Proceedings of the 4th WSEAS Int. Conf. on Information Security, Communications and Computers, Tenerife, Spain, December 16-18, 2005 (pp369-373)

MLP/BP-based Decision Feedback Equalizers with High Skew Tolerance in Band-Limited Channels

Terng-Ren Hsu, Jyh-Neng Yang, Terng-Yin Hsu[*], and Chen-Yi Lee
Department of Electronics Engineering, National Chiao Tung University
1001, University Road, Hsinchu 300, Taiwan
[*] Department of Computer Science and Information Engineering, National Chiao Tung University
1001, University Road, Hsinchu 300, Taiwan
Tel: +886-3-5712121 Ext. 54789; Fax: +886-3-5724176

Abstract: - A multi-layered perceptron neural network with backpropagation algorithm (MLP/BP) is realized as a waveform equalizer for distorted nonreturn-to-zero (NRZ) data recovery in band-limited channels. Moreover, the proposed approach can tolerate sampling clock skew and channel response variance. According to simulation results, the proposed design can recover severe distorted NRZ data with better performance than LMS DFEs in the band-limited channel that the data rate is ten times as much as the channel bandwidth. Under the 20% channel response variance and the 30% sampling clock skew, the proposed approach can provide an acceptable performance.

Key-Words: - Clock Skew, Decision-Feedback Equalizer (DFE), Intersymbol Interference (ISI), Multi-Layered Perceptron Neural Network with Backpropagation Algorithm (MLP/BP), Minimum Mean Square Error (MMSE), and Nonreturn-to-Zero (NRZ).

1 Introduction

In a wireline digital communication system, the source signal is transmitted over an intersymbol interference (ISI) channel, corrupted by noise, and then received as a distorted nonreturn-to-zero (NRZ) signal without zero crossing. It is the noisy signal that degrades the system performance. In most cases, the additional white Gaussian noise (AWGN) can be used to model the background noise. In this work, we consider the band-limited channels that the data rate is about ten times as much as the channel bandwidth. In such channels, the tail of each pulse in the received signal will be elongated, resulting in lack of zero crossing for the received signal. Moreover, sampling clock skew and channel response variance will lead to worse performance. Therefore, it is necessary to apply data equalizers to recover the original waveform from the distorted one in practical communication systems [1]. A good equalization design can enhance the whole system performance with an acceptable cost.

Conventionally, the NRZ signal recovery is based on either linear equalizers (LEs) [1], [2], or decision feedback equalizers (DFEs) [1], [2], [6]. The linear equalizer can restore the original transmitted signal in a band-limited wireline channel, but it also amplifies high-frequency noise and severely degrades the system performance.

The decision feedback equalizer employing previous decisions to remove the ISI on the current symbol has been extensively exploited to serve intersymbol interference rejection. The least mean squares (LMS) algorithm is used to estimate the coefficients of the equalizer [1], [2], [6] whose accuracy determines the system performance

Recently, various equalizer designs based on artificial neural networks have been applied to the severely distorting signal recoveries. Having the capability of classifying the sampling pattern and fault tolerance, artificial neural networks have more flexibility and better performance than conventional equalization techniques.

Based on the MLP/BP neural network [3-5], the feedforward equalizers [7], [8], and the decision feedback equalizers [9], [10] have been widely used to NRZ signal recovery in severe ISI channels.

For high speed wireline data communication, it is familiar to use waveform equalization technique to improve the data rate or reduce the error rate [11-13]. In practice circuits, the channel responses of different interconnect paths of parallel data I/O are different. The receiver must detect correct data under such variance. Furthermore, sampling clock skew makes the problem more severely.

This work is based on the most popular MLP/BP neural network [3-5]. By selecting suitable training patterns, the MLP/BP-based DFEs can tolerate larger sampling clock skew and more channel response variance, meaning that we can use a preset equalizer to replace an adaptive one.

This paper is organized as follows. The equivalent channel model, and the proposed approach are presented in section 2 while section 3 shows the simulation results. Finally, the conclusions are presented in section 4.

2 Proposed Architecture

In this section, an equivalent channel model is presented first followed by the proposed approach. The architecture and configuration of the proposed method are discussed in detail.

2.1 Channel Models

If the transmitted data rate is higher than the channel capacity, the received signal pulse is unable to complete its transition within a symbol interval. The equivalent model for the band-limited channels is shown in Fig. 1 where a finite impulse response (FIR) filter is used to model the ISI channel response with the AWGN as the background noise.

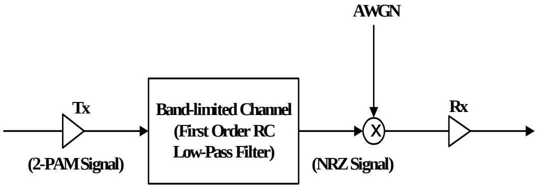

Fig. 1. Equivalent Model for the Band-Limited Channel.

The ISI channel response with AWGN can be written as follows:

$$H(z) = f_0 + f_1 \cdot z^{-1} + f_2 \cdot z^{-2} + \ldots + f_L \cdot z^{-L} \tag{1}$$

$$y_k = \sum_{i=0}^{L} f_i \cdot x_{k-i} \tag{2}$$

$$\hat{y}_k = y_k + n_k \tag{3}$$

where $H(z)$ is the transfer function of the ISI channel; L is the length of the channel response; x_k is the input sequence; y_k is the channel output which is warped by ISI only; n_k is the AWGN; $\hat{y}_k$ is the received signal which is distorted by both ISI and AWGN.

In this work, several band-limited channels, with different sampling clock skew, are used to verify the proposed approaches. These channels are practical in many wireline communication systems, whose transfer functions of several band-limited channels are shown in Table 1. These channels with different F_{3dB}/F ratio represent different but analogous channel conditions. For example, the channel responses of different interconnect paths of parallel data I/O are similar. The frequency responses of these channels are illustrated in Fig. 2. The transmitted signal is expected to be deteriorated substantially by the band-limited channel and the AWGN.

Table 1 Transfer Function of Several Band-Limited Channels

ID	F_{3dB}/F	Channel Impulse Response
1	0.08	[0.3951 0.2390 0.1446 0.0875 0.0529]
2	0.09	[0.4319 0.2454 0.1394 0.0792 0.0450]
3	0.10	[0.4665 0.2489 0.1328 0.0708 0.0378]
4	0.11	[0.4990 0.2500 0.1252 0.0627 0.0314]
5	0.12	[0.5295 0.2491 0.1172 0.0551 0.0259]

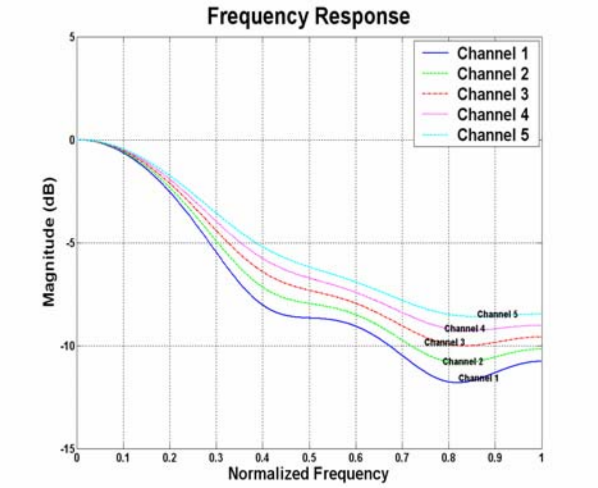

Fig. 2. Frequency Responses of Several Band-Limited Channels

Furthermore, sampling clock skew makes the problem more severely. Base on foregoing channels, clock skews between +/- 30% are considered to represent a worse situation of the practical wireline high speed communications.

2.2 The MLP/BP-based DFE

Artificial neural networks are systems that are deliberately constructed to make use of some organizational principles resembling those of the human brain. An artificial neural network consists of a set of highly interconnected neurons such that each neuron output is connected to other ones or/and to itself through weights with or without lag. Recently, there are many different artificial neural networks had been proposed, but the multi-layer perceptron neural network with backpropagation algorithm (MLP/BP) is the most important and most popular one. [3-5]

The MLP/BP neural networks are supervised learning. It means that a training set includes an input vector and a desired output vector. The training patterns must represent the system characteristic. Suitable training patterns can improve the training quality.

Using the MLP/BP neural networks to solve problems includes two phases, one is training procedure and another is test procedure. In the training phase, we use the gradient steepest descent method to minimize the error function for updating the weights. After that we apply the training results to obtain the network response in the test phase. The outcome is really a sub-optimal solution

Different network configurations, different initial condition or different learning rate, will lead to different performance. In general, we could perform quite a few independent runs and choose the most suitable outcome as the final solution. In this work, we execute fifty independent runs and select the best one as the final result.

The block diagram of the MLP/BP-based DFEs is shown in Fig. 3. This MLP/BP-based DFEs is the single hidden layer MLP architecture. The inputs of the MLP/BP-based DFE consist of feed-forward signals, which come from the input symbols by a tapped-delay-line register, and feedback signals, which come from previous decisions by another tapped-delay-line register.

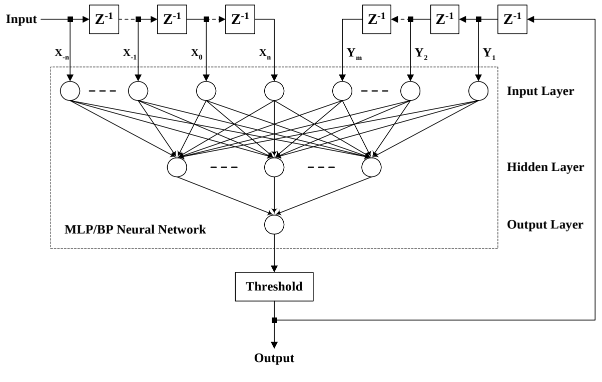

Fig. 3. MLP/BP-based DFEs

3 Simulation Results

In this work, the performance of the MLP/BP-based DFE is evaluated through the simulations for the distorted NRZ signal recovery in the band-limited channel that the data rate is ten times of the channel bandwidth.

All equalization schemes in this work have eleven symbols in the forward part and five symbols in the feedback part. The number of neurons in the input layer is equal to 16. The MLP/BP-based DFEs uses the single hidden layer MLP architecture. The number of neurons in the hidden layer is 2 times of that in the input layer. Since all the proposed equalization schemes have a single output, the number of neurons in the output layer is equal to 1.

In the training procedure, the length of the training set is equal to 10^4 symbols and the total training epochs are 10^2. The two-phase learning is used with the learning rate of 0.5 when the mean square error of the training set is larger than 10^{-3}, and the learning rate of 0.125, otherwise. When the training epochs exceed eighty percent of the total epochs, the best parameters will be recorded to achieve the lowest mean square error of the training set in the last twenty percent of the training epochs. Hence the steady-state training results can be recognized. In fact, the simulations indicate no unstable problems as all training processes are converged.

Because different initial conditions lead to different effects, the non-training evaluation set that has 10^5 symbols is used to examine the training quality of numerous independent simulation outcomes. After numerous independent training and evaluation runs, those yielding better outcomes will be chosen to perform a long trial with the test set, and then the best one will be the final test result. The length of the test set is 10^6 symbols, and the evaluation set is a subset of it.

At first, a band-limited channel (Channel 3) described by the transfer function, $H_3=0.4665 + 0.2489z^{-1} + 0.1328z^{-2} + 0.0708z^{-3} + 0.0378z^{-4}$, is used to estimate the system performance of the LMS DFE and the MLP/BP-based DFE, where the training noise and the evaluation noise are assumed to be SNR=20dB, and SNR of the test signal is between 10dB and 25dB. This channel response indicates that the data rate is ten times of the channel bandwidth.

Subsequently, several different band-limited ISI channels (Channels 1, 2, 4, and 5) are used to describe different channel bandwidth vs. data rate ratios that the data rates are eight, nine, eleven, and twelve times the channel bandwidth, respectively. The training result of Channel 3 is applied to these channels, directly. These experiments are used to evaluate the tolerance under different channel response variances. The BER performance for the LMS DFE and the MLP/BP-based DFE in different channels is shown in Fig. 4. The proposed approach can outperform the LMS DFE.

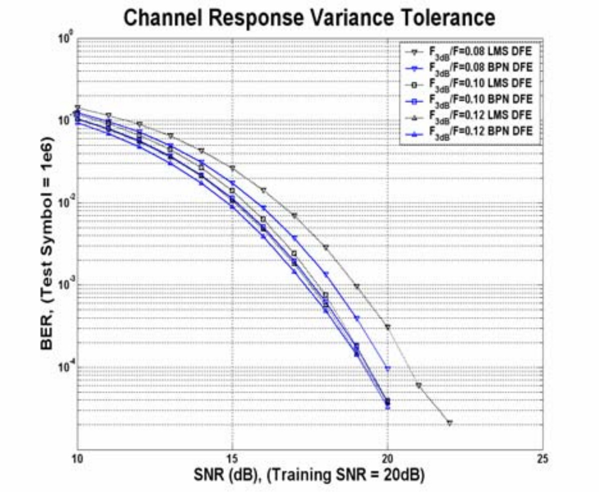

Fig. 4. BER performance for different types of equalizers in different channels

At last, -30%, -20%, -10%, +10%, +20%, and +30% sampling clock skews are considered, respectively. Similarly, the training result of Channel 3 is applied to these situations, directly. The comparisons of the BER performance for the LMS DFE and the MLP/BP-based DFE in different channels with different clock skews are shown in Fig. 5, Fig. 6 and Fig. 7, respectively.

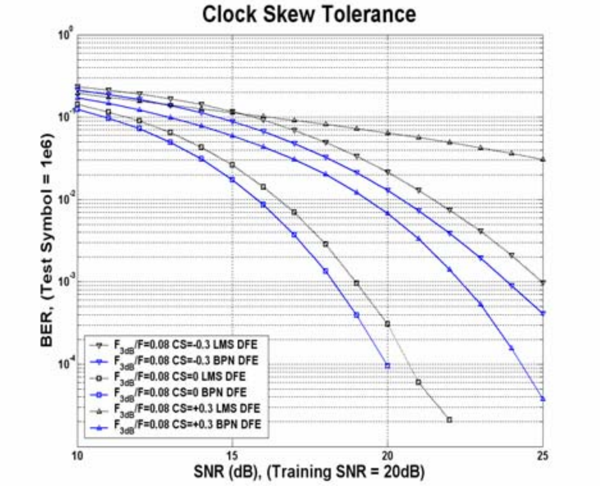

Fig. 5. BER performance for different types of equalizers with different clock skews in Channel 1

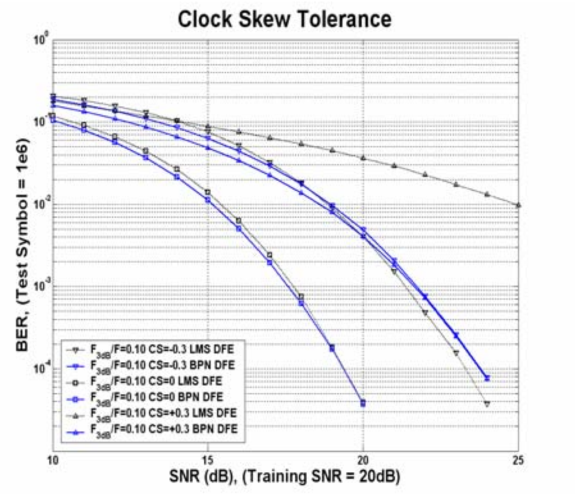

Fig. 6. BER performance for different types of equalizers with different clock skews in Channel 3

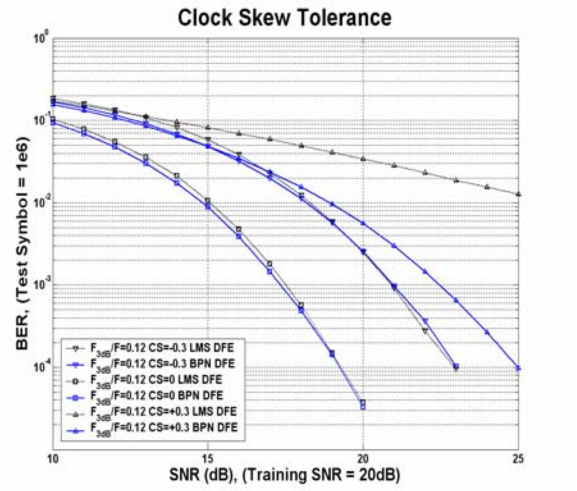

Fig. 7. BER performance for different types of equalizers with different clock skews in Channel 5

In view of different channel response variances without sampling clock skew at SNR=20dB, the BER performance of the LMS DFE and the BPN DFE is shown in Fig. 8(a). Considering different clock skews in different channels at SNR=20dB, the comparisons of the BER performance for the LMS DFE and the BPN DFE are shown in Fig. 8 (b) to Fig. 8(f).

From Fig. 5, Fig. 6 and Fig. 7, the proposed approach reports better BER performance under +/- 20% channel response variances and +/- 30% sampling clock skews. The advantage of the proposed approach can be represented in Fig.8. As the variances increase in the wireline communication environment, the proposed approach achieves more improvement over the LMS DFEs.

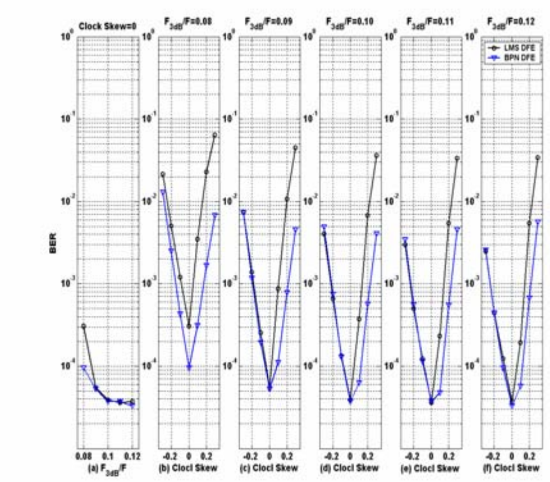

Fig. 8. BER performance for different channel conditions at SNR=20dB

4 Conclusion

The simulation results show that the proposed equalizer can provide a significant improvement over the LMS DFEs in band-limited channels that the data rate is about ten times of the channel bandwidth. Moreover, the proposed approach can tolerate clock skew and channel response variance. The clock tree design and data interconnection planning can be simplified. Because the MLP/BP-based DFEs can tolerate larger sampling clock skew and more channel response variance, we have an opportunity that uses a preset equalizer to replace an adaptive one for low cost.

References:

[1] S. Haykin, *Communication Systems 3e*, Chapter 7, Wiley, 1994.

[2] J. G. Proakis, and M. Salehi, *Contemporary Communication Systems using MATLAB*, pp. 264-282, Brooks/Cole, 2000.

[3] M. M. Nelson, and W. T. Illingworth, *A Practical Guide to Neural Nets*, pp. 43-52, pp. 121-123, and pp. 138-139, Addison Wesley, 1991.

[4] R. L. Kennedy, Y. Lee, B. V. Roy, C. D. Reed, and R. P. Lippmann, *Solving Data Mining Problems Through Pattern Recognition*, pp. 10.23-10.32, Prentice Hall, 1998.

[5] C. T. Lin, and C. S. G. Lee, *Neural Fuzzy Systems*, pp. 205-217, pp. 235-250, pp253, Prentice Hall, 1999.

[6] B. S. Song, and D. C. Soo, "NRZ Timing Recovery Technique for Band-Limited Channels", *IEEE J. Solid-State Circuits*, vol. 32, no. 4, pp. 514-520, 1997.

[7] G. J. Gibson, S. S., and C. F. N. Cowan, "Multilayer Perceptron Structures Applied to Adaptive Equalisers for Data Communications", *Proc. IEEE Int. Conf. on Acoustics, Speech and Signal*, vol. 2, 1989, pp. 1183-1186.

[8] T. R. Hsu, T. Y. Hsu, H. Y. Liu, S. D. Tzeng, J. N. Yang and C. Y. Lee, "A MLP/BP-based Equalizer for NRZ Signal Recovery in Band-Limited Channels", *Proc. the 43rd IEEE Midwest Symp. Circuits and Systems*, vol. 3, 2000, pp. 1340-1342.

[9] S. Siu, G. J. Gibson, and C. F. N. Cowan, "Decision Feedback Equalisation Using Neural Network Structures and Performance Comparison with Standard Architecture", *IEE Proc. Communications, Speech and Vision*, vol. 137, pt. I, no. 4, Aug. 1990, pp. 221-225.

[10] K. A. Al-Mashouq, and I. S. Reed, "The Use of Neural Nets to Combine Equalization with Decoding for Severe Intersymbol Interference Channels", *IEEE Trans. Neural Networks*, vol. 5, no. 6, Nov. 1994, pp. 982-988.

[11] Y. S. Sohn, S. J. Bae, H. J. Park, C. H. Kim, and S. I. Cho, "A 2.2Gbps CMOS Look-Ahead DFE Receiver for Multidrop Channel with Pin-to-Pin Time Skew Compensation", *Proc. IEEE Custom Integrated Circuits Conference (CICC)*, 2003, pp. 473-476.

[12] J. E. Jaussi, G. Balamurugan, D. R. Johnson, B. Casper, A. Martin, J. Kennedy, N. Shanbhag and R. Mooney, "8-Gb/s Source-Synchronous I/O Link with Adaptive Receiver Equalization, Offset Cancellation, and Clock De-Skew", *IEEE J. Solid-State Circuits*, vol. 40, no. 1, Jan. 2005, pp. 80-88.

[13] S. J. Bae, H. J. Chi, H. R. Kim, and H. J. Park, "A 3Gb/s 8b Single-Ended Transceiver for 4-Drop DRAM Interface with Digital Calibration of Equalization Skew and Offset Coefficients", *Proc. IEEE Int. Solid-State Circuits Conference (ISSCC)*, 2005, pp. 520-521.