

High Speed Optical Controller Area Networks (CAN)

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In every day R&D work employing network technologies like e.g. CAN proper shielding often is impossible as frequent adjustments and new configurations have to be applied to the systems and therefore the outer system surface has to be kept open. Therefore EMI problems are commonplace. This leads to the problem that a lot of effort is distracted from the development of the circuit itself and spent on dealing with the resulting CAN errors. A very cost efficient way to avoid such problems is to use a low-cost optical CAN. For this only the physical layer has to be changed and these changes are such that existing electrical CAN segments can be merged with the optical segments. In such a configuration the hub or switch which is needed for these star topologies must be suited for real-time error detection in optical segments to avoid the breakdown of the whole network. Also the hub or switch should be able to support real-time connection or disconnection of the node when CAN nodes are connected or disconnected to the network, to avoid bus conflicts with the other network sharing units. We have developed a low-cost optical CAN network and have successfully implemented it in a hybrid drivetrain testbed. The previous problems of destroyed CAN messages due to heavy EMI resulting from power electronics like DC/DC converters were solved. Electric network segments were merged with optical segments.

Introduction

A hybrid testbed needs several different actors and sensors like power electronics or emission probes. All units have to communicate through one network. Drivetrain components as high voltage batteries, power converters and electric machines produce a high amount of EMI. Especially in the hybrid testbed with spatially separated control units bad shielding leads to signal distortion.

The modular concept of the hybrid testbed with parallel or serial hybrid configurations employs various power modules, an internal combustion engine (ICE) and several traction modules; in such a setup EMI is a major problem. The use of CAN as network topology is a must due to the use of different automotive components and the availability of nodes with CAN bus interface. So an optical solution seemed promising.

The specifications for that are:

- Support of high speed up to 1 Mbit/s due to control loops via CAN
- Integration in existing electrical Controller Area Networks
- Support of connection to electrical CAN nodes via optical lines

The CAN's physical layer is based on the ISO 11898 standard. The microcontroller's CAN interface is connected via a transceiver chip to the two line twisted-pair bus. The two states of the CAN bus are dominant and recessive which are driven with differential signals. The CAN network's basic structure therefore results in a bus topology with termination on both ends to avoid superposition of electrical signals. If these twisted-pair lines are shielded with a minimal distance between shielding and wires they show good symmetric characteristic and are less sensitive to inductive coupling. Good shielding requires that all nodes are connected properly to the shielding. This, however, normally is not the case in R&D environments so ground level shifts are produced leading to longer propagation times between bus nodes and a decrease in bit rate performance and bus length. These problems can be avoided if opto couplers are used between the microcontroller and the CAN transceivers however the opto couplers do need a separate power supply like a small DC/DC converter or something similar. This results in additional cost while the use of purely optical CAN networks seems to be much cheaper and user friendly because less constraints must be considered. The

optical subsystem itself is connected to the electrical subsystem through a CAN transceiver chip called "minibridge". This minibridge collects electrical or optical pulses and transfers them to the other subsystem. This way a data link is established between different physical media.

The optical hub needs additional logic on the optical side to ensure that only dominant bits received at one port are distributed to all other ports to guarantee proper operation [1].

The next two sections describe the electrical and optical interfaces so far as it is necessary to understand the optical connection. Then the proposed optical hub and possible network topologies are introduced. This is followed by some measurements to prove the functionality.

Electrical Signal Propagation Time

The physical layer must provide recessive or dominant bit states to allow non-destructive arbitration [2]. During arbitration the receive and send bits are compared and a decision is made if arbitration is lost due to a low priority or not. As a result a dominant bit which is sent by another node must arrive within this bit time. Only then it is possible to detect if arbitration is lost and the sender has to be cut off. With the knowledge of the bus speed and the delay of the node the maximum bus length for electrical high speed CAN can be calculated [3].

First the propagation time of a 1Mbit/s bus speed has to be calculated:

$$t_{prop} \leq (N_b - N_{tseg2} - 25 \cdot N_b \cdot \Delta t_q) \cdot t_q$$

$$t_{prop} \leq (8 - 2 - 25 \cdot 8 \cdot 0,003) \cdot 125 \text{ ns}$$

$$t_{prop} \leq 675 \text{ ns}$$

Further the delay time of the ECU is needed. The delay of the transceiver (in this case PCA80C250) and the delay of the electronic circuit between micro-controller and transceiver add up to:

$$t_{elen} = t_{transceiver} + t_{electronic}$$

$$t_{elen} = 365 \text{ ns} + 7 \text{ ns}$$

$$t_{elen} = 372 \text{ ns}$$

This finally leads to a maximum bus length for pure electrical high speed networks of:

$$l_{elec} = \frac{1}{2} \cdot \lambda \cdot (t_{prop} - t_{elen})$$

$$l_{elec} = \frac{1}{2} \cdot 0,2 \frac{m}{ns} \cdot (675 - 372) \text{ ns}$$

$$l_{elec} = 30,3 \text{ m}$$

Optical Signal Propagation Time

A similar calculation is used to determine the maximum length of an optical network. Here additionally the damping of the polymer optical fibres (POF) has to be considered to ensure that the damping is within the limits so that the signal power is high enough for a proper detection at the receiver LED. Therefore fast optical converters from the audio realm [4], [5] were used to allow a simple and low-cost setup of optical networks. These receiver and transmitter circuits allow a transfer rate of up to 10 Mbit/s. This ensures that the signal edge can be reliably detected within a short time delay. The delay of the optical receiver and transmitter circuits amounts to 30 ns each. This leads to a cumulated delay time between an optical node and the optical hub of:

$$t_{optn} = 2 \cdot t_{opto} + t_{electronic} + t_{hub}$$

$$t_{optn} = 2 \cdot 30 \text{ ns} + 7 \text{ ns} + 22 \text{ ns}$$

$$t_{optn} = 89 \text{ ns}$$

With this we can calculate the theoretical maximum fibre length between hub and node to:

$$l_{pof} = \frac{1}{2} \cdot \lambda \cdot (t_{prop} - t_{optn})$$

$$l_{pof} = \frac{1}{2} \cdot 0,2 \frac{m}{ns} \cdot (675 - 89) \text{ ns}$$

$$l_{pof} = 58,6 \text{ m}$$

Next we have to consider the maximum cable length due to damping, temperature dependence and aging of the LEDs and POFs. The temperature dependence and aging is accounted for with an overall damping of 5 dB. The nominal power output of the transmitter and the minimum power input of the receiver are given by -15 dBm and -27 dBm. The damping of the POF is accounted for with

0,2 dB/m This leads to a maximum cable length of:

$$l_{pof} = \frac{P_{rx} - P_{tx} - P_{res}}{0,2 \frac{dB}{m}}$$

$$l_{pof} = \frac{-15 \text{ dBm} - (-27 \text{ dBm}) - 5 \text{ dB}}{0,2 \frac{dB}{m}}$$

$$l_{pof} = 35 \text{ m}$$

With a duplex connection the distance between hub and one node amounts to:

$$l_{hubnode} = \frac{l_{pof}}{2} = \frac{35 \text{ m}}{2} = 17,5 \text{ m}$$

So a maximum distance of 17,5 m is allowed between every connected node. All abbreviations are explained in tab. 1

| abbr. | unit | description |
|-------------------|---------|---|
| t_{prop} | seconds | Propagation time |
| t_{elen} | seconds | Delay time of electrical node |
| $t_{electronic}$ | seconds | Delay time of electronic circuit |
| t_{hub} | seconds | Accumulated delay time of passive hub |
| t_{opto} | seconds | Delay time of optical transceiver modules |
| $t_{transceiver}$ | seconds | Delay time of 80C250/251 |
| t_{opn} | seconds | Accumulated delay time of optical connection |
| t_q | seconds | Nominal time length of one bit |
| Δt_q | seconds | Relative error of time length which causes from quartz jitter |
| N_b | integer | Number of time slots per bit |
| N_{tseg2} | integer | Number of time slots in time segment 2 |
| l_{elec} | m | Cable length of electrical CAN |
| l_{pof} | m | Cable length of optical CAN |
| $l_{hubnode}$ | m | Distance between passive hub and optical node |
| P_{rx} | dBm | Minimum power input of optical receiver module |
| P_{tx} | dBm | Maximum power output of optical transmitter module |
| P_{res} | dB | Reserve due to damping and aging |

Table 1: Abbreviations of equations

Optical Hub

The optical hub was built up with an EPM9300, a complex logic device from Altera's MAX family. The delay of the programmed logic device between TTL

input and TTL output of an optical transmitter and receiver module is 22 ns. During this time error detection and message handling is processed. Also the ports are supervised if any error frames occur. This may be a connection or disconnection of a node, error frames due to broken POFs or a node with errors. The hub has also an electrical uplink which can be switched off if pure optical networks are needed. Four optical ports and one electrical uplink are provided in this assembly.

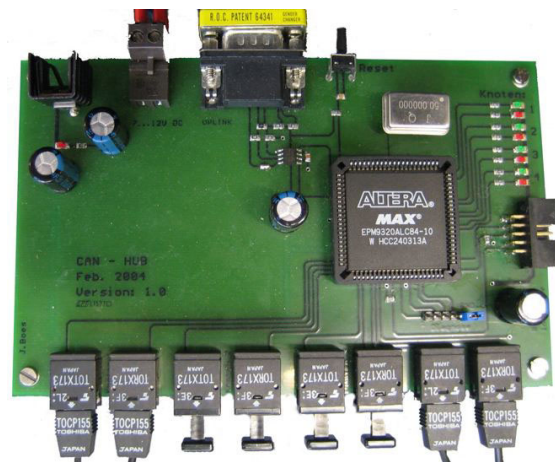


Figure 1: Optical hub with one electrical and four optical connectors

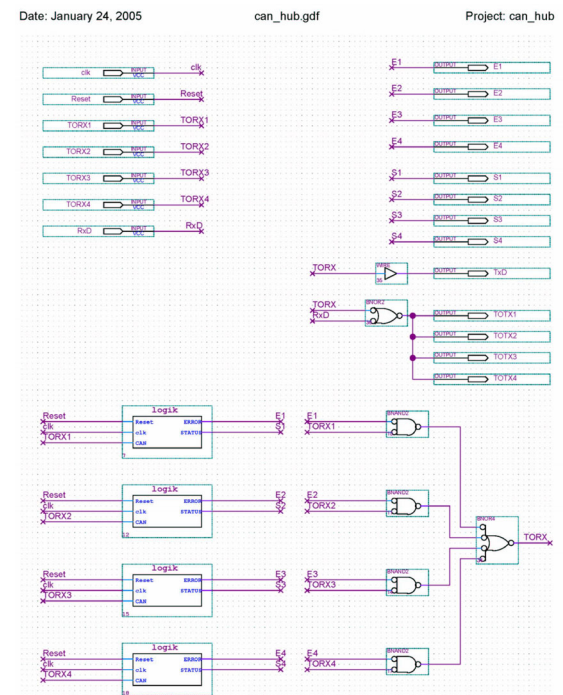


Figure 2: Programmable logic - toplevel

The number of ports depends on the maximum available logic arrays. With the four optical ports given here the logic is

utilized by 80 %, this means 254 logic cells are utilized. Fig. 1 shows this optical hub. Fig. 2 shows an overview of the internal structure of the programmable logic. The four sub-modules which are numbered "logik" belong to one optical port. If the programmable logic device has enough logic cells these modules can be copied to the number of favored optical ports. The sub-module "logik" contains a clock acknowledge and an error detection module as shown by fig. 3.

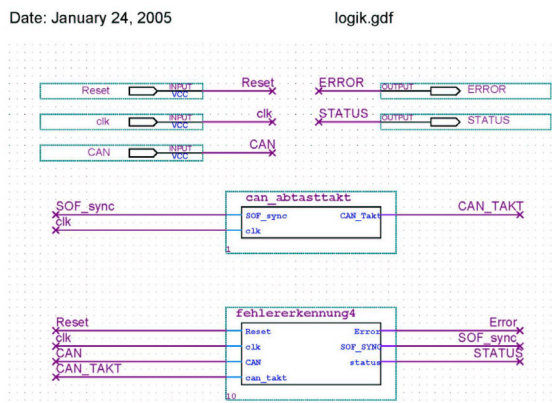


Figure 3: Programmable logic - optical port with clock and error detection

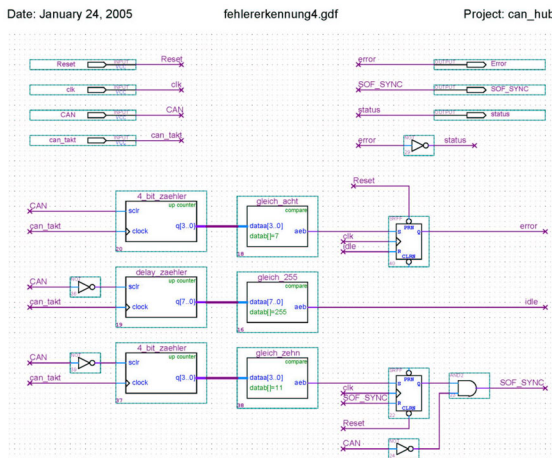


Figure 4: Programmable logic - error detection and error handling of an optical port

The error detection sub-module is shown in fig. 4. This is the most important sub-module because a misinterpreted dominant bit inevitably leads to an error which produces an error frame. The first sub-module checks if more than eight dominant bits are consecutively counted. A stuff error occurs at the 6th dominant consecutively counted bit. To not interfere with the CAN specification an error is generated after the 8th consecutively

counted bit. The second sub-module checks if the optical port is in idle. This happens when no dominant bits are counted. The last sub-module identifies the start of frame (SOF). This is necessary to synchronize to the incoming CAN messages.

The nodes which can be connected to the hub are shown in fig. 5. The nodes support only optical CAN connections up to a maximum speed of 1 MBit/s. In fig. 6 the schematic of the proposed hub is shown.

The optical hub is also called "passive hub" to differentiate between the second hub, a so called "active hub" which is below-mentioned.

The advantages of the optical hub as proposed here are:

- Hot plugging (nodes can be connected or disconnected although the network operates at high speeds)
- Nodes with permanent errors are switched off automatically
- If a temporarily switched off port goes recessive it is immediately switched on again
- The electrical uplink connector allows to integrate an optical sub-segment in an existing electrical network
- The hub supports purely optical networks

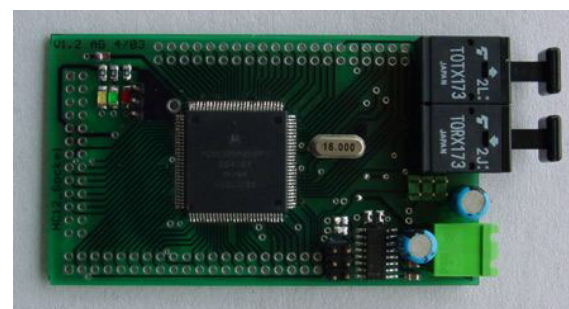


Figure 5: Optical node (HC9s12DP256)

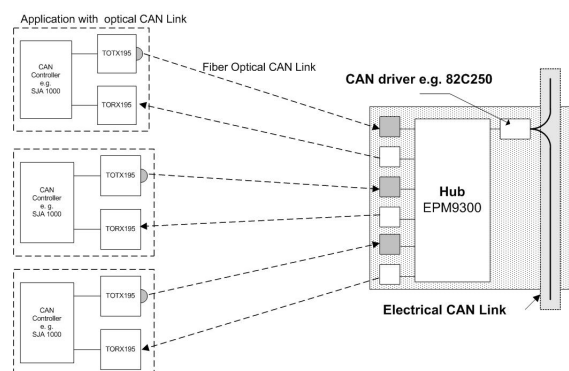


Figure 6: Schematic of optical hub

A major difficulty arises when an additional standard industry node with electrical interface is to be connected to the optical hub. Connection via the electrical uplink may or may not work in the EMI surroundings. To ensure proper functionality this connection should be done via an optical channel, too.

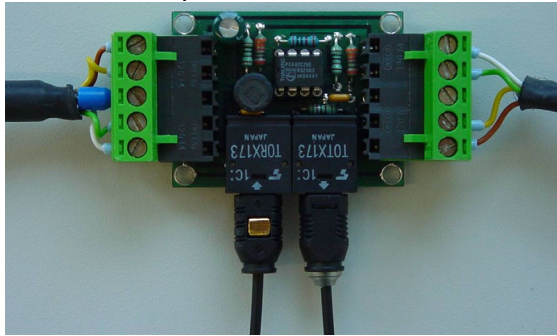


Figure 7: "Minibridge" to support branch lines

A minibridge (see fig. 7) does connect an electrical to an optical subsystem. However, a minibridge does not provide a CAN stack on the optical side. Therefore the CAN stack has to be supplied by a microcontroller on a so called "active hub" between the minibridge(s) and the original optical hub. This way also in that case the connection between the CAN application and the hub is realized completely via optical media. Fig. 8 shows the schematic of this hub.

The disadvantage of this solution is that messages can get lost if the bus load increases above 50 % because during the processing of messages of different priority it cannot be guaranteed that every low priority message can be sent.

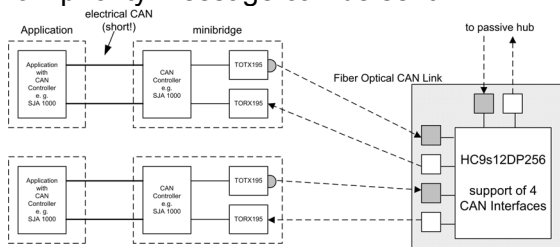


Figure 8: Schematic of "active hub"

To ensure data integrity a new hub with integrated CAN stacks is being developed. This hub is implemented with an Altera Cyclone FPGA to overcome this problem.

Bus Topologies

The optical high speed network allows several different bus topologies:

- Optical branch lines within an existing electrical CAN (fig. 9). This way even for long branch lines bus termination problems are avoided. A low-cost solution is to use an optical node with a minibridge [1] (see fig. 7).

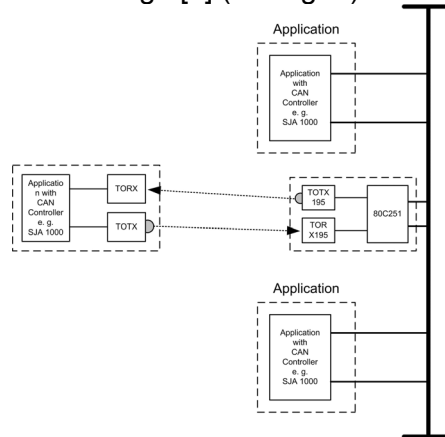


Figure 9: Branch line connection

- Purely optical networks with optical nodes. This is supported by the passive hub. In this configuration the electrical uplink can be switched off to minimize the total delay time (fig. 6).
- Mixed optical networks with an electrical bus and an optical star as sub-segment like it was proposed above. If the overall bus length is within the specifications multiple optical sub-segments can be added (fig. 10).

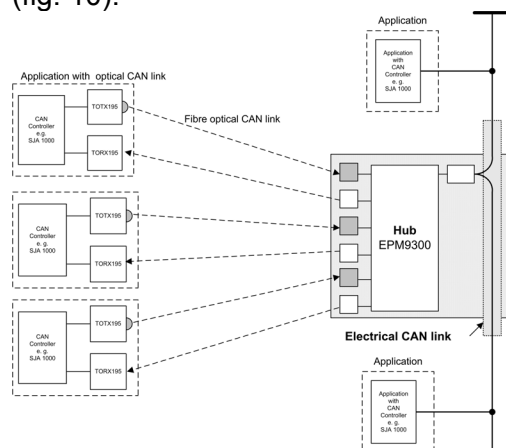


Figure 10: Mixed network

- A token ring with pure optical nodes is also possible if a logic circuit is inserted between the optical transmitter and receiver modules. This allows for an overall ring length of

35 m with the introduced optical-two-TTL modules (fig. 11).

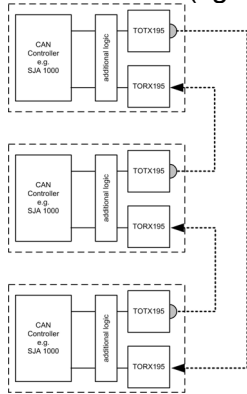


Figure 11: Optical token ring network

Measurement

Fig. 19 (last page) shows the communication structure of the hybrid drive-train testbed. The figures 1 and 2 identify two optical sub-segments. The sub-segment 2 also connects three commercial electrical CAN nodes with minibridges to an active hub.

Fig. 12 shows a screenshot of the CANalyzer during high bus loads running with 1 Mbit/s bus speed. Due to the short delay times of the electric circuits and the optical hub no error frames are produced. In these measurements the CANalyzer was connected to the electrical uplink and four optical nodes were connected to the optical hub.

| Busstatistik | | | |
|---------------------|--------|--------|-------------------|
| | CAN 1 | CAN 2 | LIN 1 |
| Busload [%] | 98.79 | 0.00 | Busload [%] |
| Peakload [%] | 98.99 | 0.00 | Peakload [%] |
| Std. Data [fr/s] | 0 | 0 | Data [fr/s] |
| Std. Data [total] | 0 | 0 | Data [total] |
| Ext. Data [fr/s] | 10145 | 0 | TransmErr [err/s] |
| Ext. Data [total] | 637777 | 0 | TransmErr [total] |
| Std. Remote [fr/s] | 0 | 0 | CSErr [err/s] |
| Std. Remote [total] | 0 | 0 | CSErr [total] |
| Ext. Remote [fr/s] | 0 | 0 | RcvErr [err/s] |
| Ext. Remote [total] | 0 | 0 | RcvErr [total] |
| Errorframe [fr/s] | 0 | 0 | SyncErr [err/s] |
| Errorframe [total] | 0 | 0 | SyncErr [total] |
| Chip state | Active | Active | Wakeup [total] |
| | | | Chip state |

Figure 12: CANalyzer screenshot of optical hub (high bus load)

A major challenge is to ensure short time delays between receiver and transmitter modules. Fig. 13 shows a measurement of the delay time between the TTL input and TTL output of the logic device.

The overall time delay produced by the logic device is 22 ns with the electrical uplink switched off.

Fig. 14 shows a measurement between electrical CAN and TTL output pin of the optical hub with an optical transmitter

module connected. The time delay is expanded to 60 ns. This is because the electrical transceiver delays the rising edge up to 40 ns.

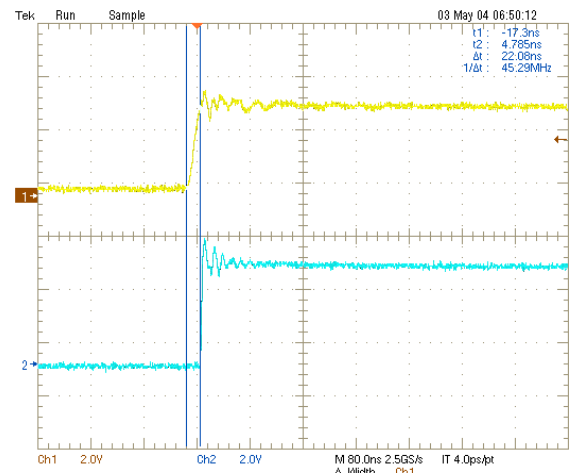


Figure 13: Delay time between TTL transmitter and receiver pins of CPLD (electrical uplink switched off)

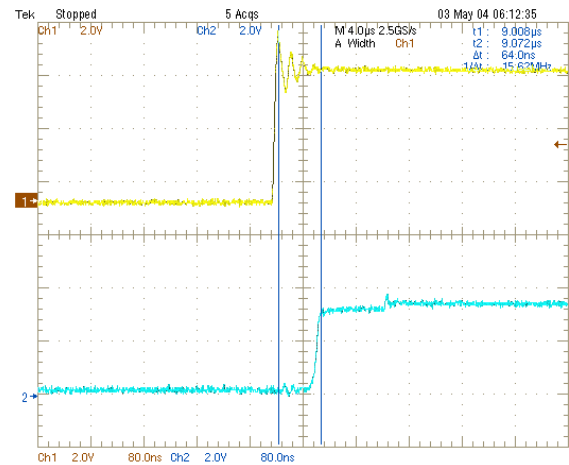


Figure 14: Delay time between electrical transmitter and optical receiver (used as a sub-segment)

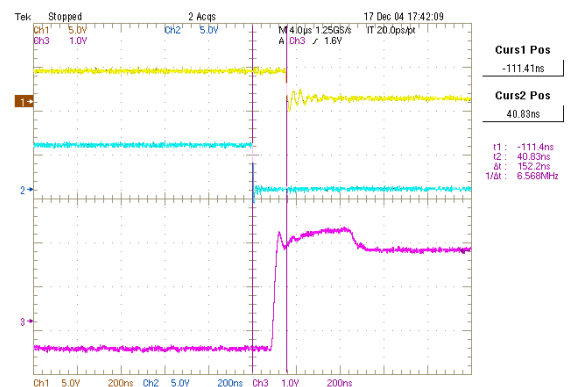


Figure 15: Delay time between two optical nodes with a cable length of 3 m each

The two top curves in fig. 15 show a measurement between the TTL signals of the optical transmitter of one node and the optical receiver of another node. Both of the nodes were connected with two POFs of 3 m each. The measuring points were the TTL input and output of the optical modules respectively. The bottom curve shows the response of the electrical CAN to the incoming signal into the passive hub.

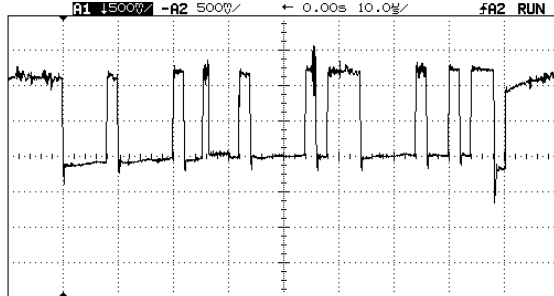


Figure 16: CAN with DC/DC converter switched off (bad shielding)

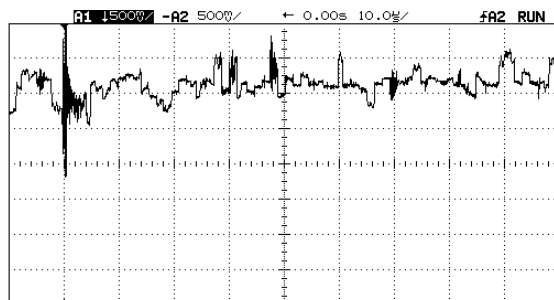


Figure 17: CAN with DC/DC converter operating (bad shielding)

Fig. 16 and fig. 17 show a measurement where badly shielded nodes were placed near the DC/DC converter which transforms a dc link voltage of 150 V to a second dc link voltage of 640 V with a peak power output of 40 kW at a switching frequency of 4 kHz. The same measurement is shown in fig. 18 where all nodes that are exposed to high level EMI are connected optically.

Summary

Employing optical connections between CAN nodes ensure reliable CAN communication even under high level EMI conditions with a minimum of modifications of the existing electrical CAN network. Using star topology it is possible to reach unfavorably positioned nodes without exceeding the maximum cable length. The

electrical uplink allows to incorporate an existing electrical CAN network and expand it by optical sub-segments. For connection of single CAN nodes into existing electrical CAN networks a minibridge can be used, thereby avoiding electrical branch lines.

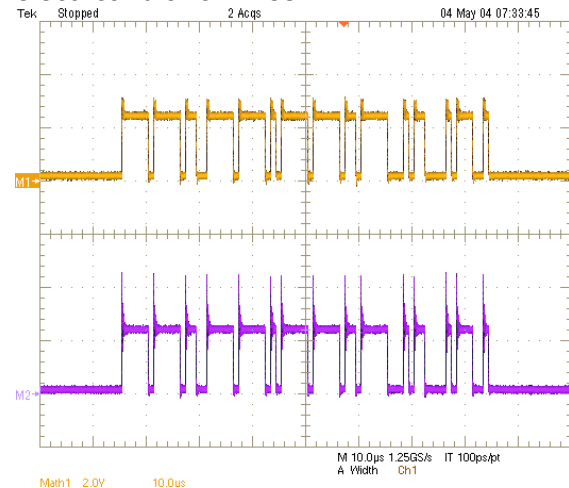


Figure 18: CAN messages where nodes exposed to high level EMI are optically connected

Replacing electrical CAN connections in heavily EMI-polluted areas by optical connections the signal-to-noise ratio can be highly improved.

To ensure reliable recognition of low priority messages which may be a problem if standard industry CAN nodes are incorporated into the system so far a more advanced solution is being developed.

Reference

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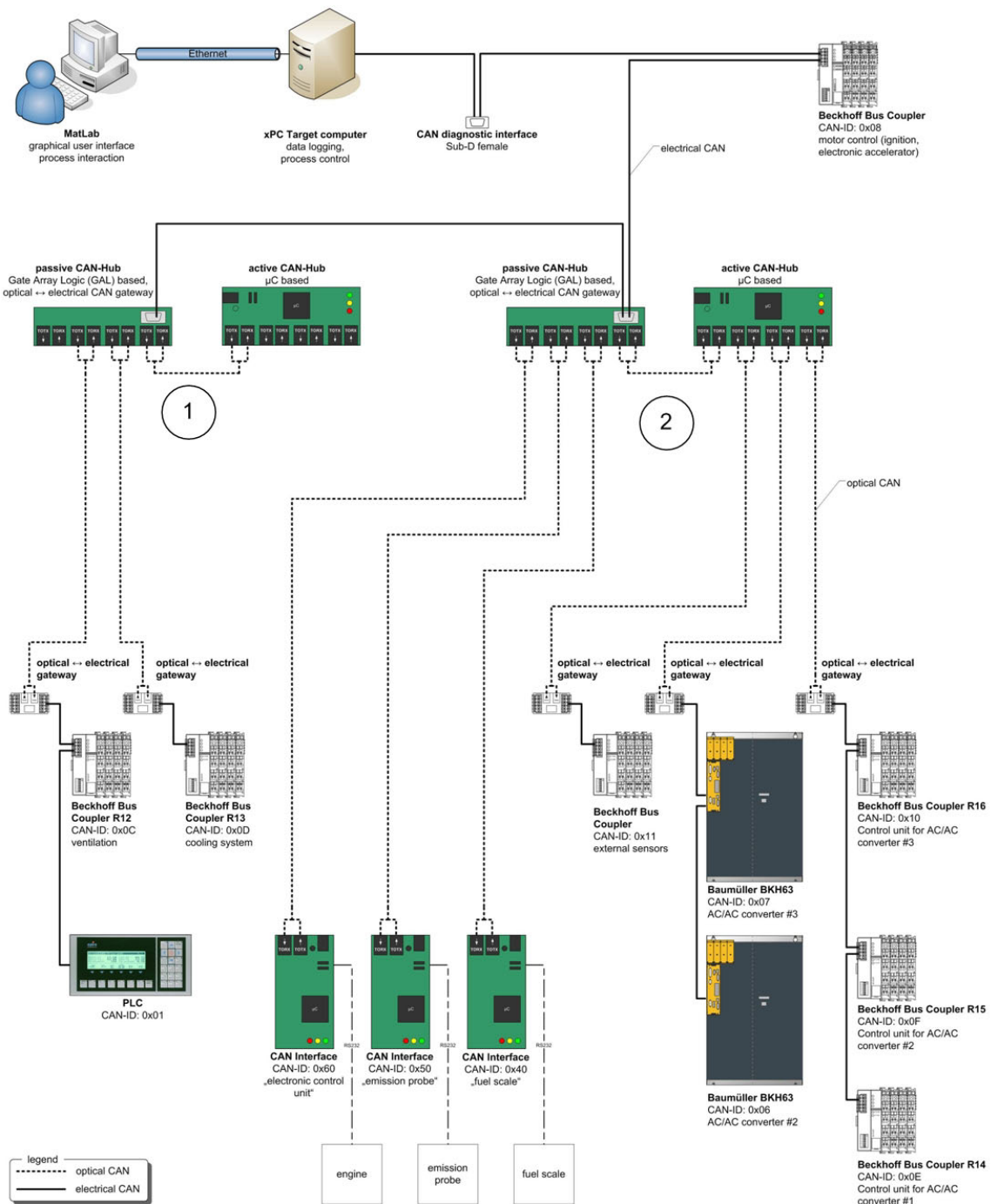


Figure 19: Communication structure of hybrid testbed