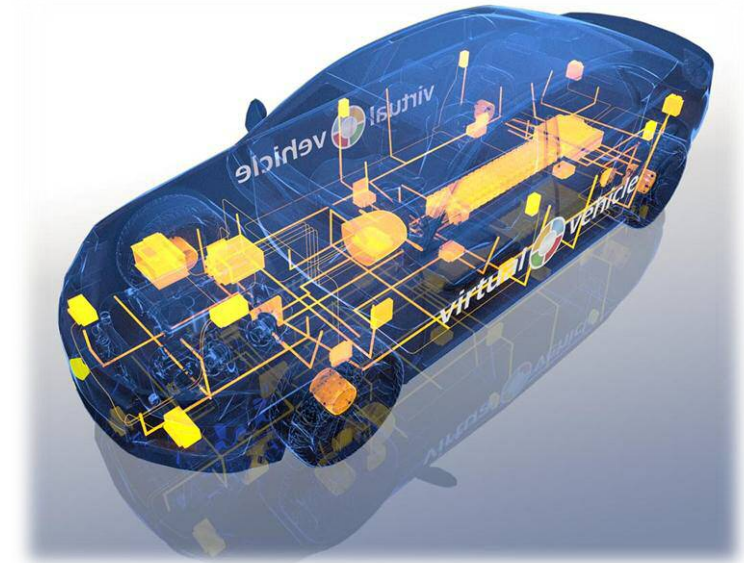
- Motivation: Automotive System Design
- Controller Area Network (CAN) Protocol

- CAN Message Acceptance Filtering – how it works
- Measuring Filtering Quality
- Optimal Filter Configuration

- Evaluation

System & Responsibilities

- many ECUs with dedicated functionality; developed by **Tier1-supplier**; (SW+HW)
- data-exchange between ECUs via networks (LIN, **CAN**, FlexRay, Ethernet)
- network design & system integration by OEM

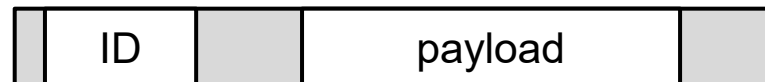


Challenges

- cost pressure of high-volume ECUs
- constrained HW-resources (CPU clock, memory)
- efficient resource usage needed

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



ID: 11 or 29 bits
 payload: 0... 8 bytes (CAN)
 0...64 bytes (CAN-FD)

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

- schedulability analysis
 (response time analysis)

Message specification:

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

$$R_m = J_m + w_m + C_m$$

$$R_m \leq D_m$$

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

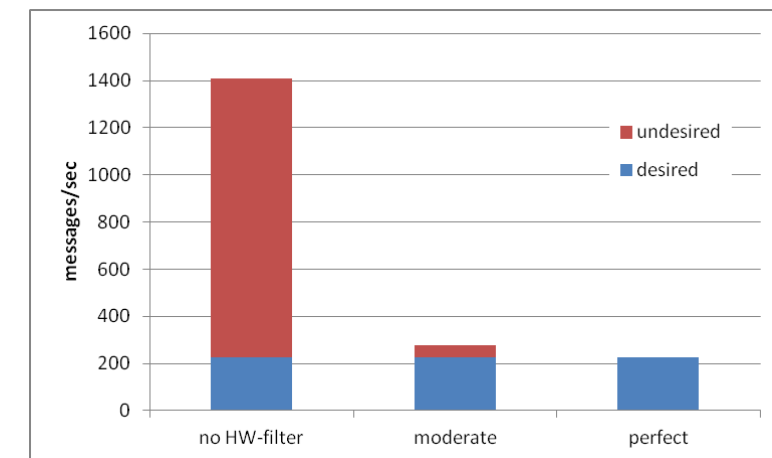
$$C_m^{29} = (80 + 10 \cdot s_m) \cdot \tau_{bit}$$

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

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

Receiving CAN Messages

- each node receives every message (i.e. broadcast bus)
 - node looks at message-ID to determine if message is relevant
 - if yes: process message
 - if not: discard → undesired message receive interrupts
-
- goal: minimize undesired message receive interrupt load
 - solution: HW-based **acceptance filtering** (widely available)
-
- question: find an optimal filter-configuration (undesired RX interrupts → min.)



Research Question & Contribution

How to measure filtering quality of given filter configuration?

- assessment method & quality metric

How to design an optimal filter configuration?

- design optimization methodology

Message Acceptance Filter: how it works

2 registers (per receive buffer):

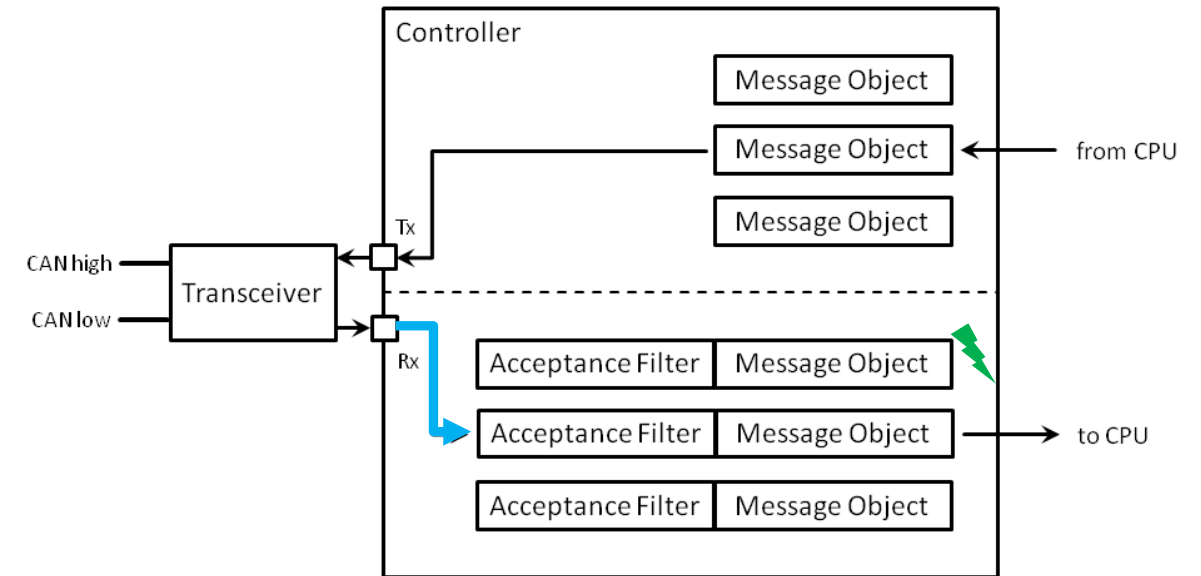
- mask: which digits are checked
- tag: which digit-values are accepted

mask : 111 1111 0011

tag : 000 1100 0000

 ID : 000 0000 0100 (4) **blocked**
 ✓✓✓ ✗✗✓✓ ✓✓✓✓

ID : 000 1100 1000 (200) **pass**
 ✓✓✓ ✓✓✓✓ ✓✓✓✓



- if message passes HW-filter, it is put into receive buffer, and raises receive interrupt
- if message is blocked, nothing happens

Message Acceptance Filter: how it works

- we use “abstract” notation (0,1,x)
x ... “don’t care”
- filters implemented in HW-logic
inside CAN-controller → no CPU load
- Most CAN-controllers: mask + tag per buffer
- Some CAN-controllers: “shared mask”
 - tag per buffer
 - mask applied to N buffers

```
mask    : 111 1111 0011
tag     : 000 1100 0000
-----
filter  : 000 1100 xx00
```

e.g.: National's CR16
15 buffers
1 mask: buffer[0]
1 mask: buffer[1..14]

How to measure Filtering Quality of given Filter Configuration

Filtering Quality

Given

- M^{all} set of all broadcasted messages (ID, period)
- M^{des} subset of messages which shall be received by node
- F filter configuration (f filter-patterns)

Calc.

$$M^{pass}$$

$$M^{block} = M^{all} \setminus M^{pass}$$

$$M^{UB} = M^{block} \cap M^{des}$$

UB ... unintended block

$$M^{UP} = M^{pass} \setminus M^{des}$$

UP ... unintended pass

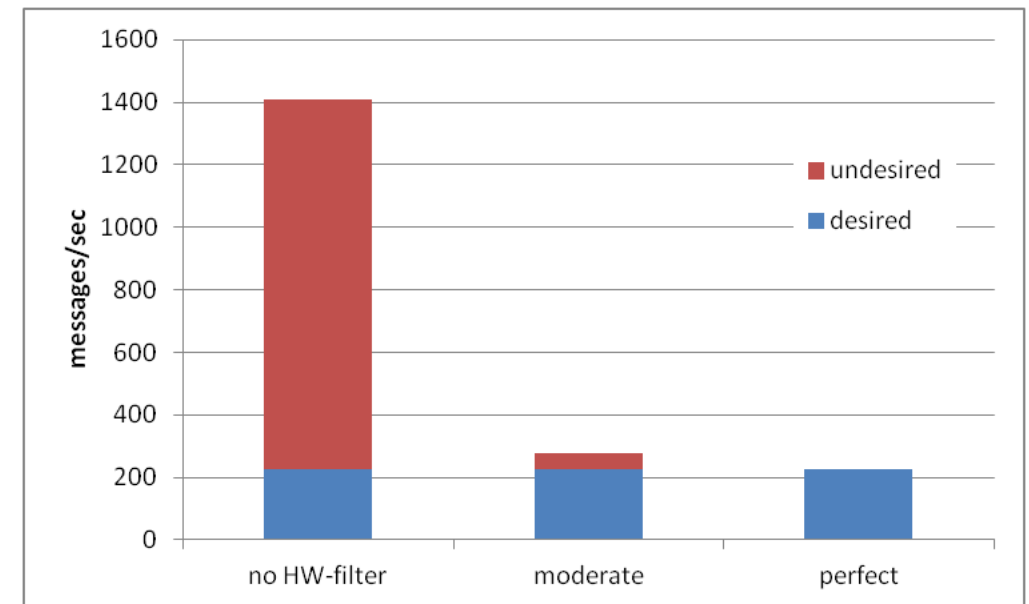
Filtering Quality

Classification

- in-feasible $M^{UB} \neq \{ \}$... some desired messages are blocked
- feasible $M^{UB} = \{ \}$... all desired messages pass
 - perfect $M^{UP} = \{ \}$... only desired messages pass

Quality

$$load^{UP} = \frac{M^{UP}}{\text{sec.}} = \sum_{M^{UP}} \frac{1}{T_m} \rightarrow \min$$



How to Design an Optimal Filter Configuration

Filter Design Problem

Given

- M^{all} set of all broadcasted messages (ID, period)
- M^{des} subset of messages which shall be received by node
- f number of available filters

Find

- filter-pattern for each of the f filters
- $load^{UP} \rightarrow \min.$

Complexity:

- problem is NP-complete
- transformation to SET COVER problem
- proof in paper

3 Cases

- $f \geq |M^{des}|$
- $f = 1$
- $1 < f < |M^{des}|$

Optimal Filter: $f \geq |M^{des}|$

- straightforward
- each filter = one message ID
- perfect filtering

Algorithm 2: Optimal Solution for $f \geq |M^{des}|$ Filters

```
Input:  $M^{des}$                                 /* desired messages */  
1 foreach  $m_i \in M^{des}$  do  
2   |  $f_i = \text{ID}(m_i)$   
3 end  
Output:  $F$                                     /* perfect filtering */
```

Optimal Filter: $f = 1$

- most constrained case
- for each filter-digit, derive filter-value from desired message's ID-digit
- ensures feasible filter

```

ID      = 000110000000 (192)
ID      = 000110001000 (196)
ID      = 000110010000 (200)
ID      = 000110011000 (204)
-----
filter  = 0001100xx00

```

Algorithm 1: Optimal Solution for $f = 1$ Filter (always feasible)

```

Input:  $M^{des}$  /* desired messages */
1 foreach ID-digit do
2   if  $\forall m_i \in M^{des}$  the ID-digit is 0 then
3     filter-digit = 0
4   else if  $\forall m_i \in M^{des}$  the ID-digit is 1 then
5     filter-digit = 1
6   else
7     filter-digit = x
8   end
9 end
Output:  $F$  /* feasible filtering */

```

Optimal Filter: $1 < f < |M^{des}|$

- simulated annealing (meta-heuristic search)

- cost function:

$$\cos t_1 = \frac{M^{UB}}{M^{des}} \quad \dots \text{avoid infeasible filtering}$$

$$\cos t_2 = \frac{M^{UP} / \text{sec.}}{(M^{all} \setminus M^{des}) / \text{sec.}} \quad \dots \text{avoid "unintended pass" load}$$

- problem encoding:

- group desired messages into f groups
- for each group: derive optimal filter (using algo.1)

- neighbour move:

- move desired message m into another group, and re-calc filters

Algorithm 3: Simulated Annealing

```

Input: t /* initial temperature */
Input: scur /* initial solution */
1 ccur = cost(scur) /* initial cost */
2 repeat
3   iterAtT = 0
4   repeat
5     iter++
6     iterAtT++
7     /* generate new solution */
8     snew = neighbour(scur)
9     cnew = cost(snew)
10    /* accept move? */
11    if cnew < cbest then
12      /* cost is improved */
13      scur = snew
14    else
15      /* cost is not improved */
16      if e(ccur-cnew)/t > random(0,1) then
17        scur = snew
18      end
19    end
20    /* remember best solution */
21    if cnew < cbest then
22      cbest = cnew
23      sbest = snew
24    end
25  until iterAtT == iterAtTmax;
26  t = t * coolingFactor
27 until iter == iterMax;
Output: sbest /* best solution found */

```


Optimal Filter: $1 < f < |M^{des}|$

- heuristic
 - sort desired messages by ID
 - assign $|M^{des}|/f$ desired messages to each filter
 - derive filter-pattern for each filter (algo.1)

- initial solution for SA

- as reference for evaluation
(no filter design algorithm in literature)

Idea:

If IDs per filter are similar, then algo.1
should find effective filter-pattern
i.e. few x in filter-pattern
few unintended pass

Evaluation (synthetic & real-world)

Large scale evaluation

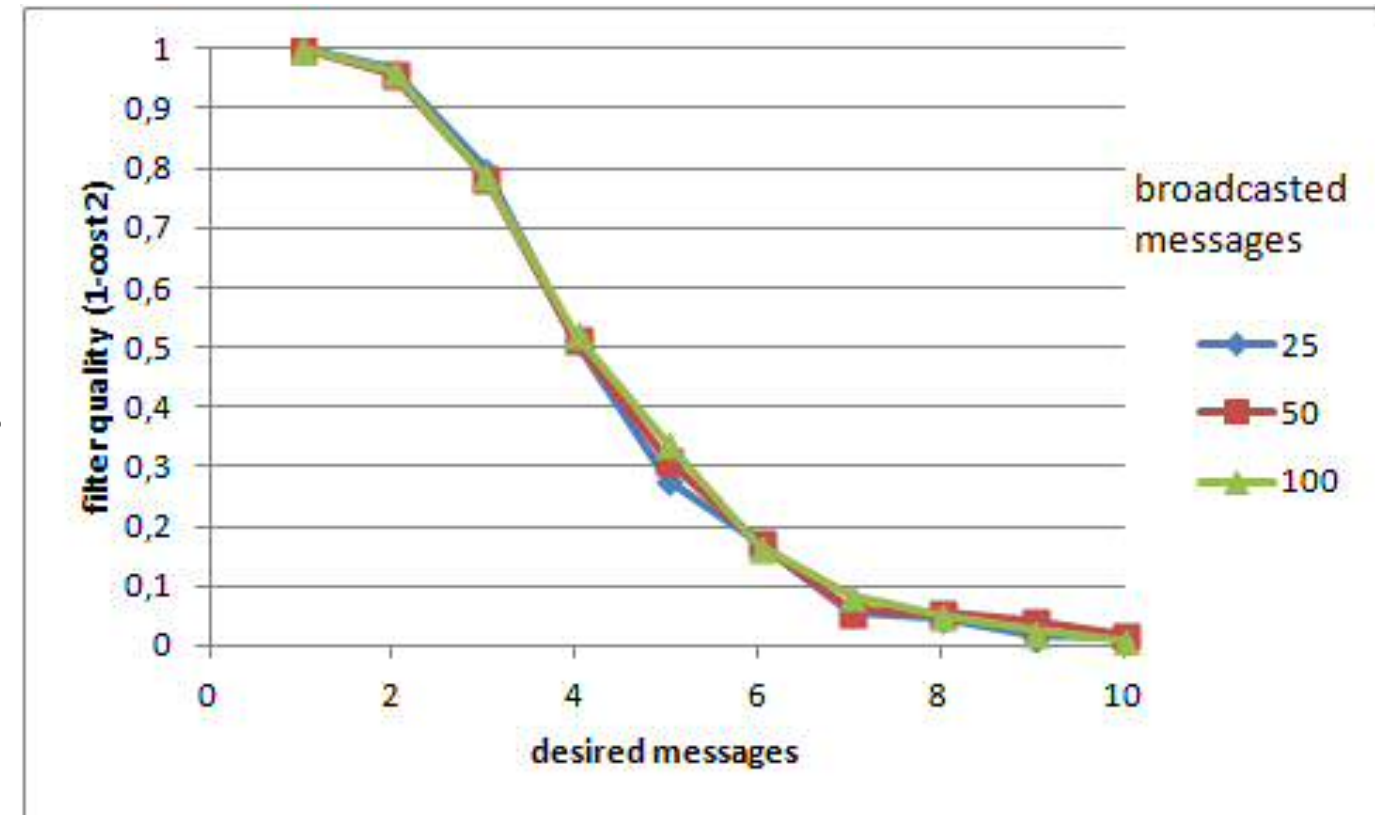
■ synthetic message-sets

- 11-bit message ID (0 ... 2047, uniform)
 - 10 ... 1000 ms message period (log-uniform)
 - 25 ... 100 broadcasted messages
 - 5 ... 40 desired messages
 - 1 ... 16 available filters
 - only schedulable message-sets considered
-
- $f=1$ 30 scenarios * 100 example-instances (algo.1)
 - $1 < f < |M^{\text{des}}|$ 68 scenarios * 100 example-instances (SA, heuristic)

Evaluation: $f = 1$

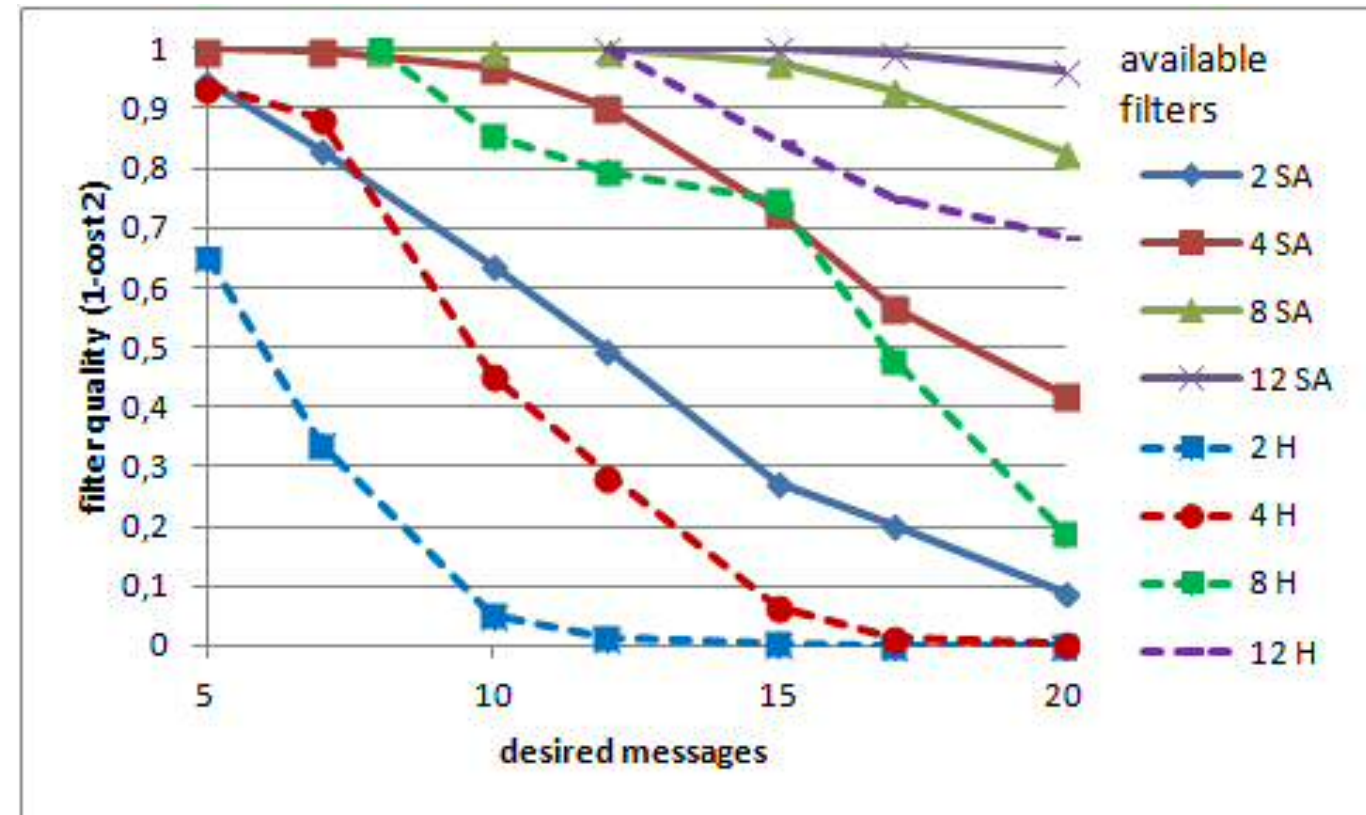
- Algo.1
- Fig.2 in paper

- $|M^{des}|$ increases ... filter-quality drops
- “good” filtering up to 3..4 des. messages
- $|M^{all}|$ has almost no effect



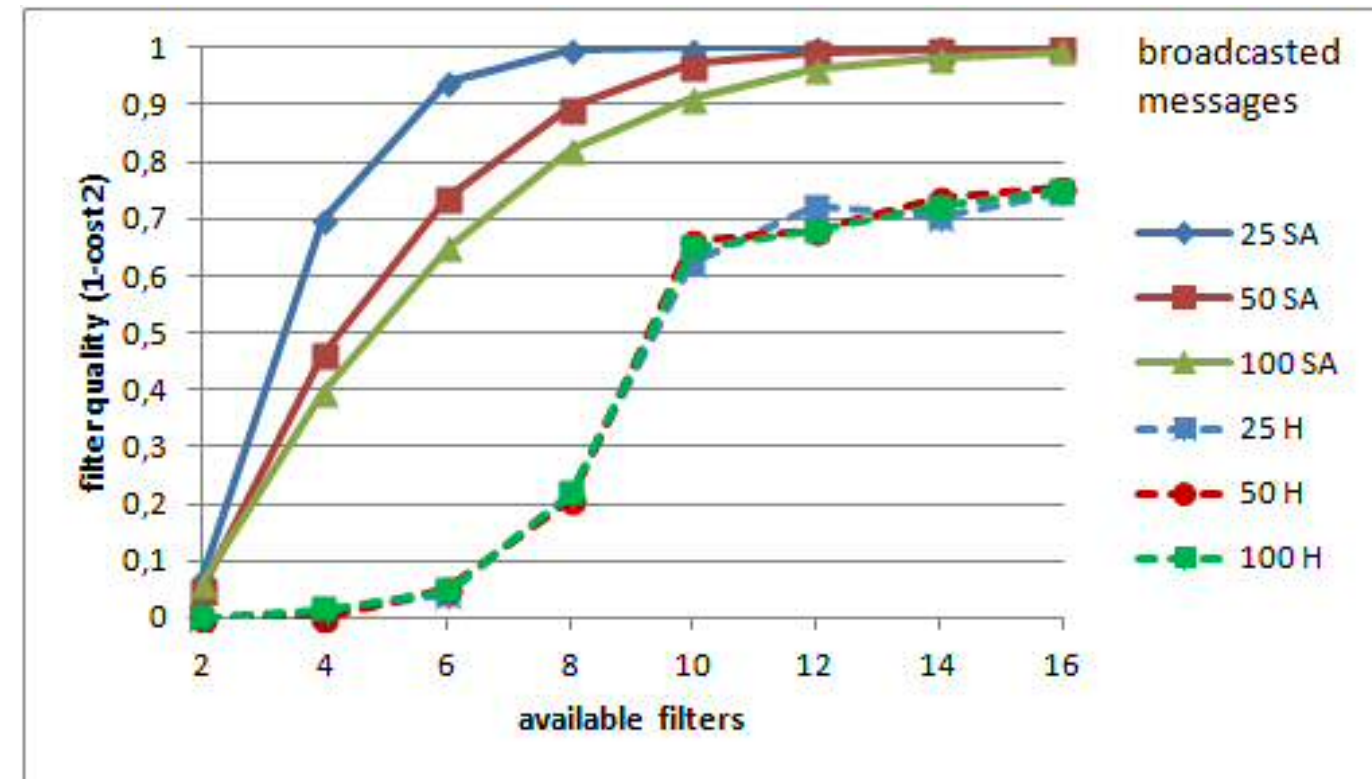
Evaluation: $1 < f < |M^{des}|$

- Fig.7 in paper
- color: nr. of filters
- solid=SA , dashed=heuristic
- $|M^{all}|=100$
- $|M^{des}|$ increases ... filter-quality drops
- $|f|$ increased ... better filter-quality
- SA always better than heuristic



Evaluation: $1 < f < |M^{des}|$

- Fig.3 in paper
- color: nr. of broadcast messages $|M^{all}|$
- solid=SA , dashed=heuristic
- $|M^{des}|=20$
- $|f|$ increases ... filter-quality increases
- $|M^{all}|$ increased ... filter-quality lower but: only minor effect
- SA always better than heuristic



Real-World Application: HVAC-controller of lightweight battery-electric car

- developed in EU-funded project www.epsilon-project.eu
- our tasks: design electric powertrain, implement HVAC-controller, integrate into CAN-network

- CAN network: 55 messages (1407 messages/sec.)
- HVAC controller:
 - receives 11 messages (227 messages/sec)
 - sends 4 messages
 - AT90CAN128 micro-controller (ATMEL 16MHz)
 - 15 CAN message-buffers
 - perfect filtering is possible (with 11 Rx-filters)

- can we optimize CAN filtering with fewer Rx-filters?



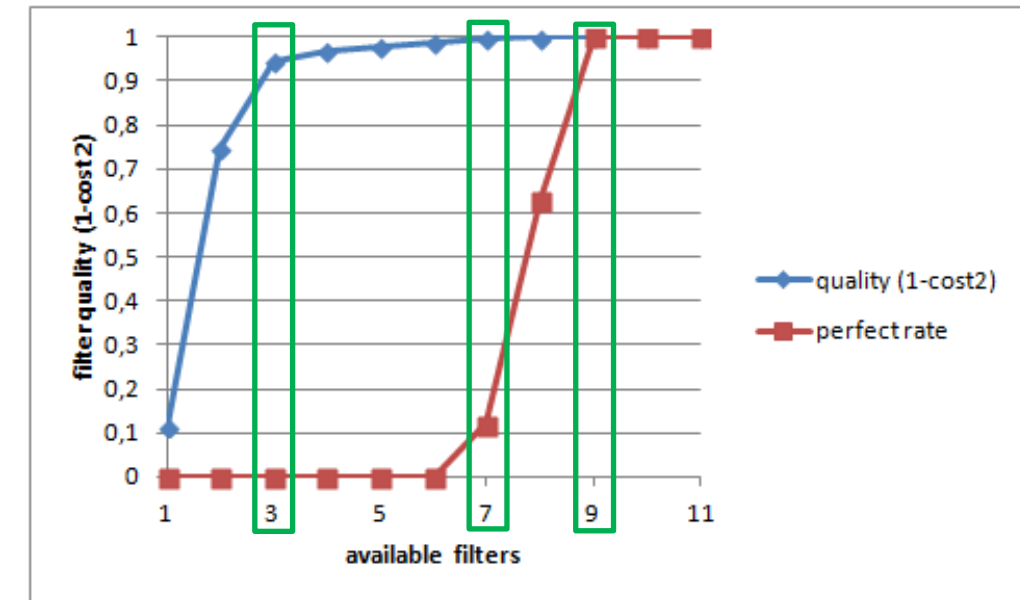
ID [hex]	T [ms]	desired	ID [hex]	T [ms]	desired
0x00A	1000		0x2F2	100	
0x010	1000	yes	0x300	1000	
0x020	100		0x350	1000	
0x060	100		0x3AC	100	
0x06A	100	yes	0x400	100	
0x06E	10		0x410	100	
0x071	100		0x411	100	
0x078	100		0x420	1000	
0x07D	100		0x425	1000	
0x081	1000	yes	0x565	500	
0x08C	100		0x610	100	
0x091	100		0x611	1000	
0x096	500		0x612	100	
0x100	10		0x613	1000	yes
0x101	10		0x614	1000	
0x102	10		0x618	100	
0x110	10		0x620	100	yes
0x120	10		0x6F0	1000	yes
0x130	10		0x6F8	1000	
0x150	10		0x700	1000	
0x160	1000		0x702	1000	
0x161	1000		0x710	1000	yes
0x200	1000		0x711	1000	
0x201	10		0x720	1000	
0x210	10	yes	0x730	1000	yes
0x220	10	yes	0x770	1000	yes
0x2F0	10		0x771	1000	
0x2F1	100				

Table 2: Network Specification of Battery Electric Vehicle (BEV) available for HVAC-Controller

Real-World Application: Results

- find best filter-configuration for different number of filters
- solve each scenario 100 times (for “perfect ratio”)

Filters	Desired [msg/sec.]	Unintended [msg/sec.]	
None	227 (11)	1180 (44)	
3	227 (11)	48 (13)	High filter quality
7	227 (11)	0 (0)	Perfect filtering (10%)
9	227 (11)	0 (0)	Perfect filtering (100%)



- Rx-interrupt handler: 13.75...38.13us (avg. 31.25us)
 - 227 desired/sec: 7.1ms/sec (0.71%)
 - 48 unintended/sec: 1.5ms/sec (0.15%)
 - 1180 unintended/sec: 36.9ms/sec (3.69%)

Filter Details (3 vs. 7 filters)

```
filter = 000xxx0x0xx
  ID = 00000001010 (0x00a) UP
  ID = 00000100000 (0x020) UP
  ID = 00001100000 (0x060) UP
  ID = 00001101010 (0x06a)
  ID = 00010000001 (0x081)
-----
filter = 0x000xx0000
  ID = 00000010000 (0x010)
  ID = 00000100000 (0x020) UP
  ID = 01000000000 (0x200) UP
  ID = 01000010000 (0x210)
  ID = 01000100000 (0x220)
-----
filter = 11xxxx00xx
  ID = 11000010000 (0x610) UP
  ID = 11000010001 (0x611) UP
  ID = 11000010010 (0x612) UP
  ID = 11000010011 (0x613)
  ID = 11000100000 (0x620)
  ID = 11011110000 (0x6f0)
  ID = 11100000000 (0x700) UP
  ID = 11100000010 (0x702) UP
  ID = 11100010000 (0x710)
  ID = 11100010001 (0x711) UP
  ID = 11100100000 (0x720) UP
  ID = 11100110000 (0x730)
  ID = 11101110000 (0x770)
  ID = 11101110001 (0x771) UP
```

```
filter = 00001101010
  ID = 00001101010 (0x06a)
-----
filter = 00010000001
  ID = 00010000001 (0x081)
-----
filter = 11000010011
  ID = 11000010011 (0x613)
-----
filter = 0x000010000
  ID = 00000010000 (0x010)
  ID = 01000010000 (0x210)
-----
filter = 11100x10000
  ID = 11100010000 (0x710)
  ID = 11100110000 (0x730)
-----
filter = 11xx1110000
  ID = 11011110000 (0x6f0)
  ID = 11101110000 (0x770)
-----
filter = x1000100000
  ID = 01000100000 (0x220)
  ID = 11000100000 (0x620)
```

Conclusion & Outlook

Conclusion

- introduced engineering-problem: CAN message acceptance filter
- method for assessing of filtering quality
- method for designing near-optimal filter-configurations
- evaluation shows effectiveness (min. undesired Rx-interrupt load)

Future

- optimize filter quality for “now” and “future extensions” (extensibility)
 - try to block “not yet defined” broadcasted messages
- combine “message ID assignment” and “message filter design”
 - assign message IDs such that messages are schedulable, and efficient acceptance-filters can be designed
- bring methods to industry (engineering tools)

Questions & Discussion

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