Parallel Extension of High-Speed Analog-Circuit FIR Equalizer for Low-Latency Optical Transceiver/Receiver

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Abstract: We experimentally demonstrate parallel extension of analog FIR equalizer. By a dual parallel extended configuration, an 18-tap FIR filter with an 18-ps tap delay is constructed, which adaptively equalizes real-time 11.1-Gbaud NRZ signals.

1. Introduction

For high-speed short-reach optical fiber telecommunication systems, such as communications in datacenters, waveform equalizers are inevitable and typically implemented in high-speed digital signal processors (DSPs) [1-3]. However, it is challenging to develop further high-bandwidth DSPs; the DSP-based systems also increase latency in their signal processing. Especially for cost-effective short-reach transmission, it is important to develop waveform equalizers without relying on DSPs. A finite impulse response (FIR) filter based on analog circuitry can be an excellent solution to such high-bandwidth equalization [4-6], where arbitrary impulse responses can be created instantly in an analog way for compensation of waveform distortion. An issue in the approach is that FIR filters have a limited number of taps due to difficulty in fabricating circuits integrated on a large scale, which causes a restricted temporal window of FIR equalization.
This paper demonstrates a parallel extension of high-speed analog FIR equalizer for high-speed, low-latency optical receiver, where impulse responses with enhanced temporal windows can be flexibly synthesized. The advantages of configuration of parallel extension of high-speed analog FIR filters are as follows: (1) great scalability, (2) low latency (3) flexible controllability. The parallel extension can flexibly enhance the scale of the FIR structure. The high-speed signal input to the equalizer is processed with the analog circuits, and the signal is output with the minimum delay without traveling through the DSP part. Independent control of FIRs allows us one-by-one update of tap coefficients by monitoring each FIR independently.

In this paper, we experimentally demonstrate parallel extension of analog FIR equalizer. By a dual parallel extended configuration, high-bandwidth 9-tap FIR filters with 18-ps tap delays are parallelized to an 18-tap one. In the frequency domain, it improves filtering resolution from 6.17 GHz to 3.09 GHz. In the time domain, temporal window of impulse response is enhanced in two times. By using the extended equalizer, we demonstrate adaptive equalization of real-time 11.1-Gbaud NRZ signals.

2. Principles of Parallel Extension of FIR Equalizers

Fig. 1 shows the concept of the parallel extension of high-bandwidth analog-circuit FIR filters. First, in the technique, the received signal is split in n with a divider. Then, divided signals are input to FIR filters arranged in parallel. Finally, the delays of the FIR filter outputs are adjusted with electrical delay lines and combined with a power combiner. This configuration allows us equalization of the received signal with a temporal window of impulse response enhanced in n times. This parallel extension assisted by a divider and a combiner flexibly enables a large-scale FIR structure even if each analog-circuits FIR circuit has limited tap numbers [6].

The mechanism of the parallel extension is explained as follows. $T,\ x(T),\ y(T), n,\ K,\ c_k,\ \tau$ correspond to the discrete time interval, input signal, output signal, number of filters, number of taps, tap coefficients, and delay between taps, respectively. And the delay of the phase shifter is $(n-1)K\tau$. Since all the inputs to the FIR filters have an equivalent waveform, $x_1(T) = x_2(T) = \cdots = x_n(T)$, the parallel extension of the FIR filter can be expressed as,

$$y(T) = \sum_{k=0}^{K} c_k x_1(T - k\tau) + \sum_{k=0}^{K} c'_k x_2(T - k\tau - K\tau) + \cdots + \sum_{k=0}^{K} c''_k x_2\{T - k\tau - (n-1)K\tau\}$$

$$\xrightarrow{\text{Parallel extension}} \quad y(T) = \sum_{k=0}^{nK} c_{\mathrm{all},k} x_1(T - k\tau) \qquad (1)$$

This equation clearly shows that the parallel configuration of the FIR filters extends the time window of the impulse responses n times with the number of FIRs.

3. Parallel Extension of high-speed analog FIR Filters

The temporal extension of impulse response can be interpreted as enhancement of filter resolution in the frequency domain. The resolution of the filter is increased by a factor of the number of the FIR filters. Here, we experimentally characterize the frequency response of the proposed parallel extended FIR filter and show that the filter resolution becomes higher.

The system was configured as shown in Fig.1. We constructed dual parallel FIRs, which means the order of parallel extension was n =2. The FIRs #1 and #2 in this setup were HMC6545LP5E manufactured by Analog Devices, Inc. The delay in each tap of the FIR filters was 18 ps. The number of taps of each FIR filter was 9. The delay between the FIR filters was adjusted to 162 ps by using the phase shifter.

Fig.2 (a) shows the measured frequency response of the system when only one tap was set to 1, which confirms that the frequency response is flat over a wide bandwidth. Fig. 2 (b), (c) shows the frequency response of the FIR filters that performs as a low-pass filter (LPF) when all tap coefficients are set to 1. Fig 2 (b) shows the frequency response of the single FIR filter alone. Fig. 2 (c) is the parallel-extended case (w/ two FIR filters). The filer resolution was improved from 6.17 GHz to 3.09 GHz. The results show that the resolution of the frequency response is increased by the parallel extension. This means that the time window of impulse response was doubled due to the parallel extension.

4. Adaptive Equalization of 11.1-Gbaud NRZ Signals

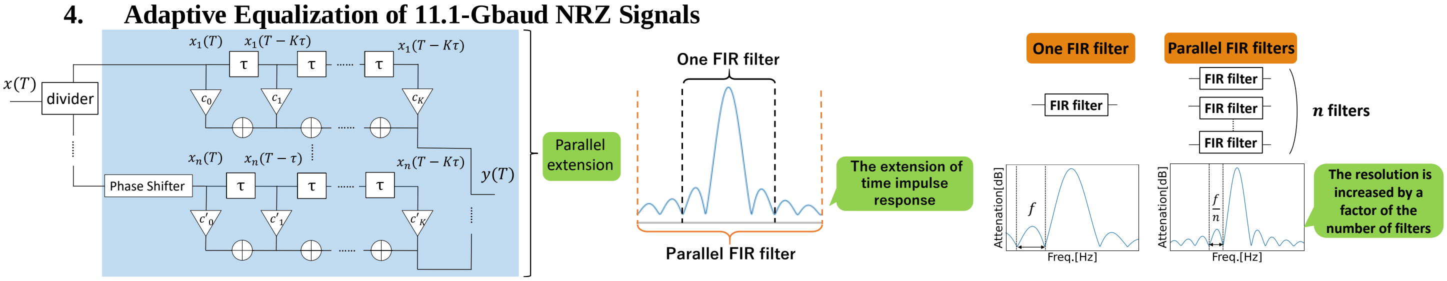

Fig. 1 The concept of the parallel extension of high-speed analog FIR filters

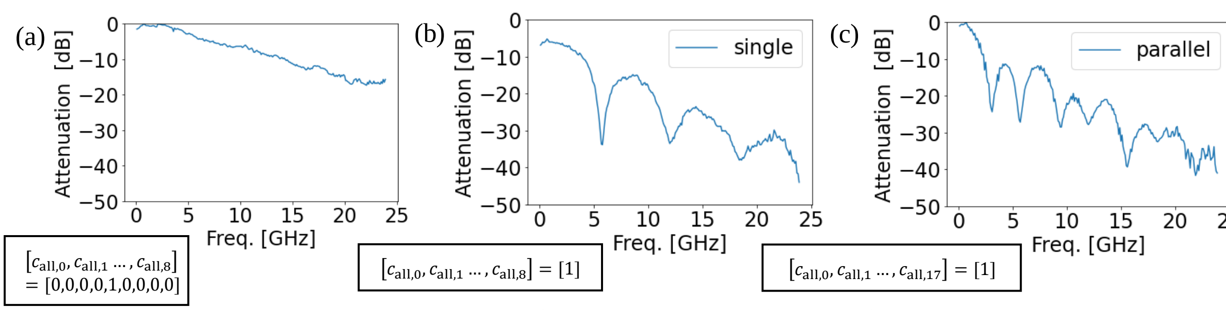

Fig. 2 The frequency response of the FIR filters

Here we demonstrate adaptive equalization of 11.1-Gbaud signals by using the parallel-extended high-speed analog FIR equalizer. Fig. 3 shows the experimental setup. The order of parallel extension was set to n =2. The parallel-extended equalizer adaptively equalizes the received signals and output equalized signals are monitored in a real-time manner.

On the transmitter side, 11.1-Gbaud NRZ signals were synthesized with an AWG clocked at 55.5 GSa/s.

In the parallel-extended equalizer, the received signals were input to the high-speed analog FIR equalizers (FIRs #1 and #2), of which details are described in the previous section. In parallel extended FIR filters system, the output of each FIR filter is independently input to the DSP. The equalized signal was digitized with a dual-channel real-time oscilloscope. The waveform of digitized signal was shaped with digital shaping filters and resampled at 55.5 GSa/s extracting the base clock of the received signals. After decisioning the symbol of resampled signal, the error signal was obtained from the difference with the target signal, and calculated the updates of tap coefficients by using least mean square (LMS) algorithm and fed back to the FIR equalizer. The equalized signal was measured in real time with a sampling oscilloscope.

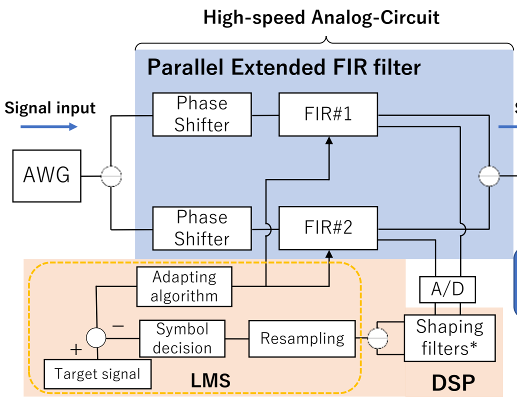

Fig. 3 Experimental setup

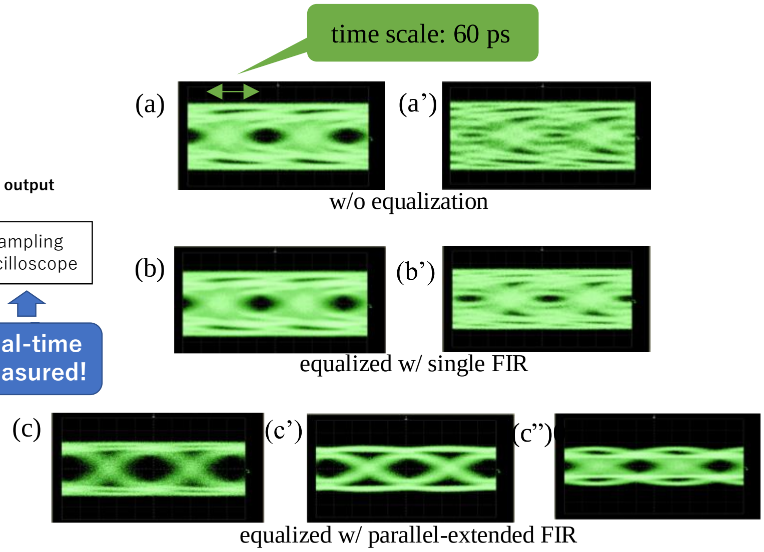

Fig. 4 Measured eye patterns of 11.1-NRZ

5.Experimental Results

First, we demonstrated adaptive equalization of 11.1 Gbaud non-return-to-zero (NRZ) signals. Fig. 4 (a), (b), (c) shows the real-time monitored eye patterns of NRZ signals.

Fig. 4 (a) shows the eye pattern observed when only one of the tap coefficients of the FIR filters was set to 1, the initial state. Fig. 4 (b)(c) are the eye patterns obtained when the signals were adaptively equalized with the FIR filter. Fig. 4 (b) shows the eye pattern obtained with the single 9-tap FIR filter; Fig. 4 (c) corresponds to the case with the parallel-extended FIR filters. It can be seen from these results that the distorted signal input to the single FIR filter cannot be perfectly equalized. This is because the temporal window of the FIR impulse response was not wide enough in this situation. On the hand, the waveform distortion was fully equalized with the parallel-extended FIR filter, where the impulse response had a time window wide enough to cover the waveform distortion.

Next, we demonstrated equalization of more distorted signals, where we intentionally gave band limitation to the signal with a root-raised-cosine (RRC) LPF with a roll-off factor of 0.9 and a cut-off frequency of 4.44 GHz. Fig.4 (a'), (b'), (c') shows the eye patterns. The distortion was successfully compensated for achieving the similar eye opening as in Fig. 4 (a), (b), (c) even if the input signal was more degraded.

Fig.4 (c") is shaped into Nyquist like waveform by LPF in the feedback section. We also demonstrated waveform shaping of the equalized signals, by adjusting the transmission characteristics of the Shaping filters in the feedback section (denoted as * in Fig.3). In the experiments the 6-GHz LPF was digitally applied after the digitization with the real-time oscilloscope.

6.Conclusions

We experimentally demonstrated parallel extension of high-speed analog-circuit FIR equalizer increasing the number of taps, enhancing temporal impulse response. By a dual parallel extended configuration, an 18-tap FIR filter with an 18-ps tap delay was constructed, which adaptively equalized real-time 11.1-Gbaud NRZ signals.

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