Application Report

SLLA279A–November 2008–Revised January 2009

Critical Spacing of CAN Bus Connections

Steve Corrigan *HPL - Industrial Interface*

ABSTRACT

This application report presents guidelines for the spacing of CAN nodes along a bus based on the lumped load capacitance of the system.

Errors such as "message priority inversion" in which high-priority messages receive low-priority placement in a queue of messages waiting to be transmitted by a controller are commonly found on buses with unevenly spaced node clusters.

CAN buses are constructed with many nodes that are often placed physically close together. When these clumps of nodes are spaced a relatively long distance from other nodes, random data errors can be generated that are not easily uncovered by a system designer.

Contents

List of Figures

1 Minimum Distance Between Node Connections

The ISO-11898-2:2003 CAN bus is a distributed parameter circuit whose electrical characteristics and responses are primarily defined by the distributed inductance and capacitance[(1)] along the physical media. The media is defined here as the interconnecting cable or conducting paths, connectors, terminators, and CAN devices added along the bus.

The following analysis uncovers a trade-off between the amount of node capacitance that can be added and the node spacing on a bus while maintaining signal integrity. For a good approximation, the characteristic transmission line impedance seen into any cut point in an unloaded CAN bus is defined by $Z = \sqrt{L/C}$, where L is the inductance per unit length and C is the capacitance per unit length. As capacitance is added to the bus in the form of devices and their interconnection, the bus impedance is lowered to Z'. When the bus impedance is lowered, an impedance mismatch occurs between unloaded and loaded sections of the bus.

(1) All capacitances are differential in this report. The differential is approximately one-half of the single-ended capacitance.

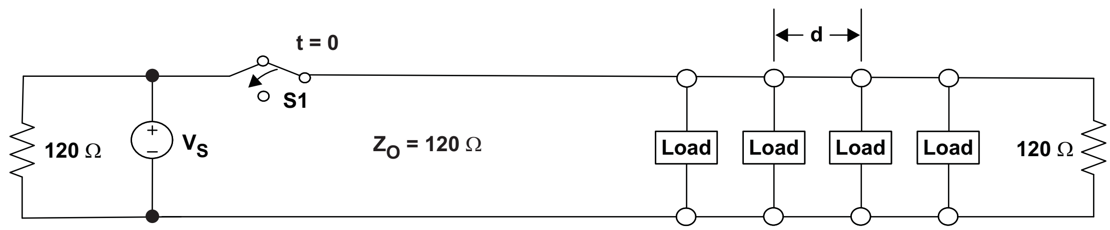

Figure 1. Imbalanced CAN Bus Schematic Diagram

A worst-case occurrence is during an arbitration when multiple dominant bits are simultaneously sent from two or more nodes. In Figure 1, when S1 switches at time zero from a dominant state to a recessive state, the CAN driver differential output voltage, V_S, moves from a dominant state to steady-state 0-V recessive differential signal on the bus. As this signal wave propagates down the line and arrives at the loaded section of the bus, the mismatch in impedance reflects the voltage back towards the source.

See the Appendix for a mathematical derivation of this condition.

The minimum safe distance between nodes, d, is a function of the device lumped load capacitance C_L, and the cable's distributed capacitance per unit length, C,

where $d > \frac{C_L}{0.98C}$ meters (if C is pF/m) or feet (if C is pF/ft).

Figure 2 displays this relationship graphically.

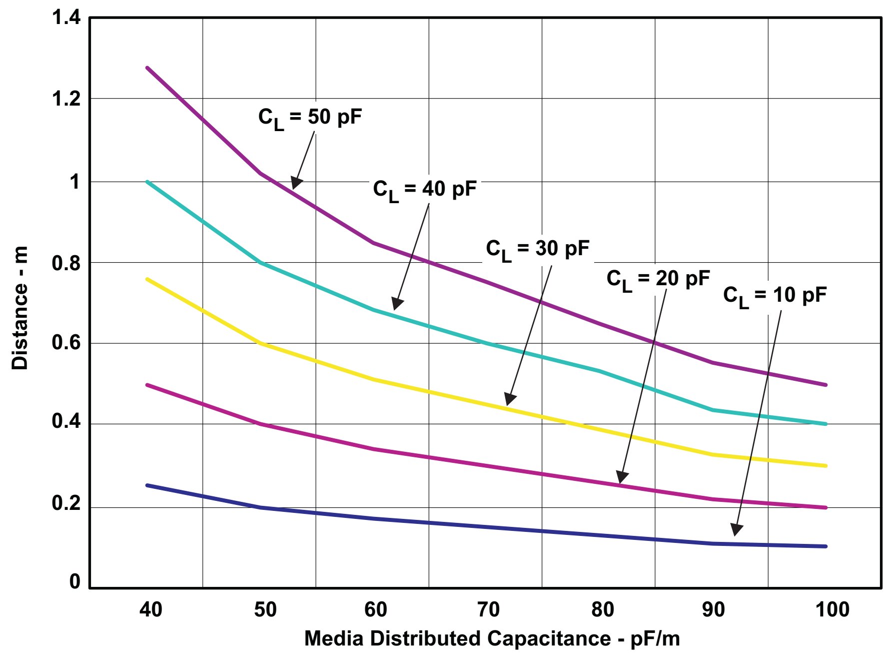

Figure 2. Minimum CAN Device Spacing

Load capacitance includes contributions from the CAN transceiver bus pins, connector contacts, printed-circuit board traces, protection devices, and any other physical connections as long as the distance from the bus to the transceiver is electrically short.

The 3.3-V supplied CAN transceivers, such as the SN65HVD233 used in this example, have about 16 pF of differential capacitance. Board traces add about 0.5 pF/cm to 0.8 pF/cm depending on their construction. Connector and suppression device capacitance can vary widely and media distributed capacitance ranges from about 35 pF/m for low-capacitance, shielded-twisted-pair cable to 70 pF/m for backplanes.

As a demonstration of this condition, Figure 3 displays 10 SN65HVD233 CAN transceivers connected to the bus with 5 inches of 120-Ω, twisted-pair cable between each node. The last node of the group is terminated with a 120-Ω termination resistor and the first node is connected through an additional 200 m of Belden 3105A twisted-pair cable to another node and terminated.

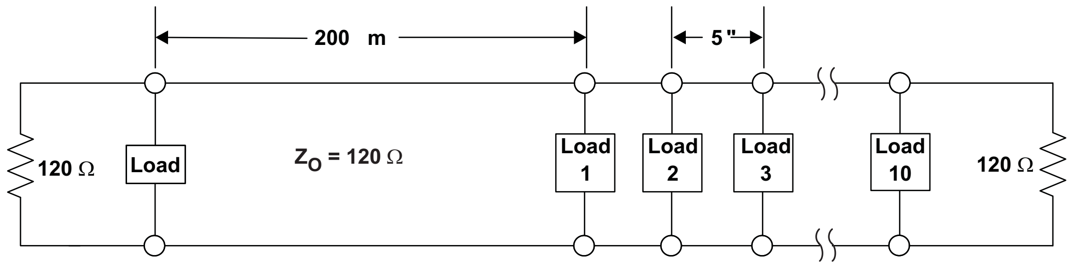

Figure 3. Capacitive Load Example

Figure 4 displays the receiving waveforms of the 250-kbps data being transmitted onto the bus from the single-node load to the capacitive clump of nodes over the 200-m cable.

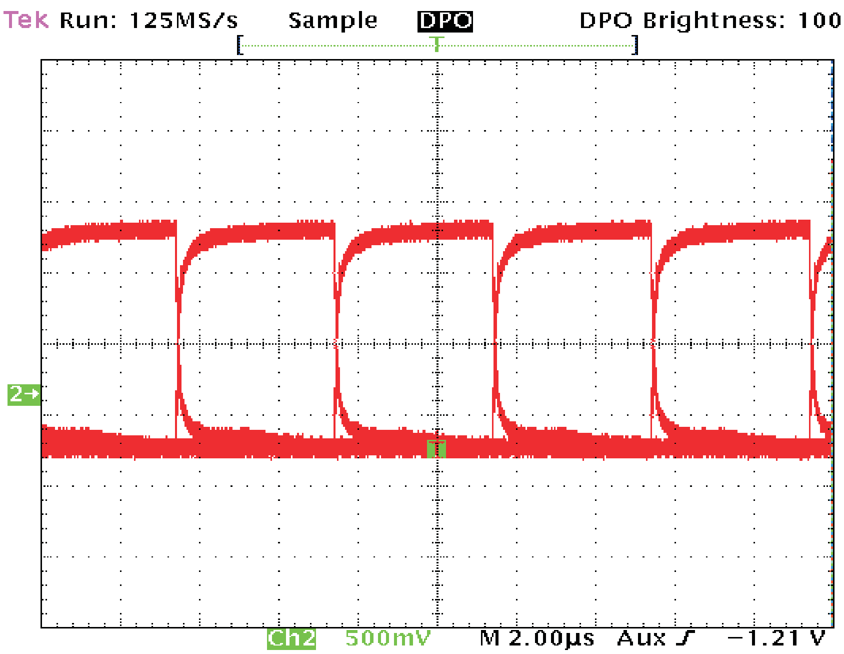

Figure 4. Normal Data Transfer

Figure 5 displays the same waveform when more than one node sends a dominant bit onto the bus during an arbitration. Note the change in magnitude when more than one node is sending a dominant bit. The propagation delay of 5 ns per meter for 200 m is 1000 ns, or 1 µs, and is clearly evident in each of the waveforms.

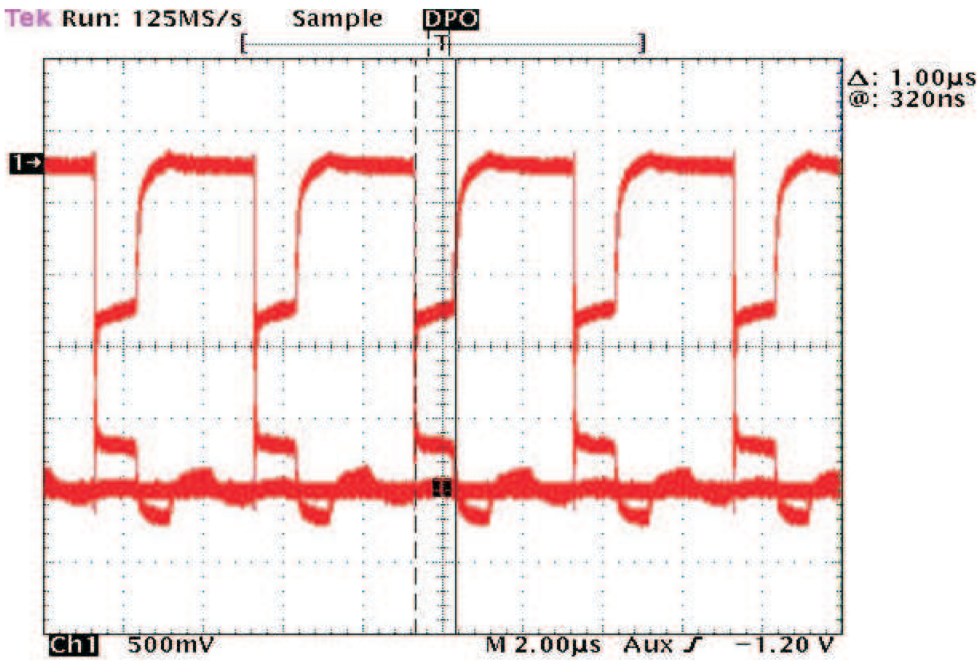

Figure 5. Multiple Dominant-Bit Distortion

The negatively charged waveform is reflected back and attenuates the waveform at the receiving clump of nodes. Figure 6 and Figure 7 present a higher resolution of this reflection.

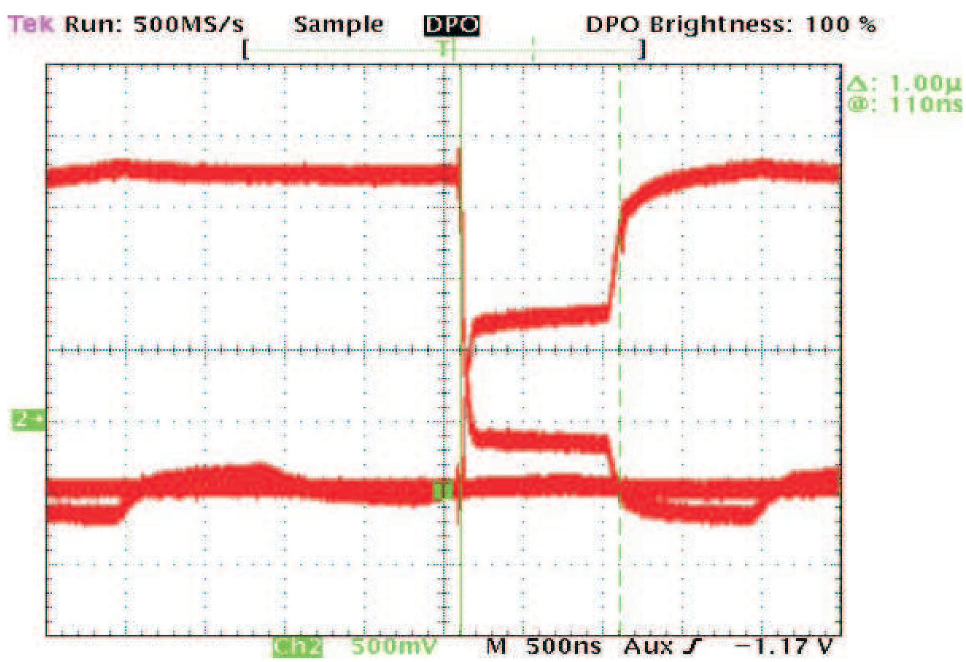

Figure 6. Multiple Dominant-Bit Reflected Wave

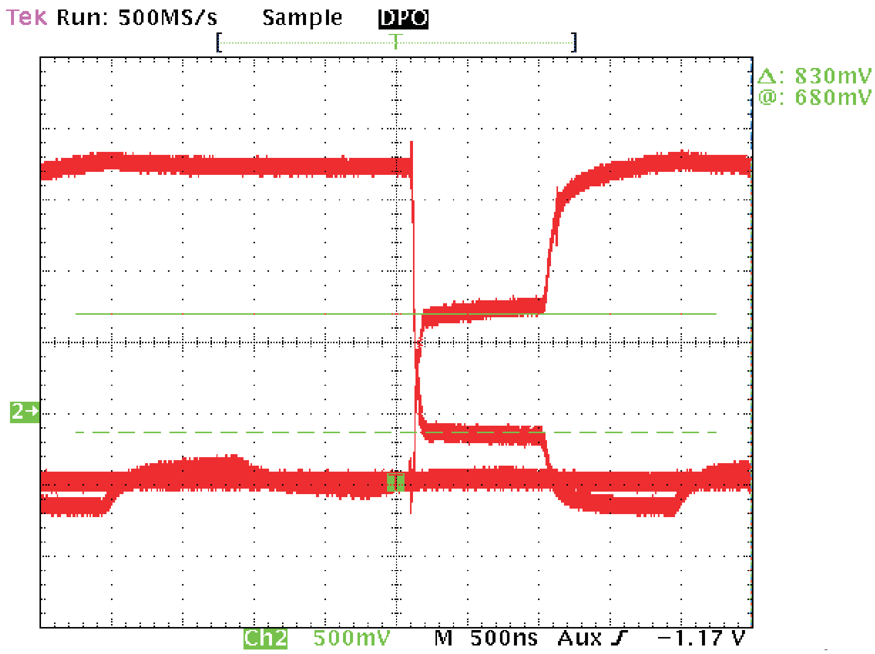

Figure 7. Multiple Dominant-Bit Negative Voltage Reduction

Figure 7 exemplifies the possible arbitration bit-error problem since the waveform voltage due to the negative reflection reduces the differential voltage magnitude of the signal below the 900-mV dominant-bit threshold. The dominant threshold may or may not be reached for the last 1 µs of the bit, and can possibly affect the sync seg of the bit. If the signaling rate is increased to 500 kbps, this reflection lasts for 50% of the 2-µs waveform. Note that is a simple bus structure and any long drop lines with additional nodes added to the bus increase the severity of the problem.

The lumped load capacitance, C_L of each CAN transceiver, board trace, and Berg connector amounts to approximately 20 pF per node in this example, and the distributed capacitance per unit length, C, is about 40 pF per meter. The calculations presented in Figure 2 for a C_L of 20 pF and a C of 40 pF indicate that a half-meter of cable added between each of the 10 clumped nodes in place of the 5-inch cable corrects the problem.

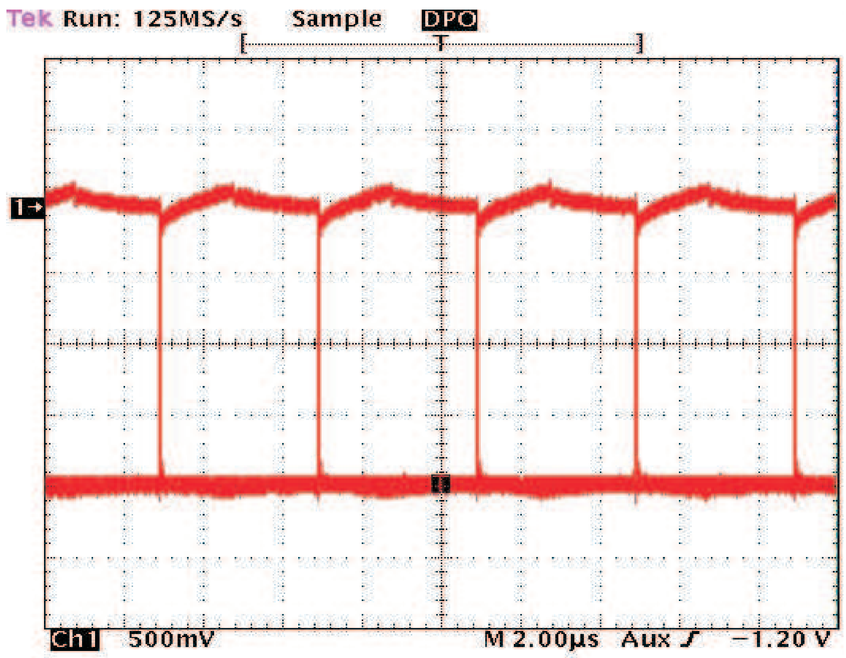

Figure 8. Half-Meter Bus Length Correction

2 Conclusion

Clearly, the calculations prove to be correct. The reflected wave has almost completely disappeared and the half-meter of twisted-pair cable rolls up neatly out of the way next to each node.

3 References

1. *High-Speed Digital Design : A Handbook of Black Magic*, Dr. Howard W. Johnson, ISBN 0-13-395724-1
2. *Using CAN Arbitration for Electrical Layer Testing* application report (SLLA123)
3. *ISO-11898-2:2003 CAN Specification*

Appendix A Mathematical Development of the Node Capacitance and Node Spacing Trade-off

The characteristic transmission line impedance that can be seen into any cut point in an unloaded CAN bus is defined by $Z = \sqrt{L/C}$, where L is the inductance per unit length and C is the capacitance per unit length. As capacitance is added to the bus, in the form of devices and their interconnection, the bus impedance is lowered to Z'. When the bus impedance is lowered on a section of the bus, an impedance mismatch occurs between unloaded and loaded sections of the bus.

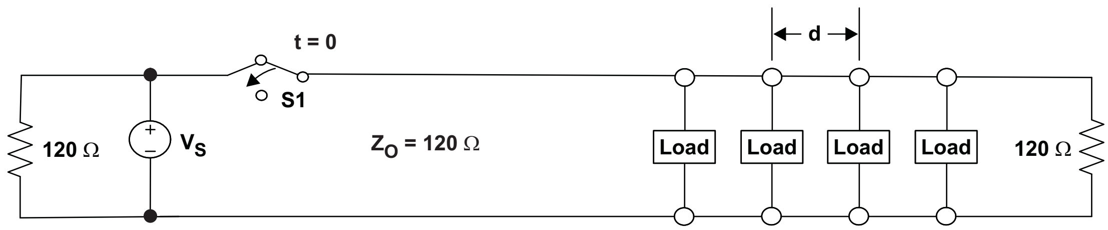

Figure A-1. CAN Bus Schematic Diagram

A worst-case occurrence is during a dominant-to-recessive transition during arbitration or an ACK bit. When S1 switches at time zero from a dominant state to a recessive steady state, the CAN driver differential output voltage, V_S, can move from a 3-V signal to a 0-V recessive state. As this signal wave propagates down the line and arrives at the loaded section of the bus, the mismatch in impedance reflects voltage back towards the source.

As the input signal wave arrives at this mismatch, an attenuation (or amplification) of the signal occurs.

The signal voltage at an impedance mismatch is $V_{L1} = V_{L0} + V_{J1} + V_{R1}$, where V_{L0} is the initial differential voltage, V_{J1} is the input signal differential voltage transition, and V_{R1} is the reflected differential voltage.

The voltage reflected back from the mismatch is $V_{R1} = pL \times V_{J1}$ where, $d > \frac{C_L}{0.98C}$ and is the coefficient of reflection commonly used in transmission line analysis. The voltage equation can now be written as

$V_{L1} = V_{L0} + V_{J1} + pL \times V_{J1}$.

Assuming the bus is terminated at both ends with the nominal media impedance, a CAN driver creates a high-to-low differential voltage change from the standard maximum of 3 V to 0 V, or a V_{J1} of -3 V. The signal voltage at the load, V_{L1}, must go below the receiver recessive bit input voltage threshold of 0.5 V. In equation form,

$$0.5 > 3 + (-3) + \rho_L \times (-3)$$

$$\rho_L > \frac{0.5}{-3} = -0.167 \qquad \text{(A-1)}$$

Now, solving for Z',

$$\rho_L = \frac{Z' - Z_0}{Z' + Z_0} > -0.167$$

$$Z' - Z_0 > -0.167(Z' + Z_0)$$

$$Z'(1 + 0.167) > Z_0(1 - 0.167)$$

$$Z' > 0.71Z_0 \qquad \text{(A-2)}$$

If the loaded bus impedance is no less than $0.71Z_0$, the minimum threshold level must be achieved on the incident wave under all allowed cases.

What bus configuration rules must be used to keep the loaded bus impedance above $0.71Z_0$?

In the derivation of the minimum loaded-bus impedance, treat the addition of devices and their capacitance in a distributed model. As such, the loaded-bus impedance can be approximated by

$Z' = \sqrt{L/(C + C')}$, where C' is the added capacitance per unit length. If the distributed inductance and capacitance of the media are known, Z' can be calculated directly. Unfortunately, these are not commonly specified by manufacturers. They generally do specify the characteristic impedance Z_0 and the capacitance per unit length, C. With these, one can solve for L, from the relationship $Z_0 = \sqrt{L/C}$, as $L = Z_0^2C$. Substituting into the equation for Z' and simplifying,

$$Z' = \sqrt{\frac{Z_0^2 C}{(C + C')}} = Z_0 \sqrt{\frac{C}{C + C'}} \tag{A-3}$$

C' is the distributed device capacitance, C_L, divided by the distance, d, between devices or $C' = C_L/d$. Substituting this into the equation and solving for d,

$$Z' = Z_0 \sqrt{\frac{C}{C + \frac{C_L}{d}}}$$

$$\left(\frac{Z'}{Z_0}\right)^2 = \frac{C}{C + \frac{C_L}{d}}$$

$$C\left(\frac{Z_0}{Z'}\right)^2 = C + \frac{C_L}{d}$$

$$d = \frac{C_L}{C\left(\left(\frac{Z_0}{Z'}\right)^2 - 1\right)} \tag{A-4}$$

Now, substituting the minimum Z' of $0.71Z_0$ gives,

$$d > \frac{C_L}{C\left(\left(\frac{Z_0}{0.71Z_0}\right)^2 - 1\right)} \text{ meters (if C is pF/m) or feet (if C is pF/ft)}$$

$$d > \frac{C_L}{0.98C} \tag{A-5}$$