Controller Area Network and Its Reduced Wiring Technology

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SUMMARY Controller area network (CAN) has been widely adopted as an in-vehicle communications standard. CAN with flexible data-rate (CAN FD) is defined in the ISO standards to achieve higher data rates than the legacy CAN. A number of CAN nodes can be connected by a single transmission medium, i.e. CAN enables us to constitute cost-effective bus-topology networks. CAN puts carrier sense multiple access with collision resolution (CSMA/CR) into practice by using bit-wise arbitration based on wired logical AND in the physical layer. The most prioritized message is delivered without interruption if two or more CAN nodes transmit messages at the same time due to the bit-wise arbitration. However, the scalability of CAN networks suffers from ringing caused by the signaling mechanism establishing the wired logical AND. We need to reduce networking material in a car in order to reduce the car weight, save the fuel and the cost, and develop a sustainable society by establishing more scalable CAN networks. In this paper, we show a reduced wiring technology for CAN to enhance the network scalability and the cost efficiency.

key words: CAN, CAN FD, bus topology, CSMA/CR, wired logical AND, bit-wise arbitration, ringing, reduced wiring

1. Introduction

Controller area network (CAN) is a message-based multi-drop network protocol designed for reliable in-vehicle control networks via electrical twisted pair cable. CAN was originally developed by Robert Bosch GmbH in 1983 and has been extended to CAN with flexible data-rate (CAN FD) by Bosch in 2012. CAN and CAN FD have been defined in the ISO 11898 standards [1], [2] and for the implementation of in-vehicle communication networks in the SAE J2284 standards with 500 kbps [3], 2 Mbps [4], and 5 Mbps [5]. The CAN FD devices coexist on the same network with the legacy CAN devices as long as the CAN FD devices do not use their extending functions. A cost-effective serial network protocol, local interconnect network (LIN) [6], is also widely utilized for some automobile components via single wiring because CAN costs are too high for every component to implement. FlexRay [7] was originally developed as an automotive control protocol via plastic optical fiber (POF) or electrical twisted pair cable by FlexRay Consortium but its expense limits it to high-end cars. As a result, CAN and LIN are the de-facto automotive control networks [8]–[12] and embedded networking [13] for which many electronic con-

trol units (ECUs) and sensors are designed. Media oriented systems transport (MOST) [14] is a high-rate multimedia network protocol. The MOST network employs daisy-chain topology or ring topology and transports audio, video, voice, and data signals via POF or electrical conductor. Peripheral sensor interface 5 (PSI5) [15] and distributed systems interface 3 (DSI3) [16] are low-rate bus protocols designed for automotive sensor applications. PSI5 and DSI3 provide a cost-effective solution but they achieve a higher data rate than LIN. 100-Mbps Ethernet (100BASE-T1) and 1-Gbps Ethernet (1000BASE-T1) were standardized in IEEE 802.3bw [17] and IEEE 802.3bu [18], respectively. Also power over data line (PoDL) for Ethernet was standardized in IEEE 802.3bu [19]. These Ethernets were designed for automobile point-to-point full-duplex networks via a single pair twisted cable to satisfy strict requirements with respect to the reliability, safety, and electromagnetic compatibility (EMC) in cars [20], [21]. However, they need high-cost switching hubs and additional wiring to accommodate three or more nodes. IEEE 1901 [22] standardized high-rate power line communications (PLCs) technology via AC or DC power line. Although IEEE 1901 can be applied to automobile power bus or automobile CAN bus [23], [24], it is not free of problems. The automobile power bus tends to radiate the signal to the air and receive the noise from the air because the automobile power cable is single wiring. Also the PLC device cost is several tens times higher than the CAN device cost because of the implementation of highly sophisticated signal processing. More than 100 ECUs and sensors are connected via several CAN buses in a part of classy cars. More and more CAN devices and buses are needed as the driving assistance and autonomous driving technology has been developing. However, we need to reduce networking material in order to reduce the car weight, save the fuel and the cost, and develop a sustainable society. Therefore, we should develop the CAN technology to establish more scalable CAN networks.

A message has the identifier (ID) in a CAN bus and all messages are fully prioritized with their IDs. A message is broadcast to all receivers on the CAN bus from a sender and the message is taken in the receivers which need it by acceptance filtering. Any CAN device does not have its address so that the CAN network is fully different from the address-based communication networks. CAN employs a carrier-sense-based access mechanism, called carrier-sense multiple access with collision resolution (CSMA/CR), and all the nodes on a CAN bus including the sending nodes listen to the

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bus voltage. While nodes are transmitting, any other nodes do not transmit their messages. If two or more nodes transmit their messages at the same time, the bus access conflict is resolved by content-based arbitration with the fully prioritized IDs. The message with the minimum ID survives the other simultaneous messages so that the mechanism of arbitration ensures that neither information nor time is lost unlike CSMA with collision detection (CSMA/CD) defined for the half-duplex Ethernet [25], CSMA with collision avoidance (CSMA/CA) [26] defined for IEEE 802.11 [27] and IEEE 802.15.4 [28], and the other collision resolution protocols (CRPs) [29]. The wired logical AND and the in-bit-time detection in the physical layer establish the mechanism of bit-wise arbitration in the medium access control (MAC) layer. The unipolar non-return-to-zero (NRZ) line code is employed for the CAN signaling. A dominant pulse with high differential voltage transmits a bit “0” and a recessive pulse with zero differential voltage transmits a bit “1.” The dominant pulse survives the recessive pulse on the shared CAN medium so that the wired logical AND is established. If a node transmitting the recessive pulse in the arbitration field detects a dominant pulse in the bit time on the CAN bus, the node terminates transmitting its message. A CAN node transmitting a bit in the arbitration field must detect the bus voltage during transmitting the current bit to decide whether to transmit the next bit or not, i.e. CAN needs the in-bit-time detection to conduct the function of bit-wise arbitration. A bit is decided to be “0” or “1” by the hysteresis comparator at the sample point in the bit time. However, if the propagation round-trip time exceeds the sample point, the mechanism of bit-wise arbitration will be destroyed. The cable length and bit rate are restricted by establishing the in-bit-time detection. Cena and Valenzano originally proposed the concept of CAN FD in 1999 to enhance the data rate of the original CAN [30]. Ziermann et al. developed CAN+ protocol, in which high-rate data are embedded in a dominant pulse, to achieve higher data rate than the Cenas’ extension [31]. However, the high-rate version of CAN had not been appeared for a long time in the market until CAN FD was developed in 2012 owing to developing higher functionality for ECUs and sensors. A CAN FD data frame is divided into the arbitration phase, in which multiple nodes may transmit, and the data phase, in which a single node transmits. The data in the arbitration phase are transmitted with the original CAN data rate and the data in the data phase are transmitted with a higher data rate [32], [33]. Also the amount of data in the data phase is getting larger to enhance the data rate of CAN FD. Several new research topics have appeared due to the development of CAN FD. Schreiner et al. proved the robustness and reliability of CAN FD from an OEM’s point of view [34]. Adamson discussed a hybrid network configuration with CAN and CAN FD devices [35], [36]. The higher-rate transmission with CAN FD cannot be exploited in networks where legacy CAN devices are connected to. Cena et al. considered the improvement of the compatibility between CAN FD and legacy CAN devices [37]. Lennartsson developed a CAN FD filter for legacy CAN controllers to

make it possible to receive CAN FD frames [38]. The control commands and sensing data transmitted through the CAN networks have relatively smaller size as compared with the maximum data amount in the extended data field of CAN FD. Garnatz and Decker proposed that a CAN FD data frame carries a number of protocol data units (PDUs) [39]. Cena et al. proposed an extension of CAN FD protocol, called CAN with extensible in-frame reply (CAN XR), in which multiple nodes share the data field in a CAN FD frame [40], [41]. The CAN XR protocol is similar to time-triggered protocols such as the FlexRay protocol [7] and the time-triggered CAN (TTCAN) protocol [42]. Security is also one of the most important topics for CAN networks [12]. Mueller and Lothspeich provided a simple distribution method of symmetric cryptographic keys between different nodes in a CAN network in a plug-and-play manner [43], [44]. Sakon proposed a simple key management scheme by considering the life cycle of a vehicle [45].

Although CAN FD was originally proposed without modifying the network topology of CAN, the data rate and network topology for CAN FD are restricted by ringing occurred in the recessive pulse after a dominant pulse [46], [47]. Actually, CAN FD with the data rate of 5 Mbps is restricted to point-to-point networks in SAE J2284-5 [5] although CAN with the data rate of 2 Mbps is applied for 24-node networks in SAE J2284-4 [4]. The ringing will make us divide a large-size CAN bus into a number of small-size CAN buses, i.e. it will cause increase of communication wiring. We have tackled the reducing wiring problems for CAN networks with low implementation cost. In this paper, we consider two approaches for reducing CAN wiring only by adding existing CAN transceivers and some discrete parts to CAN networks. One is to mitigate the ringing effect in the CAN networks. The CAN bus accommodates more CAN nodes by mitigating the ringing effects. Accommodating more CAN nodes enables us to reduce the number of CAN buses in a car. We present five developed methods to reduce the communication wiring in the CAN networks. The other is to superpose the DC power signal on the CAN bus. Some automobile DC power buses can be removed by supplying electricity through the CAN bus. The unipolar NRZ code on a CAN bus mainly contains DC component in its waveform, so that the data signal integrity will be degraded when the superposed signal is decomposed into the DC power signal and the other AC signal by analog filtering at the front end of the CAN transceiver. To solve this problem, we present an architecture to transmit and receive an alternate mark inversion (AMI) code, in which the dominants are represented by equal-amplitude alternating pulses, by using existing CAN transceivers. The AMI coded architecture helps the data signal integrity to improve because the AMI signal does not have DC component. We discuss the advantages and disadvantages of these proposed methods through simulation results obtained from a VHDL-AMS simulator, SaberRD.

The remainder of this paper is organized as follows: In Sect. 2, we describe the physical and data link layers of CAN FD. In Sect. 3, we investigate a SaberRD simulation

by comparing its result with an experiment for a point-to-point network and present a triple-star network to discuss the advantages and disadvantages of the proposed schemes. We propose five ringing mitigation schemes to reduce the communication wiring and an integrated data and power delivery scheme via a CAN bus to reduce the power wiring. In Sect. 4, we summarize the results to reduce CAN wiring and we discuss the future direction of this research topic.

2. Controller Area Network

In this section, we describe the physical and data link layers of CAN FD based on the SAE standard [4] and the ISO standards [1], [2].

2.1 Physical Layer

The CAN protocol is designed for multi-drop networks comprised of a number of nodes as illustrated in Fig. 1. The network has two terminated nodes with a resistor of $R_T = 120\ \Omega$ to match the characteristic impedance $Z_0 = 120\ \Omega$ of a shielded twisted pair (STP) cable. The transmission medium is shared with multiple nodes so that the CAN networking provides a cost-effective solution for in-vehicle networks.

A unipolar NRZ line code is employed to transmit binary data via a CAN bus. Both of conductors have 2.5 V, i.e. the differential voltage $V_D = 0\text{ V}$ if all the nodes are in the reception mode. A node drives one conductor, CAN_H, to be 3.5 V and another conductor, CAN_L, to be 1.5 V, i.e. the differential voltage $V_D = 2\text{ V}$ if the node transmits a dominant pulse of bit “0.” The impedance of the node becomes about $R_T = 120\ \Omega$ during driving the dominant pulse. The node is in the reception mode if a node transmits a recessive pulse of bit “1.” The impedance is $R_R = 30\text{ k}\Omega$ for the node in the reception mode. As a result, ringing tends to occur in the recessive pulse after a dominant pulse when a larger number of nodes are connected via a CAN bus and the data rate gets higher.

Figure 2 illustrates the bit format of CAN FD. A bit is composed of 9 time quanta where T_q stands for a quantum

Fig. 1 Multiple on-board node configuration defined in SAE J2284-4 [4] with CAN FD data rate at 2 Mbps.

Fig. 2 The bit format for CAN FD.

time so that the bit time is expressed as $T_b = 9T_q$. The synchronization segment (SS) is composed of 1 time quantum and the pulse edge is expected to be detected within this segment. The phase buffer segments 1 and 2 (PBS1 and PBS2) are used to compensate for edge phase errors. These segments are lengthened or shortened by resynchronization. The bus level is read at the sample point, the location of which is at the end of PBS1, and the respective bit is detected. Bit stuffing is employed in the CAN protocol to avoid slipping the bit timing. A bit of opposite value is inserted after 5 consecutive bits of the same value. The threshold of differential voltage transited from recessive to dominant is 0.9 V whereas the threshold transited from dominant to recessive is 0.5 V.

2.2 Data Link Layer

The frame format is categorized into classical base frame format (CBFF), classical extended frame format (CEFF), FD base frame format (FBFF), and FD extended frame format (FEFF). The base frame formats have 11-bit ID whereas the extended frame formats have 29-bit ID. In this paper, we deal with FBFF illustrated in Fig. 3. The number in the bracket stands for the number of bits. The region without the bracketed number consists of a single bit. The former arbitration phase is ranged from the start of frame (SOF) consisting of a single dominant pulse to the sample point in the bit rate switch (BRS) consisting of a single recessive pulse. The latter arbitration phase is ranged from the sample point in the cyclic redundancy check (CRC) delimiter consisting of a single recessive pulse to the end of frame (EOF). The data phase is ranged from the sample point in BRS to the sample point in the CRC delimiter. A single node survives after the former arbitration phase so that only the node transmits in the data phase. The ACK bits are transmitted from receivers successfully receiving the data in the latter arbitration phase. As a result, multiple nodes may transmit at the same time in the arbitration phase with a lower data rate and a single node transmits in the data phase with a higher data rate.

The bit detection will be reliable in the lower-rate arbitration phase because the ringing effect is relatively smaller due to the longer pulse width. However the bit detection error due to ringing in the data phase still destroys the CAN system. If a node sending a bit in the data phase detects a bit error, i.e. a mismatch between the transmitting value and the bus level, the node terminates sending the data frame and then starts transmitting the error frame. If a node receiving a data frame suffers from intensive ringing, the node may fail to pass the CRC and then start transmitting the error frame. Therefore, we have to avoid any bit detection error caused by ringing in the data phase.

3. Reduced Wiring Technology

3.1 Simulation Configuration

We employ a VHDL-AMS simulator, SaberRD [48], to eval-

Fig. 3 The FD base frame format (FBFF).

Fig. 4 The terminated node structure and the signaling for CAN FD.

uate the proposed and original CAN FD systems including analog and mixed-signal (AMS).

We first compare an experiment with a SaberRD simulation to investigate the validation of SaberRD simulations. Figure 4 illustrates the basic structure of a terminated node and an example of the CAN FD signaling. The HS CAN (High Speed CAN) generic model is used as the CAN transceiver in SaberRD simulations. A non-terminated node removes the termination composed of R_T and C_T shown in Fig. 4. PEAK-System PCAN-USB Pro FD, IPEH-004061 [49], is employed to transmit and receive data frames for the experiment. The CAN transceiver in PCAN-USB Pro FD is NXP TJA1044GT [50]. Table 1 shows the main parameters of a STP cable model on SaberRD illustrated in Fig. 5. The characteristic impedance is approximately derived as

$$Z_0 \approx \sqrt{\frac{L_H + L_L + L_{HL}}{C_{HL} + (C_{HG}^{-1} + C_{LG}^{-1})^{-1}}} \approx 119.4 \Omega. \quad (1)$$

On the other hand, we utilize an unshielded twisted-pair (UTP) cable, WAYTEK CB20-15 [51], for the experiment. Figure 6 illustrates a point-to-point network in the experiment and the SaberRD simulations. Node 1 transmits a single dominant pulse in the SaberRD simulation whereas it

Table 1 Line parameters per unit length on SaberRD.

Name	Value
DC inductance, L_H and L_L	325 nH/m
DC mutual inductance, L_{HL}	8.72049 nH/m
DC capacitance, C_{HG} and C_{LG}	87.4 pF/m
DC capacitance, C_{HL}	3.11211 pF/m
DC resistance for conductors	50 mΩ/m
Skin-effect resistances for conductors	180 μΩ/m/√MHz

Fig. 5 The STP cable model on SaberRD.

Fig. 6 A point-to-point network to compare an experiment with a SaberRD simulation.

transmits a data frame in the experiment. The bus voltage is observed at the front end of Node 1. Notice that the termination in Fig. 4 is different from those in Fig. 6 to generate characteristic ringing.

Figure 7 illustrates the received waveforms of “01” by the experiment and the SaberRD simulation on the point-to-point network with the data rate at 500 kbps. The magnitude of the dominant pulse with the SaberRD simulation is larger than that with the experiment except for its head part. Also the magnitude of the ringing in the recessive pulse with the SaberRD simulation is larger than that with the experiment. As a result, the channel in the SaberRD simulation is in a little harsher environment than that in the experiment to receive CAN FD data frames. The difference will be because the STP cable in SaberRD is not modeled on the UTP cable, WAYTEK CB20-15, in the experiment and the HS

CAN generic model in SaberRD is not specific to the CAN transceiver, NXP TJA1044GT, in the experiment. Since we need to develop the CAN system with a margin of bit detection error, it is appropriate to evaluate the proposed schemes.

A triple-star network illustrated in Fig. 8 is commonly used to evaluate the proposed schemes in the SaberRD simulations. There are 15 different channels on the triple-star network as numbered in Table 2. The received waveforms for two bit sequences are observed in the simulations. One is $B_R = 0101010111$ by which we can analyze ringing waves in the last three recessives and the other is $B_D = 010101010000$ by which we can analyze ringing waves in the last four dominants, following alternating bit sequence with high frequency. The data rate is ranged from 1 Mbps to 10 Mbps every 1 Mbps to evaluate the ringing mitigation schemes. Notice that the triple-star network has 32 nodes. The number of nodes exceeds 24 which is the permissible number of nodes in the SAE standard with CAN FD data rate at 2 Mbps [4]. The received waveforms are bit-synchronized with the timing exceeding 0.9 V at the rising edge of the first dominant pulse and the received bits are detected from the received waveforms assuming an ideal hysteresis comparator

by off-line analysis. The success ratio is defined as the percentage of successes among 30 communication conditions composed of 15 channels and two 12-bit sequences for a given bit rate over the triple-star CAN network. Our aim is to discuss the advantages and disadvantages for the proposed schemes through the received waveforms obtained from the SaberRD simulations, and not to eliminate the ringing effects for any network conditions.

3.2 Reduced Communication Wiring

In this section, we present five schemes to reduce communication wiring by alleviating influences of ringing waves. New architectures of CAN nodes are developed to reduce ringing amplitude and duration in the first three schemes. Stub registers are inserted with branch lines without modifying the CAN node architecture to reduce ringing amplitude and duration in the next scheme. A new bit detection scheme is developed to gain the reliability with three or more sample points in a bit for the original CAN signaling in the last scheme.

Fig. 7 The received waveforms of “01” by the experiment and the SaberRD simulation on the point-to-point network with the data rate of $T_b^{-1} = 500$ kbps.

Table 2 The channel number corresponding to the pair of the TX and RX nodes.

Channel	TX node	RX node
Channel 1	Node 1	Node 1
Channel 2	Node 1	Node 2
Channel 3	Node 1	Node 3
Channel 4	Node 1	Node 5
Channel 5	Node 1	Node 7
Channel 6	Node 3	Node 1
Channel 7	Node 3	Node 2
Channel 8	Node 3	Node 3
Channel 9	Node 3	Node 4
Channel 10	Node 3	Node 5
Channel 11	Node 3	Node 7
Channel 12	Node 5	Node 1
Channel 13	Node 5	Node 3
Channel 14	Node 5	Node 5
Channel 15	Node 5	Node 6

Fig. 8 A triple-star network for the SaberRD simulations.

Fig. 9 The non-terminated node structure and the signaling for SP-CAN/SIIM.

3.2.1 Short Pulse CAN with Silent Interval Impedance Matching

The short pulse CAN (SP-CAN) has been proposed in [52]–[54] to extend the CAN bus defined in SAE J2284-3 with the CAN data rate at 500 kbps [3]. High-amplitude and long-duration ringing waves can be observed especially in the recessive pulse following a dominant pulse when a higher-rate CAN bus accommodates a large number of CAN nodes. A CAN node transmits the message following the ID in the data frame where the message is transmitted in the data phase and the overhead including the ID is transmitted in the arbitration phase. In CAN FD, the arbitration phase has the same data rate as the legacy CAN and the data phase has a higher data rate than the legacy CAN because two or more distant nodes can transmit in the arbitration phase and only one node transmits in the data phase. However, the transmit node terminates transmitting the data frame and then starts transmitting the error frame if it detects a dominant bus level while transmitting a recessive pulse because of the self-ringing. We need to mitigate the ringing effects in the data phase to establish more scalable CAN buses. In SP-CAN, the dominant pulse duration in the data phase gets shorter to mitigate the ringing in the recessive pulse following a dominant pulse.

The weighted majority decision with a higher sampling rate [52]–[54] has been proposed as the bit detection for SP-CAN to mitigate the effect of the residual ringing in the recessive pulse following a dominant pulse. However this bit decision scheme requires much higher sampling rate and needs to configure the weighted threshold for each communication pair. We have proposed silent interval impedance matching (SIIM) for SP-CAN to eliminate the ringing ef-

Fig. 10 The received waveforms of the bit sequence B_R by CAN FD and SP-CAN/SIIM via Channel 8 between TX node 3 and RX node 3 with the data rate of $T_b^{-1} = 5$ Mbps.

fects [55]–[58]. The simulation results have revealed the difference in ringing waves and their ringing duration between SP-CAN without SIIM and with SIIM in [56] and we can see that SIIM is definitely effective for alleviating influences of ringing waves. For the following discussions, we deal only with SP-CAN/SIIM. Figure 9 illustrates the non-terminated node structure and an example of the signaling for the SP-CAN/SIIM. In SIIM, the impedance of the transmit node is electrically matched to the characteristic impedance of the STP cable during the silence interval from the end of the dominant pulse to the start of the next bit by using a switch as shown in Fig. 9. The voltage $V_{CC} = 5$ V drives the CAN transceiver and the switch. The transmit node does not reflect the receiving waves during the silence interval so that the residual ringing in the next bit will be mitigated with SIIM.

In this paper, we employ the half of the bit time T_b as the short pulse width, i.e. the short pulse width $T_p = T_b/2$. Also the time quantum for SP-CAN/SIIM is halved to detect the bit within the pulse duration of T_p . Figure 10 illustrates the received waveforms of the bit sequence $B_R = 0101010111$ by CAN FD and SP-CAN/SIIM via Channel 8 between TX node 3 and RX node 3 with the data rate of $T_b^{-1} = 5$ Mbps, where the sample points are drawn by circles. We observe high-amplitude and long-duration ringing for CAN FD signaling whereas the ringing effect for the proposed SP-CAN/SIIM does not affect the bit detection in the recessive pulse following a dominant pulse. We can see that the sample points of recessive pulses following dominant pulses in CAN FD explicitly have the voltage exceeding 0.9 V, i.e. they are incorrectly detected as “0.” The received bit sequence in CAN FD is incorrectly detected as 000000000011 whereas the received bit sequence in SP-CAN/SIIM is correctly detected.

Figure 11 illustrates the received waveforms of the bit sequence $B_R = 0101010111$ by CAN FD and SP-CAN/SIIM via Channel 8 between TX node 3 and RX node 3 with the data rate of $T_b^{-1} = 8$ Mbps, where the sample points are drawn by circles. In this simulation configura-

Fig. 11 The received waveforms of the bit sequence B_R by CAN FD and SP-CAN/SIIM via Channel 8 between TX node 3 and RX node 3 with the data rate of $T_b^{-1} = 8$ Mbps.

Fig. 12 The success ratio versus the bit rate in the data phase for CAN FD and SP-CAN/SIIM.

tion, the width of a received dominant pulse is too thin to detect it correctly for the proposed SP-CAN/SIIM whereas the original CAN FD signaling works well. This is because the dominant pulse energy is not enough to establish the communication due to halving the dominant pulse width for SP-CAN/SIIM. The limitation of the data rate is imposed due to the lack of the dominant pulse energy for SP-CAN/SIIM.

Figure 12 illustrates the success ratio versus the bit rate in the data phase for CAN FD and SP-CAN/SIIM. The proposed SP-CAN/SIIM achieves the same or higher success ratios than the original CAN FD for the bit rates from 1 to 7 Mbps whereas the success ratios become 0% for the bit rates from 8 to 10 Mbps. This is because the dominant pulse energy is not enough to establish the communication due to shortening the dominant pulse width. Furthermore, the original CAN FD devices cannot coexist on the network with the proposed SP-CAN/SIIM devices because the sample point for the CAN FD devices follows the end of a dominant pulse for the SP-CAN/SIIM devices.

Fig. 13 The non-terminated node structure and the signaling for CAN/IMDP.

3.2.2 Impedance Matching in the Data Phase

CAN with impedance matching in the data phase (CAN/IMDP) has been proposed in [57], [59]. In CAN/IMDP, the impedance of the transmit node is electrically matched to the characteristic impedance of the STP cable while transmitting a recessive pulse within the data phase by using a switch. Figure 13 illustrates the non-terminated node structure and an example of the signaling for the proposed CAN/IMDP. Notice that the node structure for CAN/IMDP is the same as that for SP-CAN/SIIM and only the TXD1 and TXD2 logical signaling for CAN/IMDP is different from that for SP-CAN/SIIM as shown in Figs. 9 and 13. In the data phase, the logical signal TXD1 normally inputs to the CAN transceiver whereas the logical signal TXD2 inversely inputs to the switch. The transmit node does not reflect the receiving waves in the data phase because its impedance keeps up $R_T = 120\Omega$ during the data phase as shown in Fig. 13. This is free of problems because the transmit node is single in the data phase.

Figure 14 illustrates the received waveforms of the bit sequence $B_R = 0101010111$ by CAN FD and CAN/IMDP via Channel 8 between TX node 3 and RX node 3 with the data rate of $T_b^{-1} = 8$ Mbps, where the sample points are drawn by circles. We observe high-amplitude and long-duration ringing for CAN FD and the ringing effect for CAN/IMDP does not affect the bit detection while transmitting the bit sequence of B_R . The proposed CAN/IMDP has the effect of low-pass filter (LPF) for the ringing observed in the CAN FD signaling as shown in Fig. 14. The 11th received bit in CAN FD is incorrectly detected as dominant whereas the received bit sequence in CAN/IMDP is correctly detected. It is interesting to pass the one-bit later

Fig. 14 The received waveforms of the bit sequence B_R by CAN FD and CAN/IMDP via Channel 8 between TX node 3 and RX node 3 with the data rate of $T_b^{-1} = 8$ Mbps.

Fig. 15 The received waveforms of the bit sequence B_R by CAN FD and CAN/IMDP via Channel 14 between TX node 5 and RX node 5 with the data rate of $T_b^{-1} = 6$ Mbps.

recessive bit and fail the two-bit later recessive bit following a dominant pulse in CAN FD. We need to analyze ringing within consecutive recessives and dominants.

Figure 15 illustrates the received waveforms of the bit sequence $B_R = 0101010111$ by CAN FD and CAN/IMDP via Channel 14 between TX node 5 and RX node 5 with the data rate of $T_b^{-1} = 6$ Mbps, where the sample points are drawn by circles. We can see the effect of LPF for the ringing observed in the CAN FD signaling by using the proposed CAN/IMDP. However, this ringing in the CAN FD signaling has a large low-frequency component so that the bit detection is destructively affected by the low-frequency component for the proposed CAN/IMDP although the oscillation of the ringing is mitigated by the impedance matching. The 6th and 10th received bits in CAN FD are incorrectly detected whereas the received bit sequence in CAN/IMDP is incorrectly detected as 00000000011. The proposed CAN/IMDP suffers more bit errors than the original CAN FD in the case of Channel 14 and the data rate 6 Mbps.

Figure 16 illustrates the success ratio versus the bit rate in the data phase for CAN FD and CAN/IMDP. The

Fig. 16 The success ratio versus the bit rate in the data phase for CAN FD and CAN/IMDP.

proposed CAN/IMDP achieves the same or higher success ratios than the original CAN FD for all the bit rates. On the other hand, CAN/IMDP has lower success ratios than SP-CAN/SIIM for the bit rates from 4 to 7 Mbps. Unlike SP-CAN/SIIM, the proposed CAN/IMDP devices can coexist on the network with the existing CAN FD devices because the transmit waveforms of CAN/IMDP devices are the same as those of CAN FD devices. Replacing an unreliable CAN FD device with a CAN/IMDP device can enhance the reliability of the existing CAN networks due to reducing self-reflection waves at the node.

3.2.3 Bipolar Coding in the Data Phase

CAN with bipolar coding in the data phase (CAN/BCDP) has been proposed in [59], [60] as an extension of CAN/IMDP. Figure 17 illustrates the non-terminated node structure and an example of the signaling for the proposed CAN/BCDP. CAN/BCDP employs two CAN transceivers as shown in Fig. 17 and this architecture provides us a bipolar NRZ line code. The CAN transceiver 1 is normally connected to the CAN bus whereas the CAN transceiver 2 is inversely connected to the CAN bus. In the data phase, the logical signal TXD1 normally inputs to the CAN transceiver 1 whereas the logical signal TXD2 inversely inputs to the CAN transceiver 2. The CAN/BCDP node drives CAN_H of 3.5 V and CAN_L of 1.5 V for a dominant pulse and the CAN_H of 1.5 V and CAN_L of 3.5 V for a recessive pulse in the data phase. Also the CAN/BCDP node has the impedance of $R_T = 120 \Omega$ in the data phase so that the self-ringing can be reduced as with the CAN/IMDP node. The output logical signal RXD1 of the CAN transceiver is utilized for the detection at the sample point.

Figure 18 illustrates the received waveforms of the bit sequence $B_R = 0101010111$ by CAN FD and CAN/BCDP via Channel 14 between TX node 5 and RX node 5 with the data rate of $T_b^{-1} = 6$ Mbps, where the sample points are drawn by circles. The combination of Channel 14 and the data rate $T_b^{-1} = 6$ Mbps makes it difficult to establish reliable communication for CAN/IMDP whereas the received bit se-

Fig. 17 The non-terminated node structure and the signaling for CAN/BCDP.

Fig. 18 The received waveforms of the bit sequence B_R by CAN FD and CAN/BCDP via Channel 14 between TX node 5 and RX node 5 with the data rate of $T_b^{-1} = 6$ Mbps.

quence in CAN/BCDP is correctly detected. In the proposed CAN/BCDP, in addition to the LPF effect like CAN/IMDP, the differential voltage V_D moves to the region of minus voltage so that the bit detection is quite reliable as compared with the other schemes.

Figure 19 illustrates the received waveforms of the bit sequence $B_R = 0101010111$ by CAN FD and CAN/BCDP via Channel 14 between TX node 5 and RX node 5 with the data rate of $T_b^{-1} = 5$ Mbps, where the sample points are drawn by circles. Although the data rate in Fig. 19 is lower than the previous data rate in Fig. 18, we observe that the differential voltage V_D drops more deeply, the sample points for received dominant pulses are under the threshold

Fig. 19 The received waveforms of the bit sequence B_R by CAN FD and CAN/BCDP via Channel 14 between TX node 5 and RX node 5 with the data rate of $T_b^{-1} = 5$ Mbps.

Fig. 20 The success ratio versus the bit rate in the data phase for CAN FD, CAN/BCDP, and CAN/BCDP2.

of 0.5 V, and the received bits corresponding to dominant pulses are not correctly detected. The combination of RXD1 and RXD2 makes it possible to establish a virtual hysteresis comparator, the voltage threshold of which transited from recessive to dominant is 0.9 V and the voltage threshold of which transited from dominant to recessive is -0.9 V. The received bit sequence with the dual hysteresis comparator is correctly detected for the bipolar NRZ signaling even in the case of Channel 14 and the data rate $T_b^{-1} = 5$ Mbps.

Figure 20 illustrates the success ratio versus the bit rate in the data phase for CAN FD, CAN/BCDP, and CAN/BCDP2, where CAN/BCDP2 stands for CAN/BCDP with the dual hysteresis comparator. The proposed CAN/BCDP achieves the same or higher success ratios than the original CAN FD for all the bit rates but 10 Mbps. On the other hand, the proposed CAN/BCDP2 establishes a remarkable result that it achieves 100% success ratio for any given bit rate on the triple-star CAN network with 32 nodes. As with CAN/IMDP, the proposed CAN/BCDP2 devices can coexist on the network with the existing CAN FD devices because the transmit signals of CAN/BCDP2 devices can be decoded at the CAN FD devices. Replacing an unreliable

Fig. 21 The insertion of stub resistors on the branch lines.

Fig. 22 The received waveforms of the bit sequence B_R by CAN FD and SSSL-CAN via Channel 8 between TX node 3 and RX node 3 with the data rate of $T_b^{-1} = 8$ Mbps.

CAN FD device with a CAN/BCDP2 device may enhance the reliability of the existing CAN networks due to reducing self-reflection waves at the node.

3.2.4 Stub Series Terminated Logic for CAN

The original node structure for CAN FD is modified in the proposed schemes described above. In this section, although the node itself is not modified, the CAN bus is modified to reduce the ringing. Stub series terminated logic (SSTL) has been originally applied to high-rate memory bus to mitigate the effect of signal reflection at stubs [61]. A stub resistor is inserted at each stub on the memory bus with SSTL. The high-rate CAN FD bus should be considered as a distributed constant circuit as with the high-rate memory bus. Applying SSTL to CAN FD buses has been proposed in [55], [59] as shown in Fig. 21.

Figure 22 illustrates the received waveforms of the bit sequence $B_R = 0101010111$ by CAN FD and SSSL-CAN via Channel 8 between TX node 3 and RX node 3 with the data rate of $T_b^{-1} = 7$ Mbps, where the sample points are drawn by circles. The stub resistors can make the ringing amplitude smaller but the high-frequency component in the ringing remains unlike CAN/IMDP. Also the dominant pulse amplitude in the same branch line is enlarged by the stub resistors. The received bit sequence is correctly detected because the voltage V_D at the sample point does not exceed the threshold of 0.9 V in any recessive pulse.

Figure 23 illustrates the received waveforms of the bit sequence $B_R = 0101010111$ by CAN FD and SSSL-CAN via Channel 10 between TX node 3 and RX node 5 with

Fig. 23 The received waveforms of the bit sequence B_R by CAN FD and SSSL-CAN via Channel 10 between TX node 3 and RX node 5 with the data rate of $T_b^{-1} = 8$ Mbps.

Fig. 24 The success ratio versus the bit rate in the data phase for CAN FD and SSSL-CAN.

the data rate of $T_b^{-1} = 8$ Mbps, where the sample points are drawn by circles. If the transmit node is on a branch line and it is not the received node, the dominant pulse amplitude significantly attenuates as shown in Fig. 23. Although the received bit sequence for SSSL-CAN is correctly detected, the voltage margin for dominant pulses is quite small, so that SSSL-CAN will not be robust in reference voltage variation due to temperature fluctuation and supply voltage fluctuation in a car. We should optimize the value of the stab resistor R_S so as to maximize the dominant voltage margin and reduce the ringing amplitude.

Figure 24 illustrates the success ratio versus the bit rate in the data phase for CAN FD and SSSL-CAN. The proposed SSSL-CAN achieves the same or higher success ratios than the original CAN FD for all the bit rates. Although SSSL-CAN does not achieve 100% success ratio for 3 or more Mbps as with the original CAN FD, it has an advantage of the simplified implementation since the node architecture does not change unlike the other ringing mitigation schemes.

Fig. 25 The sampling points for logical OR detection.

Fig. 26 Five sample points per bit on the bit sequence B_R by CAN FD via Channel 8 between TX node 3 and RX node 3 with the data rate of $T_b^{-1} = 8$ Mbps.

3.2.5 Logical OR Detection

The logical OR detection is a bit detection method using multiple sample points without modifying the node structure such as SP-CAN, CAN/IMDP, CAN/BCDP, and CAN/BCDP2, and the bus configuration such as SSTL-CAN. The output of the CAN transceiver at a non-terminated node will alternate logical “0” and “1” during the ringing occurred in the recessive pulse following a dominant pulse. The detection error of logical “1” occurs when the CAN node detects the CAN transceiver output of logical “0” at the sampling point. However, the CAN transceiver output may be logical “1” before and behind the sampling point with incorrect logical “0” because of the alternating property of the ringing. Taking the alternating property into consideration, the logical OR detection has been proposed in [62], [63].

A bit is composed of 9 time quanta in the CAN FD as shown in Fig. 25. The CAN FD standard [1] defines the detection at the single sampling point S_0 and the majority vote detection among 3 consecutive sampling points S_{-1} , S_0 , and S_1 as an option. In the $(2m + 1)$ -point logical OR detection, the CAN controller ORs $2m + 1$ sampling points from S_{-m} to S_m . Notice that the logical OR detection will enhance the reliability in both the data phase and arbitration phase.

Figure 26 illustrates five sample points per bit on the bit sequence $B_R = 0101010111$ by CAN FD via Channel 8 between TX node 3 and RX node 3 with the data rate of $T_b^{-1} = 8$ Mbps. The 11th received bit sequence is incorrectly detected in the case of one sample point detection (SPD-1) and 3-point logical OR detection (LOR-3) whereas it is correctly detected in the case of 5-point logical OR detection

Fig. 27 The success ratio versus the bit rate in the data phase for CAN FD with one sample point detection (SPD-1), 3-point LOR (LOR-3), and 5-point LOR (LOR-5).

(LOR-5) because the five sample points on the 11th recessive pulse are detected as 10001. Although the received bit sequence for LOR-5 is correctly detected, we can see that the voltage margin is quite small as illustrated in Fig. 26, so that even LOR-5 will not be robust in reference voltage variation due to temperature fluctuation and supply voltage fluctuation in a car. Since the rising or falling edge in the phase buffer segments (PBSs) is allowed for conducting the logical OR detection, the resynchronization is not available for the logical OR detection.

Figure 27 illustrates the success ratio versus the bit rate in the data phase for CAN FD with SPD-1, LOR-3, and LOR-5. LOR-3 achieves the same or higher success ratios than SPD-1 and LOR-5 achieves the same or higher success ratios than LOR-3. However, the logical OR detection will enhance the reliability for a CAN bus in a probabilistic manner. We need more robust and reliable communication for automobile control networks in a deterministic manner.

3.3 Reduced Power Wiring

In this section, we present an approach to reduce DC power wiring. By supplying the DC power to CAN nodes through the CAN bus, we can remove a part of automobile DC power buses. However, such DC power supply needs to superpose the DC power on the CAN signal because the CAN cable is composed of one-pair conductors, i.e. it has only one physical channel. The unipolar NRZ signal on the CAN bus contains a lot of DC component in its waveform, so that the data signal integrity is degraded after decomposing the superposed signal into the DC power and the other AC signal by analog filtering at the front end of a CAN node. We need to develop a new CAN signaling architecture without DC component while keeping the function of bit-wise arbitration.

3.3.1 Power over CAN

Power over CAN (PoCAN) has been proposed in [64], [65]. PoCAN superposes the automobile DC power of 12 V on

Fig. 28 The non-terminated node structure and the signaling for PoCAN.

both of the conductors. AMI line coding is employed for PoCAN to extract the DC power from the superposed signal with LPF because the NRZ-AMI signal does not have DC component. The DC power wiring can be reduced since the electricity is supplied to automobile devices via the CAN communication bus.

Figure 28 illustrates the non-terminated node structure and an example of the signaling for the proposed PoCAN. PoCAN utilizes two CAN transceivers as with CAN/BCDP2. The CAN transceiver 1 is normally connected to the PoCAN bus whereas the CAN transceiver 2 is inversely connected to the PoCAN bus. The odd-numbered dominant bits are transmitted via the CAN transceiver 1 whereas the even-numbered dominant bits are transmitted via the CAN transceiver 2. The DC power of 12 V is superposed on both of CAN_H and CAN_L. The odd-numbered dominant pulses have the CAN_H of 13.5 V and the CAN_L of 11.5 V, the even-numbered dominant pulses have the CAN_H of 11.5 V and the CAN_L of 13.5 V, and all the recessive pulses have both the conductors of 12 V. The logical AND of RXD1 and RXD2 provides the transmitted message. The power $V_{CC} = 5V$ drives two CAN transceivers and is converted from the superposed bus power via a 3-terminal switching regulator in the SaberRD simulations. Matsushita et al. implemented the PoCAN node structure on MAX 10 FPGA Evaluation Kit [66], employed MLT PX-10 [67] as CAN

Fig. 29 The received differential signal of the bit sequence B_D by PoCAN via Channel 14 between TX node 5 and RX node 5 with the data rate of $T_b^{-1} = 500$ kbps.

Fig. 30 The received power of the bit sequence B_D by PoCAN via Channel 14 between TX node 5 and RX node 5 with the data rate of $T_b^{-1} = 500$ kbps.

controllers and CAN transceivers, and employed JMACS CANC-50SF [68] as STP cable to demonstrate the bit-wise arbitration function on a point-to-point network with the line length of 10 m and the data rate of 500 kbps [64], [65]. In this paper, we observe the received waveforms of data and power signals for PoCAN on the triple-star network with 32 nodes and the data rate $T_b^{-1} = 500$ kbps.

Figure 29 illustrates the received differential signal of the bit sequence $B_D = 0101010000$ by PoCAN via Channel 14 between TX node 5 and RX node 5 with the data rate of $T_b^{-1} = 500$ kbps where “Bus diff” stands for the differential signal before passing the high-pass filter (HPF) and “RX diff” stands for the differential signal after passing the HPF. We can see that the transmitted bit sequence is correctly detected from the received differential signal in Fig. 29. PoCAN achieves 100% success ratio for 500 kbps.

Figure 30 illustrates the received power of the bit sequence $B_D = 0101010000$ by PoCAN via Channel 14 between TX node 5 and RX node 5 with the data rate of $T_b^{-1} = 500$ kbps where “Bus power” stands for the power signal before passing the LPF and “RX power” stands for

the power signal after passing the LPF. We can see that the power $V_{CC} = 5\text{ V}$ successfully drives two CAN transceivers without any power loss.

4. Conclusion

We have described our reduced wiring technology for CAN that enhances the network scalability and the cost efficiency in this paper. A triple-star network with 32 nodes is examined to discuss the advantages and disadvantages of the proposed schemes.

We have proposed five ringing mitigation schemes in order to reduce the communication wiring. SP-CAN/SIIM signaling can reduce the ringing observed in the CAN networks by using the impedance matching in the silent interval following short dominant pulses. However, the data rate is limited due to shortening the dominant pulse width as compared with the CAN FD signaling. A single node transmits the message in the data phase following the arbitration field in the CAN protocol. Based on the single-node transmission in the data phase, CAN/IMDP has been developed. The CAN/IMDP architecture enables us to perform impedance matching at the transmit node in the data phase. Large-amplitude and high-frequency ringing observed in the CAN FD network looks like passing through LPF in the CAN/IMDP network. However, if ringing has low-frequency component, CAN/IMDP makes it difficult to eliminate the ringing effects. CAN/BCDP and CAN/BCDP2 are defined as an extension of CAN/IMDP because they perform impedance matching at the transmit node in the data phase. Bipolar NRZ line coding is conducted by the CAN/BCDP and CAN/BCDP2 architectures using two CAN transceivers. The CAN/BCDP2 architecture with the dual hysteresis comparator establishes a remarkable result that it achieves 100% success ratio for any given bit rate over the triple-star network with 32 nodes. In the SSTL-CAN scheme, the CAN bus is improved with the insertion of stab resistors without modifying the node configuration. However, if the received node is not the transmit node and the transmit node connects to a branch line, the received node observes low-amplitude dominant pulses. We need a voltage margin on automobile networks so that SSTL-CAN is not preferable in a current form. The received bit is detected by the result of logical OR at multiple sample points in the logical OR detection. However, the logical OR detection can enhance the communication reliability in a probabilistic manner. We need to enhance the communication reliability for automobile networks in a deterministic manner. As a result, we can see that CAN/BCDP2 is one of the most promising and scalable solutions to reduce communication wiring in cars.

We have proposed the PoCAN architecture to reduce power wiring. The DC power is superposed on the CAN bus in the PoCAN system. Two CAN transceivers are utilized for a PoCAN node as with a CAN/BCDP2 node. The connection of a PoCAN node to the CAN bus is the same as a CAN/BCDP2 node. The received differential signal is correctly detected for the data rate of 500 kbps and the re-

ceived power is of good quality to establish supplying the power with two CAN transceivers. As a result, we can see that PoCAN is one of the most promising solutions to reduce power wiring in cars.

The bipolar NRZ line code for CAN/BCDP2 does not have DC component as with the NRZ-AMI line code for PoCAN. The node structure for signal transmission in PoCAN is the same as that in CAN/BCDP2. We should investigate the integration of PoCAN in the arbitration phase and CAN/BCDP2 in the data phase to reduce power and communication wiring for automobile networks as a future work.

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