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Multi-Input Multi-Output MLP/BP-based Decision Feedback Equalizers for Overcoming Intersymbol Interference and Co-Channel Interference in Band-Limited Channels

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Abstract: - This paper presents a multi-input multi-output (MIMO) multi-layered perceptron neural network with backpropagation algorithm (MLP/BP). The proposal is a waveform equalizer for distorted nonreturn-to-zero (NRZ) data recovery in band-limited channels with co-channel interference (CCI). From the simulation results, we note that the proposed design can recover severe distorted NRZ data as well as suppress intersymbol interference (ISI) and co-channel interference. As a result, the better performance as compared to LMS DFEs is achieved in the band-limited channels where the data rate is ten times as much as the channel bandwidth.

Key-Words: - Co-Channel Interference (CCI), Decision-Feedback Equalizer (DFE), Intersymbol Interference (ISI), Minimum Mean Square Error (MMSE), Multi-Layered Perceptron Neural Network with Backpropagation Algorithm (MLP/BP), 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. Moreover, co-channel interference (CCI) will lead to more distortions and worse performance. In most cases, the additive white Gaussian noise (AWGN) can be used to model the background noise.

In this work, we consider the band-limited channels with co-channel interference where the data rate is 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. Besides, adjacent signals result in color noises; the received signal will be tainted by such color noises. Intersymbol interference and co-channel interference make the received signal with large distortion. 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 originally transmitted signal in a band-limited wireline channel, but also amplifies high-frequency noise that severely degrades the system performance. The DFE 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

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feedback equalizers [9], [10] have been widely used to NRZ signal recovery in severe ISI channels. Moreover, Perceptron neural networks have been used as data equalizers in ISI and CCI channels [11], [12].

For high speed wireline data communication, it is common to use waveform equalization technique to improve the data rate or reduce the error rate [13-15]. In practice circuits, interconnect paths of parallel data I/O would cause the co-channel interference. The receiver must detect correct data under ISI, CCI, and AWGN condition.

This work is based on the most popular MLP neural network with backpropagation algorithm [3-5] and our previous study [16]. We use a multi-input multi-output (MIMO) MLP/BP-based DFE to recover the distorted NRZ data in the band-limited channels with co-channel interference.

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 with co-channel interference is shown in Fig. 1 where finite impulse response (FIR) filters are used to model the ISI channel responses and CCI responses with the AWGN as the background noise.

The ISI channel responses and CCI responses with AWGN can be written as follows:

$$H_0(z) = f_0 + f_1 \cdot z^{-1} + f_2 \cdot z^{-2} + ... + f_L \cdot z^{-L} \quad (1)$$

$$C_r(z) = g_{r0} + g_{r1} \cdot z^{-1} + g_{r2} \cdot z^{-2} + ... + g_{rM} \cdot z^{-M} \quad (2)$$

$$y_k = \sum_{i=0}^{L} f_i \cdot x_{k-i}^0 \quad (3)$$

$$c_k = \sum^{r} \sum_{j=0}^{M} g_j \cdot x_{k-j}^r \quad (4)$$

$$\hat{y}_k = y_k + c_k + n_k \quad (5)$$

where $H_0(z)$ is the transfer function of the ISI channel responses; L is the length of the ISI channel response; $C_r(z)$ is the transfer function of the CCI responses; M is the length of the CCI response; x_k^o is the input sequence of ISI response; x_k^r is the input sequence of CCI response; y_k is the channel output which is warped by ISI only; c_k is the sum of co-channel interference; n_k is the AWGN; $\hat{y}_k$ is the received signal which is distorted by ISI, CCI and AWGN.

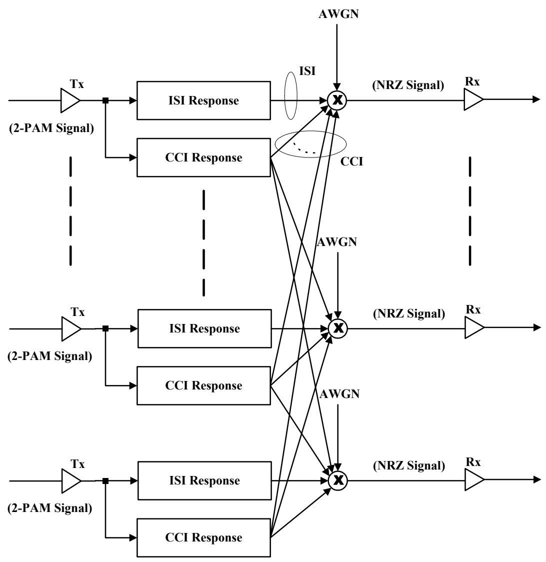

Fig. 1. Equivalent model for the band-limited channels with co-channel interference.

In this work, the band-limited channels with co-channel interference are used to verify the proposed approaches. Such channel condition is practical in many wireline communication systems, whose the transfer function of the band-limited channels is $H_0(z) = 0.4665 + 0.2489z^{-1} + 0.1328z^{-2} + 0.0708z^{-3} + 0.0378z^{-4}$ and the transfer function of the co-channel interference is $C_r(z) = 0.408 + 0.816z^{-1} + 0.408z^{-2}$. The frequency responses of the ISI and CCI are illustrated in Fig. 2. The weighting of co-channel interference between different channels is shown in Table 1.

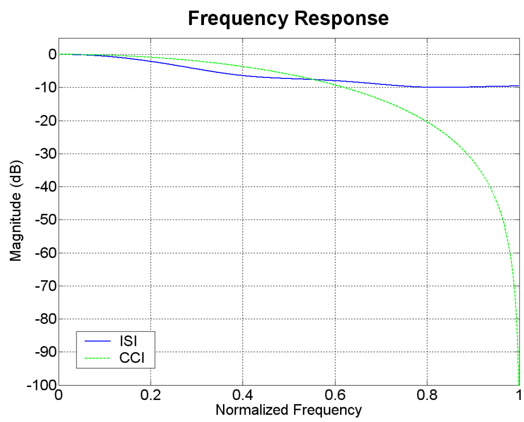

Fig. 2. Frequency responses of the band-limited channel and the co-channel interference.

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Table 1. Weighting of co-channel interference between different channels.

	1	2	3	4	5	6	7	8
1	0.2253	0.5402	0.3404	0.3298	0.4465	0.2831	0.4023	0.3974
2	0.5402	0.0944	0.4480	0.2017	0.4642	0.5114	0.3507	0.4017
3	0.3404	0.4480	0.0822	0.4380	0.4010	0.2750	0.3313	0.3290
4	0.3298	0.2017	0.4380	0.1737	0.2754	0.1670	0.2886	0.4169
5	0.4465	0.4642	0.4010	0.2754	0.1135	0.2877	0.3738	0.4772
6	0.2831	0.5114	0.2750	0.1670	0.2877	0.1451	0.0898	0.1779
7	0.4023	0.3507	0.3313	0.2886	0.3738	0.0898	0.3009	0.5230
8	0.3974	0.4017	0.3290	0.4169	0.4772	0.1779	0.5230	0.0227

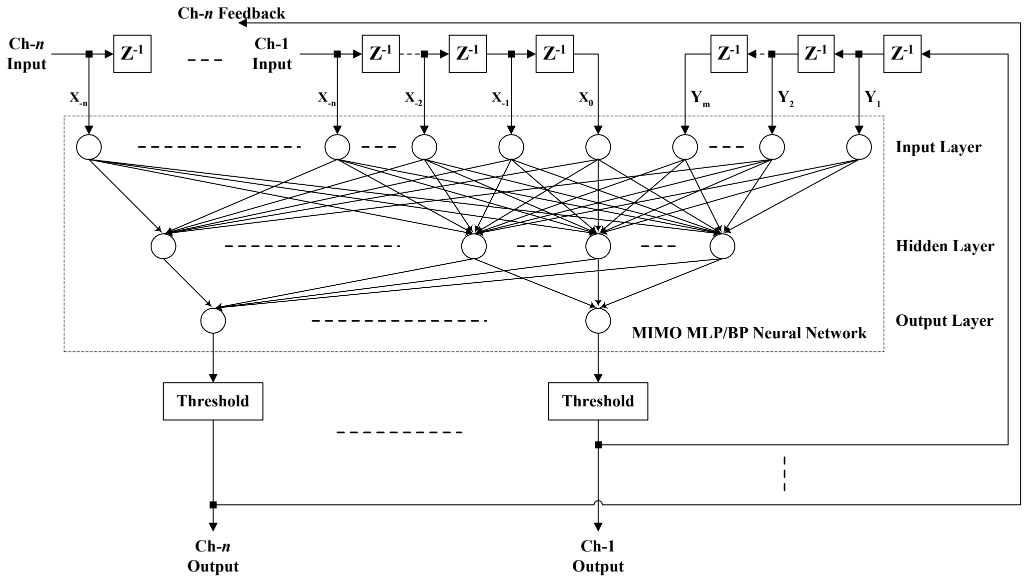

Fig. 3. The MIMO MLP/BP-based DFE.

The received signals include the intersymbol interference that caused by the band-limited channel and the co-channel interference that caused by crosstalk between different channels. The transmitted signal is expected to be deteriorated substantially by ISI, CCI and AWGN.

2.2 The MIMO MLP/BP-based DFE

Artificial neural networks are systems that are deliberately constructed to utilize some organizational principles resembling from 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 popular one. [3-5]

The MLP/BP neural networks are supervised learning, meaning 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 ten independent runs and select the best one as the final result.

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

3 Simulation Results

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

All equalization schemes in this work have eleven symbols per channel in the forward part and five symbols per channel in the feedback part. We assume there are 8 parallel channels in this system. The number of neurons in the input layer is equal to 128 (16 by 8). The MLP/BP-based DFEs uses the single hidden layer MLP architecture. The number of neurons in the hidden layer is 16. Since all the proposed equalization schemes have a single output per channel, the number of neurons in the output layer is equal to 8 (1 by 8).

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 (2^{-1}) when the mean square error of the training set is larger than 10^{-3}, and the learning rate of 0.125 (2^{-3}), 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 10^7 symbols, and the evaluation set is its subset.

The band-limited channel described by the transfer function, $H_0(z) = 0.4665 + 0.2489z^{-1} + 0.1328z^{-2} + 0.0708z^{-3} + 0.0378z^{-4}$, with the co-channel interference described by the transfer function, $C_r(z) = 0.408 + 0.816z^{-1} + 0.408z^{-2}$, is used to estimate the system performance of the LMS DFE and the MLP/BP-based DFE. This ISI channel response indicates that the data rate is ten times of the channel bandwidth. The training noise and the evaluation noise are assumed to be SNR=20dB, and SNR of the test signal is between 10dB and 25dB. The signal to co-channel interference ratio (SIR) is equal to 10, 12.5, 15, 17.5, and 20, respectively.

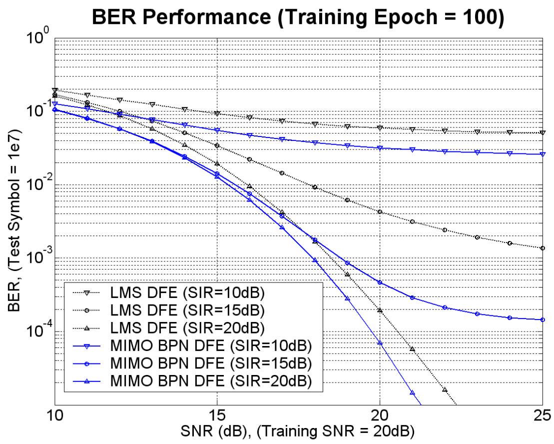

Fig. 4. BER vs. SNR for different types of equalizers in the band-limited channels with co-channel interference at SIR=10, 15, and 20dB.

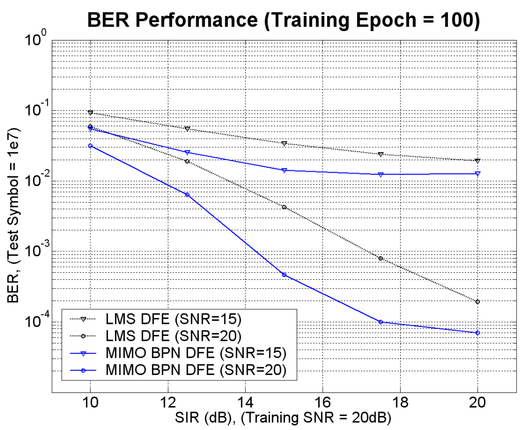

Fig. 5. BER vs. SIR for different types of equalizers in the band-limited channels with co-channel interference at SNR= 15 and 20dB.

Fig. 4 shows the comparisons of the BER performance vs. SNR for the LMS DFE and the MIMO MLP/BP-based DFE in the band-limited channels with different SIR. Considering different SIR in the band-limited channels at SNR= 15dB and 20dB, Fig. 5 also shows the comparisons of the BER performance vs. SIR for the LMS DFE and the MIMO BPN DFE. From Fig. 4 and Fig. 5, the proposed approach reports better performance under larger intersymbol interference and larger co-channel interference.

4 Conclusion

The present scheme can overcome ISI while suppress CCI. According to the simulation results, the proposed MIMO MLP/BP-based DFE can recover severe distorted NRZ signals and suppress CCI to achieve better BER performance than LMS DFEs in the band-limited channels in which the data rate is ten times as much as the channel bandwidth. Because the proposed equalizer is a multi-input multi-output architecture, we can extend the input and output number for more complex system.

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] Z. Xiang, G. Bi, and T. Le-Ngoc, "Polynomial Perceptrons and Their Applications to Fading Channel Equalization and Co-Channel Interference Suppression", *IEEE Trans. Signal Processing*, vol. 42, no. 9, Sep. 1994, pp. 2470-2480.

[12] D. P. Bouras, P. T. Mathiopoulos, and D. Makrakis, "Neural-Net-Based Receiver Structures for Single- and Multiamplitude Bandlimited Signals in CCI and ACI Channels", *IEEE Trans. Vehicular Technology*, vol. 46, no. 3, Aug. 1997, pp. 791-798.

[13] 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.

[14] 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.

[15] 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.

[16] T. R. Hsu, J. N. Yang, T. Y. Hsu, and C. Y. Lee, "MLP/BP-based Decision Feedback Equalizers with High Skew Tolerance in Wireline Band-Limited Channels", *WSEAS Trans. Communications*, vol. 5, no. 2, Feb. 2006, pp. 239-245.