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A Method for Cable Fault Diagnosis and Time Synchronization Compatible with both CAN and CAN-FD

Jongbae Lee[1], Choongchae Woo[2]

Bos Semiconductors Co., LTD., Dept. of Electrical and Electronic engineering, Hanseo University,
jongbae@naver.com[1], woo9@hanseo.ac.kr[2] (Corresponding Author)

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***Abstract* - This paper introduces a method for diagnosing cable faults and achieving time synchronization in automotive CAN networks. It proposes a "bus check frame" approach, enabling simultaneous fault diagnosis and synchronization using existing CAN data frames. The method's compatibility with CAN and CAN-FD protocols is highlighted. The approach is experimentally validated, demonstrating efficient fault diagnosis, accurate synchronization, and improved network resilience.**

***Keywords* - fault diagnosis, fault location identification, Fault Tolerance, IVN (In-Vehicle Network).**

INTRODUCTION

Recently, the vehicle is equipped with an electronic control unit (ECU) that operates various functions for the driver's safety and convenience. Anti-lock braking system (ABS) and advanced driver assistance systems (ADAS) are the good examples of those tools that improve driver's safety and convenience. In-vehicle network protocols include LIN(local interconnect network)[1], CAN(controller area network)[2] [4], FlexRay [3], and so on. Among them, CAN is the most used. As the amount of data interface increases in modern vehicles, the CAN-FD(CAN with Flexible Data-Rate)[2][5] was created to meet consumer's demands. The CAN network uses a bus topology, and nodes are connected with cables. Cables have a tendency that comes to breakdown (short and open) due to aging and improper maintenance.

In several recent papers, a fault diagnosis of the CAN bus has been popular topic in various aspects. Kelkar et al. [6] proposed a fault diagnosis that the master node transmits test frames sequentially to all nodes in a network and receives a result in message frame.

Chang et al. [7] [8] proposed a method that diagnoses a fault in bus by putting test points to each end of CAN network. Barranco et al. [9] proposed an active star topology to solve cable faults in CAN networks using a bus topology.

Individual oscillators supply clock to each ECU in the vehicle. In general, the oscillator's clock is affected nonlinearly by various external conditions such as temperature, barometric pressure, and humidity. As a result, clock offsets accumulate several seconds a day, causing the system to fail. Figure 1 illustrates the concept of time offset and the impact of time synchronization. Over time, the difference between the master clock M(t) and the slave clock S(t) progressively grows in a linear manner. To rectify this escalating offset, time synchronization is applied at regular intervals (Ts). When time correction is implemented, the slave clock will align closely with the master clock.

In recent papers, time synchronization has been studied in various aspects.

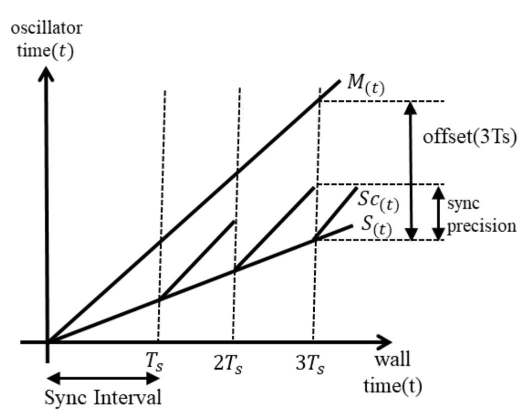

Figure 1 Time Offset Correction [11][12]

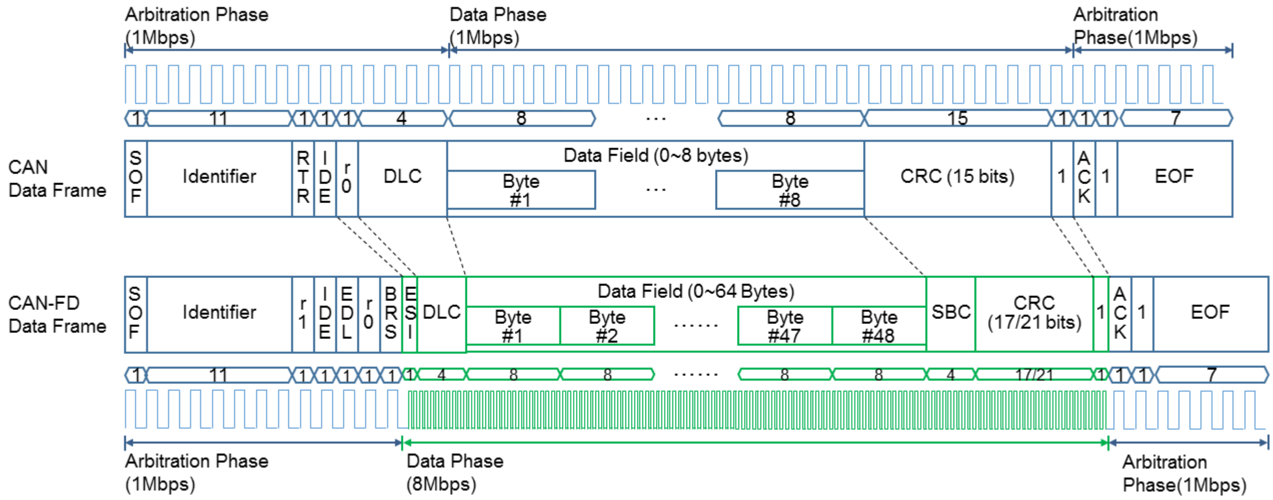

Figure 2. Data frame structures of CAN (1 Mbps speed, 8 bytes payload) and CAN-FD (8 Mbps speed, 64 bytes payload)

Proenza et al. [11] proposed a method to perform synchronization using time stamps. However, it requires additional hardware. Breaban et al. [12] introduced a time synchronization technique for CAN networks integrated into multi-processor system on chips (MPSOCs). MAC layer has been implemented to synchronize by using Time stamp.

S. Park et al. [13] implemented the IEEE 1588 algorithm in CAN.

As a result, current research in automotive CAN networks with real-time communication is not a suitable solution. In this paper, a CAN bus cable fault diagnosis and time synchronization method using classic CAN and CAN-FD data frames are proposed as resolution. Using classic data frames, cable faults and time synchronization can be performed simultaneously without a separate device. With only one data frame, you can simultaneously diagnose and time-synchronize nodes on 11 classic CAN and 123 CAN-FD. In a vehicular network that is closely related to the user's safety, there should be no disconnection in communication due to cable failure. In this paper, solutions for a cable fault are proposed.

BACKGROUNDS

I. CAN_FD

The amount of data has increased due to improved vehicle functions. To solve this problem, CAN-FD was developed by Bosch based on CAN and standardized to ISO 11898-1: 2015. CAN-FD has the advantage of being highly compatible with existing CAN.

The big difference from classic CAN is the increase in payload and data transfer rate. Current 8-byte payload has been expanded to 64-byte and the speed of data transferring has increased from 1 Mbit/s to 8 Mbit/s. Figure 2 illustrates the distinction between CAN and CAN-FD data frames. CAN-FD divides into arbitration phase and the data phase, EDL, BRS, and ESI bits are added and DLC bit was modified in control field. SBC is added in the CRC field.

- Placing all commas and periods either inside (American) or outside (British) of quotation marks.
- EDL (extended data length): It differentiates between CAN format and CAN FD format frames.
- BRS (bit rate switch): Determines if the bit rate is altered within a CAN FD format frame.
- ESI (error state indicator): Indicates the error status of the current node.
- DLC (data length code): The length of the data field has been extended. The extended data lengths are shown in Table 1.
- SBC (stuff bit count): Located before the CRC, it consists of three gray coded bits and a parity bit.

Table 1.
Experiment Parameters

DLC	1001	1010	1011	1100	1101	1110	1111
Byte	12	16	20	24	32	48	64

Table 2.
CAN Bus Cable Failures

	open		short						
CAN_H	F	N	B	N	V	N	G	N	H
CAN_L	N	F	N	B	N	V	N	G	L
Operation	X	X	O	X	O	X	X	O	X

* N: Normal operation, F : Cable open, X : Not working, O: working, B: Shorted to battery voltage, V: Shorted to VCC voltage, G: Shorted to GND

II. Bus Cable Fault

There are two types (open and short) of cable faults in CAN BUS. CAN uses two lines CAN_H and CAN_L to represent the digital signals 0 and 1 as the voltage difference between the two lines. Table 2 shows the cable faults that can occur in CAN bus. If both cables are shorted, all nodes in the CAN network become incapable of communication. Therefore, it is impossible to detect a specific fault location.

In this paper, it is possible to inform the user of a fault condition when a suspected cable-short is detected. CAN bus cable open fault can be classified into two cases according to its location as shown in Figure 3.

Local cable fault: If a cable fault occurs at this location, as shown in Figure 3, node A cannot participate in the communication. Or, even if a system failure of node A occurs, node A cannot participate in the communication.

Backbone cable fault: If node B transmits a data frame, node A initiates bus communication to receive the data frame. Node C and Node D are disconnected from bus communication and cannot receive data frames.

Vehicles that use real-time communication are closely tied to your safety. Therefore, when a failure occurs, it is necessary to accurately diagnose the presence and location of the failure. In addition, in the case of vehicle communication, even if the communication is lost for a few seconds, a fatal accident can be caused. Therefore, when a bus cable fault occurs, accurate diagnosis and countermeasures must be accompanied.

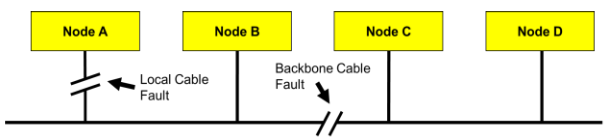

Figure 3. Examples of cable fault occurrences at various locations in a CAN network

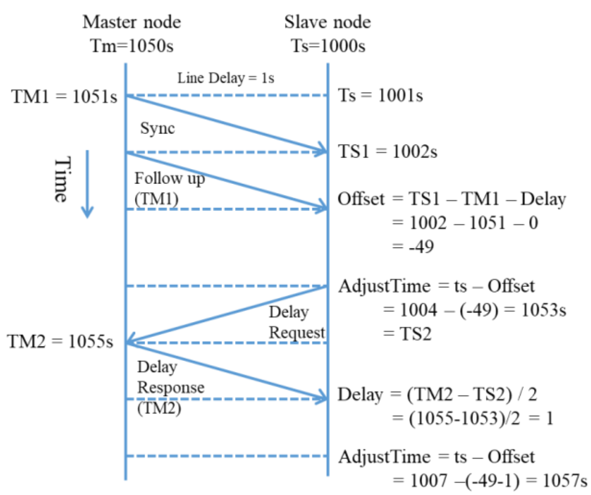

Figure 4. IEEE 1588 Synchronization

III. IEEE1588

IEEE1588 is called PTP (precision time protocol) and is one of representative time synchronization techniques. It is an international standard widely used in embedded systems [14]. IEEE1588 performs time synchronization by exchanging messages between master and slave nodes. The node with the optimal clock on the network becomes the master and all others act as slaves. The synchronization process of IEEE 1588 is depicted in Figure 4. The operational process unfolds as follows:

Step 1:

- The master node dispatches a 'Sync' message to the slave.
- The master node logs the current timestamp (TM1) and then sends a 'Sync' message.

The slave node records the current timestamp and subsequently receives the 'Sync' message (TS1).

Step 2:

- The master node transmits a 'FollowUp' message that includes the measured timestamp value (TM1) to the slave.
- The slave computes the time difference between the two nodes by utilizing the received TM1 value and TS1 value, subsequently rectifying the error by adjusting the slave clock with this calculated value. The offset calculation is as follows.

Step 3:

- After correcting clock error in step2, slave sends ‘DelayRequest’ message to master.
- Slave records TS2 timestamp the moment it sends ‘DelayRequest’ message.
- Master records TM2 timestamp the moment it receives a ‘DelayRequest’ message.

Step 4:

- Master sends ‘DelayResponse’ message with TM2 timestamp value to slave.
- The slave calculates the delay value using the received TM2 value and TS2 value to correct the clock. The delay calculation is as follows.

Synchronization with the IEEE 1588 algorithm applied to CAN requires a total of four data frame messages [13]. In addition, four message identifiers of high priority are required to complete the synchronization. CAN acquires control of the bus based on the priority of the message identifier. If the high priority four message identifiers are occupied for the synchronization process, the ability to cope with an emergency in a vehicle network may be reduced. Therefore, there is a need for modification to apply IEEE 1588 to automotive CAN networks.

THE PROPOSED METHODOLOGY

In this section, it explains how to diagnose CAN cable faults and time synchronization in the in-vehicle CAN network. And specific resolution for cable fault is proposed. Our main idea is that current CAN data frames can be used to simultaneously perform fault diagnosis and time synchronization. The method is workable with current CAN and has the advantage of being applicable to both CAN and CAN-FD. It is called ‘bus check frame ‘that has CAN frame which is proposed in this paper.

I. CAN Bus Faults Diagnosis

I.1. Shorted Cable Diagnosis

If a short occurs on the bus cable, node communication cannot be made. When a short circuit occurs, the master node will receive the recessive bit if it transmits the dominant bit. The master node that received recessive bit generates and transmits an active error frame due to a bit error. It transmits an active error flag consisting of six dominant bits, yet a bit error occurs due to a short circuit after receiving a recessive bit. As shown in Figure 5, successive bit errors eventually become a bus-off state. A bit error occurs to each bit when it is in active error state. In passive error stage after IFS, a dominant bit is transmitted in SOF state. But short circuit makes to receive recessive bit and it comes to a bit error. As such, it is a pattern of bit errors which occur continuously. This pattern lasts about 302 us. In other words, if a continuous bit error pattern comes out for 300us, bus cable short is suspected. Thus, the master node can diagnose short faults by recognizing unique error patterns.

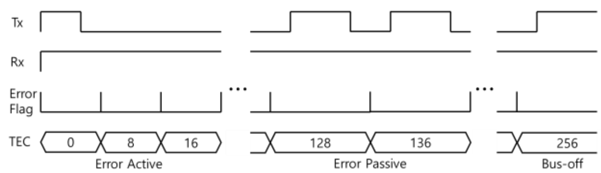

Figure 5. Bus cable shorted diagnosis

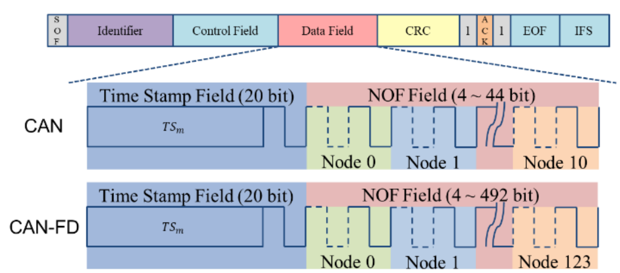

Figure 6. Data field definition

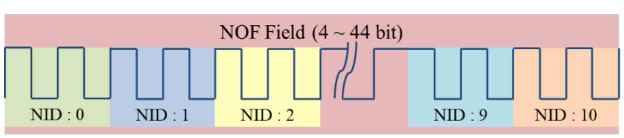

Figure 7. Description of NID in the NOF field

I.2. Open Cable Diagnosis

Our method defines a new data fields of conventional CAN data frames. Since the data field is used, the operational method in CAN and CAN-FD are same. Therefore, only the case of CAN is described here. As shown in Figure 6, it is defined as time stamp field and NOF field in data field. The time stamp field is used for time synchronization and the NOF field is for cable fault diagnosis. Nodes participated in the network have 4 bits of allocation in the NOF field.

In the case of CAN, the NOF field is limited to 44 bits, so up to 11 nodes can be diagnosed with a single data frame. Nodes in the network have their own unique node ID (NID), as shown in Figure 7. NID is allocated by configuration register setting at system startup. With NID value, a specific location is given in NOF field. Therefore, if the value of the data field is different from the predefined signal value, the difference could be diagnosed as a node failure. In accordance with the CAN protocol definition, the length of the data field fluctuates based on the configuration of the DLC value. Accordingly, the length of the newly defined NOF field can also be variable by the number of participating nodes. When there are an even number of slave nodes participating in the network, 4 bits remain because there are more bits in the data field set according to the DLC value than the required bits in the NOF field. The remaining 4 bits are filled with '1010' dummy bits. The reason for setting the dummy bit value to '1010' is to avoid bit stuffing and to make easier calculation of CRC value. The bus check frame operation operates when a user-defined specific ID value is received. In this way, the node with the proposed method performs cable fault diagnosis and synchronization, and the existing CAN node is recognized as a general data frame, so that the CAN node with the proposed method and the existing CAN node can be compatible. The assigned 4 bits of each node in the NOF field have different roles of the upper 2 bits and the lower 2 bits. This section describes the functions of the upper two bits. The upper two bits are used for cable fault diagnosis and sent by the slave to the master. The master broadcasts the upper two bits to all nodes with '11'. The slave that received the frame responds with '10'. CAN has a higher priority for dominant (0) than recessive (1) on the bus, so the upper two bits will be represented by a '10' value sent by the slave rather than a '11' value sent by the master. In normal operation state, the upper 2 bits of each position should be shown as '10' and '11' indicates a fault condition. The operation of the proposed method is explained in detail through the following three situations. The nodes participating in the network are assumed to be one master and four slave nodes.

Scenario 1: Normal operation

The situation is illustrated in Figure 8 when all nodes are operating normally. The master node broadcasts the NOF field of the data frame to a value of '1110_1110_1110_1110_1010'. Slave node that has bus check frame respond with ‘10’ which is the upper two bits of each unique position in the NOF field. Bits of the NOF field are represented in sequence as '1010_1010…….' on the bus, so it can be confirmed that all participating nodes do not have a fault.

Scenario 2: Local cable fault

As shown in Fig. 9, local cable fault occurred at node 0. This situation has two cases.

- *case 1:* Node 0 transmits normal data frame, but disconnection occurs on the bus.
- *case 2:* A node of system failure of node 0 cannot transmit an accurate data frame.

In both cases, the value of the node0 unique position in the NOF field will be expressed as '1010'. The user can check the data field and check the corresponding node and cable for quick repair.

Scenario 3: Backbone cable fault

The diagnosis of the backbone cable fault is shown in Figure 10. When reading the data value of the NOF field represented on the bus, it is possible to diagnose the faults of node 1 and node 3. The probability that two nodes will fail at the same time is very low. Thus, the user knows the initial network configuration as shown in the upper right corner of Figure 10, and node 0 has no faults, so it can diagnose that a fault has occurred in the bus cable from the master to node 1 and node 3.

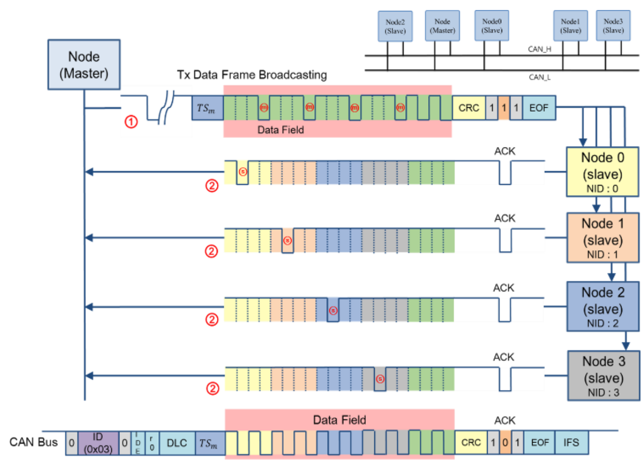

Figure 8. Normal operation

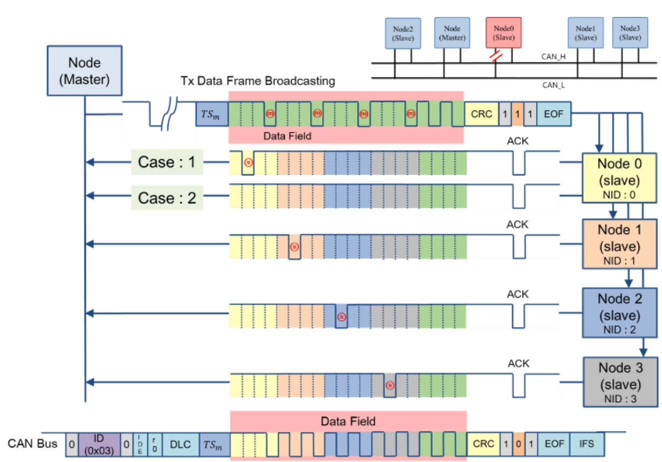

Figure 9. Local cable fault

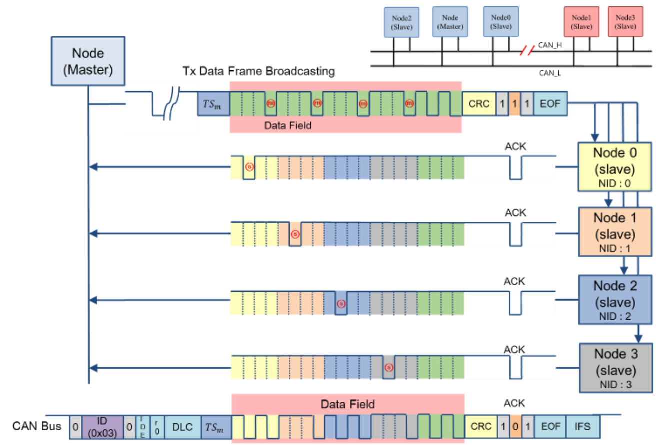

Figure 10. Backbone cable fault

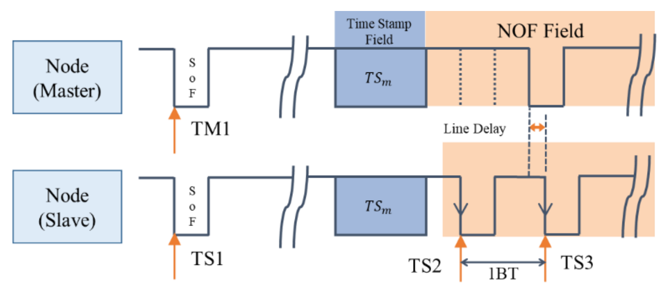

Figure 11. Proposed time synchronization

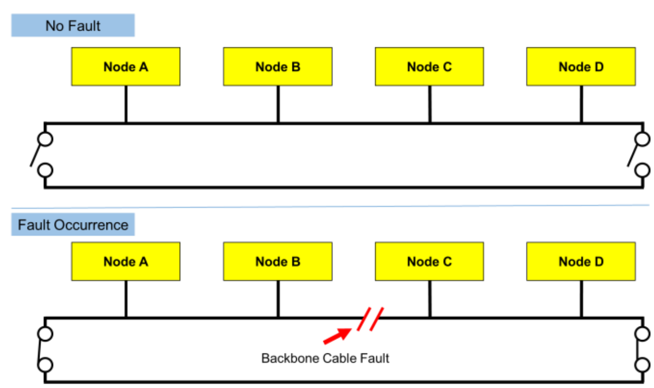

Figure 12. Cable fault tolerance method

II. CAN Bus Time Synchronization

In this section, the method of synchronizing time using the lower two bits of the NOF field is detailed. The lower two bits of the NOF field fulfill two distinct roles. First, it is a delimiter to protect the lower 0 bits of the upper 2 bits on the bus. Second, it is used for time motive and its role is as follows. Our time synchronization method is based on IEEE 1588. The lower two bits of the NOF field are bits transmitted from the master to the slave. The time synchronization method is shown in Figure 11. The master records the time stamp (TM1) at the beginning of the SOF and writes the recorded value in the time stamp field and sends it to the slave.

Table 2.
Comparison of conventional methods and proposed methods

	CAN prop. (Fault Diagnosis + Synchronization)	CAN-FD prop. (Fault Diagnosis + Synchronization)		Conv.1[6] (Fault Diagnosis)	Conv.2[13][14] (Synchronization)	Conv.3[6][13][14] (Fault Diagnosis + Synchronization)
Time stamp bits	18	18		N/A	16	16
Number of frames required for diagnosis	int((n-1)/11) + 1	int((n-1)/123) + 1		2*n	4*(n-1)	6*n-4
Total bits required f or diagnosis	int((n-1)/11)*111 + int((((n-1)%11)+1)/2)*8+71	n≦11	int((((n-1)%123)+1)/2) *8+84	222*n	220*(n-1)	442*n - 220
		12≦n≦19	156			
		20 ≦n≦ 27	188			
		28 ≦n≦ 35	225			
		36 ≦n≦ 43	257			
		44 ≦n≦ 59	321			
		61 ≦n≦ 91	449			
		92 ≦n≦ 123	577			
n=2, Total bits	79	92		444	220	664
n=11, Total bits	111	124		2442	2200	4642
n=29, Total bits	317	225		6438	6160	12598

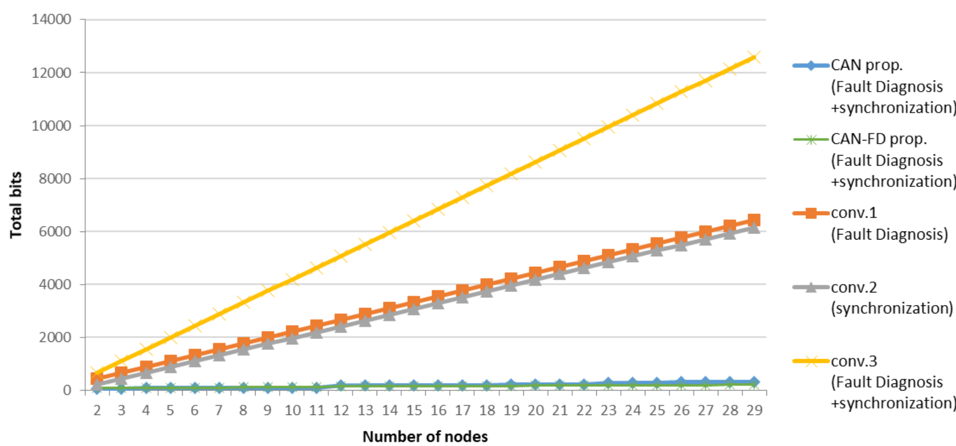

Figure 13. Comparison of conventional methods and proposed methods

The slave records a time stamp (TS1) in the SOF and a time stamp (TS2) at the falling edge of 1 to 0 of the upper two bits of the diagnostic response in the NOF field. Record the time stamp (TS3) at the falling edge of 1 to 0 of the lower 2 bits received from the master in the NOF field. Using the recorded time stamp value, calculate the transmission delay and offset value and correct the error. The transmission delay and offset calculation is as follows.

$$\text{offset} = TS_1 - TM_1 - Delay \qquad (1)$$

$$Delay = \frac{(TS_3 - TS_2 - 1BT)}{2} \qquad (2)$$

The conventional time synchronization method using IEEE 1588 required four data frames, but the proposed method can perform time synchronization using only one data frame.

III. Fault Tolerance Method

In-vehicle network is based on real time communication. If data connection is not secured even a few seconds, that is direct threat to driver's safety. Therefore, we will introduce a method to guarantee real-time communication in the event of a cable fault in the CAN network. Our idea is to connect a switch-controlled emergency cable to both ends of the bus topology. The cable will be offed and not in use when all conditions are normal. By switching-on the cable emergency cable will be replacing a fault cable. The basic concept is shown in Figure 12. Turing on/off by switch system is preferred than ring topology that connects two end of bus topology. The reason for this is as follows. As the length of the cable increases, the resistance and propagation delay increase.

Increased resistance and propagation delay result in fatal communication errors. Therefore, to prevent this, a switch was used so that it can be used temporarily only in an emergency.

IV. Comparison of Diagnostic Methods

Table 2 contrasts the proposed approach with the traditional method. The conventional method [6] requires two data frames to diagnose a node. The conventional time synchronization method requires four data frames for synchronization. The proposed method can perform fault diagnosis and time synchronization on 11 nodes in CAN mode and 123 nodes in CAN-FD mode simultaneously with one data frame. The total number of bits needed for the diagnosis is related to the bit rate and the smaller number means the more bits can be sent at the same time. Thus, a small total number of bits is good for performance. The total number of bits needed for the diagnosis according to the number of nodes is shown in the graph in Fig. 14 compared with CAN, CAN-FD and the conventional methods. When the number of nodes is 2, 11, and 29, the total number of bits required is calculated. As a result, the proposed method reduces the time taken to complete the fault diagnosis and time synchronization from 88%~97%.

EXPERIMENTAL RESULT

The proposed method is verified in the experimental environment of Figure 14. The CAN-FD controller utilizing the suggested method was delineated using Verilog HDL. This implementation was carried out on an FPGA and validated on a test board, as illustrated in Figure 15. The test board was composed of FPGA using XILINX's Spartan6-XC6SLX9, and the CAN transceiver was configured using INFINEON's TLE9250V. In Fig. 15, 1 master node, 4 slave node and 1 measurement node were implemented and connected.

The measurement node is used to verify the time synchronization behavior. It collects, stores and transmits time clock information of five nodes to a PC. Every 10ms, time clock information of all nodes is read and stored in memory. The experiment progressed that the master transmits a standard data frame and then sends a bus check frame once per second. That is, the cable fault diagnosis and time synchronization are performed once every second. The standard data frame 11-bit ID is set to 0x002 and the ID of the bus check frame is set to 0x003. Most vehicles today use CAN at 250~500 kb/s.

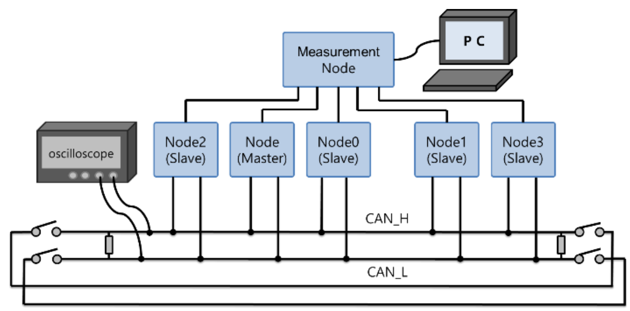

Figure 14. Experimental environment

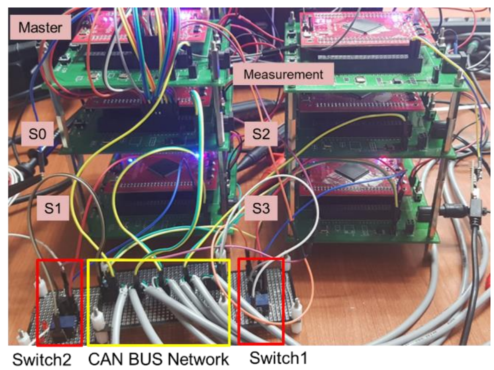

Figure 15. Test board

Figure 16. Cable diagnosis (normal operation)

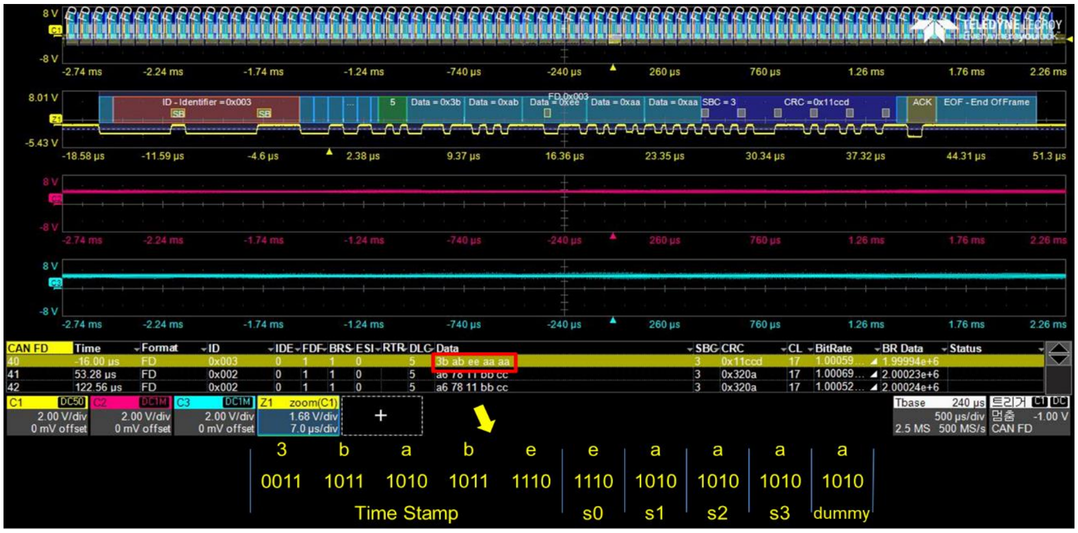

Figure 17. Cable diagnosis (local cable fault)

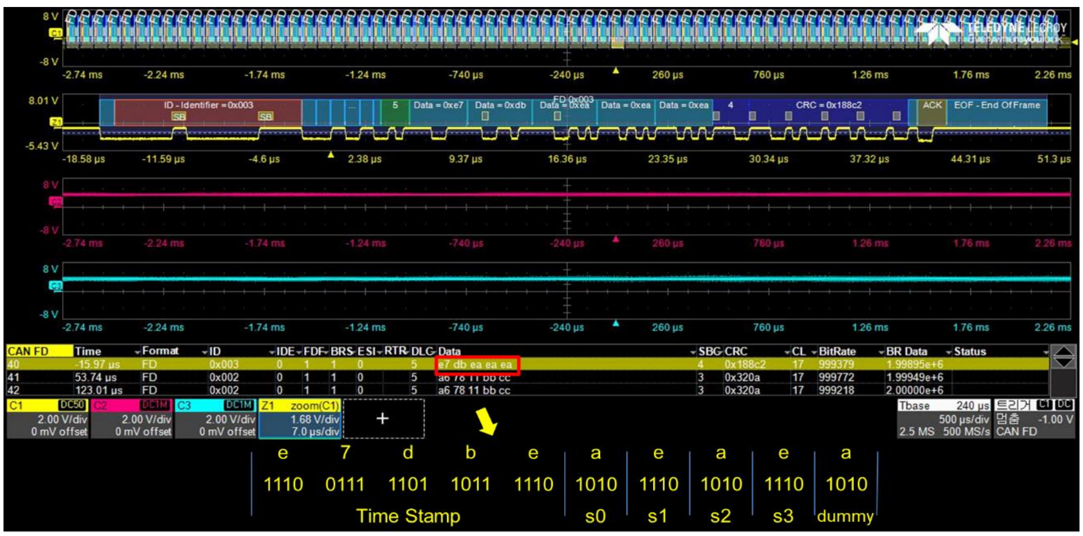

Figure 18. Cable diagnosis (backbone cable fault)

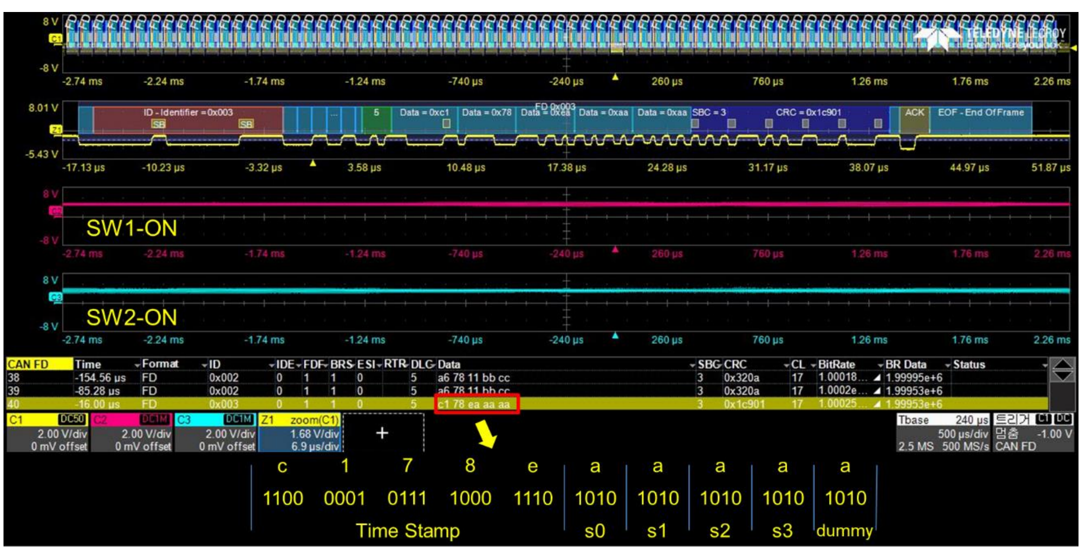

Figure 19. Cable fault recovery method

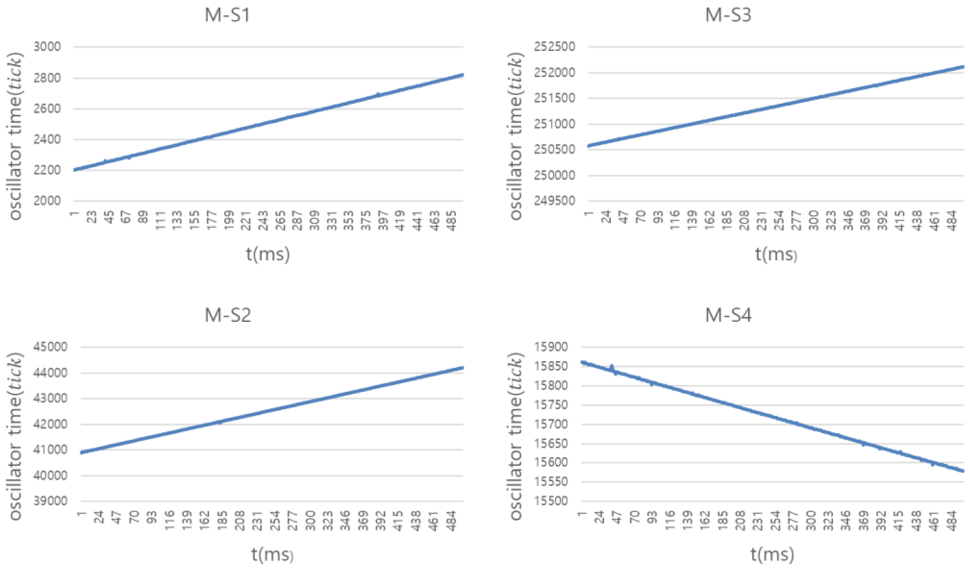

Figure 20. No synchronization operation

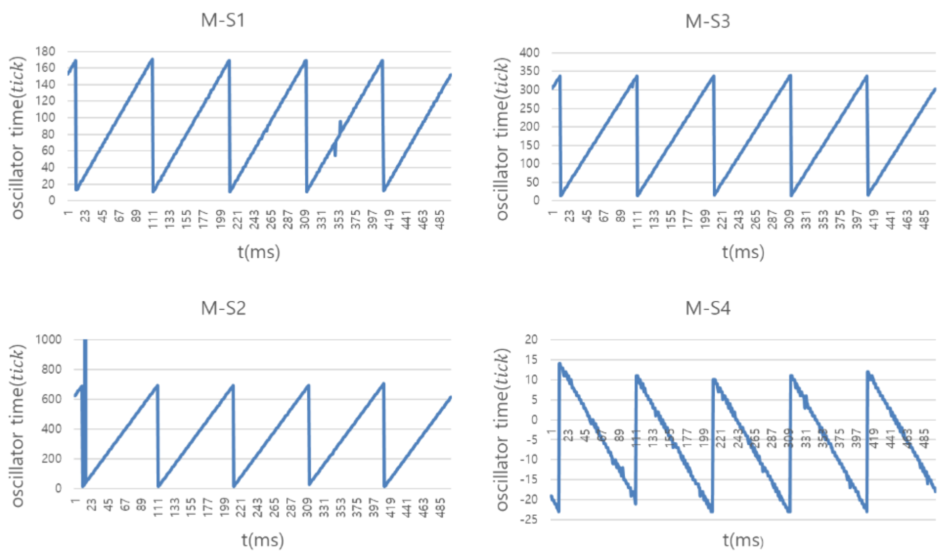

Figure 21. Time synchronization

CAN-FD uses 2 Mb/s and gradually transitions to 5 Mb/s. Therefore, our experiment was conducted with CAN-FD 2Mb/s. The experiment proceeded with the three situations described above. As a result of experiment, oscilloscope could capture CAN-FD data frames and it is shown on Figures 16, 17, and 18, respectively. In the first normal operation, since the unique position values of the slave nodes s0, s1, s2, and s3 of the data field are all identified as '1010', it is known that the operation is normal. In the second experiment, we created a local cable fault condition at node s0. The experiment shown in Figure 17 confirms that the data value of node s0 is '1110', so we can diagnose the cable fault. The third experiment was conducted by creating a backbone cable fault condition connected by s1 and s3.

As shown in the experiment in Fig. 18, the data value of s1 and s3 is '1110', so it can be diagnosed that a backbone cable fault has occurred between s1 and s3. Finally, we verified the proposed method to cope with cable faults. Successful operation could be confirmed by turning on switches at the end of each cable when there is operation failure. As shown in Figure 19, the values of SW1 and SW2 are high (switch on) to communicate using the emergency cable. As all slave data values are '1010', it can be confirmed that it is normal operation. In order to verify the time synchronization, the data values measured and transmitted every 10ms by the measurement node were checked on the PC. The time clock information of the slave node and the time clock information of the master node were compared, respectively.

You can see in Figure 20 that the time difference between the master and slave nodes gradually increases when synchronization is not performed. Upon conducting time synchronization, as depicted in Figure 21, the disparity in time clock values between the master and the slave expands initially, subsequently converges to a particular value, and eventually diminishes. As a result of the experiment, we could confirm the cable fault diagnosis and location, and confirm that time synchronization is performed.

CONCLUSION

In this paper, we introduce an approach that is compatible with both classic CAN and CAN-FD protocols, and it concurrently conducts cable fault diagnosis and time synchronization. We also proposed a method to cope with cable faults for real-time communication. Our proposed method improves the durability of the CAN network because it can diagnose faults and cope with them in real time. And with time synchronization, the accuracy of the CAN network is also improved. Our method has reduced the time required for cable diagnostics and time synchronization of conventional CAN networks from 88%~97%. In addition, one data frame has the advantage of simultaneously diagnosing and time synchronizing 11 nodes in classic CAN mode and 123 nodes in CAN-FD mode.

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AUTHOR INFORMATION

Jongbae Lee, Ph.D. Engineer in Boss Semiconductors Co., Ltd.

Choongchae Woo, Professor, Department of Electrical and electronic engineering, Hanseo University.