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# Optimization of waveform shaping for multi-valued signaling by using variation evaluation of received signals

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**Abstract.** High-speed data interconnections have become extremely important for very large scale integration (VLSI) systems. Although CPU performance has advanced, it is difficult to increase the data-rate across electric wirings because of the low-pass effect. This effect creates inter-symbol interference (ISI) at a receiver. Thus, the overall performance of VLSI systems is restricted by data-rates. To achieve better high-speed interconnections, several waveform-shaping techniques, which remove ISI at the receiver, have been proposed. This paper leverages Tomlinson–Harashima precoding (THP), which can remove the ISI using digital signal processing. To optimize THP, a new evaluation method using multi-valued data transmission at the receiver, is proposed. The experimental results of THP optimization using the evaluation method is presented.

## 1. Introduction

Recently, very large scale integration (VLSI) system data-rates have increased beyond the giga-bits per second (Gbps) order. An accelerated data-rate is required for high performance semiconductor systems. However, it is difficult to increase data-rates because of the low-pass effect of transmission lines. As shown in Figure 1, the received waveform is distorted by the low-pass effect of electric wirings, causing inter-symbol interference (ISI), which contributes to bit errors. To accelerate the data-rate, a waveform-shaping technique is therefore required to remove the low-pass effect.

To remove ISI at the receiver, a Tomlinson-Harashima precoding (THP) [1][2]-based high-speed data transmission system has been proposed [3][4]. However, it is difficult to determine a correct THP coefficient after implementation, because it depends on the environment. Thus, an optimization technique is required.

This paper presents the optimization technique of the THP-based transmitter system. To optimize the THP coefficients, an evaluation method of multi-valued signaling is proposed. In our method, signal integrity can be evaluated by leveraging the dispersion of received symbols.

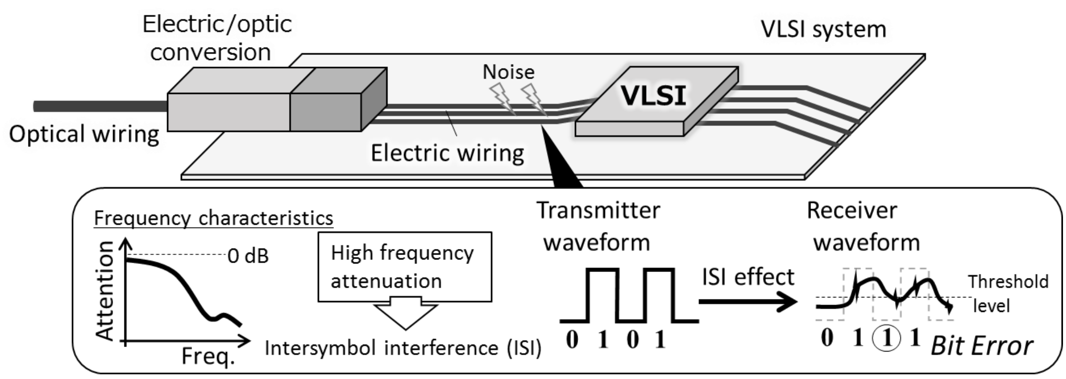


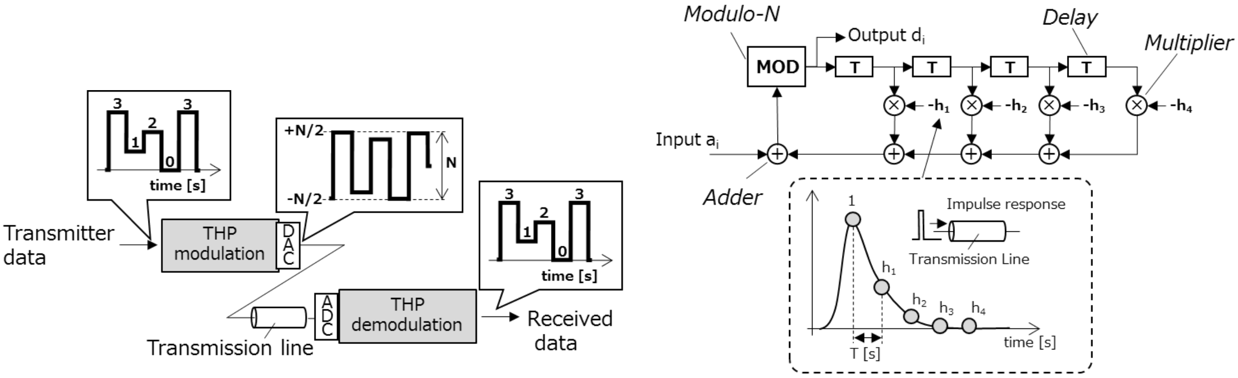

Figure 1 Low-pass effect of transmission lines in high-speed data transmission

## 2. PAM-4 data transmission with Tomlinson-Harashima precoding

This section describes a multi-valued data transmission system using the THP. In section 2.1, pulse amplitude modulation (PAM)-4 data transmission system with the THP is described. Section 2.2 shows experimental results of PAM-4 data transmission with the THP.

### 2.1 Overview of PAM-4 data transmission system with THP

Figure 2 shows a block diagram of PAM-4 data transmission system with the THP. The THP circuit consists of an inverse filter and a modulo-N adder. As shown in Figure 2, transmitter data is modulated at a transmitter. Using the modulo-N adder at the transmitter, the THP can limit a peak power of the transmitter signals between –N/2 to +N/2. And, it can also limit an average power. At the receiver, transmitter data symbol is recovered by modulo-N reduction in the THP demodulation. The THP coefficients are determined by an impulse response of an interconnection. By obtain the characteristics of the interconnection in advance, the THP can remove an ISI at the receiver completely.



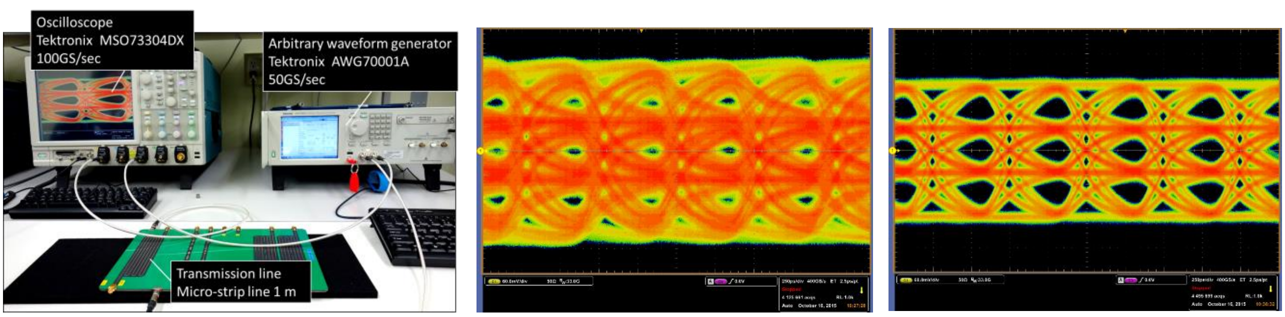

(a) Transmission system with THP (b) THP modulation circuit

Figure 2 Overview of PAM-4 data transmission system with THP

### 2.2 Experimental results of PAM-4 data transmission with THP

Figure 3 shows an eye-diagram of 2 giga-symbols per second (Gsps) PAM-4 data transmission without/with THP on a micro-strip line. In this experiment, the micro-strip line is 1-m length. As shown in Figure 3(a), transmitter signals are generated in arbitrary waveform generator (Tektronix AWG70001A), and the eye-diagram is measured by using oscilloscope (Tektronix MSO73304DX).

As shown in Figure 3 (b), the receiver waveform is distorted without the THP, and the eye is closed. On the other hands, as shown in Figure 3(b), the THP can open the eye at symbol decision timing. In this experiment, THP coefficients were determined using impulse response, which is measured in advance. The THP can remove ISI completely if the transmission line characteristics can be obtained before THP implementation.




(a) Measurment system (b) Eye-diagram w/o THP (c) Eye-diagram w/ THP

Figure 3 Experimental results at 2 Gsps PAM-4 data transmission without/with THP

## 3. PAM-4 evaluation by using variation analysis of received signals

Because THP-coefficient optimization depends on the transmission environment, a new eye-opening monitor (EOM) for multi-valued data transmissions, using statistical evaluation, has been proposed [5]. In the EOM, signal integrity is evaluated via the dispersion of sampling data at the receiver. Figure 4 shows an overview of the EOM for the PAM-4 data transmission. PAM-4 doubles the number of bits in serial data transmissions by increasing the number of levels of pulse-amplitude modulation. As shown in Figure 4, received data, sampled and converted to digital data by an analog-to-digital converter, are evaluated with a histogram. To evaluate the multi-valued data transmission comprehensively, the EOM synthesizes the histogram of each symbol, and signal integrity is evaluated using both the average and the dispersion of the composition histogram. The average value of the composition histogram shows the variation of a symbol interval, $V_{S\text{-}S}$. If each symbol interval is equal and $V_{S\text{-}S}$, the average value of the histogram becomes $V_{S\text{-}S}/2$. The dispersion shows an average value of the eye-height.

Figure 5 shows a block diagram of the EOM. The dispersion, σ, is calculated by the following equation.

$$\sigma = \frac{1}{N}\sum (x_i - \bar{x})^2 = \frac{1}{N}\sum x_i^2 - \bar{x}^2$$

In the equation, *N* is the amount of data. $x_i$ is data of i$^{th}$, and $\bar{x}$ is an average of $x_i$. As shown in Figure 5, the EOM can consist of multiplier, division, and integration circuits. The EOM can be implemented without a large memory, accumulating sampling data.

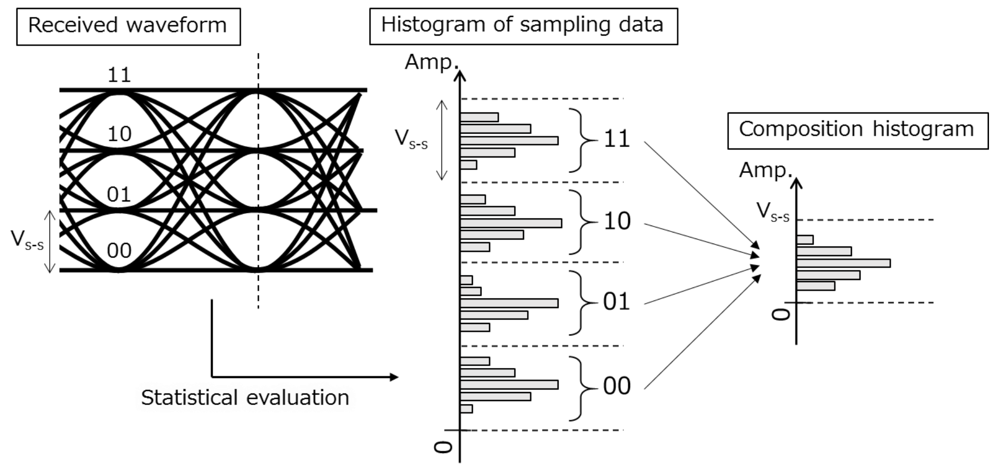



Figure 4 Overview of EOM evaluation for PAM-4 data transmission

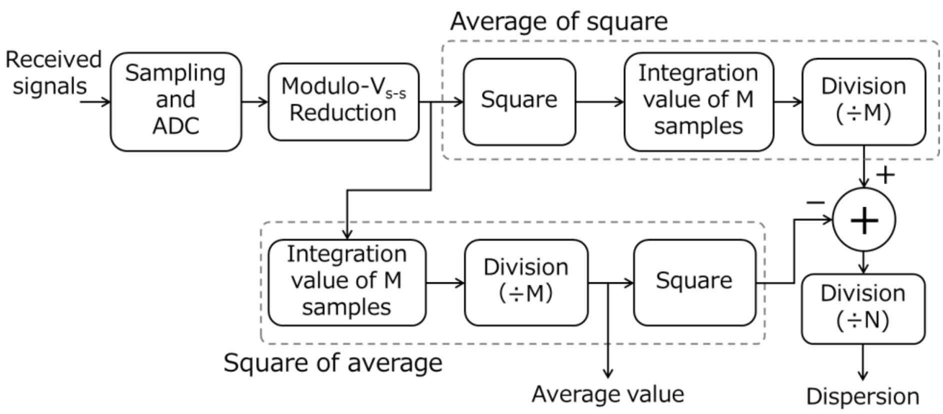
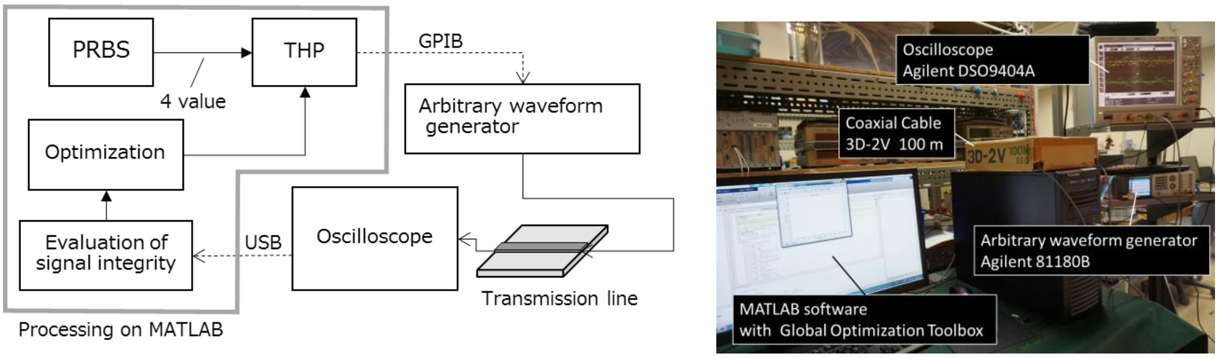



Figure 5 Block diagram of proposed EOM circuit

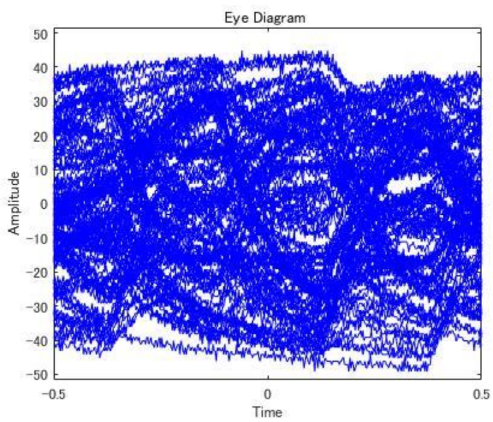
## 4. Experimental results of THP optimization

The THP optimization demonstration, using the proposed EOM evaluation, is shown in Figure 6. Figure 6(a) shows the experimental system, which integrates MATLAB software and a high-frequency measuring instrument. An arbitrary waveform generator (Agilent 81180B) is used as the transmitter, and the oscilloscope (Agilent DSO9404A) is used as the receiver. MATLAB generates PAM-4 transmitter data with THP modulation, and sends it to the arbitrary waveform generator via general-purpose interface bus communications. At the receiver, the received data is obtained from the oscilloscope via a USB communication, and the EOM evaluation is calculated with MATLAB. The THP coefficients are optimized by using MATLAB Global Optimization Toolbox.

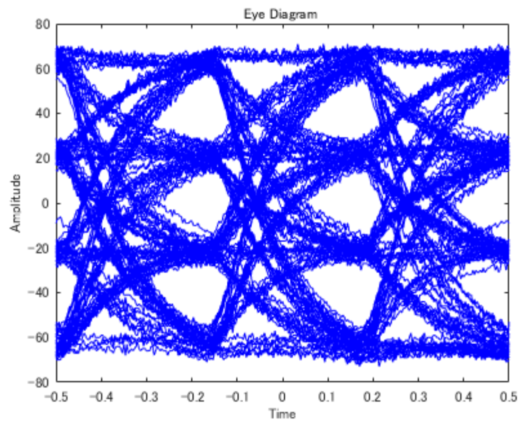
Figures 6(b) and 6(c) show optimization results using a genetic algorithm. In these results, a 100-m coaxial cable (3D-2V) was used as the transmission line. Figures 6(b) and 6(c) are eye-diagrams of 100 mega-samples per second (Msps) PAM-4 data transmission at the receiver before and after optimization, respectively. Comparing Figures 6(b) and 6(c), the eye can be opened after optimization, as shown in Figure 6(c). The signal integrity has been improved after optimization using the proposed EOM method.




(a) Experimental system




(b) Before optimization




(c) After optimization

Figure 6 Experimental result of THP optimization using the proposed EOM method

## 5. Conclusion

This paper presents a new EOM for multi-valued data transmissions, and shows an experimental evaluation with PAM-4 data transmission. By using the proposed EOM, comprehensively evaluation of multi-valued data transmission can be realized.

## Acknowledgements

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