Digital-analog hybrid transmitter equalizer for multi-valued signaling

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Abstract: High-speed data transmission over electric wiring in a VLSI system is achieved by employing equalization circuitry for waveform shaping. This letter presents a novel transmitter that incorporates waveform shaping techniques especially for multi-valued signaling. The combination of digital and analog equalizers and adjustment of the digital parameter can improve the waveform distortion of rising and falling edges. Simulation and experimental results of multi-valued data transmission are shown to demonstrate the feasibility of the proposed transmitter, which is capable of controlling the received waveforms flexibly and improve the signal integrity.

Keywords: Multi-valued logic, PAM-4, Equalization
Classification: Transmission systems and transmission equipment for communications

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1 Introduction

A high-speed serial link beyond several tens of Gbps is required for chip-to-chip, backplanes, and data center transmission. However, at high-speed data rates, electric wires behave as low-pass filters that destroy the high-frequency characteristics of the transmission lines. The limited bandwidth of the channel, therefore, causes intersymbol interference (ISI) at the receiver; hence, waveform shaping techniques are required to remove the ISI. Moreover, multi-valued (MV) signaling is widely used to increase the information capacity per symbol [1, 2]. Compared with binary signaling, which transmits the digits 0 or 1, MV signaling can transmit more than double the information capacity in each symbol. However, because the waveform distortion becomes complex owing to the many data transition patterns of MV signaling, controlling the received waveforms becomes difficult.

To solve these problems, we previously proposed waveform shaping techniques based on Tomlinson-Harashima Precoding (THP) at the transmitter to double the operating frequency compared with the symbol rate, which can sharpen the transition edge of the received waveform [3, 4]. However, these techniques incur additional hardware costs as a high-speed digital-to-analog converter (DAC) is required because of the doubled symbol rate.

This letter proposes a new waveform shaping transmitter that combines digital and analog equalizers to lower the DAC operating frequency. This transmitter operates at the frequency of the symbol rate, obviating the need for DACs that operate at twice the frequency of the symbol rate. The transmitter cooperates with analog pre-emphasis at half the symbol rate that can improve the edges of received signals by setting the parameters of the digital circuits. A simulation and experiments are used to demonstrate the feasibility of the proposed transmitter and its ability at the architecture level in order to control the received waveforms flexibly and improve the signal integrity.

2 Waveform shaping technique for PAM-4 signaling

2.1 PAM-4 data transmission

In 4-level pulse amplitude modulation (PAM-4) data transmission, 2-bit binary data are converted to 4-level MV data, thereby enabling PAM-4 to transmit 2-bit data as one symbol. Compared with binary signaling, PAM-4 is advantageous in that it uses half the Nyquist frequency and twice the throughput for the same Baud rate, and hence the lowpass effects of channels are reduced. However, as shown in Fig. 1(a), the PAM-4 eye shape becomes nonuniform in each symbol owing to the 12-types different transition patterns of MV signaling [5]. The eye width of the symbols between
Fig. 1. PAM-4 data transmission; (a) Transition patterns of PAM-4, (b) pulse response of MSL 1 m on each symbol levels

1-2 is restricted by both the transition patterns of 0 → 2 and 3 → 1. Fig. 1(b) shows the 1 ns pulse responses of a micro-stripe line (MSL) 1 m for each symbol level. Because the waveforms of the pulse responses are different, the edge slope changes in accordance with the transition pattern. The different edge patterns have a profound effect on the eye diagrams of received MV signaling.

2.2 Waveform shaping technique
The signal distortion due to ISI can be improved using signal-processing techniques known as equalization. Feed-forward equalizer (FFE) at the transmitter can be realized by digital filter circuits composed of adders, multipliers, and delay circuits at the symbol rate $T_s$. Output signals are generated by the product sum of the FFE coefficients $a_1, a_2, \ldots, a_n$ and input data. The number of taps is determined by the transmission line characteristics, and the delay time of $D$ is set the same as the symbol rate $T_s$. Although the FFE can remove the ISI effect, shaping the waveform such that the eye shape is modified is difficult, especially to improve the rising and falling edges of waveforms. This is because the frequency characteristics of FFEs are restricted by the operating speed of FFE circuits, which corresponds to the inverse of the delay time in the FFE.

To improve the edges and expand the eye, we previously proposed double-rate THP (DTHP) equalization techniques that employ $T_s/2$ delay operation [4]. The technique can control the eye shape more flexibly compared with a conventional FFE by operating at double the symbol rate. However, the DTHP needs a high-speed DAC that operates at double the symbol rate, which increases the hardware cost.

3 Hybrid transmitter combining digital and analog equalizer
To control the received waveform flexibly to improve the rising and falling edges, this letter proposes new waveform shaping transmitters for MV signaling by combining digital and analog equalizers. This transmitter does not require a DAC that operates at double the symbol rate, avoiding an increase
in the hardware cost. Fig. 2(a) shows an overview of the transmitter. The proposed transmitter is realized by operating the FFE at symbol rate $T_s$, and is equipped with a DAC and analog circuitry. Transmitter signals are generated by subtracting the FFE output signals from the PAM-4 signals. The PAM-4 input data are converted by 2-bit resolution DAC1, and data processed by the FFE is converted by DAC2. The output signal is then generated by subtracting the output signals of DAC1 and DAC2 using the analog circuitry. In the transmitter, DAC2 is operated by inverse clock timing compared to DAC1 to realize delay with a doubled symbol rate ($T_s/2$).

The proposed transmitter generates the high-frequency components of signals by subtracting signals with an inverse timing. The high-frequency component contributes to the improvement of rising and falling edges of signals. Moreover, the output waveforms can be controlled digitally, by tuning the FFE parameters $a_1, a_2, \ldots, a_n$. The parameters, therefore, can be changed easily according to the environment after hardware implementation. Fig. 2(b) shows the simulated output waveforms of the proposed transmitter.

Fig. 2. Proposed transmitter; (a) Overview, (b) Simulated output waveforms
Fig. 3. Simulation and experimental results (1 UI=500 ps): (a) Evaluation system setup, (b) PAM-4 with conventional FFE at 2 Gsps, (c) PAM-4 with proposed transmitter at 2 Gsps, (d) Timing mismatch of −5% between DAC1 and DAC2 outputs, (e) Timing mismatch of +5% between DAC1 and DAC2 outputs

The frequency of the transmitter signal is double that of the PAM-4 signal and FFE output. The high-frequency signal generated by the proposed transmitter can control the received waveform flexibly and sharpen the rising and falling edges of the signals.

4 Experimental results

As proof-of-concept at the architecture level, an arbitrary waveform generator (AWG) AWG70001A was used to emulate the DAC operation with FFE and
an analog subtractor (Fig. 3(a)). The imported FFE-modulated random signal data were calculated by numerical simulation considering a 4-tap FFE with 2-bit and 6-bit resolution for DAC1 and DAC2, respectively. Figs. 3(b) and (c) show the results of the simulation and measurement of the PAM-4 eye diagrams with conventional FFE and the proposed transmitter at 2 Gsps. In conventional FFE, fine tuning the delay time is difficult. As a result, it is difficult to adjust the shape of the eye. In contrast, because the proposed transmitter is composed of digital circuitry, digital fine adjustment is possible, thereby achieving flexible waveform shaping by setting the FFE coefficients. Compared with conventional FFE, the proposed transmitter can improve the rising and falling edges of the received waveform to widen the eye width from 0.46 UI to 0.68 UI (UI: unit interval).

Because the processing speed limits conventional FFE to the high-frequency characteristics, it is difficult to emphasize the edges of the received waveform. In contrast, the proposed transmitter can realize high-frequency characteristics simply by subtracting the PAM-4 and FFE delayed signal to obtain $T_s/2$ delay. The effect of boosting the high-frequency components can especially widen the time axis direction of the eye diagram. The extension of the time axis direction significantly contributes to the improvement of the jitter tolerance, especially for PAM-4 data transmission.

The non-ideal duty ratio of the clock signal and the nonlinearity of the analog subtraction circuit cause a timing mismatch between the outputs of DAC1 and DAC2. To evaluate the imperfection, these effects were simulated for the case of a $T_s/2$ delay with an error of plus or minus 5% (in this case, ±12.5ps). As shown in Figs. 3(d) and (e), the timing mismatch does not have a significant impact on the output eye diagram. Although the analog subtraction circuit can operate faster than the DACs, the operating frequency and nonlinearity of the analog circuitry deteriorate the shape of the transmitter signal. Because this limitation and effect are strongly dependent on the topology of the analog circuit, evaluations of the imperfection using transistor-level circuit simulation are needed as a future task.

5 Conclusion

This letter presented a new waveform shaping transmitter combined with digital and analog equalizers. The proposed transmitter can control the received waveform flexibly and is suited to PAM-4 data transmission without using high-speed equalizers and DACs. The experimental results showed that the proposed equalizer can compensate for the effect of waveform distortion, especially by expanding the eye width opening.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Numbers JP18H01488 and JP18K11232.