Practical testing of the CAN physical layer

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The health of the physical layer of a CAN bus is important. The robustness of the CAN physical layer such as ISO 11898-2 cover up many electrical problems such as open, shorted, leaky, out-of-spec or unbalanced lines. The system reliability and stability can be reduced and may not be readily noticed and preventative testing should be done. Standard equipment such as voltmeters and standard oscilloscopes are limited in value for testing with CAN networks, because the data traffic on a CAN bus is not normally repetitive enough to make meaningful measurements as it would be with a steady state signal. Special techniques and equipment are necessary to effectively design and troubleshoot the physical layer of a CAN network.

Voltmeter

Voltage: At the idle or rest state, a digital voltmeter connected to the two CAN wires (CAN_H and CAN_L) will measure 0 V- this is the logical "1". With CAN messages present on the bus, the voltmeter will register 0.5 V or so depending on the nature of the bus traffic. This will be the average voltage differential of the bus less those effects too high in frequency for the voltmeter to respond to. This makes voltage readings almost useless for servicing CAN. A voltmeter will, however, effectively measure the DC offset of both wires of the differential CAN bus. The CAN bus will tolerate a DC offset to the design limits of the transceiver chip.

Resistance: Voltmeters are useful in detecting CAN line shorts to ground, battery or to each other using the Ohm-meter function. Typical default resistances are sometimes published by the equipment OEMs and will vary depending on the network design. There is normally 60 Ohm between the two wires of the bus. The network must be powered down to accurately measure the resistance of the CAN bus. Problems with voltage on the CAN bus: Ohm-meters will not give accurate readings if there is any voltage present on the bus. Ohm-meters work by putting a low DC voltage across a circuit and measuring the resulting current. The resistance in Ohm is calculated and displayed.

Therefore, an external voltage will cause an erroneous measurement by adding or subtracting to the Ohm-meter voltage.

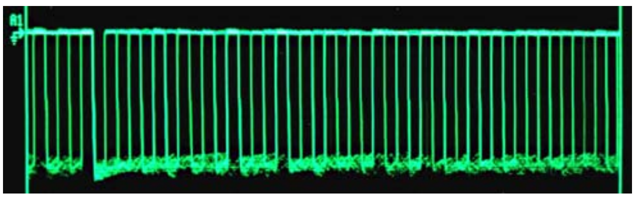


Fig. 1: Unsynchronized CAN frames on analog oscilloscope

A clue that network messages are present is if the Ohm-meter gives different resistance readings when the probes are reversed. If in doubt, use the voltmeter to test for zero Volt across the CAN lines and to the vehicle ground before making resistance measurements. To test the resistance from the voltage supply to either CAN_H or CAN_L, the supply must be disconnected. If not, these voltages will render resistance measurements useless.

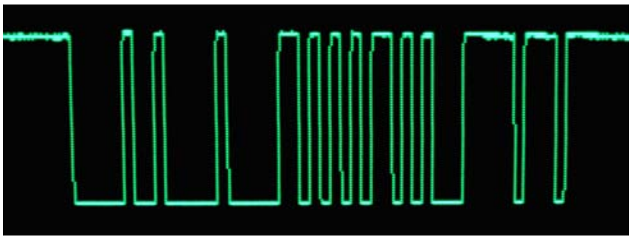


Fig. 2: Example CAN frame ID hex 010, data hex 55

Shorts and opens: The CAN controllers will tolerate a short circuit of one of the two lines to ground because of the characteristics of the differential bus. It cannot tolerate both CAN bus wires shorted to ground or to each other. It will tolerate one of the CAN lines being open or disconnected.

Corrosion of connectors and wires can cause a higher or lower resistance of the CAN bus and degrade the network. This would cause erratic or intermittent failures that are difficult to detect and diagnose. An Ohm-meter is the perfect instrument for detecting anomalous DC resistance values. You can tell a great deal about the functionality of a CAN network by its resistance values.

Termination resistors: The CAN specification requires a 120-Ohm termination resistor at each end of the CAN bus for termination. This will result in a resistance of about 60 Ohm across the CAN_H and CAN_L wires if these two resistors are installed. The load from the CAN nodes will lower this value further but only slightly.

Practical measurements example: On a new Toyota vehicle the resistance between the CAN lines was measured as 62 Ohm. From one CAN line to ground was 7 kOhm on one vehicle and 13 kOhm on another model. These values were well within the vehicles' specifications.

The resistance for the CAN lines to the battery was invalid due to the voltage issue as described above.

Frequency: Some voltmeters (and oscilloscopes) have a frequency function. This is not normally very useful as the CAN messages are not periodic enough for the meter to properly measure. CAN messages generally confuse frequency measurement instruments.

Oscilloscope

Non-repetitive signals: The network traffic on many buses, including CAN, is not repetitive and therefore rather difficult for a standard oscilloscope to reliably trigger on and display. Digital storage oscilloscopes are needed to effectively view these waveforms. Ordinary oscilloscopes rely on displaying the same image repeatedly and this requires a stable and repetitive signal for a clear and jitter-free display.

The blurred oscillograph of figure1 is a result of many CAN messages on top of each other and at different times as the oscilloscope sweeps overwrites its screen multiple times. It is an image from an analog oscilloscope. Figure 2 is one CAN message sampled once and stored in the oscilloscope's memory for display. Compare this with the same frame digitally sampled and stored in figure 2 to see the difference.

In figure 1 it can be seen that the approximate voltage of the bus is correct and that the CAN signals are present and not shifted high or low and the top or bottom is not clipped. It does not prove they are CAN frames. Many circuit defects will have abnormal oscilloscope waveforms. Figure 2 is an 11-bit CAN frame with identifier 0x010 and one data byte with a value of 0x55. It was captured with an Agilent 54645D 100 MHz digital storage oscilloscope. While it is easy to see the overall waveform is clean, of proper voltage and frequency, it is time-consuming to manually calculate the identifier and data values. This is made easier with the newer CAN-capable oscilloscopes available from Le Croy, Agilent and Yokogawa.

Frequency: The oscilloscope can easily determine the frequency of a CAN message. Simply measure the width of the narrowest pulse in the waveform and divide

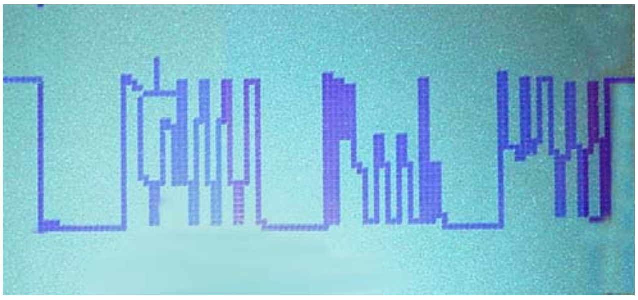


Fig. 3: Low resolution 100 KHz digital oscilloscope CAN waveform

invert it to calculate the frequency. For example, in figure 2 the first pulse will suffice as there are no pulses more narrow. This pulse measures 2 µs. This is equivalent to 0.000002 seconds or 2x10-6 second. Inverting this (divide 1 by 0.000002) with a calculator returns 500,000 or 500 Kbit/s, which is the speed of this CAN bus. Some oscilloscopes have methods to calculate this automatically. All you need to do select the pulse to be measured.

Signal Faithfulness: The smallest bit pulse of figure 2 could be represented by a 250 KHz sine wave and the wider pulses with lower frequencies. They will then have rounded corners and sloped sides. A oscilloscope with a 250-KHz bandwidth would display a rectangular waveform as a sine wave diminishing its usefulness. The square corners of the waveform that is caused by odd harmonics at multiples of 250 KHz (750; 1,250; 1,750; etc.) as well as noise pulses and other anomalies all having frequencies somewhat greater that 250 KHz will not be displayed or will be severely attenuated. This would have severe limits on the usefulness of such a oscilloscope. Some digital oscilloscopes found in automotive scan tools have such limitations and software techniques might be used to artificially "square up" the waveform. This is not good engineering practice.

Figure 3 shows three CAN frames with a 10 kHz digital automotive oscilloscope. Compare this signal with figure 2. It is clear the waveform is figure 3 has been "squared up" with mixed results. The CAN frame is difficult to decipher and does not faithfully reproduce the waveform. It does provide some basic information that is useful such that a signal is present and a technician will recognize, with considerable experience, that the bus is somewhat operational.

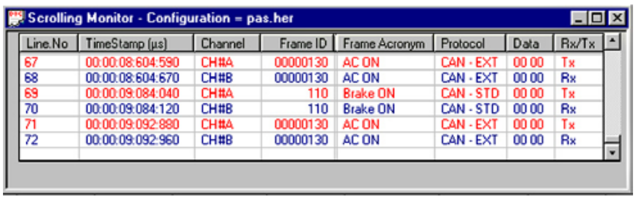
Connecting oscilloscopes

With the CAN differential pair, the CAN_H and CAN_L lines will operate opposite of each other. If you connect an oscilloscope hot lead to one of the CAN lines and the oscilloscope ground lead to the vehicle ground, you will just see one half of the CAN waveform. You could use the second channel of a dual channel oscilloscope to see the other side of the waveform but to properly combine them a special differential probe is needed. This probe will take each of the CAN lines, subtract them and present this to the oscilloscope. Many oscilloscopes can algebraically sum the two channels into one screen trace. This is effective but on some oscilloscopes it can be difficult to configure and adjust. However, you can take advantage of the fact that the ground of the oscilloscope and of the CAN system are not usually connected together. Connect the oscilloscope hot lead to one CAN line and the ground to the other CAN lead. The differential waveform will display correctly. This is how figures 1 and 2 were made. If the vehicle and oscilloscope grounds are connected, this would short one CAN lead to the vehicle ground through the oscilloscope ground lead.

Integrity testing

Most CAN systems use a twisted wire differential pair. This means that the CAN signals will be 180 degrees out of phase and interference from outside will be in-phase. Careful transceiver circuit design will respond to the out of phase signals and reject those that are in-phase. This is referred to as Common Mode Rejection of a differential pair. This is the essence of a differential pair.

Working properly, such a system is "balanced" and noise immunity will be high. An unbalanced condition will result in less than optimum noise and interference rejection and a potential increase in bus errors. It is important that interference signals be the same on both lines in order for them to be cancelled out. An oscilloscope will show this by examining the two lines on separate channels and then on one channel as described above. No interference should be visible when the CAN message is displayed on one channel. Using two chan-



Scrolling Monitor - Configuration = pas.her

Line.No	TimeStamp (µs)	Channel	Frame ID	Frame Acronym	Protocol	Data	Rx/Tx
67	00:00:08:604:590	CH#A	00000130	AC ON	CAN - EXT	00 00	Tx
68	00:00:08:604:670	CH#B	00000130	AC ON	CAN - EXT	00 00	Rx
69	00:00:09:084:040	CH#A	110	Brake ON	CAN - STD	00 00	Tx
70	00:00:09:084:120	CH#B	110	Brake ON	CAN - STD	00 00	Rx
71	00:00:09:092:880	CH#A	00000130	AC ON	CAN - EXT	00 00	Tx
72	00:00:09:092:960	CH#B	00000130	AC ON	CAN - EXT	00 00	Rx

Fig. 4: Analyzer display of CAN frames

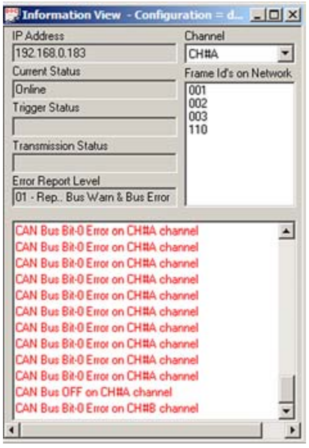


Fig. 5: Bus error window on the Gryphon

nels, any noise visible on one channel must be the same on the other channel. This is why the two bus wires must be physically located and twisted together.

Analyzer tools

A standard CAN bus analyzer can read CAN traffic, put user specified messages on the bus and provide statistical information such as bus loading and bus error information. It can also display the CAN messages giving the identifier and any data values. Many analyzers are able to display the acronym for a particular CAN message from associated databases. The physical layer must have fairly high electrical integrity as these analyzers are essentially a sophisticated CAN node.

Figure 4 shows a typical display from the Dearborn Group Gryphon/Hercules analyzer (www.dg-tech.com/product/gryphon/flier/gryphon.pdf). It displays the identifiers, data values and a timestamp shown. The Gryphon connects directly to the OBDII CAN connector on the vehicle and will capture OBDII codes and/or proprietary messages similar to that shown in figure 4.

Bus errors

The CAN bus was designed to be very robust and operate in electrically harsh environments. Bus errors can regularly occur and aborted messages are resent if possible. If the number of bus errors exceed a threshold, a node will take it itself off the bus and enter the Bus Off mode. The number of bus errors that occur and how this number changes can give a good indication of the health of the bus. Few commercial CAN nodes track bus errors even though this information is available from the CAN controller. A bus analyzer that tracks and displays these errors is useful. Figure 5 shows the bus errors and a bus off condition detected by the Gryphon. Defective busses will contain a large number of errors and these can be tracked or tested against historical information.

Conclusion

CAN bus errors should be tracked to ensure a functional physical layer. Intermittent or transient problems could be caused not by software bugs, but by a network susceptible to outside interference or borderline operating characteristics. This is especially true in harsh vehicle, outdoor and factory environments. Instruments and testing techniques described in this article can repair such unusual and difficult to find errors to minimize breakdowns.

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