Electrical Dispersion Compensation for 10 Gbit/s Transmission Systems : Simulation Results

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Abstract

In this paper we will compare two electrical signal processing techniques to mitigate the influence of chromatic dispersion in long-haul fiber optic systems at 10Gbit/s. The presented techniques are easy to integrate in existing systems and can significantly improve the dispersion limited distance in transmission spans. In particular we analyse the performance of the decision feedback (DF) equalizer with only one or two coefficients and we will compare the performance with a linear equalization filter. We describe methodes to determine the coefficients of the DF as well as an optimal filter design in the mean square error (MSE) sense for the equalization filter.

Keywords
Electrical dispersion compensation, Decision Feedback equalization

1. INTRODUCTION

Electrical signal processing at the receiver improves the performance without modifying the transmission format. Furthermore it can be adaptive to time varying sources or channel conditions. The optimal receiver for compensating intersymbol interference (ISI) is the Maximum-likelihood-detector [Winters, 91]. However, a realization with today's technology is not practical in high speed transmission systems. The decision-feedback detector is closely related to the Maximum-liklihood detector, but it is very simple to realize and can significantly reduce the effect of ISI due to chromatic and polarization dispersion in optical fibers as well as interference between signals in a wavelength division multiplex system, e.g. interference due to nonlinearity. In section 2 we will briefly describe the simulation model and will then give a short introduction to the theoretic backround of the DF as well as the linear equalization (section 3). In order to investigate the performance of the proposed equalization techniques we will only consider the chromatic dispersion in the fiber as the main source of distortion. In section 4 we discuss the improvement of the

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eye opening and the bit error ratio (BER).

2. SIMULATION MODEL

A filtered nonreturn to zero (NRZ) input data stream is used as a modulating signal which is assumed to be chirp-free. The complex envelope at the fiber input is $y_T(t)$ which is propotional to the square root of the optical laser output power. As mentioned the dominant source of distortion is the chromatic dispersion in the fiber. The frequency response of the fiber is given by $H(f) = exp(-jbf^2) \bullet\!\!-\!\!\circ\, h(t)$, $b = \pi D(\lambda_T)\lambda_T^2/cL$, with $\lambda_T = 1550nm$, $D(\lambda_T) = 17ps/nm/km$ for standard single mode fibers (SSMF), L the fiber length and c the speed of light. The fiber output signal is $y_r(t) = h(t) * y_T(t)$. The PIN diode at the receiver converts the electrical field into an electrical signal proportional to the signal power $y(t) = |y_r(t)|^2$. The overall system is thus nonlinear due to the square root and the magnitude squared operation even though the fiber itselfs is a linear filter.

3. COMPENSATION TECHNIQUES

3.1 Decision feedback equalization

The decision feedback equalization is a nonlinear technique to compensate for both linear and nonlinear distortions. Already detected bits are used to generate an error signal $e(k)$ which ist substracted from the sampled imput signal $y(k)$. Figure 1. shows a block diagram of a 2^{nd} order DF-detector. For better comprehension we will consider a linear transmission system with the overall impulse response $g(t)$. The noisefree receiver input baseband signal is : $y(t) = \sum_{l=-\infty}^{\infty} d_l \cdot g(t - l \cdot T_b)$, where $d_l \in \{0, 1\}$ are the transmitted bits and $f_b = 1/T_b$ is the symbol rate. Sampling this signal gives $y(t_0 + kT_b) = d_k g(t_0) + \sum_{\substack{l=-\infty \\ l \neq 0}}^{\infty} d_{k-l} \cdot g(t_0 + l \cdot T_b)$ where t_0 denotes the sampling instant of the impulse response $g(t)$. If $g(t) = 0$ for $t < 0$ the actual weighted bit to be decided is $d_k \cdot g(t_0) = y(k) - \sum_{l=1}^{\infty} d_{k-l} \cdot g(t_0 + l \cdot T_b)$ where the 2^{nd} term is the error signal $e(k)$. Note that the eye-opening is given by $V_{DF} = g(t_0)$ and the decision threshold is $S = g(t_0)/2$. Knowledge of the impulse response and of the previously detected bits is sufficient to remove ISI completely. Even if the impulse response is well known, the

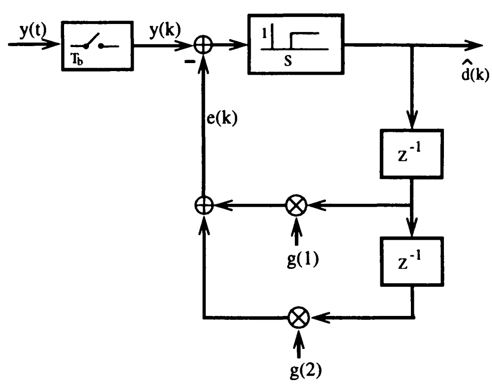


Figure 1: DF detector 2^{nd} order

performance of the DF is a function of the sampling instant t_0.

3.2 Linear equalization

As an alternative to the DF a linear equalization filter can be used to compensate for the linear part of the distortion. The key issue for designing this filter is the knowledge about the impulse response of the system. We will first estimate the impulse response in the mean square sense by a given sequence of the received signal and the original data input stream and will then design the equalization filter.

Let $y(t)$ be the receiving signal (e.g. measurement results) and $\hat{y}(t)$ the output of the estimated linear system $g_e(t)$, where index e denotes estimate. For simulation these signals are sampled by the sampling rate $f_s = N \cdot f_b$, where N is the oversampling factor. We define the following vectors :

$$\mathbf{D} = \begin{bmatrix} d_0 & 0 & 0 & 0 & \cdots \\ 0 & d_0 & 0 & 0 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ d_1 & 0 & d_0 & 0 & \cdots \\ 0 & d_1 & 0 & d_0 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \quad \begin{aligned} \mathbf{d} &= [d_0 d_1 \cdots d_{N_d}]^T \\ \mathbf{g_e} &= [g_e(0)\ g_e(1) \cdots g_e(L \cdot N)]^T \\ \hat{\mathbf{y}} &= \mathbf{D} \cdot \mathbf{g_e} \\ \mathbf{y} &= [y(0)\ y(1) \cdots y((N_d + L)N)]^T \end{aligned}$$

$\mathbf{D}$ is the convolution matrix of the input data $d(k)$, $\mathbf{g_e}$ is the vector of the linear impulse response which is set to zero for $t > L \cdot T_b$ and N_d is the number of transmitted data. Minimizing $\boldsymbol{\epsilon}^T \boldsymbol{\epsilon} = (\mathbf{y} - \mathbf{D} \cdot \mathbf{g_e})^T (\mathbf{y} - \mathbf{D} \cdot \mathbf{g_e})$ which is the square sum of the estimating error gives

$$\mathbf{g_e} = \left(\mathbf{D}^T \mathbf{D}\right)^{-1} \mathbf{D}^T \mathbf{y} \tag{1}$$

With the estimated impulse response we can now design the equalization filter $e(t)$. An ideal transmission channel is $c(t) = \delta(t - t_d)$ where t_d is the signal time delay. To reach nearly ideal conditions we set $e(t) * g_e(t) = \delta(t - t_d) + \epsilon(t)$ where $\epsilon(t)$ is an error signal. The time continuous functions are sampled with the sampling rate f_s. Let $\mathbf{G}$ be the convolution matrix of the estimated linear system so that $\mathbf{G} \cdot \mathbf{d} = \hat{\mathbf{y}}$ and $\mathbf{e} = [e(0)\ e(1) \cdots e(N_e)]^T$ the vector of the equalization filter. The optimal equalization filter in the mean square sense is then given by

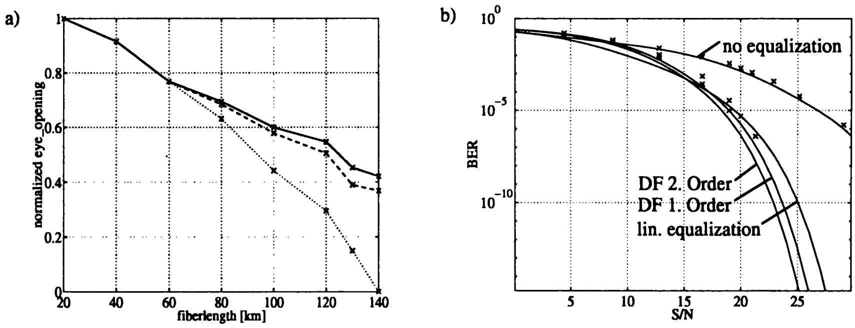
$$\mathbf{e} = \left(\mathbf{G}^T \mathbf{G}\right)^{-1} \mathbf{G}^T \boldsymbol{\delta} \tag{2}$$

which is the same as equation 1. Note that $N = 1$ gives the well known taped delay line [Winters 90].

4. RESULTS

Figure 2.a shows the normalized eye opening versus the fiber length. Without equalization the eye is totally closed after 140 km due to chromatic dispersion in the fiber and nonlinear properties of the PIN envelope demodulation.

Accepting an eye opening of 50 % in the considered case, the repeaterless distance could be increased from 90 km to more than 125 km for a 2nd order DF equalizer. In Figure 2.b simulation results of the BER applying the differ-



ent approaches are shown. The BER is determined by adding white gaussian noise and counting the occured errors (Monte Carlo Simulation). An alternative approach to determine the BER is the quasianalytic method [Jeruchim, 92]. In a practical range ($\sim 10^{-12}$) the DF-equalizer is more efficient then the linear equalizer filter. Note that most of the ISI is removed with only one feedback coefficient. For very low S/N the performance of the DF-equalizer decreases due to error propagation.

5. SUMMARY

The performance of a DF-equalizer of 1st and 2nd order is presented and compared to a linear equalizer in a simulated 10Gbit/s lightwave system. We evaluated the performance both in terms of eye opening and BER. Simulation show that equalization in the electrical part of the receiver can significantly compensate for distortion due to chromatic dispersion. It has been shown, that for the dispersive channel DF is superior to linear equalization. Moreover DF allows simpler realization. It is proposed, that future receiver chip designs should contain the very simple DF-structure.

6. REFERENCES

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