Two Enhanced Decision Feedback Equalizers for 10Gb/s Optical Communications

Matthew Hagman, Student Member, IEEE
Department of Electronics
Carleton University
Ottawa, Canada
mhagman@doe.carleton.ca

Tadeusz Kwasniewski, Senior Member, IEEE
Department of Electronics
Carleton University
Ottawa, Canada

Abstract—In this work, two unique decision feedback equalizers (DFE) for use in 10Gb/s optical communications are presented. These equalizers are effective at cancelling post-cursor ISI as well as pre-cursor ISI without the use of a feed-forward equalizer (FFE). The removal of the FFE equalizer is desirable as it is very expensive from a chip real-estate perspective. The synthetic transmission lines used to achieve the analog delay in FFE filters also suffer from performance issues such as limited bandwidth, impedance mismatches, and nonlinearities which degrade the efficacy of the filter. The proposed filter structures will be evaluated via numerical simulation, and a comparison with standard FFE/DFE techniques will be made.

Keywords—Electronic Dispersion Compensation, Decision Feedback Equalizer, IIR, Equalization, Chromatic Dispersion.

I. INTRODUCTION

With the recent trends in commoditization of 10Gb/s optical components and the continuing improvements in CMOS and SiGe processes, it has now become attractive to implement Electronic Dispersion Compensation (EDC) techniques to enhance the reach of 10Gb/s optical links, or to replace legacy 2.5Gb/s links. There are two fundamental challenges with EDC. The first challenge is the processing speed of the electronics to deal with the high frequency distortions which occur in the optical channel. The second more fundamental challenge is the non-linear square-law detection that is used to convert the intensity modulated optical signal to an electrical signal [2]. Chromatic dispersion is in fact a linear distortion that can be quiet effectively “un-done” in the optical domain with the use of dispersion shifted fiber, or with optical FIR filters [1]. These optical techniques are bulky, expensive, and inherently non-adaptive. It should be mentioned however, that optical methods of chromatic dispersion compensation do offer the advantage of multi-channel compensation which is the reason that dispersion compensation modules (DCFs) are still used in many legacy long haul systems.

At the present time, EDC has been successfully used in two different systems configurations. In long haul systems, it is common to use coherent detection, optical QPSK, or post-distortion techniques [2]. These techniques when combined with EDC are particularly powerful as the electronic compensation is able to recover the phase information which is usually lost in intensity modulated direct detection (IM/DD) systems. Coherent detection techniques are much more expensive due to the specialized optical components required. In shorter metro-reach links (40km to 120km) it is still advantageous to use EDC even with the square-law detection. In these applications, EDC is effective in extending the reach from 60km to 100km by partially compensating for ISI due to chromatic dispersion. The most common EDC approach for IM/DD systems is FFE/DFE. It has been shown that a 7-tap, T/2 spaced FFE filter with a 1 tap DFE section can extend the reach of a 10Gb/s link to 100km [1], [3] and [4]. Non-linear equalizers such as MLSE have demonstrated reach extensions up to 200km. These equalizers are particularly robust. However, they come with the price of high power consumption. To the author’s knowledge, the most recent 10Gb/s MLSE-EDC solution was implemented in 90nm CMOS, utilizing a 4-state Viterbi algorithm and it consumes 4.5W. For this reason, the discussion here is restricted to FFE/DFE-based EDC.

One of the challenges of FFE/DFE based EDC is the feed-forward continuous time filter section. This filter is typically designed using a delay line such as an LC-ladder or synthetic transmission line. A series of variable gain amplifiers usually serve as the filter taps. Process variation alone can add up to 20% uncertainty in the achieved delay from this filter architecture. In the work by S. Reynolds et al., [5] it has been shown that a 7-tap FFE filter can take 5mm of chip real estate. Experimental evidence also shows that the bandwidth limit imposed by the FFE section, as well as non-linearity in the tap scaling amplifiers reduces the effectiveness of this filter. Since the DFE section is effective at cancelling only post cursor ISI, the FFE section is generally used with DFE to cancel at least the linear portion of ISI. In further sections of this paper, modifications to the DFE filter structure will allow for some pre-cursor ISI and thus making it possible to remove the FFE section.

II. SIMULATION MODEL

In order to simulate an optical links, it is essential to model the effects of chromatic dispersion. Although chromatic dispersion combined with square-law detection is a difficult impairment to mitigate, it is actually quite easy to simulate accurately. Using MATLAB™ a PRBS 2^11-1 NRZ signal is
transmitted. The electro-absorption (EA) transmitter (most common in metro links) is modeled with a 30ps rise and fall time, an extinction ratio of 10dB, and optical chirp characteristic of slightly positive (3GHz peak-to-peak) transient chirp. These values were selected by consultation of the datasheets of two commercially available 10Gb/s EA transmitter modules. The chromatic dispersion is applied directly to the transmitted signal using both the intensity and frequency modulation characteristics with an over-sampling of 40 samples per bit (much more than required). The transmitter output is shown in node “A” in Figure 1.

The mathematical models for chromatic dispersion were found in the derivation shown in [6]. The simulated eye-diagrams from 0km to 130km show good agreement with measured results. The signal shown at node “B” in Figure 1 is the unfiltered optical signal after 80km of single-mode optical fiber. The signal at node “C” is the point where amplifier noise is added for bit error ratio (BER) analyses. Node “D” shows the received signal where the pre-amplifier has applied a bandwidth limit of 7.5GHz.

The trans-impedance amplifier in optical communication links serves as the matched filter and pre-amplifier. Here, the trans-impedance and photo-detector are modeled by a 4th order Bessel Thompson filter and a gain factor of 1kΩ. This is typical of optical receivers used in the field. It is important to mention here that when using this type of EDC, it is essential to have a linear optical receiver with a suitable automatic gain control to keep the output voltage amplitude at a constant. This type of trans-impedance amplifier is readily available in the field.

For noise analyses, the noise generated in the trans-impedance amplifier is treated as the dominant noise source. This assumption is only valid for un-amplified links and metro links are generally un-amplified. In order to simulate an amplified link, it is necessary to add Gaussian noise before the detector. This adds the complexity of having to treat non-linear noise which has a X-squared distribution due to the squaring function of the optical detector.

III. THE PROPOSED 1-BIT PREDICTIVE DFE FILTERS

A. Digital 1-bit Predictive DFE

The design of this filter structure attempts to exploit some of the features of ISI resulting from chromatic dispersion. It can be shown from equations (1), (2) and (3) that the ISI resulting from chromatic dispersion has temporal symmetry. The primary problem with any attempt to remove the FFE section is the fact that the feed-forward equalizer is the only element which treats pre-cursor ISI. The proposed modified DFE shown in Figure 3 uses a second order DFE circuit followed by a 100ps delay. The un-delayed DFE circuit serves as the 1-bit predictor to cancel the ISI due to the “future” bit.

One of the unique features of this filter is the fact that only two coefficients are needed. Using temporal symmetry, it is obvious that the ISI from the (k+1)th bit has the same influence on the kth bit as the (k-1)th bit. The argument of temporal symmetry however, does not take into account the impulse response of the 10Gb/s optical receiver. As mentioned earlier, the receiver consisting of a photo-detector and trans-impedance amplifier functions as the matched filter and is frequently modeled as a 4th order Bessel-Thompson filter. This type of low pass filter does not have a temporally symmetrical impulse response. However, since the length of the impulse response of the optical receiver is short compared to the effects of ISI due to chromatic distortion. In practice, there may also be small differences in the d1 and d2 coefficients as only one of the DFE experiences the bandwidth limitations and nonlinearities of the analog delay element. For this work, these effects have been neglected.

B. Analog 1-bit Predictive DFE

The following DFE filter was designed to address one of the weaknesses of the filter described in the previous section. Although it will be shown later that the digital predictive DFE filter offers an improvement in system BER, there still exists an issue with error propagation due to the possibility of
incorrect decisions being made at the slicer circuits (in this case, the combined slicer and D flip-flops).

This circuit replaces the un-delayed DFE section with an analog filter section. This is used as the predictor and can be described as an IIR filter with transfer function:

\[ H(z) = \frac{1 - c_f z^{-1}}{1 - c_b z^{-1}} \]

(1)

Where the “c” coefficients are shown in Figure 3 along with the block diagram.

For stability, “c_fb” must be constrained to the range of -1< c_fb<1. Simulations show that at 130km of single mode fiber, c_fb takes a typical value of -0.3. This value rapidly approaches 0 for shorter fiber reaches and thus, stability is not a concern. The interesting feature of this proposed filter is the fact that the IIR filter section can be shown to approximate the FFE filter in the popular FFE/DFE architectures used in 10Gb/s optical links where “c_ff” offers 100ps of pre-cursor ISI reduction, and the feed-back coefficient “c_fb” cancels post-cursor ISI. From the simulations, there was a high degree of similarity in the impulse response of the optimized symbol-spaced FFE filters, and the proposed IIR structure. This was observed after the FFE filter taps were set via an LMS algorithm with 75km, 100km, and 130km of chromatic dispersion.

IV. RESULTS

The unfiltered (no EDC) electrical output of the receiver is shown in Figure 4. This was simulated assuming a EA-type transmitter with virtually zero chirp and 30ps rise/fall time and 130km of SMF-28 fiber. The modeled receiver has a linear response with a trans-impedance gain of 1kΩ and a 4th order roll-off with a bandwidth of 7.5GHz. The output of a 2nd order DFE at 130km with no FFE section is given in Figure 5. The asymmetry is due to the lack of pre-cursor ISI reduction. Finally, the digital 1-bit predictive DFE gives an electrical output waveform as shown in Figure 6. The symmetry is restored, and there is 1dB additional eye opening. In order to estimate the dispersion penalty, the eye opening was measured for various lengths of optical fiber and the results were plotted in Figure 7. Here, the 1-bit predictive DFE offers approximately 20km (3dB power penalty) additional reach over the standard DFE. At fiber lengths below 80km, there is little difference between the standard DFE and the predictive DFE. Given that error propagation is a known issue in DFE filters, some bit error rate simulations were carried out to compare the two proposed predictive DFE filters. The BER simulations assume that the primary noise mechanism is due to the input referred noise of the optical receiver. This assumption is a safe one considered that the optical links discussed here are unamplified. Figure 8 shows the simulated BER performance of all of the filters discussed in this paper. The optical receiver is assumed to have a back to back sensitivity of -19dBm with an input optical extinction ratio of 10dB. This is common to most PI1 based 10Gb/s receivers in the field.
From the BER measurements, there is marked performance improvement in the analog realization of the 1-bit predictive DFE filter. As mentioned earlier, this is due to lower error propagation from incorrect decisions made at the slicer in the DFE. In these numerical results, the 7-tap FFE, 2-tap DFE structure outperforms both predictive DFE designs. This was expected given that the FFE structure allows for more pre-cursor ISI reduction. The IIR-like response of the proposed predictive design still offers comparable performance with a significantly shorter physical length.

V. CONCLUSION

Two modified DFE filter structures have been presented and their system performance has been analyzed using numerical simulation. The 1-bit predictive DFE offers comparable performance to the FFE/DFE structure commonly used in today’s optical links with a significantly shorter physical length and fewer implementation complexities. When completed, a circuit implementation in 0.13µm CMOS will be added to this research. The present design takes up a space of less than 1mm by 1.5mm offering a greater than 3-fold reduction in chip area [5]. The power consumption determined by simulation is 75mW and this may be reduced with further optimization. This is four times less power than FFE structures offering similar reach enhancement.

REFERENCES


