

Locating Wire Short Fault for In-Vehicle Controller Area Network with Resistance Estimation Approach

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ABSTRACT

Wire shorts on an in-vehicle controller area network (CAN) impact the communication between electrical control units (ECUs), and negatively affects the vehicle control. The fault, especially the intermittent fault, is difficult to locate. In this paper, an equivalent circuit model for in-vehicle CAN bus is developed under the wire short fault scenario. The bus resistance is estimated and a resistance-distance mapping approach is proposed to locate the fault. The proposed approach is implemented in an Arduino-based embedded system and validated on a vehicle frame. The experimental results are promising. The approach presented in this paper may reduce trouble shooting time for CAN wire short faults and may enable early detection before the customer is inconvenienced.

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INTRODUCTION

With the increasing customer demand for new features, more and more electrical control units (ECU), actuators and sensors are equipped in modern vehicles. These components are connected via various communication networks and require a high degree of signal integrity. However, the wire and connectors making up the network could be damaged due to quality, design and assembly issues or worn out in harsh environments which may result in intermittent or permanent open and short faults. These faults increase the warranty cost, negatively impact customer satisfaction and may lead to 'walk home' situations. Therefore, research on fault diagnostics and prognostics for communication networks has grown in recent years [1, 2, 3].

Controller area network (CAN) is widely used in the automotive industry [4]. CAN is a multi-master serial bus standard, originally developed in the 1980s [5]. In 1996, the onboard diagnostics (OBD-II) standard became mandatory for all cars and light trucks sold in the US, and CAN is one of five supported protocols. CAN bus, the network using CAN protocol, is designed to allow ECUs and devices to communicate with each other using a single wire or a pair of wires. Therefore, CAN enables a huge reduction in wiring complexity. However it complicates diagnostics and prognostics of vehicle wiring. For instance, a single wire open may result in message corruptions from the modules on each side of the open location. The corruption is irregular and depends on the status of ECUs on the network. Hence the fault is hard to locate or isolate. The troubleshooting of CAN faults, even without isolating the fault or

locating the fault, is a complicated and time-consuming process for mechanics or technicians [6]. It's even more challenging to trouble shoot intermittent faults or multiple faults.

The approaches to diagnosing CAN bus faults fall into two categories namely, message-based approaches and physical-signal based approaches. The message-based approaches utilize CAN message (frame) or message error counters generated by the CAN transceiver to isolate or locate faults. Hu et al. proposed an online fault diagnosis approach using the error frame counter [7]. Each node sends a fault message to a node, called manager when the error frame counter increases. The manager will update the error records, calculate the failure times for each node, send a message to the node to confirm the link quality and determine the quality of the link based on the failure time. Kelkar et al. proposed an adaptive diagnostic approach [8] to find the faulty nodes in the network and, in turn, informing the status of faulty nodes to all of the healthy nodes as well as reducing the diagnostic messages. Lei et al. used a stochastic process model called generalized, zero-inflated, Poisson process [9] to monitor and model the intermittent connection faults. The model parameters are estimated with a maximum likelihood estimation approach. The degradation can be monitored by the shifted error distribution. Message-based approaches, while easy to implement, are not capable of locating certain faults. For example, when wire short faults occur, regardless of whether they are between two bus wires or a single wire shorted to ground or power, most, if not all, bus messages are corrupted. The message or error frame counter can't provide enough information to isolate or locate the fault.

Physical-signal based approaches employ voltage, current or other physical characteristics to diagnose bus faults. A detailed survey of aircraft wiring fault detection is conducted [10] where various physical-signal based approaches are introduced and compared. Among all approaches, time domain reflectometry (TDR) is a typical physical-signal based approach which uses the reflection of an electrical signal to locate the impedance discontinuities due to wire opens or shorts. Papers [11, 12, 13, 14] provide several reflectometry-based approaches which are successfully applied in signal distribution wiring harnesses. Hassen et al. proposed an orthogonal multi-tone time domain reflectometry approach to locate faults in CAN buses [15]. The proposed approach is capable of removing location ambiguities in branched networks and avoiding noise interference. Hofman proposed a passive TDR approach [16] for CAN bus fault diagnosis to avoid potential electromagnetic interference inherent in active TDR approaches. The TDR approach is robust and accurate to detect and locate the fault. However, a TDR-based diagnostic tool is usually expensive because it requires a very high sampling rate to record and analyze electrical signals within several nanoseconds. Furthermore, the TDR is sensitive to the impedance change which poses obstacles for calibration. Other than TDR-based approaches, Chung et al. proposed the inductance and capacitance based approaches to locate open and short faults for power distribution wire harness [17]. Kamdor and Furse proposed an approach using a standing wave [18] for locating faults. Unfortunately, these test approaches inject active signals into the wiring harness, and may potentially interfere with CAN bus applications. Suwatthikul et al. proposed a hybrid approach using a fuzzy inference system [19] to diagnose bus faults. The bus resistance and error frames are used to identify the network health. However, it is not able to isolate and locate the fault.

In summary, so far there is no low-cost, in-vehicle solution to isolate and locate CAN bus faults, especially the wire short fault which is one of the most challenging faults to locate. In this paper, we will focus on detecting and locating CAN short faults. Our objective is to develop a low-cost, feasible and accurate approach to detect and locate the wire short fault in CAN bus wiring harnesses. We will propose a resistance-based approach and validate it with real vehicle CAN bus frame.

CAN BUS MODELING IN THE SCENARIO OF WIRE SHORT FAULTS

In this section, the characteristics of the CAN bus in the scenario of wire short faults are analyzed and the bus is modeled using an equivalent circuit model. The model is developed according to the CAN bus specification.

The physical layer characteristics for the CAN bus are specified in ISO-11898-2. The physical layer of the CAN bus consists of wires, terminators and ECUs equipped with the CAN transceiver to receive and transmit messages. The schematic of a typical high-speed CAN bus is shown in Fig. 1 where the bus has three ECUs and two terminators. Parallel wires with a nominal impedance of 120 Ω (95 Ω minimum and 140 Ω maximum) are normally utilized. A maximum length of 40 meters is specified for CAN at a data rate of 1 Mb. At

lower data rates, longer wires are possible as well. The two signal lines of the bus are called CANH and CANL. In the recessive state, the bus voltages are equal to 2.5 V. The dominant state on the bus typically takes CANH to 3.5 V, and CANL to 1.5 V, creating a 2 V differential signal. Terminations are placed at each end of the bus. Each terminator includes two resistors of approximately 60 Ω each and a coupling capacitor which couples high-frequency noise to a solid ground potential. The typical capacitor value for a high-speed CAN termination is 100 nF.

When an ECU transmits messages, the CAN transceiver of this ECU can be modeled as a voltage source. Its schematic is shown in Fig. 2 which is Infineon TLE 6250G CAN transceiver [20]. Similarly the schematic for an isolated CAN transceiver can be found from TI ISO1050 specification [21]. Here V_{cc} is typically equal to 5V and CANH and CANL voltages are 3.5 and 1.5V, respectively. When other ECUs receive messages, the input circuit is also shown in the bottom of Fig. 2. According to the ISO_11898-2, the differential internal resistance is between 10Kohm to 100 KOhm which is much higher than termination resistance. Since each ECU/transceiver is parallel connected to the terminator, the ECU which receives messages can be omitted from the whole bus model. This results in the equivalent circuit model shown in Fig. 3.

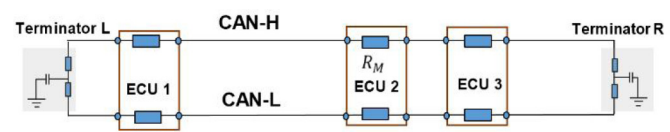


Figure 1. The schematic for a typical high-speed CAN bus with 3 ECU nodes.

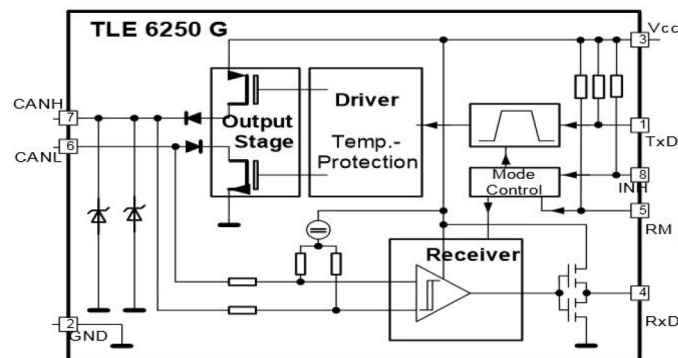


Figure 2. The schematics for Infineon TLE 6250G CAN transceiver [20].

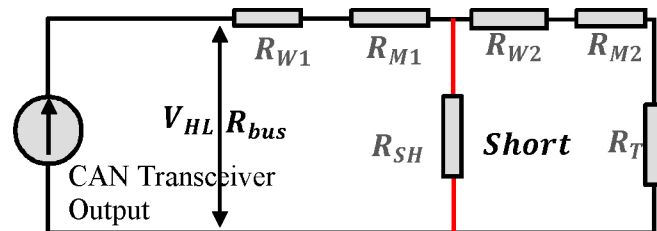


Figure 3. Equivalent circuit for CAN bus in the scenario of wire short faults

In Fig. 3, the power source represents the ECU that transmits messages. R_{W1} and R_{W2} are the bus wire resistance and R_{M1} and R_{M2} are the ECU module resistances. Module resistance is introduced from the copper traces on the ECU circuit board connecting the bus

input port and output port. The subscripts, 1 and 2, correspond to two parts of the bus which are separated by the wire short fault. R_{SH} is the short resistance between CANH and CANL. In this study, we assume R_{SH} is in the milliohm level since it's the contact resistance between CANH wire and CANL wire. Since R_{SH} is much smaller than R_T , the right-side of R_{SH} is neglected as well as the other side of the bus with another terminator. The bus resistance R_{bus} can be simply calculated as follows,

$$R_{bus} = R_{W1} + R_{M1} \quad (1)$$

When no ECU transmits a message on the bus, there is no power source on the bus. The bus voltage, i.e. CANH voltage and CANL voltage, is equal to 2.5 V. Due to the wire short fault, all ECUs are in error mode since the dominant bit cannot be transmitted. Based on the CAN specification 2.0 [22], the bus behavior during a wire short fault can be analyzed as follows. Whenever any ECU tries to send a frame on the bus, the CAN transceiver on this ECU will detect a bit error since the start of frame is a dominant bit but the voltage between CANH and CANL is close to zero due to the wire short fault between CAN-H and CAN-L. Note that all nodes on the bus start out in error active mode. In error active mode, each transmit error increments the transmit error counter by 8 counts. After the bit error is detected, it leads to an immediate and automatic transmission of an active error flag which consists of 6 consecutive dominant bits. When the error counter exceeds 127, i.e. the ECU sends the active error flag 16 consecutive times, the ECU will enter the error passive mode. In the error passive mode, the ECU will send a passive error flag which comprises 6 recessive bits. After that, the ECU will send 8 bits of delimiter, 3 bits of bus inter-frame space and 8 bits of passive mode inter-frame space, which totals 25 (6+8+3+8) bits. The ECU will then try to send the message again, triggering another passive error frame. If the counter rises above 255, which happens after 16 more message transmit attempts, i.e. $16 \times 25 = 400$ bits, the node will enter the bus off state. The bus status can be observed in Fig. 4 which shows the data collected from a real CAN bus using an oscilloscope. The data rate is 500Kbps, i.e. each bit is 2 microseconds. The blue line is the current from the transmission control module (TCM) and the green line is the voltage between CANH and CANL. Based on this analysis, during a wire short fault the module current is continuously high only in the error active mode for 16 bits. In all other CAN modes the current is either unstable or equal to 0. Since the bus resistance is estimated from the ratio of the bus voltage and the module current, and 0 current makes the ratio become infinity, the estimation can only be carried out in the error active mode.

THE SOLUTION FOR WIRE SHORT FAULT LOCATION DETERMINATION

Based on the equivalent circuit model and analysis in the previous section, the following resistance-estimation based solution is proposed. To estimate resistance, the voltage and the current need to be measured first. Since the CAN transceiver doesn't include a voltage sensor or a current sensor, the two sensors are required to be added to one ECU on the bus. The current sensor based on a Hall effect sensor is expensive. Therefore, in this work, we propose to use a shunt resistor to convert the current value to voltage, which is

shown in Fig. 5. Considering the symmetry of the CAN outputs, two resistors with the same resistance are added between the CANH and CANL bus wires and the CAN transceiver. In order not to impact bus performance, the value of the shunt resistance is selected to be about 1 ohm. The resistance value should be accurate; otherwise, it will increase the potential error in the distance estimation. V_{HL} (Voltage between CAN high and CAN low) and V_S (the voltage across the shunt resistor) are then measured by the microcontroller.

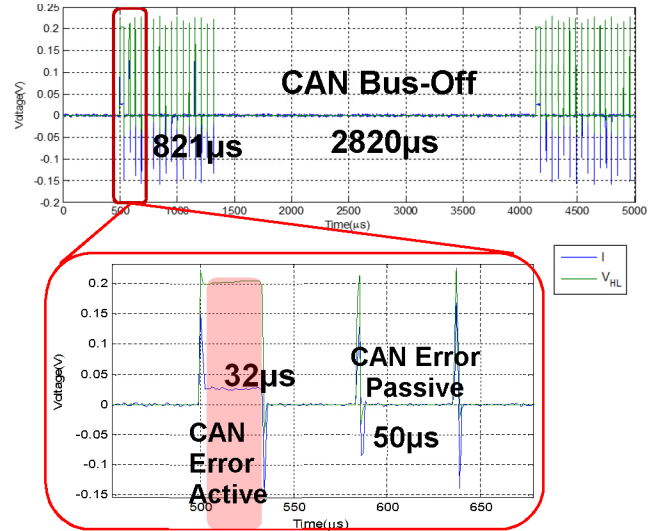


Figure 4. The voltage recorded from a vehicle frame CAN bus when a wire short fault is injected.

When there is a wire short fault between CAN high and CAN low, the bus resistance is about 0 to 4 Ω , depending on the wire short location in the network. The closer the short location is to the monitor node, the smaller the bus resistance is. Since the wire resistance and module resistance are impacted by temperature, the resistance is scaled by temperature before mapping to distance. Based on the equivalent circuit model, the bus resistance at wire short fault location R_k can be calculated using the following equation.

$$R_k(25) = \sum_{i=1}^k (2\lambda(25)D_i + R_{Mi}(25)) \quad (2)$$

where 25 is the temperature in Celsius degrees, k is the number of nodes on the bus, D_i is the distance for each link between two ECUs, R_{Mi} is the ECU module resistance and λ is the resistance/distance coefficient for the bus wire.

Since our objective is to find out the distance from the monitor ECU to the fault location, i.e. $\sum_{i=1}^k (D_i)$ using R_k and, the following method is used which is shown in Fig 6. The inputs are (1) N points of sensing voltage, V_{HL} and V_S (2) 1 point of vehicle temperature (ambient temperature T). The parameters used in the algorithm include (1) The resistance to distance mapping table $R(D, k)$ and (2) The temperature coefficient for the bus wire α . The outputs are the estimated resistance value, corresponding to temperature, and location information (NodeID, LinkID and distance).