Comparison of system level networking solutions with high-speed CAN networks

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There are applications, where both maximum available bandwidth and reliability are needed. In those applications many issues - like effects of harsh environment, power supply, network length, available bandwidth, bus load, bus topology - must be taken into account to meet the requirements.

There are different solutions to build CAN-networks and every solution has it's own benefits and drawbacks. The packet structure of CAN frames causes most of the limitations, when compared i.e. with Ethernet. Especially with high bit rates, up to 1 Mb/s, those limitations force to very careful network design.

This paper will present, that in all selections of networking solutions must be done by taking into account the requirements of the application. Bus, star and tree topologies are examined with active and passive HUBs, repeaters and switches and many pitfalls are found and analyzed. In high speed CAN-networks, inter-segment routing has been found to be one of the most reliable implementation in complex systems.

Based on the comparisons can be stated, that the most general solution for combining high-speed CAN-segments, which also meets standards, is to use switches with fully isolated CAN-interfaces. Those systems are electrically reliable, easy to assemble and terminate and maintain over system's life cycle.

Introduction

There are many solutions for cabling CAN-networks, most of them have been used with low speeds and/or fault tolerant CAN. High baud rates are needed because of various reasons:

- Closed-loop control in the subsystem buses
- Multiplexing many parallel manual drive demands
- System-level information sharing over backbone bus of the system

This paper will compare the different topologies from high-speed CAN point of view. The measurements and simulations presented in this paper are focused to system level instead of transmission line level. A primary target has been to find out solutions for implementation of different topologies for up to 1Mbps baud rate and without decreasing the 25m maximum bus length.

Because the system integration and life cycle control of the systems have been the primary points of view, common standards have been used as primary references.

Linear topology

Linear topology is the only one defined in standards /9,10,13,14/ and other approved specifications /8,11,12/. The maximum length of the linear bus is inversely dependent on the baud rate used. Maximum amount of nodes connected to the bus is primarily limited by fan-out of the transceivers /1,2,3,4/.

The linear bus must be terminated in both ends with resistors so, that the net impedance of the bus is 50..65Ω. Size of the termination resistors depends on /12/:

- Amount of nodes connected to the bus
- Bus length
- Transceiver fan-out
- Cable impedance

Use of split-termination concept improves noise immunity of the bus and signal symmetry around the recessive level /5/ in conjunction with high-end transceivers /4/. The effect of the split termination compared with standard single resistor one is presented by Figures 1 and 2. Even better EMC-performance can be achieved by terminating all nodes so, that the total impedance do not exceed the specified range /5/. Terminating all nodes is difficult in mass production, because the size of the terminators vary in function of node count.

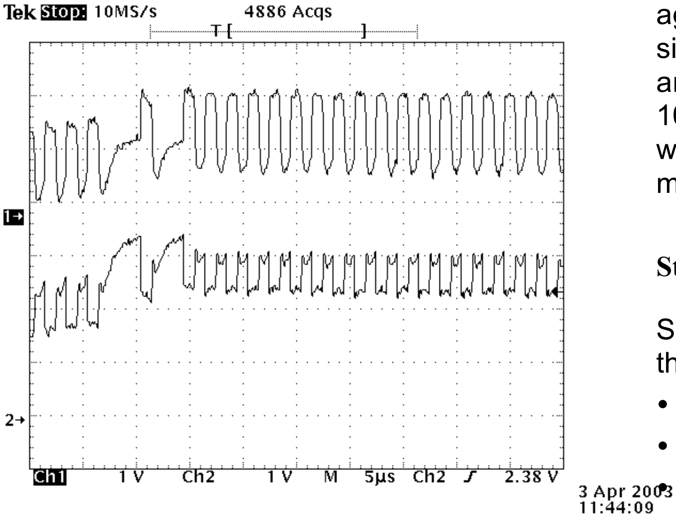

Figure 1: 1Mbps bus with single resistor termination

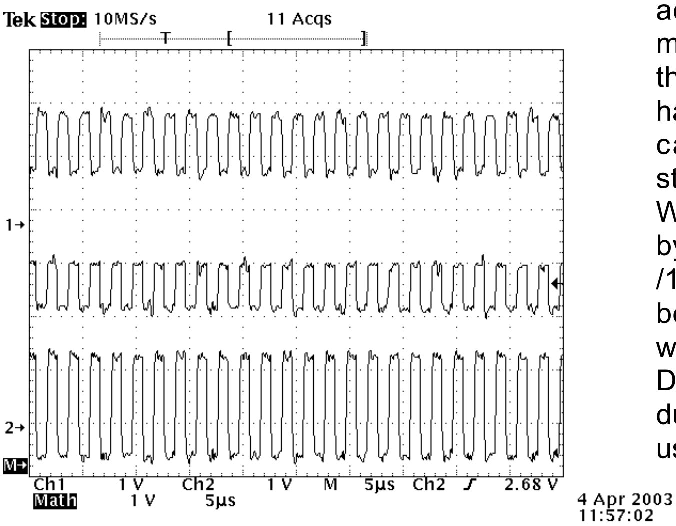

Figure 2: 1Mbps bus with split termination

There are very detailed specifications available for constructing correctly operating linear CAN-networks, containing also limitations for disturbing things, like unterminated stub lines /10,12,14/.

Supplying power for nodes via CAN-cable may cause problems with nodes consuming high currents. Voltage drop in the bus cable must not exceed specified 2V between any two nodes in the galvanic bus segment. Ringing, transients and voltage variations between nodes may also disturb the data transmissions. The low-cost solution is to use separate power supply and signal ground wires. A special care must be taken, that transient protection components do not provide alternative current return paths through signal wires. The optimal solution is to galvanically isolate CAN from the other system. That kind of isolation protects against unusual return current paths and signal ground level jitter. With state-of-the-art high-speed digital isolators, less than 10ns propagation delay /7/ of the isolation will not significantly decrease the maximum equivalent bus length.

Star with passive HUB

Star topology can be used with CAN, but there are many limiting issues:

- Reflections
- Application specific termination
- Transceiver fan-out

In theory, the star topology would increase reliability if it could be implemented according to standards. Reflections are more difficult to control if compared with the linear topology. Most of star networks have their own termination scheme, which can not be standardized without standardizing the physical structure /15/. When the reliability will be tried to improve by enabling disconnecting faulty branches /16/, the terminator of the branch will also be disconnected and the bus impedance will no more meet specifications. Determining faulty branch will take time, during which none of the branches can be used for operational data transmissions.

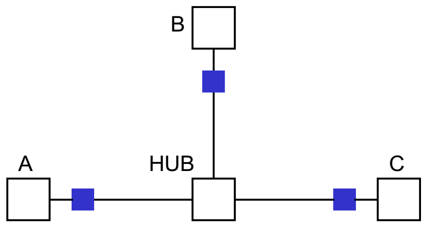

Figure 3: Star-topology with passive HUB

There are simulation- and test results of using termination in the HUB, but that kind of solutions limit both baud rate and length of the branches and net length of the galvanic bus /15/.

Using star-topology will provide more convenient cabling structure and -work, but it does not meet the physical layer specifications /8,10,14/. Tree topology is much more complex than star and a reliably working network can not be constructed with passive HUBs, which can be seen from results in Table 1.

Test	Total frames	Error frames
Linear (reference)	5792188	0
All 3-branches	5786427	0
2-of-3 branches	5265299	3
3-of-4 branches	5027815	376

Table 1: Passive HUB test statistics

The results in Table 1 has been measured at 1Mbps baud rate and 43% bus load. Figures 4 and 5 show, how the location of the transmitting node in the star network can affect on the quality of the signal. Both signals have been captured from network with all branches connected and properly terminated.

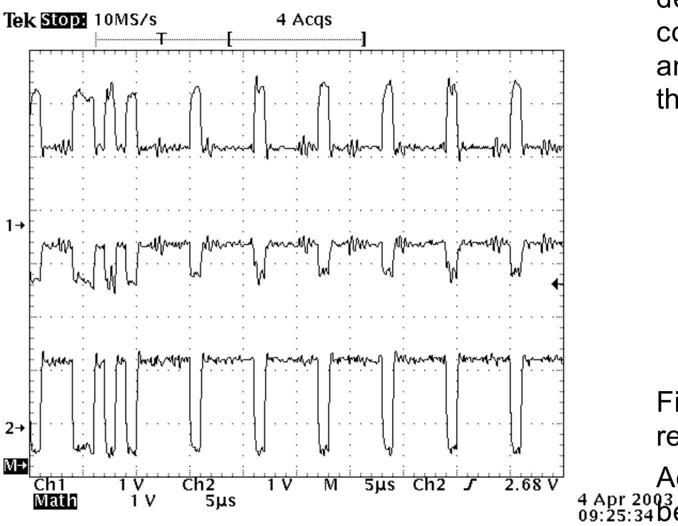

Figure 4: Better signal captured from star

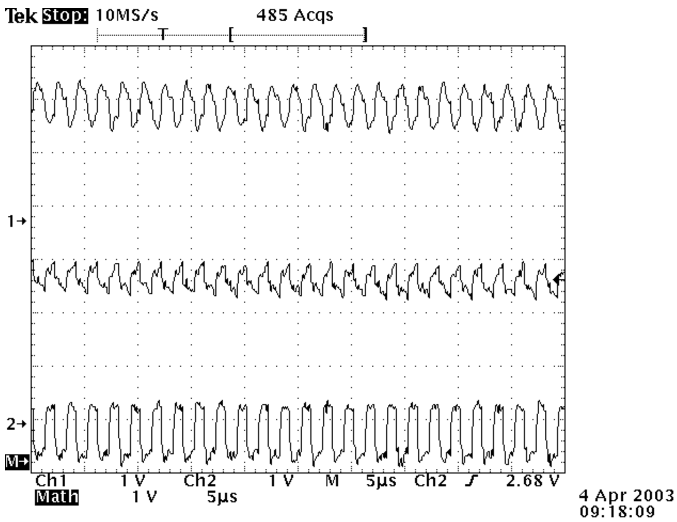

Figure 5: Worse signal captured from star

Star topology with repeaters

Repeaters solve the termination problems mentioned before – every bus segment has individual terminators (small boxes in the Figure 6). Because a repeater is an active element, it has internal propagation delay which will limit the baud rate in conjunction with timing requirements of arbitration and in-frame acknowledging of the CAN physical layer protocol.

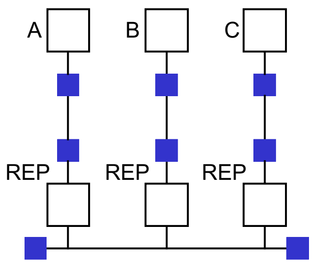

Figure 6: Star topology implemented with repeaters

According to Figure 6, when data have to be transmitted from one bus to another, the frames have to go through two consecutive repeaters, both limiting the baud rate. The limitation is directed on the propagation segment inside the bit-time of the CAN /8,9/.

According to the specifications of device manufacturers, star network implementations with repeaters can be used only with lower baud rates, 800kbps and lower /17,18/. Repeaters have not been tested because of the restrictions and the similarity to the active HUB.

Star topology with active HUB

Compared with the repeater, active hub is more efficient element - in star with repeaters, data from one branch to another must go through two consecutive networking elements and in star with active HUB, that data must go only through one networking element. Still the HUB can not handle dominant level echoes from branch to branch faster than repeater, because the net loop delay of the transceiver and bus cabling propagation delay are the most critical parameters.

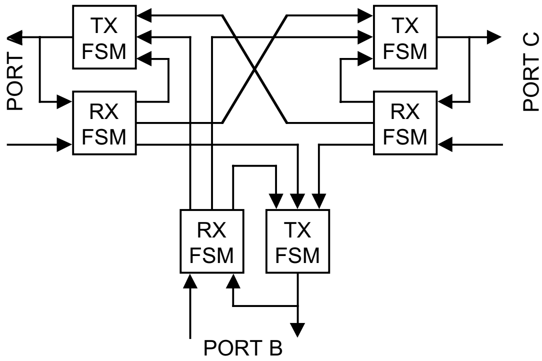

Figure 7: Structure of active HUB

The receiver FSM will recognize whether the dominant state of the current bus segment is transmitted from an external node. If so, the dominant state will be echoed to other ports (ECHO-state). If current state is a consequence of an echo from other port, echo is not generated (PASS-state). WAIT-states are modeling the delay required for waiting over the net loop delay of a branch.

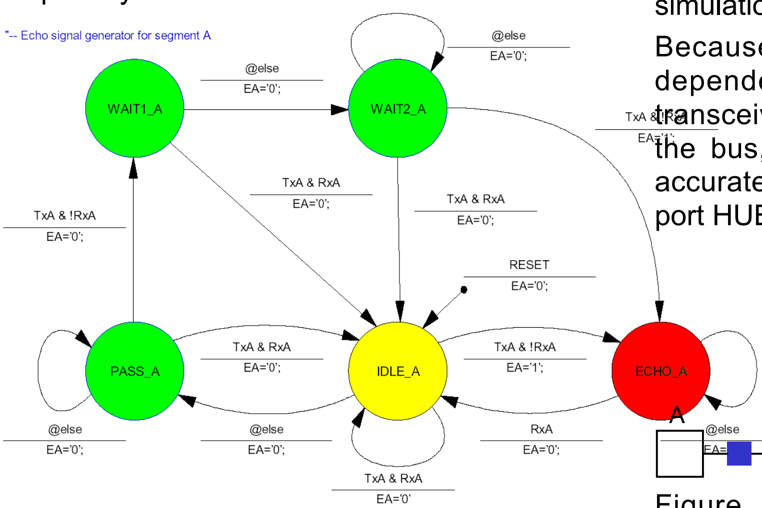

Figure 8: Port receiver state-machine

Transmitter state-machine handles the dominant state transmission based on the echo signals of all ports and prevents infinite echo feedback.

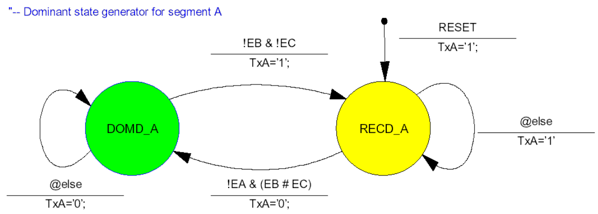

Figure 9: Port transmitter state-machine

Active CAN-HUB for ISO11898 physical layer was not found as a commercial product and therefore a conceptual simulation model was developed. The model has been created as finite state machines into StateCAD/StateBench-environment.

The idea of the active HUB is to:

- Isolate different branches physically (also galvanic isolation possible)
- Echo dominant levels between branches without possibility to a hang-up caused by infinite feedback

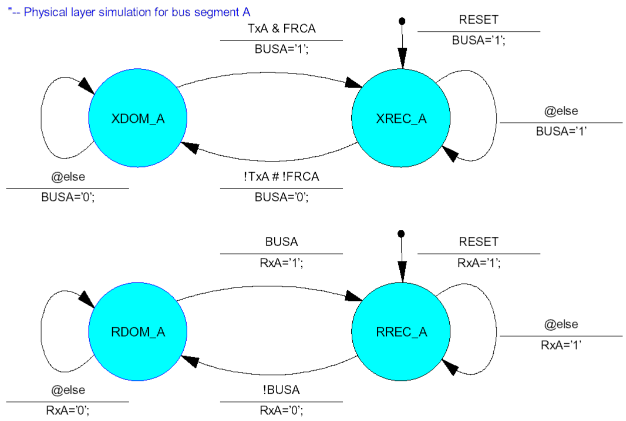

Figure 10: Simplified physical layer simulation model for one branch

Because active HUB concept is only dependent on the loop delay of the transceiver and the propagation delay of the bus, very rough behavioral model is accurate enough. For simplicity, only a 3-port HUB design was simulated.

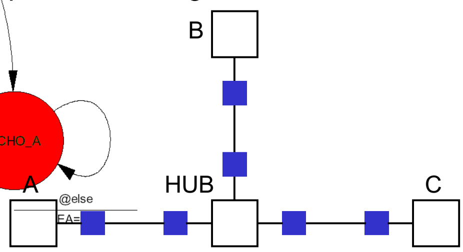

Figure 11: Structure of the simulated virtual network

Notice, that using the active HUB, the topology of every physical bus remain linear and all issues concerning about linear structure are valid. The small boxes in the Figure 11 represent termination resistors.

From the simulation results can be seen, that the active HUB concept works well, but radically limits the maximum baud rate. The limit is caused by double length propagation delay /8,9/ in certain situations. In the Figures 12 and 13 the solid line presents the bus status received by the HUB and the dashed line the bus status forced by the HUB.

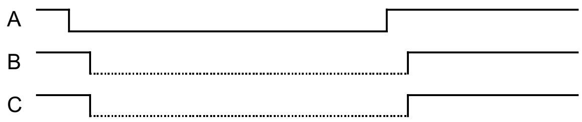

Figure 12: Normal dominant state echoing from branch to another

In the easiest case, shown in Figure 12, only one node is transmitting at a time, when the dominant states from one branch are directly echoed to other branches. In this kind of echoing, additional waits are not needed.

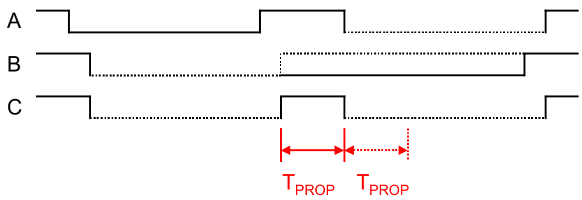

Figure 13: Echoing of overlapping dominant states between branches

In the most complex case shown in the Figure 13, dominant states from two or more branches are partially overlapped. At the end of the dominant state of one branch, additional delay occurs before the system can echo dominant state from the other branch. The difference between states of TxD and RxD after loop delay of a bus is the only way to determine, if there is a node forcing a branch to dominant state (marked with solid arrow in the previous Figure). During the loop delay time, the bus can settle after removed echo from the HUB. Another loop delay (marked with the dashed arrow in the Figure) is needed to allow other branches to settle before sampling. The result is *doubled propagation segment* in CAN physical layer timing.

Star topology by switch

Switched networks are de-facto with Ethernet and TCP/IP-protocol suite, but with fieldbuses they are less used. Using active data routing element for connecting one or more bus segments together allows each segment to have different frame transmission rate, baud rate, higher level protocol, identifier length and physical layer /19/. Bus segments can also be galvanically isolated from each other to provide maximum level of signal integrity and protection against power supply failures. Maximum coverage is also reached because of the separate physical buses. Every bus can connect maximum amount of nodes and maximum length limited by the baud rate can be used in every individual bus.

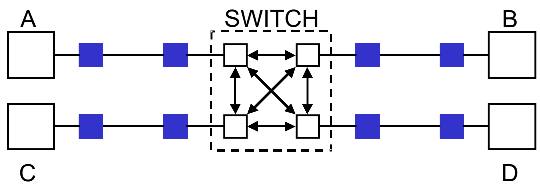

Figure 14: Star topology implemented with switch

The only limitations for switched CAN-networks come from application, not from CAN-timing requirements. If timing framework of the application allows, any topology can be implemented with switch elements. The only drawback of the switch is unit cost - every port in the switch needs own CAN-controller, transceiver and isolator(s) and isolated physical layer power supplies if galvanic isolation is used.

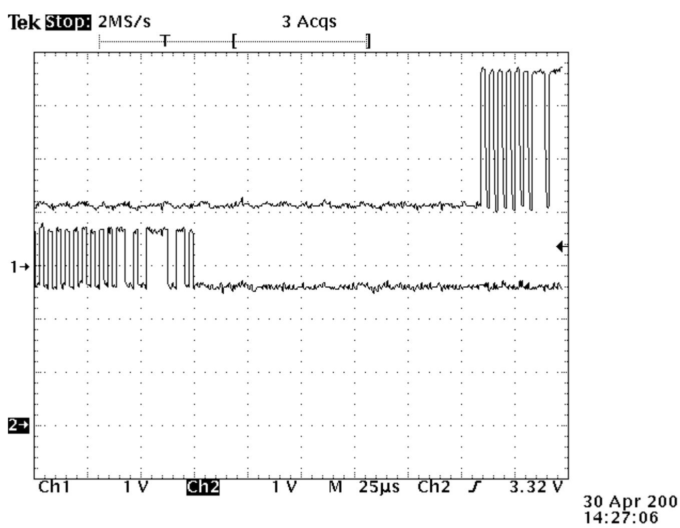

Figure 15: 135µs routing delay of the switch

There are not big differences between MCU- and PLD-based implementation, because MCUs contain maximum 3 CAN-controller per chip and for multi-port switch external CAN-controllers are needed. The best performance is reached of course with PLD-based solution, where the data routing engine and CAN-interfaces are made by SIP (silicon intellectual property)-blocks. In that kind of platform, active HUB and switch functions can be combined according to the application requirements.

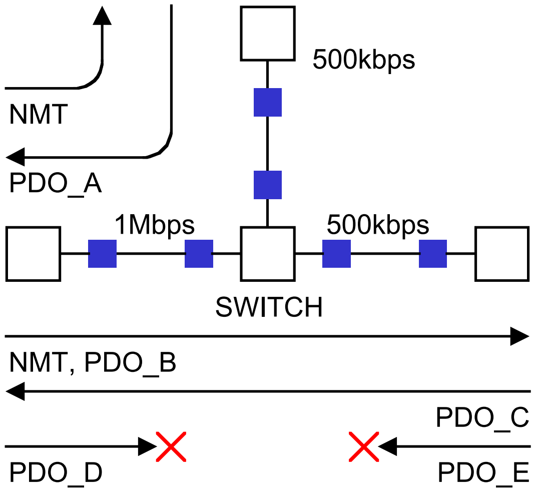

Figure 16: Load distribution by switch

The test switch unit operated fully according to the Figure 15. Due to arbitration, the intervals of some messages varied ±1ms from the nominal 10ms transmission interval with software filtering only. The switch also supports user configurable hardware filtering. The actual performance will be so application dependent, that the total performance test has not been performed.

The net bus length can be multiplied by amount of channels, because every bus segment is independent from the others, also logically. Any error in one bus segment will not disturb message transfer between other bus segments. Only messages normally received from the faulty channel are disappearing from the target channels, when ASAP transmission policy is used. The use of cyclic transmission type has to be avoided if heartbeat or node guarding is not used, because out of date signals would be sent without any indication of data validity.

Coverage

When actual coverage of the galvanic star is compared with the coverage of the linear bus, one must remember that the net bus length of the star must be 75% of the maximum bus length of the linear bus /15/. The example structures are typical in the machine instrumentation.

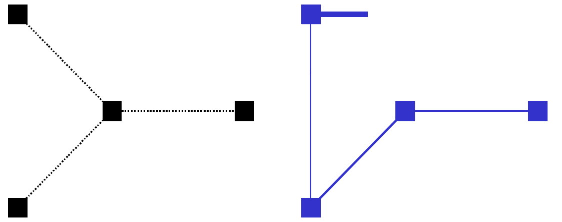

Figure 17: Comparison of connecting 4 nodes

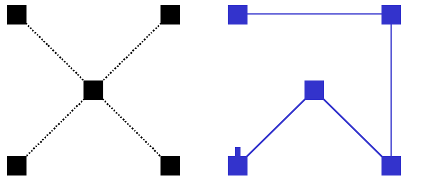

Figure 18: Comparison of connecting 5 nodes

Figures 17 and 18 show, that connecting nodes in equal structures, the star topology (left) has slightly smaller coverage than the linear structure (right). The bold lines present the unused part of the linear bus when all nodes are connected with a maximum length bus.

When a star is constructed with repeaters, the coverage will be in high baud rates approximately equal to the star topology because of the bus length reduction caused by the propagation delay of the repeater(s). In lower baud rates the reduction will decrease, because the propagation delays of the repeaters are much shorter than the propagation delay of the buses.

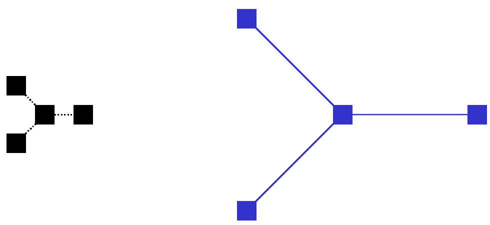

Figure 19: Coverage comparison between galvanic and switched star

Figure 19 shows the difference in coverage between galvanic star and similar structure implemented with switch. The branch lengths are 4 times longer in switched network compared with the galvanic star.

Conclusions

Based on the literature review, simulations and measurements presented in this document, the most reliable and flexible networking element for high-speed CAN-networks is a switch. With switch, different baud rates, frame schedules, higher level protocols, physical layers and even ground domains can be connected together without conflicts. The only limitation is the propagation delay of the switch compared with the propagation delay margins of the application. All bus segments fully meet CAN-specifications and standardized cables, terminators and connecting rules can be utilized. With switch, any topology can be created and only an application can cause restrictions, not CAN.

For lower baud rates, active HUBs and/or repeaters can be used, but timing requirements of CAN-frame must be met. With both active HUBs and repeaters galvanic isolation can be utilized for dividing systems into separate ground domains. With active HUBs/repeaters the maximum galvanic length of the buses is determined through timing, but every branch can connect maximum amount of nodes.

Passive HUBs or junction boxes can not be recommended, because CAN specifications don't allow use of other galvanic topologies than linear. The test results in this document support the literature, where star topology has been found problematic with 500kbps and higher baud rates. For galvanic star structure, maximum node amount is reduced from maximum node count of the linear bus and the total bus length should be reduced from the maximum length derived from baud rate.

Galvanic isolation will be needed in general to protect the nodes against reverse supply through protection components by separating signal and supply grounds.

Discussion

Configurable hardware, like FPGA or CPLD, is the most flexible platform for networking device implementations. Implementing an active HUB or repeater will leave more space for other processing elements, but will provide less flexibility. Although the switch implementation consumes much silicon resources, it will provide the maximum flexibility and performance for networking with the minimum amount of components.

Configurable hardware allows any kind of combinations of HUBs and switches to reach the 100% response for the requirements.

Microcontrollers and embedded DSPs will offer easier approach for building mobile processing platforms with high processing performance combined with single or multiple on-chip CAN controllers.

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