Silent-interval Impedance Matching for Short Pulse CAN to Enhance Scalability

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***Abstract*—Controller area network (CAN) is a communication standard for in-vehicle networks and is widely employed by a number of vehicle lines. Recently, it is required for CAN to enhance the scalability of bus topology and bit rate because the functionality of in-vehicle devices is becoming high and their number is increasing. However, the scalability enhancement of CAN will cause ringing waves with higher amplitude and longer duration as compared with those of pulse waves. The short pulse CAN (SP-CAN) has been proposed to enhance the scalability of CAN but it does not remove the ringing effect perfectly. In this paper, silent-interval impedance matching (SIIM) is proposed for SP-CAN to enhance the scalability of bus topology and bit rate. The simulation and experimental results show that the proposed scheme can remove the ringing effect perfectly for the scalable bus topology and bit rate.**

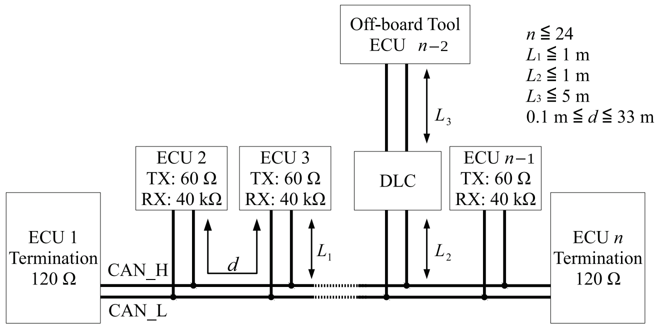

Fig. 1. The CAN network structure complied with SAE J2284.

I. Introduction

Recently, mechanical/hydraulic control in vehicles has been moved on to electronic control so that there are a number of electronic control units (ECUs) to control actuators and gather sensing data in vehicles. A wired network has been constructed to connect such devices, in which high reliability and low latency are required to achieve human safety and comfort [1]. Nowadays, several car lines have 100 or more communicating devices. Gateways will be utilized to connect different types of network systems such like body, powertrain, chassis, and telematics systems. With the diversification and sophistication of in-vehicle networks, the in-vehicle spaces may be limited and networks will be more complicated so that the simplification of in-vehicle networks and the reduction of the network components are highly desirable.

Controller area network (CAN) is one of communication standards and is widely distributed for a variety of wired control networks [2]. In particular, SAE J2284 standardizes CAN-based PHY and medium access control (MAC) layers for in-vehicle communications, which has a single rate of 500 kbps, the node capacity of 24 nodes, and the maximum length between transmitting and receiving nodes of 33 m [3]. If the number of nodes exceeds 24, multiple CAN buses are required to communicate with all the nodes in SAE J2284. As a result, additional cost and in-vehicle space are needed with increasing sensors and actuators in vehicles. CAN with higher rate and capacity will be desirable to avoid consuming additional cost and in-vehicle space. However, a large number of high-rate nodes in the same CAN bus will cause severe inter-symbol interference (ISI) so that all the communications among nodes may result in failure.

In this paper, we propose silent-interval impedance matching (SIIM) for the short pulse CAN (SP-CAN) to enhance the scalability of bus topology and bit rate, where SP-CAN has been proposed to mitigate severe ISI due to high rate and capacity [4] but it did not remove the ISI perfectly so that waveform shaping with majority vote was required. Severe ISI will occur by shortening the bit duration and adding a number of waves reflected from impedance mismatch points at the device front-ends and bus branches, and it will be observed as ringing in the next bits. The short pulse line codes enable us to mitigate the effect of ringing by shortening the dominant pulse duration. SIIM can reduce the amplitude and time duration of ringing waves. The analytical results show that the proposed scheme achieves the bit rate of 1 Mbps and the node capacity of 32 nodes for all the pairs of transmitting and receiving nodes. A simple node architecture is proposed to conduct experimental trails without modifying the CAN controller. Experimental trails show the effectiveness of the proposed schemes.

II. Controller Area Network

Let us describe CAN based on SAE J2284. The network structure for CAN is illustrated in Fig. 1. The transmit medium is twisted pair (TP) cable, the characteristic impedance of which is $Z_0 = 120\ \Omega$. The CAN bus allows us to connect at most 24 nodes. Terminators are located at most distant two ends on the CAN bus. The distance between any two nodes should be less than or equal to 33 m. To diagnose the CAN bus, off-board tool ECU will be connected via a data link connector (DLC). The distances L_1, L_2, and L_3 in Fig. 1 should be less than or equal to 1 m, 1 m, and 5 m, respectively.

A. PHY Layer

A TP cable is composed of two conductors. The voltages on a CAN bus are illustrated in Fig. 2. Both of conductors have 2.5 V when no node transmits. Bit "1" is represented as a recessive signal, in which both of conductors have 2.5 V whereas bit "0" is represented as a dominant signal, in which one has 3.5 V and the other has 1.5 V. The conductors of 3.5 V and 1.5 V in the dominant signal are denoted as CAN_H and CAN_L, respectively. The CAN bus signal is designed as a non-return-to-zero (NRZ) line code.

Let us model CAN nodes in this paper based on off-the-shelf CAN devices as shown in Fig. 3. The CAN controller provides the medium access control (MAC) mechanism and the CAN transceiver converts logical signals with high "1" and low "0" into CAN bus signals and vice versa. The receiver is always connected to the CAN interface whereas the transmitter is connected to it in parallel only in the dominant transmission. The impedances of the receiver in the terminated and non-terminated CAN nodes are assumed to be 120 Ω and 40 kΩ, respectively. The impedance of the transmitter in the CAN node is assumed to be 60 Ω. A non-terminated node has the impedance of 40 kΩ in the RX mode and that of about 60 Ω in the TX mode whereas a terminated node has the impedance of 120 Ω in the RX mode and that of 40 Ω in the TX mode. As a result, the channel of the CAN bus is time-varying. A hysteresis comparator in the CAN receiver will be employed

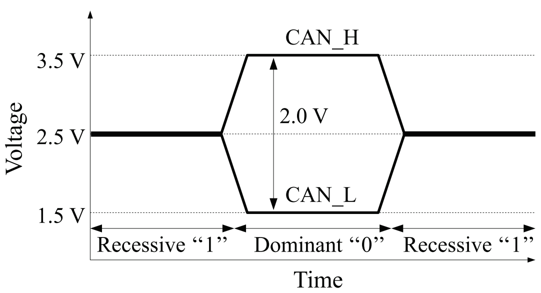

Fig. 2. An example of signal voltage on the CAN bus.

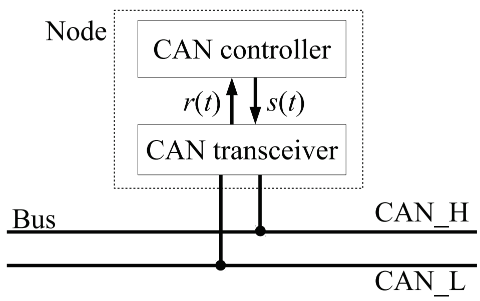

Fig. 3. The CAN node architecture.

to detect whether the bus signal is dominant or recessive. the thresholds are 0.9 V from recessive to dominant and 0.5 V from dominant to recessive.

The basic time unit in CAN is denoted as time quantum, T_{q}. The total number of time quanta in one bit shall be 8 to 25. The bit time is divided into four time segments in the order of synchronization segment (SS), propagation time segment (PTS), phase buffer segment 1 (PBS1), and phase buffer segment 2 (PBS2). The sample point, which is located at the end of PBS1, shall be the point of time at which the logical level is read and the bit of "0" or "1" is detected.

B. Data Link Layer

In the data link layer of CAN, carrier sense multiple access with collision resolution (CSMA/CR) is employed. CAN has an arbitration function to achieve prioritized transmission of data. Each data frame has an arbitration field just after a start of frame (SOF) bit.

Let us assume that a node starts transmitting a data frame. The transmitting node monitors the bus level and compares the signal transmitted from the transmitter with one received at the receiver. If a recessive symbol is transmitted but the bus level is dominant in the arbitration field, the transmitting node presumes the existence of other prioritized nodes on the CAN bus and stops transmitting the data frame. Also if a transmit symbol is mismatched with the bus level in the data field, the transmitting node stops transmitting and then starts transmitting the error frame. The transmitting node should decide whether the transmission continues or not according to the current bus status. Therefore, ISI will be serious for the CAN system.

The source node should receive an ACK (acknowledgement) dominant bit in the ACK slot from nodes. Therefore, the transmission delay should be brief relative to the bit duration.

III. Silent-interval Impedance Matching for SP-CAN

In this section, let us describe the ringing effect, SP-CAN, and SIIM.

A. Inter-symbol Interference by Ringing

A node will receive a number of reflection waves so that ringing will be observed at the node. The reflection ratio ρ_{B} at a branch is expressed as

$$\rho_{\mathrm{B}} = \frac{1-N}{1+N}, \tag{1}$$

where N is the number of injecting lines. As the number N becomes larger, the reflection ratio ρ_{B} approaches to -1, i.e., the injecting wave will be almost fully-reflected with antiphase. The reflection ratio ρ_{H} at the front-end of a node is expressed as

$$\rho_{\mathrm{H}} = \frac{R-Z_0}{R+Z_0}, \tag{2}$$

where R is the input impedance of the node. In the RX mode of a high-impedance node with $R = 40$ kΩ, the reflection ratio

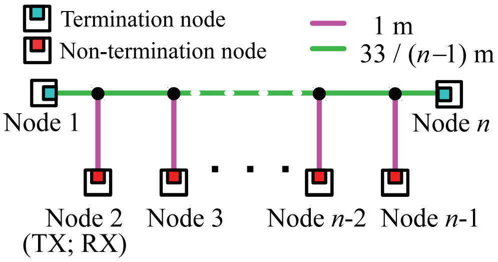

Fig. 4. A linear bus network model.

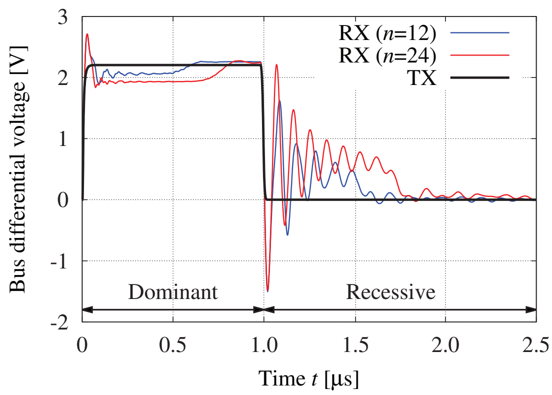

Fig. 5. The transmit and received signals at node 2 when n = 12 and 24.

is $\rho_{\mathrm{H}} = 0.99$ whereas it is $\rho_{\mathrm{H}} = -0.33$ in the TX mode. As a result, nodes generally observe ringing waves with higher amplitude and longer duration from the start of recessive symbol just after a dominant symbol. Figure 4 illustrates the linear bus network with the same distance between two adjacent branch points whereas Fig. 5 illustrates the ringing waves received at node 2 transmitting at node 2 in the case of n = 12 and 24. The ringing wave tends to be observed with higher amplitude and longer duration when the number of connected nodes becomes more.

The higher-rate CAN node will suffer from severe ISI caused by ringing because the bit duration becomes shorter. The ringing with high amplitude and long duration at a node during transmitting recessive bits will act destructively on communications via the CAN bus. This is because the node stops transmitting the frame when the node detects self-ringing as a dominant symbol. As a result, the CAN bus with high rate and capacity may not work at all.

B. Short Pulse Line Codes

To solve the ringing problems for the scalable bus topology and bit rate, SP-CAN has been proposed. The dominant in the short pulse line code has pulse duration T_{p} shorter than the original CAN dominant duration T_{b} as shown in Fig. 6. The ringing amplitude is expected to be attenuated during the duration T_{SI} from the end of the dominant short pulse to the beginning of the recessive duration. However, the ringing wave may remain in the recessive duration so that some sophisticated symbol detection should be employed [4].

A simple implementation of the SP-CAN is shown in Fig. 7 without modifying the CAN controller. A pulse converter is inserted between the CAN controller and the CAN transceiver. It converts a logical signal $s(t)$ with the NRZ code output from the CAN controller into the logical signal $s_1(t)$ of short pulse line codes input to the CAN transceiver. Also it converts a logical signal $r_1(t)$ with hysteresis comparator into the logical signal $r(t)$ of the NRZ code with some symbol detection. In [4], the pulse converter with majority vote pulse shaper was implemented with a field programmable gate array (FPGA). Figure 8 illustrates the components of the transmission delay at in the SP-CAN system [4]. The delay at transmitting nodes consists of the pulse-shaping delay of 44 ns at FPGA and the device delay of 55 ns at the transceiver whereas the delay at receiving nodes consists of the pulse-shaping delay of 110 ns at FPGA and the device delay of 50 ns at the transceiver. The group delay in the network is dependent on the impedance between transmitting and receiving nodes. Note that the delay at FPGA is depend on how to implement the pulse-shaping.

C. Silent-interval Impedance Matching for SP-CAN

As described in the above subsection, the ringing wave may remain in the recessive duration just after a dominant pulse transmission for some CAN buses even if the short pulse line codes would be employed. To remove the remaining ringing effect in the recessive duration, a novel ringing

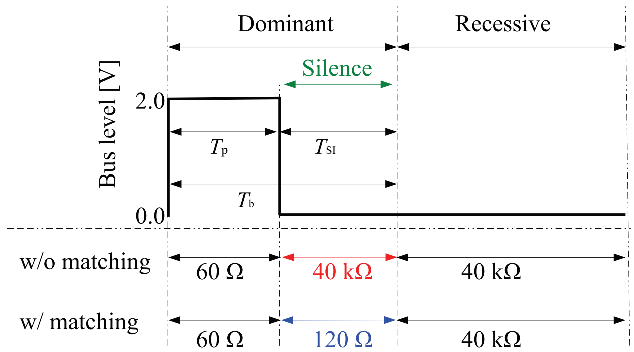

Fig. 6. Short pulse line codes and silent-interval impedance matching.

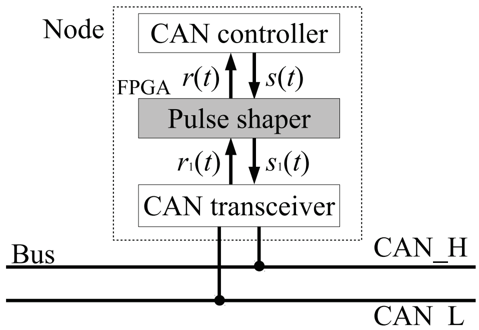

Fig. 7. The implementation of short pulse line codes.

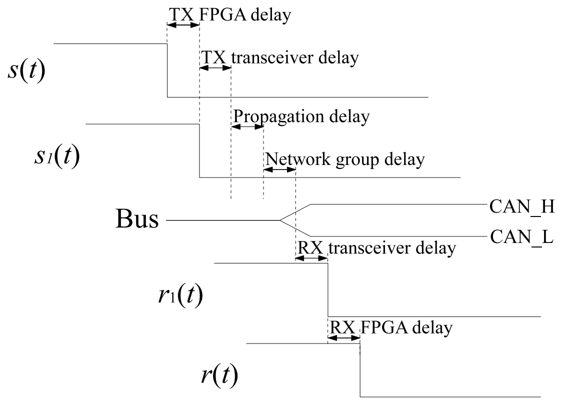

Fig. 8. The components of the transmission delay.

mitigation scheme is proposed for SP-CAN, called silent-interval impedance matching (SIIM). As shown in Fig. 6, non-dominant level signal will be deterministically transmitted on the CAN bus in the duration between the preceding dominant short pulse end and the next symbol start since all CAN nodes in the CAN bus sense the bus status so that the duration is called silent-interval. In SIIM, the load impedance of the transmitting node is matched to the characteristic impedance of the TP cable in the silent-interval T_{SI}, i.e. the transmitting node makes the load impedance into $Z_0 = 120\ \Omega$ in the silent-interval T_{SI}. The transmitting node will not generate reflection waves in the silent-interval so that the ringing wave will be significantly reduced just after a dominant pulse. As a result, SP-CAN with SIIM will enable to enhance the scalability of bus topology and bit rate.

IV. Performance Evaluation

In this section, simulations and experimental trials are conducted to evaluate the performances of the proposed scheme.

A. Test Network and Performance Index

The test network in this paper is illustrated in Fig. 9 and higher-amplitude and longer-duration ringing waves will be observed for some transmitting and receiving nodes on it in the high-rate CAN. The CAN bus has the bit rate of 1 Mbps, 30 non-termination nodes, 2 termination nodes, 32 m main line, and 2 m branch lines, the values of which are an extension of SAE J2284 [3]. The central two nodes will be employed as off-board tool ECU.

The transmitter and receiver at a central node are denoted as "TX1" and "RX1", respectively and the receiver at the other central node is denoted as "RX2" as shown in Fig. 9. Let us assume that TX1 transmits a single dominant pulse to evaluate the ringing effect. The voltage received at RX1 is expressed as $v_{\mathrm{R1}}(t)$. The RX1 signal $v_{\mathrm{R1}}(t)$ is converted to the logical signal

$$r_1(t) = \begin{cases} 0\ \mathrm{V}, & (v_{\mathrm{R1}}(t) \geq \Gamma(t)), \\ 5\ \mathrm{V}, & (v_{\mathrm{R1}}(t) < \Gamma(t)), \end{cases} \tag{3}$$

with the hysteresis comparator, where $\Gamma(t)$ is a threshold voltage signal and is defined by

$$\Gamma(t) = \begin{cases} 0.9\ \mathrm{V}, & (r_1(t-\Delta t) = 5\ \mathrm{V}), \\ 0.6\ \mathrm{V}, & (r_1(t-\Delta t) = 0\ \mathrm{V}), \end{cases} \tag{4}$$

for a minute time Δt. The residual ringing time from the next recessive start time, T_{r}, is defined as

$$T_{\mathrm{r}} = \sup\{t - T_{\mathrm{b}} | r_1(t) = 0\ \mathrm{V}\}, \tag{5}$$

where $t = 0$ indicates the start time of the dominant pulse transmitted from TX1. If T_{r} is equal to 0 or minus, the ringing does not affect the next recessive symbol.

Figure 10 illustrates the signals transmitted from TX1 and received at RX1 when a single dominant pulse transmits from a central node on the test network in Fig. 9 for the conventional CAN with NRZ, which is obtained from a simulation program with integrated circuit emphasis (SPICE). The residual ringing time in Fig. 7 is $T_{\mathrm{r}} = 1300$ ns so that the conventional CAN with NRZ may fail to detect the next recessive symbol.

Figure 11 illustrates the signals transmitted from TX1 and received at RX1 for SP-CAN without and with SIIM when the pulse duration is $T_{\mathrm{p}} = 0.5$ µs. The residual ringing time is $T_{\mathrm{r}} = 786$ ns without SIIM whereas it is $T_{\mathrm{r}} = -65$ ns with SIIM. SP-CAN without SIIM may fail to detect the next recessive symbol even when the pulse duration is shorter whereas SP-CAN with SIIM definitely succeeds to detect it because the residual ringing of the dominant short pulse does not affect the next recessive symbol completely.

B. Simulation Results

SP-CAN with silent-interval impedance matching is analyzed with a SPICE simulator. Figure 12 illustrates the residual ringing time T_{r} at RX1 for given pulse duration T_{p} without and with silent-interval impedance matching. The pulse duration T_{p} is from 0.1 µs to 0.9 µs at 0.1 µs intervals. The residual ringing time T_{r} with the silent-interval impedance matching is lower than that without it for any given pulse duration T_{p}. In the conventional scheme without matching, the residual ringing time is positive, i.e. the ringing wave may affect the detection of the next recessive symbol, and linearly increases with the increase of the pulse duration. In the proposed

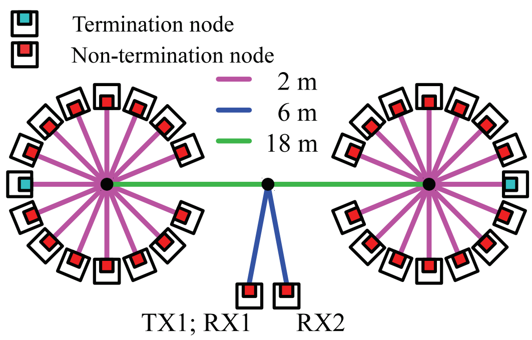

Fig. 9. The test network.

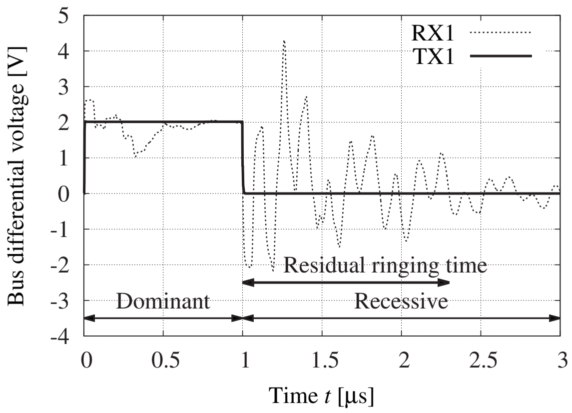

Fig. 10. Transmit and received signals at a center node for conventional CAN with NRZ.

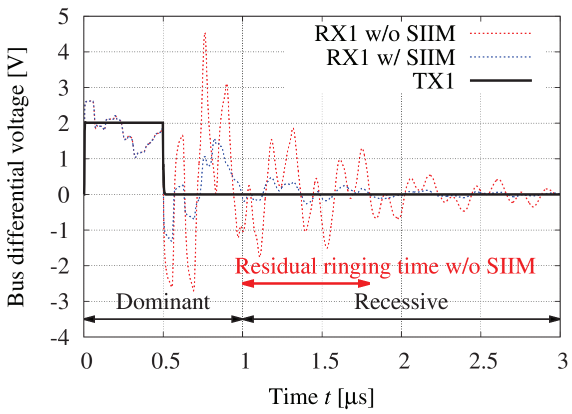

Fig. 11. Transmit and received signals at a center node for SP-CAN without and with SIIM.

scheme with matching, the residual ringing time is negative when the pulse duration is 0.5 μs or less. The difference in residual ringing time between the conventional and proposed schemes will decrease with the increase of the pulse duration. It becomes smallest for the pulse duration of 0.7 μs or more. The round-trip distance of a central node to a most distant non-termination node is 54 m and the round-trip time will be 297 ns because the propagation time of TP cable is 5.5 ns/m. To avoid the reflection wave from most distant non-termination nodes, the silent-interval T_{SI} should not be less than 297 ns, i.e. the dominant pulse duration T_{p} should not be 703 ns or more.

C. Experimental Trials

Experimental trials are conducted with the test network of Fig. 9 and a prototype unit including a pulse shaper for SP-CAN with silent-interval impedance matching to evaluate the performances of the proposed scheme. The block diagram of the prototype unit is illustrated in Fig. 13. A matching module is inserted between the CAN transceiver and the CAN bus, and it establishes the silent-interval impedance matching. The load

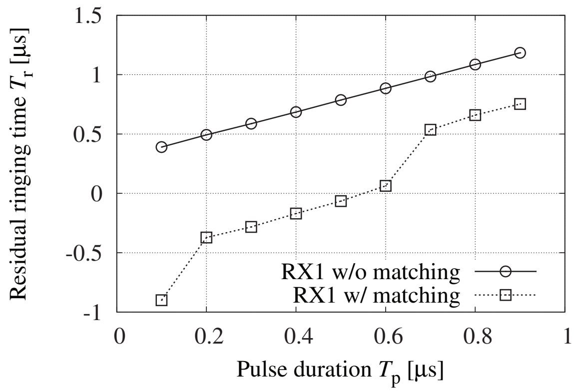

Fig. 12. Residual ringing time versus pulse duration.

impedance of the prototype unit is determined by the CAN transceiver and the matching module as shown in Fig. 14. The control signal transmitted from FPGA to the matching module synchronizes with the falling edge of $s_1(t)$, i.e. the timing to alter the logical voltage from recessive level to dominant level. The switches A and B in the CAN transceiver turn on during $s_1(t)$ is in dominant level and vice versa. The switch C in the matching module turns on within the silent-interval and vice versa. In the duration of T_{p} shown in Fig. 6, the load

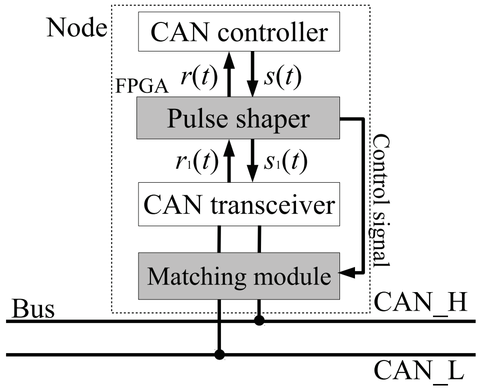

Fig. 13. The block diagram of the prototype unit.

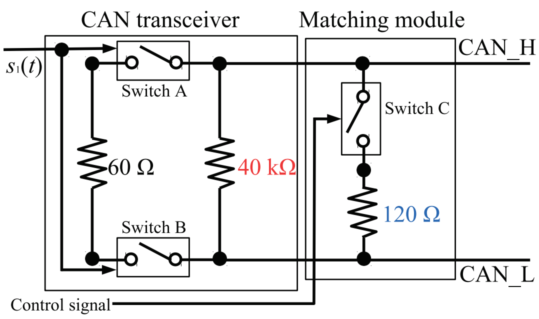

Fig. 14. The load impedance at the prototype unit.

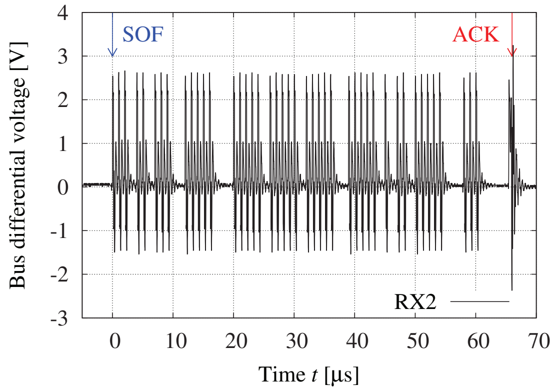

Fig. 15. The bus signal observed at RX2.

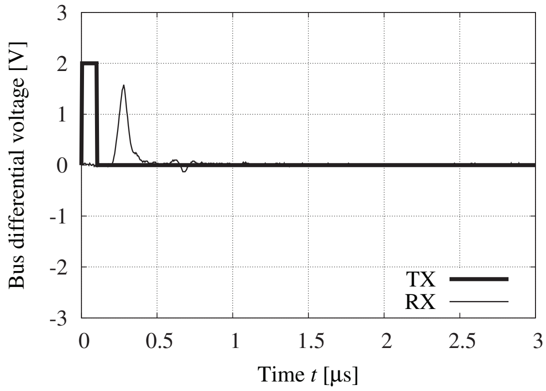

Fig. 17. The waveform between termination nodes.

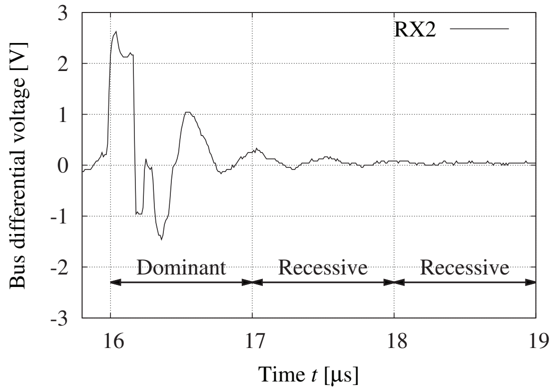

Fig. 16. The enlarged view of Fig. 12 in the range of 16 to 19 µs

TABLE I
THE FRAME TRANSMISSION RESULTS FROM TX1 TO RX2.

Pulse duration T_p	Result
100 – 500 ns	success
600 – 800 ns	failure
900 ns	—
1000 ns (NRZ)	failure

impedance of the prototype unit approximates to 60 Ω because the switches A and B are on and the switch C is off. In the duration of T_{SI} shown in Fig. 6, the load impedance of the prototype unit approximates to 120 Ω because the switches A and B are off and the switch C is on.

A frame transmission is conducted from the transmitter TX1 to the receiver RX2 in Fig. 9. The bus signal received at RX2 with the pulse duration of $T_p = 200$ ns is shown in Fig. 15. The ACK dominant pulse is observed at RX2 so that the frame transmitted from a central node will be correctly received at the other central node. For given pulse duration T_p, the frame transmission results from TX1 to RX2 are shown in Table I. For $T_p = 100$ to 500 ns, the frame transmission is successful. In the proposed scheme for $T_p = 600$ to 800 ns and the original NRZ coding, the transmitting node stops the frame transmission on the way because it will detect discrepancy between the transmitting level and the bus level. For $T_p = 900$ ns, the silent-interval impedance matching cannot be established due to the response speed of switch C.

In the pulse duration of $T_p = 100$ to 500 ns, the residual ringing time is minus in the simulation and the frame transmission from TX1 to RX2 is successful so that majority vote pulse shaping will not be required. The pulse duration of $T_p = 100$ ns can achieve the minimal residual ringing time as shown in Fig. 12 but there is a problem to implement it. Figure 17 illustrates a single dominant pulse transmitted from a termination node and the signal received at the other termination node with the pulse duration of $T_p = 100$ ns. The signal received at the termination node attenuates and its maximum level is away from the dominant level of 2.0 V. As a result, the pulse duration of $T_p = 200$ to 500 ns will be suitable for the test network of Fig. 9.

V. CONCLUSION

In this paper, we have proposed the silent-interval impedance matching for SP-CAN in order to enhance the scalability of bus topology and bit rate. SP-CAN without and with silent-interval impedance matching is analyzed for a test network which suffers from ringing waves with high amplitude and long duration. The simulation and experimental results have shown that the propose scheme can perfectly remove ISI on the next symbol just after a dominant short pulse for given scalable bus topology and bit rate.

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