Nonlinear Electrical Dispersion Compensation in Optical Communication System

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ABSTRACT

We introduce the Radial Basis Function (RBF) network for electronic dispersion compensation in optical communication systems with on-off-keying and a direct detection receiver. The RBF method introduces a non-linear equalization technique suitable for optical communication system. A bit error rate performance comparison shows that the RBF equalizer out performs the conventional linear feed-forward equalizer. Finally, the feasibility of the RBF method is validated by experimental results.

Keywords: RBF, Optical Fiber Communication, Equalizer, Dispersion.

1. INTRODUCTION

Compensation methods for inter-symbol interference (ISI) caused by chromatic dispersion (CD) and polarization-mode dispersion (PMD) together with optical amplification have significantly improved performance of high capacity transmission systems. The demand for reducing cost per gigabytes is one of the main reasons for using electronic equalizers [1, 2], which are very cost effective.

It is well known that the application of linear filters in optical communication system for channel equalization is sub optimum, especially due to the square-law operation of the photodiode in direct detection systems. Substantial performance improvements may be achieved by using nonlinear methods.

Here we introduce a nonlinear filter based on the Radial Basis Function (RBF) network technique and compare the performance of such a filter to conventional ones. The RBF network is structurally equivalent to an optimal Bayesian equalizer [3], [4] and this intimate connection can be exploited to develop fast training algorithms for implementing a Bayesian equalizer.

2. MATHEMATICAL CHANNEL MODEL

The link distance is assumed to be up to a couple of hundreds of km where ISI dominates, but the signal is still recoverable. The output of the single mode fiber u(t) is obtained by convolving the data stream In with the convolution of the laser shape with the linear channel impulse response. In direct detection systems the photodiode forms a square-law operation and the received electrical signal is given by:

$$y(t) = |u(t) + n_s(t)|^2 + e(t) \qquad (1)$$

where $e(t)$ is the receiver additive white noise which is assumed to be a zero-mean, Gaussian with variance σ_e^2 and $n_s(t)$ represents the additive spontaneous emission noise. An equalizer follows the photodiode in order to mitigate the corrupted signal. The equalizer output is followed by a decision circuit with output of values 1 or 0 which classifies the equalizer signal sampled output. The channel state c_j is defined by using the noise free version of $y(t)$.

3. THE RBF EQUALIZER

An RBF with m inputs $\mathbf{r} = [y(i-1)\dots y(i-m)]^T$and a scalar output implements a mapping according to [3]:

$$\hat{y}(i) = f(\mathbf{r}(i)) = w_0 + \sum_{j=1}^{K-1} \phi_j(\mathbf{r}(i)) \cdot w_j, \qquad (2)$$

where $\mathbf{w} = [w_0 w_1 \dots w_{K-1}]$ the filter's weights and $\phi_j(.), 1 \le j \le K-1$, are the hidden nodes which introduce the nonlinear transformation. These nonlinear expansions are known by the neural networks community as the hidden layer. The outputs of the hidden nodes are given by :

$$\phi_j(\mathbf{r}(i)) = \phi(\|(\mathbf{r}(i) - \mathbf{s}_j\|/\alpha_j),\ 1 \le j \le K-1 \qquad (3)$$

Where $\mathbf{s}_j \leftarrow R'''$are called the RBF centers, α_j are positive scalars known as width, and $\|.\|$ denotes Euclidean norm. For general applications, the nonlinearity can be chosen from a wide class of nonlinear functions.

1. The Bayesian decision equalizer

The equalization process can be viewed as a classification problem in which the equalizer's task is to partition the input space $\mathbf{r}(k) \leftarrow R'''$into two distinct regions, given that the transmitted symbols are binary. The boundary points that separate these two regions are referred to as the decision boundary. The

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partitioning which results in the minimal probability of misclassification is known as the Bayesian solution. As explained above, in order to minimize the probability of misclassification, given that the received vector is $\mathbf{r}(k)$, the estimated symbol should be chosen by determining which transmitted signal I has the maximum a posteriori probability (APP) $p(I(k-d) = s|\mathbf{r}(k))$. This leads to the following decision rule:

$$\tilde{I}(k-d) = sgn(f_b(\mathbf{r}(k))) = \begin{cases} 1, & f_b(\mathbf{r(k)}) \geq 0 \\ 0, & f_b(\mathbf{r(k)}) < 0 \end{cases}, \tag{4}$$

where d is the channel delay and $f_b(\mathbf{r(k)})$compares the APP of the binary transmitted symbols.

Assuming that the conditional PDF is Gaussian the Bayesian decision function becomes [4]:

$$f_b(\mathbf{r}(k)) = \frac{1}{N_s} \sum_{c_j \epsilon c_c^+} (2\pi\sigma_e^2)^{-m/2} exp\left(-\|\mathbf{r}(k) - \mathbf{c}_j\|^2/2\sigma_e^2\right)$$

$$-\frac{1}{N_s} \sum_{c_j \epsilon c_d^-} (2\pi\sigma_e^2)^{-m/2} exp\left(-\|\mathbf{r}(k) - \mathbf{c}_j\|^2/2\sigma_e^2\right) \tag{5}$$

where $\mathbf{c}_j = [c_j(k) \dots c_j(k-m+1)], 1 \leq j \leq N_s$ are the vector channel states, and each element c_j is the noise free version of $y(t)$, i.e. $c_j(k) = |u(kT)|^2$, T is the bit duration time, $1/N_s$ is the a priori probability of c_j, N_s being the number of vector channel states. It is obvious by comparing (2) and (3) to (5) that the structure of the RBF network realizes exactly the Bayesian decision function.

The RBF in optical communication system

The Bayesian equalizer and RBF networks structures are identical and are specified by three components, the channel state locations, noise variance and nonlinearity $\phi(.)$. In order to implement RBF networks in an optical communication system the three components need to be set correctly. Two cases are considered, without and with optical amplification. In the case of a system without optical amplification the PDF is a mixture of multi-variable Gaussian as presented in (5). In an optically amplified system the conditional PDF is a non-central chi-square [5], and the Bayesian decision function can be expressed by:

$$f_b(\mathbf{r}(k)) = \sum_{c_j \epsilon c_d^-} \left(\frac{\mathbf{r}(k)}{c_j}\right)^{(N-2)/4} exp - \frac{(\mathbf{c}_j + \mathbf{r}(k))}{2 \cdot \sigma_o^2} \cdot I_{N/2-1}\left(\frac{\sqrt{\mathbf{r}(k) \cdot \mathbf{c}_j}}{\sigma_o^2}\right) \cdot$$

$$-\sum_{c_j \epsilon c_d^-} \left(\frac{\mathbf{r}(k)}{c_j}\right)^{(N-2)/4} exp - \frac{(\mathbf{c}_j + \mathbf{r}(k))}{2 \cdot \sigma_o^2} \cdot I_{N/2-1}\left(\frac{\sqrt{\mathbf{r}(k) \cdot \mathbf{c}_j}}{\sigma_o^2}\right)., \tag{6}$$

where $I_n(x)$ is the n-th order modified Bessel function of the first kind, $\sigma_o^2 = P_{ASE}/N, P_{ASE}$ PASE is the amplified spontaneous emission (ASE) noise power, B is the ASE noise bandwidth, T is bit duration time and N is the number of chi-square degrees of freedom, where $N = 2BT$.

4. NUMERICAL RESULTS

Computer simulations were carried out with the mathematical model given above. The summary of the system parameters in our simulation is as follows: The laser transmitter is assumed to be chirp free with Gaussian envelope shape given in [6] and its FWHM is 0.1ns; the bit rate is 10-Gbit/s with OOK format and a 214 pseudorandom bit sequence; The fiber model is taken from [6], with CD parameter 17 ps/nm/km and the fiber length is 100 km. According to the physical link parameters the ISI spans three symbols.

Figs. 1-3 present the RBF equalizer comparison analysis using BER curves versus SNR with the physical parameters given above and with RBF parameters of channel delay $d = 1$ and number of bits observation inputs $m = 3$.

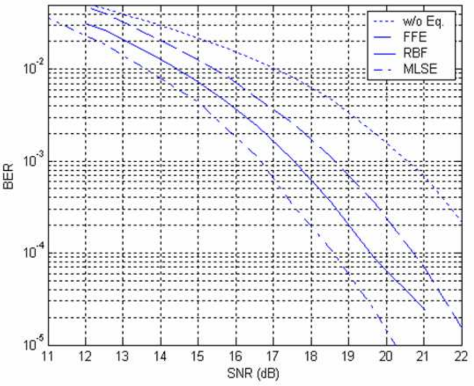

Fig.1: *BER versus SNR with fiber length of 100km, without optical amplification*

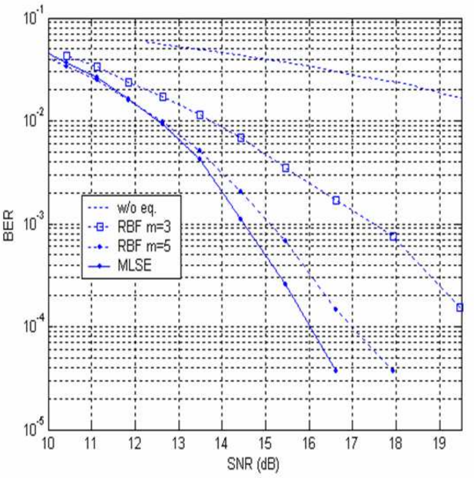

Fig.2: *BER versus SNR with fiber length of 120km, with optical amplification and 6 degrees of freedom in the noncentral chi-square*

In Figs. 1 and 3 the RBF equalizer is compared with feed-forward equalizer (FFE). The FFE contains three taps and is adapted by using the LMS method [7]. FFE with four and five taps didn't show any performance improvement. In Figs. 1 and 2, the RBF is also compared with the Maximum Likelihood Sequence Estimation (MLSE), which is known to be the optimal sequence estimation equalizer. Fig. 2 and 3 represent BER curves for an optically amplified system. Fig. 3 presents the performance difference between the noncentral chi-square and Gaussian function as the RBF nonlinear functions. In addition, Fig. 3 compare the performance of the RBF equalizer for $m = 3$ and $m = 5$ observation inputs.

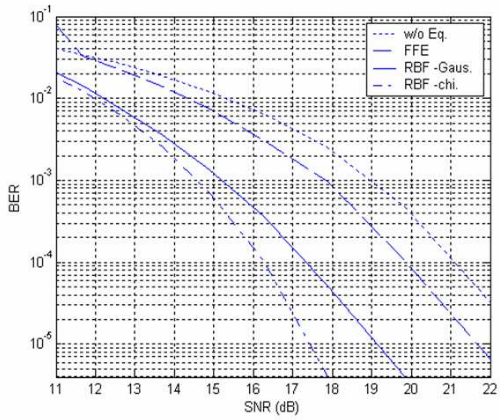

Fig.3: *BER versus SNR with fiber length of 100km, with optical amplification and 4 degrees of freedom of the noncentral chi-square (N).*

5. EXPERIMENT SETUP AND RESULTS

In order to examine the proposed RBF methods, transmit-receive experiment with fiber length of 80km was carried out. The experimental set up is shown in Fig. 4. The BER tester output at data rate of 9.953 Gbit/sec is connected to MZ modulator with zero chirp, 12dB extinction ratio and 5 dBm optical output power of a DFB laser. The MZ modulator is followed by an 80 km standard single mode fiber which gives a GVD value of 1360 ps/nm. The single mode fiber is followed by VOA and EDFA with optical output power of 17 dBm and NF of 7 dB. An optical filter with 0.15 nm noise equivalent bandwidth is following the EDFA. A digital communication analyzer scope with an optical module is used as the receiver, triggered by the BER tester. The scope electrical filter is a 4th order Bessel Thompson filter with 7.5 GHz bandwidth. The scope output electrical signal is loaded into the computer, and in turn, is processed and equalized offline.

The resulting signal processing of the experiment discussed above is shown in Fig. 5. There are three BER curves in the Figure. The two lowest curves represent RBF equalizer performance for computer simulation (dots) and experimental measurements (squares). In the experimental results the RBF equalizer was obtained by using the histogram estimation method. The highest BER curve of Fig. 5 represents experimental results with no equalization. The comparison in Fig. 5 indicates very good agreement between the simulation and laboratory experimental results. It is clear that the RBF equalizer is feasible and achieves good results. In this experiment the amount of signal samples was limited to a few thousands. However, in practical implementation the histogram estimation might perform better since it can accumulate more signal samples and therefore, the tail regions of the histogram can be estimated more accurately.

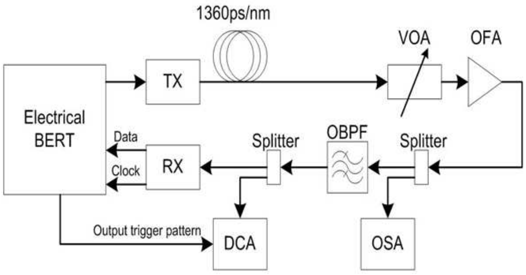

Fig.4: *Schematic of the measurement set-up.*

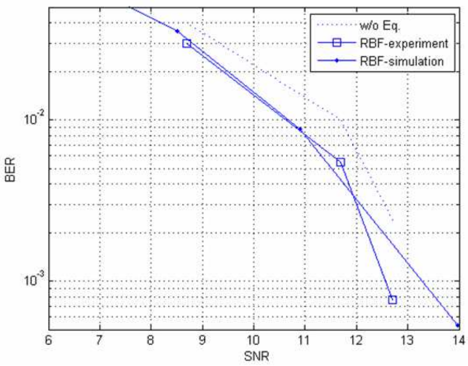

Fig.5: *BER versus SNR experiment and simulation results for fiber length of 80km with 3-bit ADC for RBF equalizer using histogram estimation method.*

6. SUMMARY AND CONCLUSIONS

We introduce a nonlinear equalizer using the RBF network for electronic dispersion compensation in optical communication system. The RBF method introduces a non-linear equalization technique suitable for optical communication direct detection systems that include a non-linear transformation at the photodetector. It has been shown that the RBF equalizer can achieve BER superior to that offered by a linear FFE. The difference between the MLSE, which is known as the optimal sequence estimation equalizer and the RBF equalizer, has been shown. In addition, the performance difference between a Gaussian versus noncentral chi-square, as the nonlinear function in the RBF equalizer, was performed in optically amplified systems. Finally, using experimental results the feasibility of the RBF method is validated.

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Gilad Katz received the B.Sc. and M.Sc. in electrical and computer engineering from Ben Gurion University, Beer-Sheva, Israel in 1997 and 2000, respectively. Between 1997-98 he worked as a development engineer in Motorola semiconductors. His M.Sc. was on the subject of optical coherent multiplexing CDMA. Between 2000-2003 he worked as electrical engineer in the free space optics field, developing advanced laser transmitters and optical receivers. He has completed the PhD studies, where he investigated electrical dispersion compensation for optical communication systems. Currently he develops and researches OCDMA systems for PON. His current research interests include optical CDMA, optical free space optics and electrical compensations for optical communication systems.

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