Dynamic Electronic Dispersion Compensation for Efficient Micro & Millimetre Wave Optical Transceivers

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Abstract — **As the optical communications goes up from 10Gbit/s/channel, efficient dispersion compensation management is asked at the receiver edge. Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD) and fiber temperature fluctuation as other arbitrary transmission impairments can originate Inter Symbol Interference and severely penalize the optical channel. The Feed Forward Equalizer (FFE) is stated as a suitable Electronic Dispersion Compensation (EDC) base solution to be embedded in micro & millimeter wave optical transceivers, to overcome optical channel residual dispersion. Defense applications for EDC filters are promoted, brought out together with optical channel lightweight and electro-magnetic interference (EMI) immunity capabilities.**

I. INTRODUCTION

Electronic equalization is a well-established technique, largely used in automatic phone line equalization [1] that can also be applied in high-speed lightwave transmission systems to overcome fiber dispersion in metro links [2]. Electronic Dispersion Compensation (EDC) devices are in general based on analog domain transversal filters that are able to operate at high bit rate signals (10Gbit/s - 40Gbit/s and potentially above) [3][4].

Inter Symbol Interference (ISI) due to Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) is the main impairment that affects pulse shape in optical high-speed systems and should be mitigated. Fiber temperature effects also have significance on CD and PMD specially, when in presence of high range of temperature fluctuations [5].

A major advantage of EDC is the possibility of electronic adjustment, making possible to compensate changes in non-ideal receiver response or other distortions due to ageing and/or temperature variations.

Monolithic Microwave Integrated Circuit (MMIC) techniques allow the realization of high-performance, reliable microwave circuits and are thus suitable for implementing such circuits as filters in nowadays, high bit rate electro-optical transceivers. A standard established development could make this device a suitable low-cost solution for high bit rate optical channel equalization. Looking forward to full optical network transparency, EDC can also play a fundamental role in residual dispersion compensation when placed at the network edge for each single channel from a multi-wavelength link. Applications within multimode inter-modal dispersion compensation can also be reliably performed by EDC.

Immunity to electro-magnetic interference (EMI) makes optical links especially suitable for environments where EMI is a critical issue. Our extended bandwidth filters may have a key role on Radio Over Fiber applications towards lightweight integration within defense avionics and warships communication solutions. Other defense equipment (eg. cruise missiles, war tanks) may also take nuclear profit from these kinds of filters. The addition of the electrical (thermal) noise to the equalized signal can be stated as the main counter back when using EDC in optical channel equalization.

Simple electrical equalizer model is presented in section II where Feed Forward Equalizer (FFE) comes up as the nuclear device in the EDC process. Section III introduces a short overview on the FFE dynamic control while section IV resumes the FFE CD and PMD compensation performance. Simulation numerical results are presented at this stage. Final Conclusion comes out in section V.

II. SIMPLE ELECTRICAL EQUALIZER MODEL

Figure 1 shows a simple Transversal Filter (TF) model where the incoming signal is delayed, by one bit period per stage in the Synchronously Spaced Equalizer (SSE) or by less then one bit period in the Fractionally Spaced Equalizer (FSE). For high-speed systems the FSE is best choice in order to avoid aliasing in the equalized signal [6]. Both configurations are known as Feed Forward Equalizers (FFEs).

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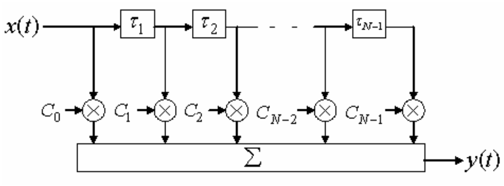


Figure 1 – Simple Transversal Filter (TF) Model

The incoming signal is tapped and weighted by stage coefficients - C_n - that can adaptively be changed so that the resulting filter response equals as much as possible the inverse of the channel response.

For $\tau_k = \tau \ ,\forall_k \in \mathrm{Z}$ we can write down the filter output, *y(t)*, as in (1).

$$y(t) = \sum_{k=0}^{N-1} C_k . x(t - k\tau) \qquad (1)$$

Also from (1) we may see that if *N* is taken finite, the output signal takes $(N-1).\tau$ time of response duration.

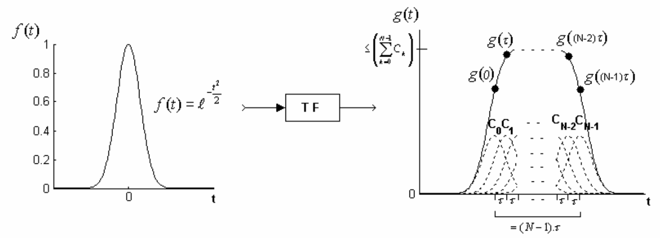


Figure 2 – Transversal filter response to a Gaussian input pulse

$$g(t) = y(t)\Bigg|_{x(t)=\ell^{-\frac{t^2}{2}}} = \sum_{k=0}^{N-1} C_k . \ell^{-\frac{(t-k\tau)^2}{2}} \qquad (2)$$

Looking at figure 2 it is clear that higher the number of TF coefficients within the same time window, higher is our control over the output pulse shape. By the other side the filter electrical noise figure increases proportionally with the number of coefficients.

Relating the filter frequency response expression as in (3), with the Fourier series exponential form, we may say the TF has a periodic behavior in the frequency domain with $1/\tau$ Hz period. An important feature of its structure is that there are no poles on its transfer function. Consequently it is unconditionally stable, but rarely capable of exactly providing the required model, which would often contain poles as well.

$$H(f) = \sum_{k=0}^{N-1} C_k . \ell^{-j2\pi f k\tau} \qquad (3)$$

Having *N* finite number of taps - FIR filter -, we can have a piecewise linear phase response for these kind of filters [6][7].

a. Transversal Filters (TF) Practical Implementation Considerations

Transversal filters for 10Gbit/s and 40Gbit/s have been designed using high speed GaAs MMIC technology [8][9]. A distributed configuration was used and is well suited to implementing a high-bandwidth delay line as the feed-forward topology requires. Artificial Transmission Line (ATL) sections implemented with microstrip inductances, making use of the active device capacitance, provide the necessary delays. Gilbert cell or cascode variable transconductance based configurations are used to implement the multiplying blocks [8][10]. In distributed electronic circuits, a tradeoff exists that relates bandwidth and delay similarly to the gain-bandwidth product seen in lumped designs. Therefore the way the ATL sections are implemented is fundamental to guarantee constant delay values between taps. Of most importance is phase linearity, which depends strongly on the behavior of series and shunt elements that compose the ATL sections. The Heaviside condition LG = RC (where L and R are series inductance and resistance, respectively and C and G are shunt capacitance and conductance, respectively) relates incremental elements in a transmission line section for maximum phase linearity and should be enforced within the desired filter bandwidth.

Additional considerations related with stability, input and output matching, input dynamic range and noise require careful circuit design and layout.

III. DYNAMIC CONTROLLING DEVICE

An alternative to exact equalization is to minimize the impact in received signal quality caused by arbitrary transmission impairments like temperature fluctuations [5]. To this effect some sort of signal quality measure has to be obtained at the received signal, and the filter coefficients adjusted iteratively in order to optimize it. This coefficient dynamic adjustment should be made by means of an optimization algorithm.

Linear algorithms such as Simplex, do not require derivation methods for function optimization. Convergence speed is also a relevant issue, and can be translated by the number of objective function evaluations required for convergence. In fact, for a same filter structure, different algorithms may converge to different coefficient sets due to the presence of local optima and other issues such as algorithm resolution in soft improvement regions. That is, there is no guarantee that the result is indeed the optimum set of coefficients.

By linear algorithm analysis, Simplex algorithm was asserted as obtaining suitable optimization range and requiring low function evaluations thus being a good choice for filter coefficient dynamic control.

The Simplex algorithm was successfully implemented in a low cost micro-controller capable of dynamic adjustment of 5 filter coefficients without any initial guesses - blind optimization. Note that from the algorithm point of view, the nature of the objective function is completely irrelevant, that is, any signal quality measurement scheme may be used as feedback signal for the coefficients optimization.

IV. FEED FORWARD EQUALIZER (FFE) NUMERICAL PERFORMANCE

Looking forward to establish the EDC capabilities on CD and PMD compensation, a numerical simulation set up was developed, where the EDC block is presented by the FFE ideal frequency response, with 5 coefficients and a tap delay equal to one half of the incoming bit rate. This FFE is placed after the photo-detector in the optical receiver and its transfer function hereafter presented (4).

$$H_{FFE}(f) = \sum_{k=0}^{4} C_k . \ell^{-2.\pi fk\tau} \qquad (4)$$

C_k is the k[th] order coefficient and τ equal to one half of the incoming bit rate. For coefficients updating, a simplex algorithm with the eye opening height as objective function was enabled [11]. A noise factor of 10dB and upper cut frequencies of 13 GHz and 43 Ghz for 10 Gbit/s and 40 Gbit/s bit rates correspondingly, were also attested within the FFE performance.

An optical signal amplifier is placed prior to the photo-detector to compensate for overall optical losses. Amplification Spontaneous Emission noise (ASE) is consequently added to the signal in order to have a defined Optical Signal to Noise Ratio (OSNR) at the optical receiver input, measured over 0.1nm and 0.34nm of the optical bandwidth for the 10Gbit/s and 40Gbit/s versions correspondingly.

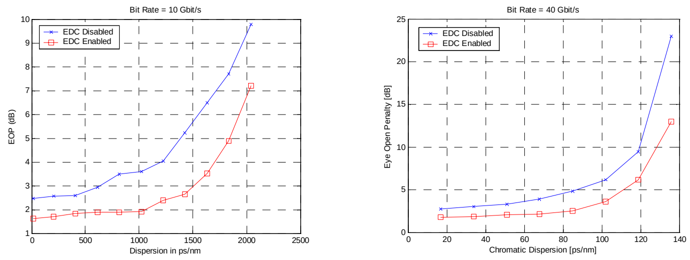
An Eye-Opening Penalty (EOP) ratio was also defined for signal quality assessment. EOP expression is presented in (5) where H_{ref} states for the eye opening in a back-to-back configuration and H is the eye opening measured after the signal had crossed the link.

$$EOP = -10.\log\left(\frac{H}{H_{ref}}\right) \text{(dB)} \qquad (5)$$

a. FFE Performance on CD Mitigation

For attesting FFE performance on CD mitigation, fiber group velocity dispersion (GVD) parameter, D [ps/nm/km], was set equal to 17 ps/nm/km and the fiber CD rate modeled by D.Z [ps/nm], being Z [km] the fiber length representation. Fiber PMD effect was not taken into account at this stage.

A 2^9-1 NRZ Pseudo Random Bit Sequence (PRBS) was transmitted trough the fiber channel at both 10Gbit/s and 40Gbit/s rates. At the optical link edge, EDC is performed by the FFE as in (4), with coefficients adaptive control being enabled by Simplex algorithm in order to optimize EOP. Results are hereafter presented for the 10Gbit/s, figure 3-a, and 40Gbit/s, figure 3-b, transmission channels when stating an OSNR equal to 13dB just before optical-to-electrical signal conversion.



(a) (b)

Figure 3 – EOP Vs Chromatic Dispersion

Considering a 3 dB EOP as a margin measurement for reliable detection at the decision device, we get around 1500 ps/nm and 110 ps/nm values of FFE dispersion compensation for 10Gbit/s and 40Gbit/s correspondingly. See "EDC Enabled" curves on figure 3, from where we can also note that, at the previous measurement stages, the FFE is able to regenerate for 2.5 dB of the EOP from the original transmitted signal.

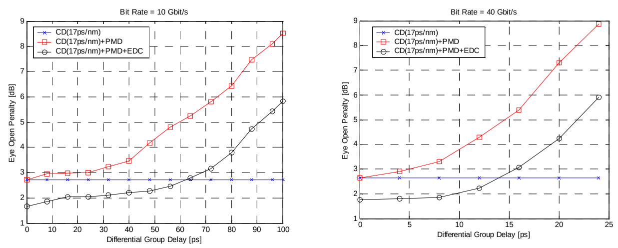
b. FFE Performance on PMD Mitigation

Simulations were also carried out regarding FFE PMD mitigation capabilities. CD was stated constant at 17ps/nm while PMD factor (D_P) was stepping up increased such that Differential Group Delay (DGD) consequently increases. See expression (6).

$$DGD = D_P.\sqrt{Z} \qquad (6)$$

Optical Channel DGD was modeled by splitting the optical power between low and fast fiber polarization axis, traveling 70% of the power through the fast one.

Three curves are presented in figure 4-a and figure 4-b where *CD(17ps/nm)* depicts for the output electrical signal affected with 17 ps/nm of CD. When adding a DGD [ps] between both polarization axis, we get the *CD(17ps/nm)+PMD* curve. Equalized signal is shown in *CD(17ps/nm)+PMD+EDC* curve.



(a) (b)

Figure 4 – EOP Vs Polarization Mode Dispersion

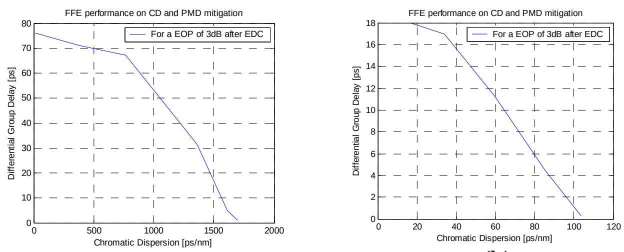
By looking at Figure 4-a we see that FFE is able to fully compensate for roughly 64ps of DGD for a 10Gbit/s fiber link while showing an EOP improvement of 2.5dB. For a 40Gbit/s fiber link, figure 4-b, we can attest for 18 ps of DGD full compensation while achieving 2.5dB of EOP improvement.

C. FFE Performance on CD and PMD Mitigation

The overall FFE performance on CD and PMD mitigation can be jointly investigated, accounting by this way for the simultaneously effect of the GVD and DGD within the same optical channel. Both are pulse distortion parameters from where a trade-off relationship is expected, when considering the single FFE device capabilities. That comes because both are strong ISI sources able to drastically influence the pulse shape at the receiver detector.

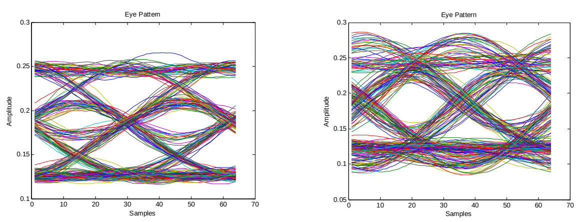
A 3dB maximum admissible EOP in the eye closure is set at the optical link output. CD and DGD are then varied, and the output pulse regeneration performance is attested, by action of the FFE device. When looking at figures 5-a and 5-b, we see a decrease on DGD mitigation as CD compensation turns out more effective.

Results for a 10Gbit/s optical channel are depicted in figure 5-a, from where we can see that our FFE is able to compensate for 10ps of DGD together with 1575ps/nm of CD. When considering 825ps/nm of CD compensation, 66ps of DGD compensation are expected for the same device. For a 40Gbit/s channel, results in figure 5-b, shows that the same device is able to compensate for 100ps/nm of CD while mitigating 1ps of DGD. For a DGD of 10ps a 64ps/nm of CD compensation is achieved. Edge eye openings are presented in figure 6 for a 10Gbit/s channel.



(a) (b)

Figure 5 – EOP Vs Polarization Mode Dispersion



(a) (b)

Figure 6 – Eye Openings for a 10Gbit/s channel (a) Unequalized channel, 1615ps/nm of Cd and 65ps of DGD (b) Equalized channel, 1615ps/nm of CD and 65ps of DGD

V. CONCLUSIONS

The electrical Feed Forward Equalizer (FFE) is a suitable low-cost solution for optical channel equalization in high bit rate optical communication channels. Its Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) compensation performances are assessed along this paper. This kind of Electronic Dispersion Compensation (EDC) device is promoted within optical transceivers integration for defense applications, where electro-magnetic interference (EMI) immunity and lightweight capabilities are stated as critical issues.

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