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Adaptive Chromatic Dispersion Compensation Using Electrical Transversal Filters

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***Abstract*—This paper describes the possible use of electrical transversal filters as chromatic dispersion compensators in partially compensated light-wave systems. A particular case of a five-tap transversal filter is considered, and its performance evaluated based on the quality factor of the signal at the receiver. The bit-rates considered for computer simulations are 10Gbit/s and 40Gbit/s.**

***Index Terms*—Chromatic dispersion compensation, slope compensation, adaptive equalization.**

I INTRODUCTION

As the use of optical amplifiers allowed light-wave systems to achieve greater transmission distances without electrical regeneration, signal attenuation limits due to fiber loss became easily managed and compensated. Since there is no reshaping of the signal at the amplifier stages, chromatic dispersion (CD) due to frequency dependence of the fiber refractive index accumulates over the entire signal path, making chromatic dispersion the actual limit for transmission distance in long-haul light-wave systems.

Though chromatic dispersion compensation is a well studied topic and proven methods are available “off the shelf”, recent advances in technology have taken their toll, and the performance of the now standard compensation methods may not meet the demands of next generation light-wave communication systems.

II CHROMATIC DISPERSION

Chromatic Dispersion is caused by the different group velocity of the various spectral components of a light-wave propagating inside the fiber core. This varying group velocity is a consequence of the frequency dependence of the fiber core refractive index. The solution of the wave equation for a single pulse propagating inside the fiber, neglecting non-linear effects and higher order dispersion, can be written as [1]

$$A(z,t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\overline{A}(0,\omega)\exp\left(\frac{i}{2}\beta_2 z\omega^2-i\omega t\right)d\omega \qquad (1)$$

where $\overline{A}(0,\omega)$ is the Fourier transform of $A(0,t)$, the initial pulse at the fiber input and

$$D=-\frac{2\pi c}{\lambda^2}\beta_2 \qquad (2)$$

is the first order dispersion parameter. Dispersion induced degradation of the signal is expressed through the $\exp\left(i\beta_2 z\omega^2/2\right)$ factor in (1).

The equivalent low-pass transfer function for the fiber can be modeled as [3]

$$H\left(f_{LP}\right)=\exp\left(\frac{j\pi DL\lambda^2 {f_{LP}}^2}{c}\right) \qquad (3)$$

where D is the first order dispersion parameter of the fiber, L is the fiber length, λ is the optical carrier wavelength, c is the speed of light, and f_{LP} is the low pass equivalent frequency defined as

$$f_{LP}=f-f_{OC} \qquad (4)$$

where f is the optical signal frequency and f_{OC} the optical carrier frequency.

The common goal of all dispersion management techniques is to compensate for the phase distortion expressed in (3) so as to return the signal to its original shape, or to maintain signal distortion below acceptable levels.

The major problem in trying to compensate for chromatic dispersion in the electrical domain is that the majority of implemented systems, using direct detection of double side band (DSB) signals, cause spectral backfolding, and information about the signals original phase is lost. In this situation the overall system is no longer linear, and signal distortion due to chromatic dispersion cannot be compensated by applying a post-detection filter with a transfer function inverse of (3).

Though spectral backfolding can be avoided through the use of coherent detection, this technique is not generally available in already deployed networks and is incompatible with the use of optical amplifiers. Another possible way of avoiding spectral backfolding and subsequent loss of phase information is the use of optical single side band (OSSB) modulation [2][3], which is being currently researched.

Loss of phase information in DSB direct detection systems makes linear equalization with an inverse fiber transfer function impossible. We propose the use of transversal filters together with a numerical multi-dimensional optimization algorithm as a suitable technique for electrical compensation of chromatic dispersion in DSB transmission with direct-detection.

III Fiber Dispersion Compensation Issues and Applications

The use of dispersion compensating fiber (DCF) is the most widely accepted and commercially available method for CD compensation, and has provided suitable results for most of the commercially implemented systems. With the increase of transmission bit-rate and subsequent increase in spectral bandwidth, the slope mismatch between the frequency-dependent first order dispersion parameter (D) of the DCF and the SMF (Standard Monomode Fiber) becomes significant on the performance of dispersion management using DCF, as it is responsible for a residual amount of dispersion which is cumulative throughout the all network.

The problem of partially compensated networks is more evident when dealing with WDM networks. In these multi-channel networks usually a wide range of frequencies is occupied, of which only a single one can be perfectly compensated trough the use of DCF. The farther the other WDM channels are from the fully compensated one with the DCF, the larger will be the amount of residual dispersion in the link. Whereas this is not a big problem for WDM channels at 2,5Gbit/s or even at 10Gbit/s, residual dispersion in WDM channels at 40Gbit/s can severely limit the range of such systems, and some mean of slope compensation will be needed if normal DCFs are to be used as primary compensators.

Another situation in which adaptive equalization of chromatic dispersion may prove to be useful is the predicted deployment of all-optical networks. The change in signal paths in optical switched networks will lead to time varying channel characteristics. An adaptive dispersion compensator can then be used to maintain and improve signal quality over time, independently of signal routing.

IV Transversal Filter Model

Use of transversal filters as equalizers is well known in electrical systems in a wide range off applications. The filter user in this study is modeled as an N-tap transversal filter as shown in figure (1) [4].

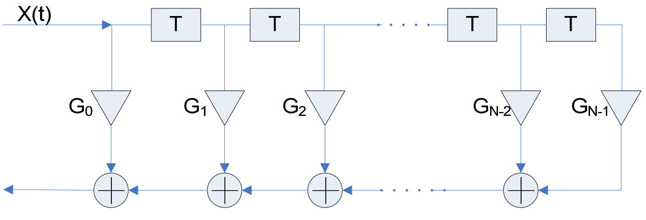

Figure 1: Ideal N-tap transversal filter

The transfer function for such a N-tap filter is

$$H(j\omega) = G_0 + \sum_{k=1}^{k=N-1} G_i e^{-j\omega Tk} \qquad (5)$$

The temporal response is the sum of delayed replicas of the input signal weighed by the individual tap gains G_i.

$$y(t) = \sum_{k=0}^{k=N-1} G_k x(t-kT) \qquad (6)$$

Adaptability of the transversal filter is strongly related to the number of taps and to the time delays between them. The transfer function (5) is periodic in frequency with period 1/T [5], which puts an upper limit to the tap delays in order to maintain full configurability throughout a given bandwidth. On the other hand configurability of the frequency response over this band depends on the number of filter taps N.

The frequency response in (5) cannot completely match the phase distortion induced in the fiber without an infinite number of coefficients and the delays tending to zero. In fact, the impulse response associated with (5) can be written as

$$h(t) = G_0\delta(t) + G_1\delta(t-T) + G_2\delta(t-2T) + ... \qquad (7)$$

which can be seen as sampling of an arbitrary function $h'(t)$ with sampling frequency 1/T, where the sampled values are the tap gains G_i. Considering the impulse response associated with the inverse of the overall distortion to be the arbitrary $h'(t)$, matching of the transversal filter would require an infinite number of taps and infinitely small tap delays.

Since matching the filter response to an arbitrary system is impossible, an alternative approach is to try to compensate not directly the chromatic dispersion itself, but to minimize the effect it as at the receiver.

V Multi-dimensional Optimization

A multidimensional optimization algorithm was required to automatically calculate the optimum set of coefficients that would minimize chromatic dispersion effects. The SIMPLEX unconstrained algorithm proposed by Nelder & Mead [6] was chosen for its simplicity and robustness. The algorithm was modified to include optimization constraints in order to include physical limitations on the gain available in each tap.

A criterion is needed as input to the optimization algorithm, capable of translating the ISI caused by chromatic dispersion in the received signal. Most of the algorithms used in electrical equalization depend on knowledge of the original transmitted signal shape. This requires transmitting dedicated sequences to calibrate the system, which is not always possible and results in additional overhead.

In our case, the SIMPLEX is a blind algorithm: it depends only on its input (regardless of the physical meaning) and does not require additional information. Whereas this has the obvious advantage of isolating the equalization process in the receiver from the rest of the system, it introduces the problem of extracting meaningful data reflecting signal quality exclusively from the received signal.

Our approach is based on the eye diagram of the received signal. Chromatic dispersion induced ISI manifests itself trough scattering of the sampled values around the ideal value.

The numerical value used as input in the optimization process is a function of both the standard deviation and mean value of the sampled signal. We define this input as being the Quality Factor

$$Q = \frac{m_1 - m_0}{\sigma_1 + \sigma_0} \tag{8}$$

where m_i and σ_i are the mean and standard deviation values at the sampling point for the logical symbols “1” and “0”.

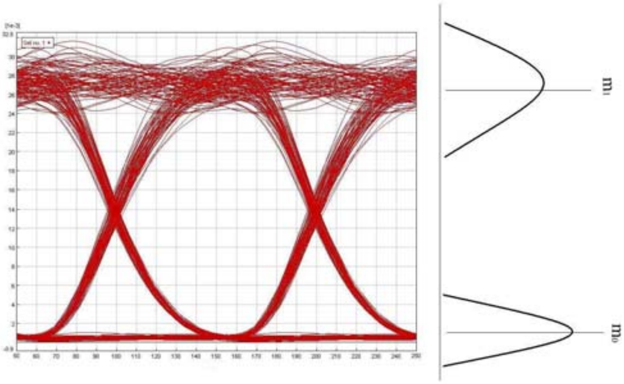

Figure 2: Data acquisition through eye diagram analysis

The value of Q increases as the standard deviation of the samples decreases and the difference between the mean value of both binary symbols increases. The decrease in the standard deviation values reflects smaller ISI, while the mean values dependence is a penalty for closing of the mean eye opening.

Maximizing Q insures minimization of chromatic dispersion induced ISI while preventing degradation of eye opening.

VI SIMULATION SETUP

In order to estimate the efficiency of the transversal filter in chromatic dispersion compensation a testing scheme was devised. Channel effects and data acquisition were simulated in Matlab, while a control board based on a microcontroller with the SIMPLEX algorithm implemented closed the loop and calculated the optimum set of coefficients.

A model of a five-tap filter with tap delays of half the bit period was used in all simulations.

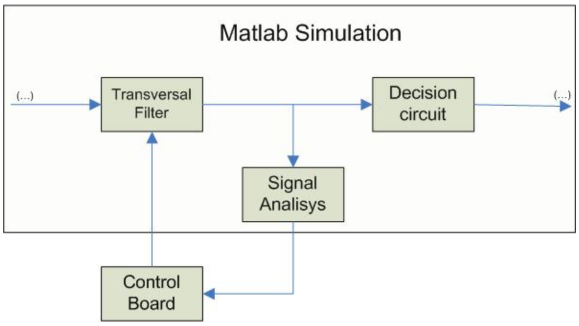

Figure 3: Setup for coefficients calculations

The fiber model used in Matlab implements the transfer function described in (3). Transmission is simulated modulating in amplitude a sinusoidal carrier with a square pulse train at 10Gbit/s and 40Gbit/s with modulation index m=0,5, and the receiver simply squares the received signal, simulating a simple square-law device such as a PIN photodiode. A 3rd order Butterworth low pass filter with cutoff frequency of one-half the bit rate is then applied, followed by a model of an ideal five-tap transversal filter. The value of Q is calculated according with (4) and passed to the optimization algorithm.

The SIMPLEX algorithm is implemented in a microcontroller interfacing with Matlab through a RS232 protocol. The reason for not implementing the algorithm in Matlab is to estimate its performance when running in a low resolution machine such as a microcontroller. Coefficients have 8-bit resolution with a dynamic range of [-1 , 1].

The sets of coefficients obtained through this setup were then tested using the VPITransmissionMaker software package for a wide range of dispersion values in the signal, both at 10Gbit/s and 40Gbit/s, in order to obtain more realistic results. Simulations included laser chirp and electrical noise, as well as a detailed model of light propagation inside single-mode fibers. Amplitude modulation with m=0,5 was used.

The system model simulated in VPI is shown below, as well as the model for the transversal filter.

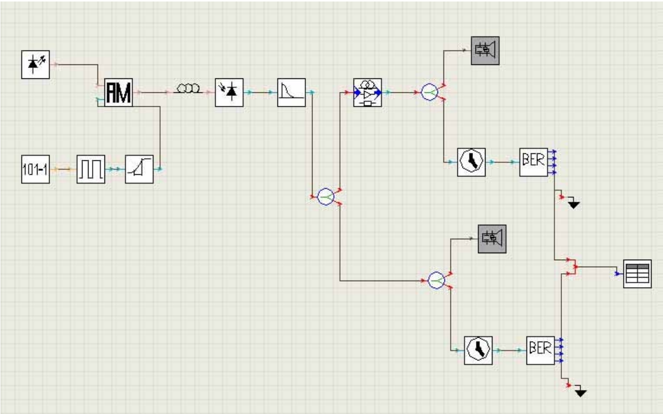

Figure 4: VPI Setup for coefficient testing

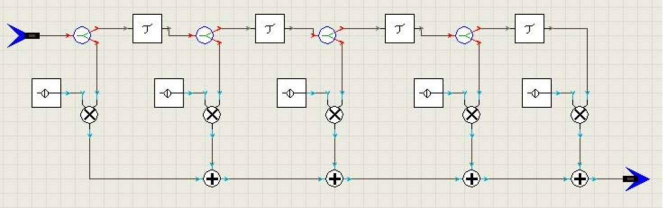

Figure 5: Modeling of a five-tap transversal filter in VPI

VII RESULTS

Using the VPI simulator, figure 6 shows the estimated Q for a sweep of various values of dispersion. The plot represents the estimated Q for the case in which no method of compensation was used and for the case in which a transversal filter controlled by the modified SIMPLEX algorithm was used.

Note that due to the different simulation conditions in the Matlab setup and the VPI simulations, the coefficients obtained in Matlab are not the optimum for the VPI simulations, and further improvement in the results depicted in figure 6 is to be expected.

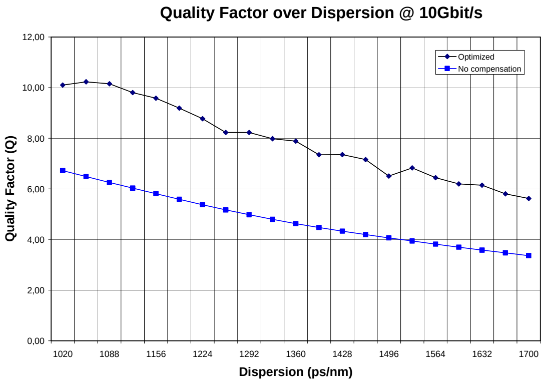

Figure 6: Measured Q with and without adaptive equalization

The uncompensated channel's Q drops below 6 at about 1140 ps/nm of dispersion (equivalent to 67 Km of G.652 SMF with D=17 ps/nm/Km at a transmission rate of 10Gbit/s). The value of "6" for Q was chosen for comparison having in mind that it yields a BER of 10^9 under Gaussian statistics approximation, which is not the case in presence of dominant chromatic dispersion interference. Even though, the adaptively compensated channel extends this limit up to 1660ps/nm (equivalent to 98Km of SMF at 10Gbit/s).

Noting that the improvement in Q remains somewhat constant over the dispersion values (a medium increase of 2,5), even if the Q estimations are not correct in absolute value, it is reasonable to expect an increase of about 500ps/nm in dispersion tolerance for a given BER (approximately 30 Km of SMF G652 at 10Gbit/s).

Figures 7 and 8 show the resulting eye diagrams for compensated and uncompensated channels at 40Gbit/s after 6Km of propagation

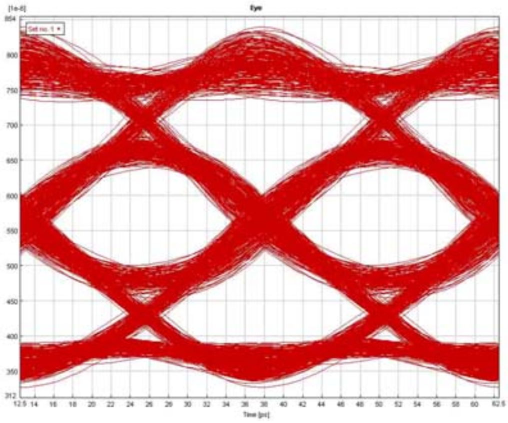

Figure 7: Eye diagram at 40Gbit/s after 6Km without optimized transversal filter

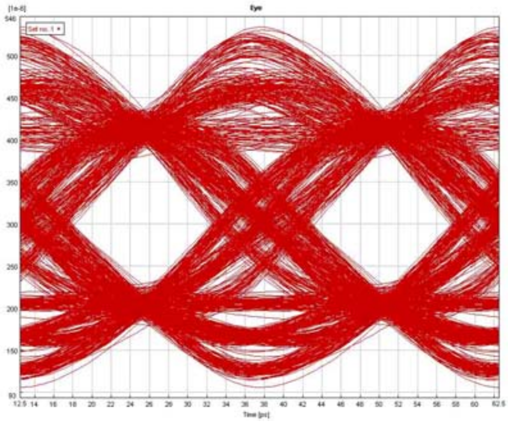

Figure 8: Eye diagram at 40Gbit/s after 6Km with optimized transversal filter

The compensated eye diagram exhibits a better defined eye opening, and reduced ISI in the sampling points, resulting in an increased Q.

VIII CONCLUSION

The adaptive algorithm relies only on signal quality measured at reception. This means that a minimum signal quality is needed at reception for correct functioning. Together with the transversal filter limitations in compensating for large amounts of signal dispersion, this implies that this is not a suitable stand-alone method for dispersion compensation in long-haul systems.

It may though prove to be useful as a complementary system in partially compensated networks, such as WDM networks and switched optical networks, where the partial compensation guarantees a minimum signal quality factor at the receptor. The filter can then be used not only to compensate for the residual dispersion caused by imperfect compensation through DCF but also to compensate cumulative dispersion due to slope mismatch between the DCF and SMF.

REFERENCES

[1] Govind P. Agrawal, “Fiber-Optic Communication Systems”, John Wiley & Sons Inc., 1997

[2] T. Maia, E. Costa, A. Pinho, P. Monteiro, R. Ribeiro, M. Violas, J. F. da Rocha, “10 Gbit/s Optical Single Sideband Transmission Using Zero Forcing Equalization”, Proceedings of the 3rd IASTED International Conference, 2003, pp. 104-109, July 2003.

[3] M. Sieben, J. Conradi, D. E. Dods, “Optical Single Sideband Transmission at 10Gbit/s Using Only Electrical Dispersion Compensation”, Journal of Lightwave Technology, Vol. 17, No. 10, October 1999.

[4] A. Borjak, J. O'Reilly, P. Monteiro and I. Darwazeh, "High Speed Generalised Distributed Transversal Filter Topology for Optical Communication Systems", IEEE Transactions on Microwave Theory and Techniques, Vol. 45, Nº 8, pp. 1453-1457, 1997.

[5] A.Bruce Carlson, “Communication Systems, Third Edition”, McGraw-Hill, 1986

[6] R. E. Massara, “Optimization Methods in Electronic Circuit Design”, Jonh Wiley & Sons Inc., 1991.

REFERENCES

[1] Govind P. Agrawal, “Fiber-Optic Communication Systems”, John Wiley & Sons Inc., 1997

[2] T. Maia, E. Costa, A. Pinho, P. Monteiro, R. Ribeiro, M. Violas, J. F. da Rocha, “10 Gbit/s Optical Single Sideband Transmission Using Zero Forcing Equalization”, Proceedings of the 3rd IASTED International Conference, 2003, pp. 104-109, July 2003.

[3] M. Sieben, J. Conradi, D. E. Dods, “Optical Single Sideband Transmission at 10Gbit/s Using Only Electrical Dispersion Compensation”, Journal of Lightwave Technology, Vol. 17, No. 10, October 1999.

[4] A. Borjak, J. O'Reilly, P. Monteiro and I. Darwazeh, "High Speed Generalised Distributed Transversal Filter Topology for Optical Communication Systems", IEEE Transactions on Microwave Theory and Techniques, Vol. 45, Nº 8, pp. 1453-1457, 1997.

[5] A.Bruce Carlson, “Communication Systems, Third Edition”, McGraw-Hill, 1986

[6] R. E. Massara, “Optimization Methods in Electronic Circuit Design”, Jonh Wiley & Sons Inc., 1991.