Physical Layer Simulation Technology for Automotive Ethernet

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The introduction of high-speed automotive Ethernet to in-vehicle networks has been accelerated by the increase of communication volume resulting from the spread of advanced driving assist systems (ADAS) including autonomous driving. To ensure safety, in-vehicle network products require communication reliability even under severe conditions associated with extreme heat and noise, and therefore electromagnetic compatibility (EMC) performance is one of the important factors. However, conventional trial EMC countermeasures require a lot of efforts and development costs to ensure EMC performance. We have developed a simulation technology to efficiently verify the EMC performance of automotive Ethernet communication systems under various conditions by constructing the physical layer model of a communication system composed of connectors, wire harnesses, and electronic control units.

Keywords: vehicle, simulation, automotive Ethernet, physical layer

1. Introduction

Recently, vehicles are increasingly equipped with advanced driver-assistance systems (ADAS). Automated driving systems have also been introduced gradually. The amount of in-vehicle communication is expected to increase dramatically due to the widespread use and advancement of these systems. The bandwidth of the Controller Area Network (CAN) communication(1) that has been used in the conventional in-vehicle local area network (LAN) will not be sufficient to handle the increase. In 2015, the Institute of Electrical and Electronics Engineers, Inc. (IEEE) formulated the automotive Ethernet communication standard (100BASE-T1) that is advanced from the consumer Ethernet technology for LAN used at companies and home. The speed of 100BASE-T1 is 50-fold or more that of the CAN communication. However, IEEE has been working to formulate an automotive Ethernet standard that can achieve even faster communication.

In-vehicle products must not malfunction from the viewpoint of ensuring safety. The electromagnetic compatibility (EMC)*1 performance requirements are far more rigorous than those of consumer products. In fact, EMC is one of the most important indexes. Conventionally, it is common to practice the cycle of fabricating the prototypes of an electronic control unit (ECU), connector (CON), and wire harness (W/H) that incorporate the EMC measures to meet the target performance and verifying the effect based on the results of the EMC test. The increase in the cycle of prototype fabrication and verification has contributed significantly to the increase in the man hours and cost required for development. For ECUs, in particular, it is important to develop a scheme for efficiently reviewing the measures.

We constructed a physical layer model of an automotive Ethernet communication system including a CON, W/H, and ECU and developed a physical layer simulation technology that can efficiently verify the EMC performance of communication systems under various conditions. This technology is expected to reduce the man hours and development cost for EMC measures and to cut the cost of respective products by optimizing the components that incorporate these measures. This paper introduces the physical layer simulation technology for 100BASE-T1.

2. Overview of Automotive Ethernet

This chapter explains the overview of automotive Ethernet as an introduction to physical layer simulation.

As discussed above, automotive Ethernet is an advanced form of consumer Ethernet technology. This chapter explains the differences between consumer Ethernet (100BASE-TX) and automotive Ethernet (100BASE-T1), both of which attain the transmission speed of 100 Mbps.

The first difference is the communication method and number of cables. In consumer Ethernet, two pairs of unshielded twisted pairs (UTPs) are used in total (one pair each for transmission and reception) to achieve one-way communication. In automotive Ethernet, a transmission/reception separation circuit that is called a hybrid circuit is introduced to enable two-way communication using one pair of UTPs (Fig. 1), making it possible to reduce the number of cables, weight, and cost.

The second difference is the encoding method and

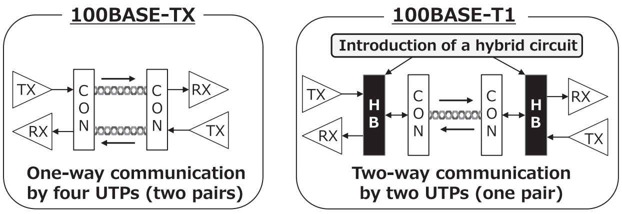


Fig. 1. Comparison of the communication method and number of cables

signal bandwidth used. In consumer Ethernet, the symbol rate is 125 M symbols/sec. However, to transmit signals as binary pulses, four bits out of five bits are handled as data to avoid continuous values (4B/5B). This is how the communication speed of 100 Mbps is achieved. In automotive Ethernet, the three-level pulse amplitude modulation (PAM3) is used. An encoding technology (3B/2T) is used to represent a ternary with one symbol and a nonary with two symbols, and handle the octonary 3-bit data. This makes it possible to achieve 100 Mbps even at the symbol rate (66.7 M symbols/sec), which is about half that of consumer Ethernet (Fig. 2), and reduce the electromagnetic radiation in the FM bandwidth used for in-vehicle radio (Fig. 3).

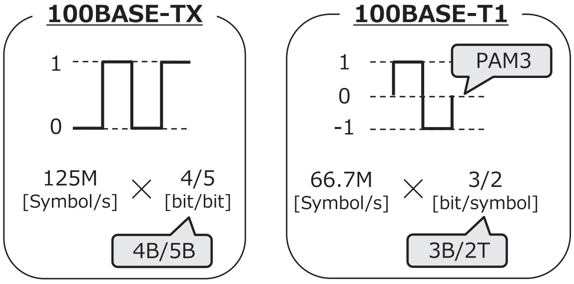


Fig. 2. Comparison of the encoding method and signal bandwidth

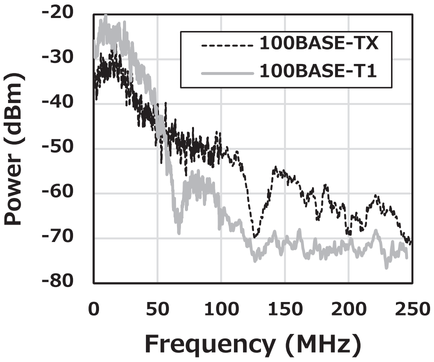


Fig. 3. Comparison of frequency characteristics of transmitted signals

3. Overview of the Physical Layer Simulation

The configuration of the physical layer simulation is shown in Fig. 4.

We used two automotive Ethernet ECU models, each of which consisted of a physical layer transceiver (PHY) model that transmitted/received automotive Ethernet signals and a front-end circuit model that included passive components (such as the common mode choke coils) and transmission lines on a substrate.

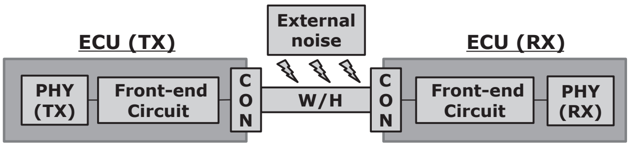


Fig. 4. Configuration of the physical layer simulation

These models were connected via a W/H model and CON model to make up a communication system. They were constructed using the Advanced Design System (ADS) simulation software developed by Keysight Technologies, Inc.

The physical layer simulation enables (1) transient analysis of signal waveforms and (2) S-parameter analysis of the entire communication system and respective components by using the ADS analysis engine. For example, in (1) transient analysis, the reception waveforms in the PHY can be displayed as an eye pattern*[2] (Fig. 5). Here, the user can freely set the external noise and quantitatively evaluate the immunity performance*[1] of a communication system when various types of external noise is applied. In addition, (2) S-parameter analysis enables review of immunity performance analysis of (1) above and design improvement by analyzing the insertion loss of differential transmission signals and characteristics of mode conversion(2) for an entire communication system and respective components.

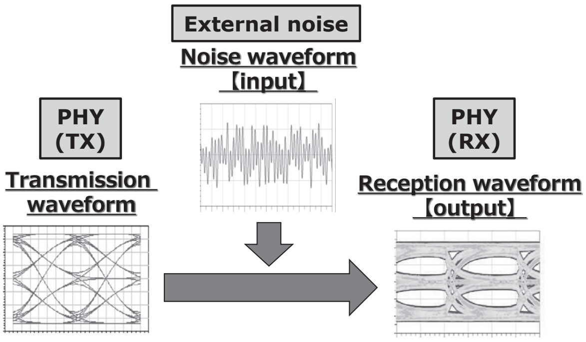


Fig. 5. Example of analysis of signal waveform by time response

4. Construction of a Simulation Model

This chapter explains the construction technique and characteristics of respective models that make up the physical layer simulation.

4-1 Construction of the PHY transmission (TX) model

Figure 6 shows the transmission blocks in 100BASE-T1.

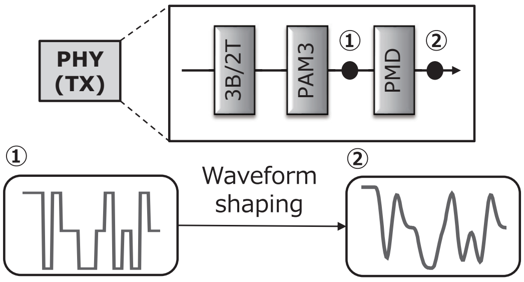


Fig. 6. 100BASE-T1 transmission block

The 3B/2T, PAM3, and PMD*3 blocks are related to the signal waveforms of 100BASE-T1. For the 3B/2T and PAM3 blocks that are common to PHY manufacturers, we utilized basic blocks supported by ADS. It should be noted that the characteristics of the PMD transmission block that performs signal waveform shaping are different among respective PHY manufacturers. We referred to the technical documents(3) of automotive Ethernet, reviewed the waveform shaping basic circuit such as filters, and set the constants for respective circuits so that they conformed to the real device waveforms of respective PHY manufacturers. The results of comparison between the real device transmission waveform of a PHY manufacturer and the transmission waveform of the constructed PHY transmission (TX) model in the time domain are shown in Fig. 7. The figure shows that the waveforms are almost identical.

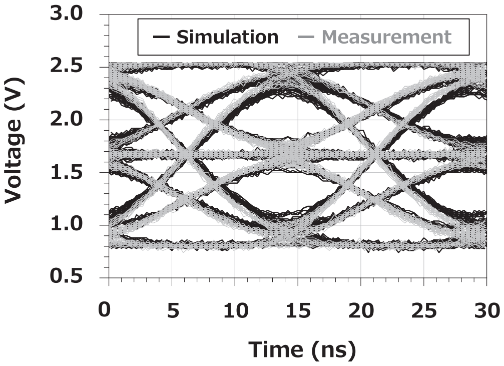


Fig. 7. Results of verification of consistency between the real device and PHY transmission model

4-2 Construction of the PHY reception (RX) model

Figure 8 shows the reception blocks in 100BASE-T1.

As explained in Chapter 3, the reception performance is evaluated based on the eye pattern of the reception waveform in the physical layer simulation. Instead of introducing 3B/2T and PAM3 blocks for encoding and modulation, we employed a design that consisted only of the PMD reception block that contributed to the waveform characteristics. This PMD reception block consisted of an equalizer that compensated the frequency characteristics of signal waveform. However, it could not measure the reception waveform in the PHY, and therefore could not verify the consistency between the measurement and simulation model. We optimized the constants by utilizing our expertise based on our track record in delivering consumer Ethernet products to communication carriers.

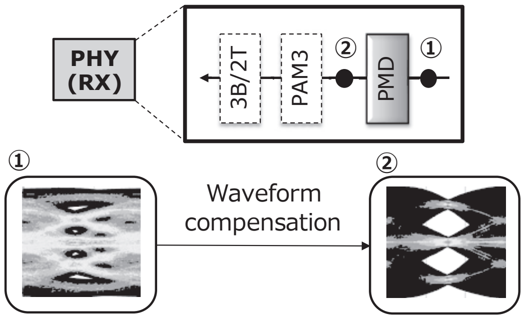


Fig. 8. 100BASE-T1 reception block

4-3 Construction of models of a front-end circuit, W/H, and CON

To model a front-end circuit, W/H, and CON, we utilized S-parameters that represent the respective characteristics.

A front-end circuit model in the physical layer simulation consisted of the transmission lines on a substrate and passive components such as common mode choke coils and capacitors. The electromagnetic field analysis software can load a design layout and enables analysis directly. For this reason, we utilized the software to analyze the electromagnetic field and derive the S-parameters for modeling.

Regarding the W/H and CON, we constructed a measurement system by using a vector network analyzer (VNA)*4 and a jig for connecting with VNA (Fig. 9) to accurately represent the changes in characteristics depending on the routing, and measured the S-parameters. The W/H and CON have differential input and output terminals. Thus, we conducted four-port measurement.

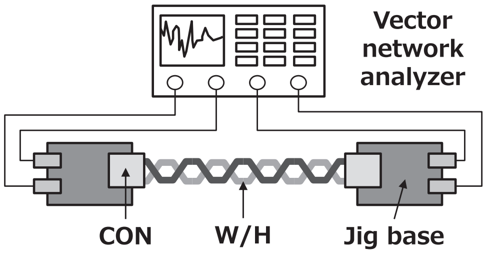


Fig. 9. W/H, CON measurement system

It should be noted that the measurement value included the influence of the jig. Thus, we conducted modeling based on the S-parameters of the W/H and CON by removing the jig characteristics by means of de-embedding.*5

5. Example of Simulation and Verification by In-Vehicle EMC Test

To demonstrate that the physical layer simulation can accurately verify the EMC performance of communication systems under various conditions, we decided to verify the consistency between the measurement results in the in-vehicle EMC test and the results calculated by the physical layer simulation. This chapter explains verification of consistency of these results in the bulk current injection (BCI) test,(4) which is one of the in-vehicle EMC tests, as an example.

In the BCI test, common mode noise is injected to a

W/H from a noise generator via a BCI probe in order to evaluate the tolerance of products. We constructed a test system in an anechoic chamber shown in Fig. 10. In this study, we obtained the signal quality indicator (SQI) value,*6 which was output by the PHY on the side of the equipment under test (EUT) when the noise of respective frequencies (1 to 100 MHz) was injected into a W/H of the automotive Ethernet, as the measurement result.

Figure 11 shows the configuration of the BCI test in the physical layer simulation. Regarding the corresponding device and EUT (development board in Fig. 11) used in the real device test, we constructed respective models based on the technique discussed in Chapter 4. Regarding the BCI probe for injecting noise, we constructed a single model by measuring S-parameters using five ports including a W/H and CON.

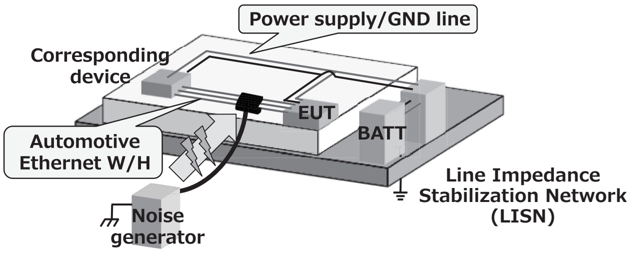


Fig. 10. Real device test system for BCI test

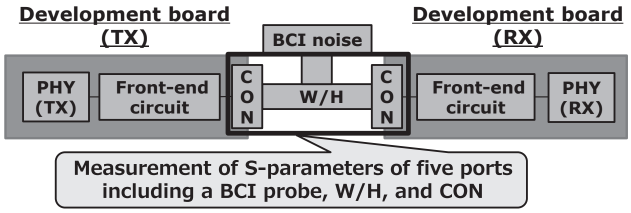


Fig. 11. Simulation configuration of the BCI test

The measurement results and simulation results for the noise injection frequency between 1 and 100 MHz are shown in Fig. 12. The horizontal axis represents the noise injection frequency. The solid line (vertical axis on the right) shows the SQI value (measurement value) of the PHY, while the dotted line (vertical axis on the left) shows the amount of noise received (simulation value) of the PHY. The lower the SQI value, the lower the quality of received signals. The figure shows that a large amount of noise that degrades the signal quality flows into the PHY in around 20 to 50 MHz, and that a small amount of noise that does not affect the signal quality flows into the PHY in 60 MHz or more. The simulation results show the same trend in the amount of noise as discussed above, and therefore are highly consistent with the measurement results. Figure 13 shows the reference simulation results of the reception waveform eye patterns of the noise injection frequency at around 25 MHz, where the amount of noise received is high and the SQI value is low, and at around 70 MHz, where the amount of noise received is low and the SQI value is high.

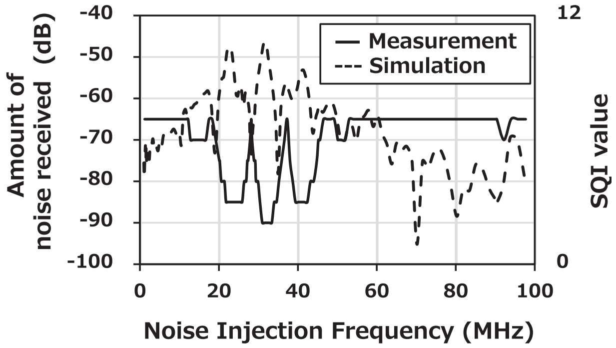
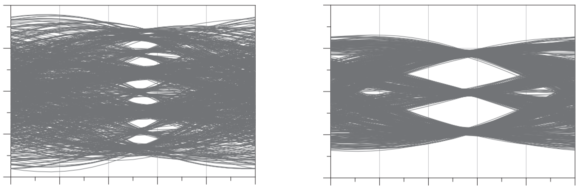


Fig. 12. Comparison between measurement and simulation results in the BCI test



(a) Noise injection frequency: around 25 MHz

(b) Noise injection frequency: around 70 MHz

Fig. 13. Simulation results of the reception waveform eye patterns

6. Conclusion

We developed a physical layer simulation technology for efficiently verifying the EMC performance of communication systems under various conditions to reduce the man hours and development cost for EMC measures and to optimize the components to implement measures. We have been using this technology to verify the EMC performance of our relevant products (ECU, W/H, CON) that are utilized in communication systems and to verify the measures for design improvement. We will apply the technology to automotive Ethernet with the transmission speed of 1 Gbps whose standardization has been completed by IEEE and 2.5 Gbps or more whose standard is currently being formulated.

Technical Terms

∗1 Electromagnetic compatibility (EMC): EMC refers to the performance of electrical and electronic equipment in operation that does not affect other equipment or systems and that is immune to electromagnetic waves generated by other equipment. The former is referred to as electromagnetic interference (EMI) or emission performance, and the latter is referred to as electromagnetic susceptibility (EMS) or immunity performance.

∗2 Eye pattern: An eye pattern refers to signal waveforms that are sampled and overwritten for a certain period of time. The name is derived from the fact that the opening in the center that is created when waveforms are overwritten is similar to an eye. Deterioration in the signal quality causes dispersion in the signal amplitude and time axis, and the eye becomes narrow. The signal quality can be evaluated quantitatively based on the width and height of the eye.

∗3 Physical medium dependent (PMD): The layer converts and amplifies the waveform depending on the transmission media such as light and electricity.

∗4 Vector network analyzer: A vector network analyzer is equipment for measuring the frequency characteristics such as the forward power and reflected power of a high frequency circuit network.

∗5 De-embedding: De-embedding is a technique to extract only the characteristics of the measurement target by removing the influence of non-targets such as the measurement jig.

∗6 Signal quality indicator (SQI) value: SQI represents the relative signal quality. The received signals are separated into transmitted signals (that make up the data) and noise, and the signal noise ratio (SNR) is calculated. The SQI value is output based on the SNR value. In general, the higher the SQI value, the lower the noise, indicating that the signal quality is good.

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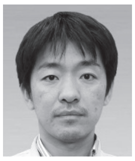

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