Optical Adaptive LMS Equalizer with an Opto-electronic Feedback Loop

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Abstract: We propose an optical adaptive Least-Mean-Squares equalizer with an opto-electronic feedback loop to determine the updating of an optical Finite-Impulse-Response filter’s weights, enabling dispersion compensation introduced by 30-km fiber based on a photonic integrated circuit. © 2022 The Author(s)

1. Introduction
Optical equalization of fiber communications systems has been used since the 1990s; e.g. adding dispersion-compensating modules (DCMs) [1]. In many systems, DSP has now replaced the DCMs [2]; being adaptive, it can also support optically-switched networks. Unfortunately, DSP chipsets consume several watts of power and per wavelength channel [3]. This is in contrast to the optical DCMs that they replace, which can ‘process’ 10-100’s of wavelength channels simultaneously in the optical domain, and only require a single optical amplifier, consuming a few watts of electrical power for all of the channels. Optical equalization could give the best of both worlds: a large processing bandwidth together with adaptive operation.

A traditional equalizer for wireless systems is the Least-Mean Squares Finite-Impulse Response (LMS-FIR) equalizer. In earlier work, we have shown that the LMS-FIR equalizer, implemented in DSP, is able to select and optimize a channel in a multi-subcarrier system [4]. Our aim in this work is to transfer the majority of the DSP into the optical domain, so we can potentially reduce power consumption and increase the processing bandwidth.

In this paper, we develop an adaptive optical LMS equalizer based on our previously reported photonic integrated circuit (PIC) FIR filter [5]. Using simulations, we present methods to implement the feedback loop using electro-optic techniques, with the mixing properties of a square-law photodetector to derive signals that can be used to update the tap weights of the filter. We demonstrate adaptive equalization of chromatic dispersion (CD) affecting Quadrature Phase Shift Keying (QPSK) signal, which shows that the equalizer converges to optimal weights to compensate CD.

2. System Design and Simulation Results
The adaptive optical LMS-FIR equalizer system is illustrated in Fig. 1. A data-carrying signal is transmitted along with a pilot tone; after de-multiplexing, the signal is processed by an optical filter then a coherent receiver, and the pilot tone serves as an optical carrier for the feedback processing. The optical FIR filter is based on a PIC that we have fabricated and tested [5]. It uses separate delays with MZIs and optical phase shifters on each arm, to allow its complex weights to be tuned. The equalization is first set in a training mode, then tracks changes in a decision-directed mode, in which the symbol error rate is low enough to generate an error signal by subtracting the estimated signal from the actual signal, e.g. by using a high-speed D-type flip-flop for quantization, then subtracting its output from the direct analog output of the equalizer, as shown in Fig. 1(c). The error signal is modulated onto the pilot tone by an IQ modulator, then added to a delayed version of the input signal and passed to a photodiode.

The photodiode multiplies the error by the delayed signals, using its square-law characteristic. The unwanted DC mixing components are removed by a passband filter, and the wanted passband signal \( e(t) x(t) \) is downconverted using a microwave IQ mixer and then selected with a low-pass filter. These signals could be sent to the pilot’s modulator directly; however, it is more flexible to implement this part of the feedback loop using DSP for the integration and adjustment of the feedback factor \( w_{i+1} = w_i + \mu e(t) x(t) \).

To verify the effectiveness of the adaptive optical LMS equalizer system, we simulated the equalization of a 40-GBd NRZ QPSK signal. The FIR equalizer has 15 taps with the inter-tap delay of 6.25 ps, which is consistent with our chip. Here, it acts as a fractionally-spaced equalizer with an FSR of 160 GHz.

Fig. 2(a) shows the influence of the number of taps on CD compensation when OSNR = 21 dB. For 10-km fiber, a 3-tap equalizer can compensate dispersion-introduced intersymbol interference; however, at least 11 taps are required for 25-km fiber to achieve BER below 20% FEC threshold. Fig. 2(b) shows the BER performance
without and with equalization for 1 to 50-km of standard single-mode fiber when implementing 15 taps at OSNR = 21 dB. Without equalization, the effect of CD is severe at 10 km; however, the equalizer system achieves good CD compensation performance with the aid of training, and can compensate 20 km of fiber without a penalty, and up to 30 km at the FEC limit. Fig. 2(c) shows the BER vs. OSNR of the signals at the 15-tap equalizer output for back-to-back, 10-km and 25-km fibers. The BER is below the 20% FEC threshold when the OSNR is >11 dB. This indicates that this adaptive equalizer system has good tolerance to noise. The BER convergence for 25-km fiber when OSNR = 21 dB is also shown. The BER decreases to $10^{-7}$ during training (2000 iterations), after which the tap weights have converged. We found that when switched to decision-directed mode (see inset), there is a small temporary increase in error rate, before returning to the same low level as during training. This glitch is because the data is derived from decisions on the received signals, which are slightly misaligned to the training data.

3. Conclusions
In this paper, we have proposed and simulated a novel adaptive optical LMS equalizer with a feedback loop using electro-optic techniques. Simulations show that this equalizer is capable of compensating CD with the feedback control signal partially calculated using the mixing properties of photodiodes. In contrast to conventional digital LMS equalizers, this adaptive optical LMS equalizer realizes part of signal processing using a photonic FIR filter, which could consume very little energy in the steady state, particularly if controlled by electrostatic techniques [6].

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References
1. L. Gruner-Nielsen et al., “Dispersion-compensating fibers,” J. Light. Technol. 23, 3566 (2005).
2. S. J. Savory et al., “Electronic compensation of chromatic dispersion using a digital coherent receiver,” Opt. Exp. 15, 12120–12126 (2007).
3. X. Li et al., “Electronic post-compensation of WDM transmission impairments using coherent detection and digital signal processing,” Opt. Exp. 16, 880–888 (2008).
4. L. B. Du et al., “No-guard-interval coherent optical OFDM with self-tuning receiver,” Opt. Exp. 19, 2181–2186 (2011).
5. Y. Xie et al., “Picosecond optical pulse processing using a terahertz-bandwidth reconfigurable photonic integrated circuit,” Nanophotonics 7, 837–852 (2018).
6. A. Boes et al., “Status and potential of lithium niobate on insulator (LNOI) for photonic integrated circuits,” Laser & Photonics Rev. 12, 1700256 (2018).