USING BIT-EDGE EQUALIZATION IN HIGH-SPEED BACKPLANE DATA TRANSMISSION

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Abstract—This paper presents an improved bit-edge equalization (BEE) method for mitigating intersymbol interference (ISI) in high-speed backplane applications. Using a least-mean-square (LMS) adaptive algorithm as a receiver (RX) error convergence engine, the proposed BEE method is based on equalizing only the edges of data bits with an adjustment of LMS error derivation points, which in turn changes the error information and affects filter coefficients for pulse amplitude modulation. As a result, the received channel far-end 3-level bit-edge eye diagrams can be optimized. This proposed BEE method employs a conventional symbol-spaced FIR (SSF) filter as transmitter (TX) pre-emphasis for bit-edge equalization. With TX data pre-coding, the received channel far-end 3-level signal to 2-level binary decoding only depends on the current received bit. No error propagation occurs. In this work, the proposed BEE method is compared with the conventional bit-center equalization (BCE) method and the duobinary signaling method. A typical Tyco 34-inch FR4 backplane channel is used as the comparison benchmark. A Matlab script based link simulation tool is used to evaluate the link performance. The simulation results demonstrate that the proposed BEE method is the most effective method for mitigation ISI in relatively high-loss channels.

Keywords—bandlimited communication; discrete time filters; intersymbol interference (ISI); jitter; least mean square methods (LMS), pulse amplitude modulation (PAM)

I. INTRODUCTION

In multi-gigabit chip-to-chip and backplane serial data transmission systems, data rates are limited not by the operating speeds of the circuits in the transceivers but by the bandwidth of the transmission media. Channel impairments such as amplitude attenuation and group-delay distortion cause intersymbol interference (ISI), which is a major factor limiting the maximum transmission length and data rate. Therefore, high-speed data transmission over a band-limited channel needs channel equalization to compensate for the channel frequency-dependent loss, and/or advanced signal processing techniques to compress data spectrum. Recently, 4-level pulse amplitude modulation (PAM-4) and duobinary signal processing techniques have been reported [1]-[4]. PAM-4 reduces the effective symbol rate by a factor of 2 and, thus, lowers the bandwidth requirements of the channel. However, with PAM-4, the signal-to-noise ratio (SNR) is sacrificed in exchange for a narrower bandwidth. In addition, all level transitions in PAM-4 result in large jitter, which is a limiting factor for its application. Duobinary signal processing is another alternative approach to compress the data spectrum by changing the uncorrelated 2-level signal into a correlated 3-level signal. Currently, the duobinary signal processing technique has gained more interest from researchers [3]-[4].

In parallel with the use of advanced signal processing techniques to compress data spectrum, the use of a discrete-time symbol-spaced FIR (SSF) filter for pre-emphasis at the transmit side and/or decision feedback equalization (DFE) at the receive side have been widely used to compensate for the channel frequency-dependent loss [5], [6]. However, conventional SSF and DFE only look at bit centers as the optimal sampling points to generate error correction matrices. Such sampling approach is based on the assumption that the received data eyes are symmetric and peaked at bit centers. But at a high data rate, severe channel group delay distortion is a major factor of jitter, which is another ISI contributor in addition to amplitude attenuation. As a result, the received data eyes are no longer peaked at bit centers, and the eye diagrams are no longer symmetric, as illustrated in Figs. 1 and 2. On the other hand, an FIR filter based on amplitude modulation not only changes pulse amplitudes, but also changes the slopes of the pulse rising and falling edges. Therefore, even though zero forcing received data bit centers is effective in correcting ISI at the sampling points, more jitter could be injected on the transition edges if the data eyes are not symmetric, which results in a reduction in the timing margin.

Recent I/O standards such as IEEE 802.3ap have suggested the possibility of equalizing the data transition edges [7]. Previous publications [8]-[11] have shown that edge equalization reduces ISI at bit edges. However, in those previous publications, researchers again took the centers of the bit time periods as the optimal bit center sampling points. This sampling approach is not true at a high data rate when the received data eyes are no longer peaked at bit centers, and the eye diagrams are no longer symmetric. Thus, neither the bit center equalization nor the bit edge equalization is optimal.

The bit-edge equalization (BEE) method proposed in [12] is based on equalizing only the edges of data bits by adjusting the least-mean-square (LMS) error derivation points. In [12], the basic equalization concept of the proposed BEE was presented, and the link performance by using the proposed BEE was...
demonstrated. This paper expands upon the previous work in [12] by providing a detailed analytical comparisons of the proposed BEE transceiver architecture with the conventional bit-center equalization (BCE) and duobinary transceiver architectures.

II. BACKPLANE CHANNEL CHARACTERISTICS

In this research, a typical Tyco 34'' (30'' trace and 2x2'' connector) FR4 backplane channel is used as the working subject, and a Matlab script based on [13] is used as the link simulation tool. Fig. 1 shows the channel amplitude attenuation and group delay distortion characteristics at high frequencies. The group delay distortion reflects the phase dispersion, which is also a major ISI contributor to zero [4], [8]-[9]. Phase-optimized edge equalization is a different way of thinking channel equalization by compensating for phase delay instead of amplitude attenuation. The difficulty in phase-optimized edge equalization is that the reference zero crossing points will shift in time with different data patterns and transmission rates. Therefore, complicated algorithms are required to achieve phase equalization [10], [11].

Using a least-mean-square (LMS) adaptive algorithm as an error convergence engine, the proposed bit-edge equalization (BEE) method aims to optimize the bit-edge amplitudes by equalizing only the edges of data bits with an adjustment of the LMS error derivation points. This proposed BEE is applied to transmitter (TX) side, and consists of four basic processes: TX pre-coding, defining the desired bit-edge data from the pre-coded data, decoding the received 3-level signal to 2-level binary signal, and optimizing equalization with adjustment of the LMS error derivation points.

A. A Comparison of the Proposed BEE with Conventional Duobinary Signaling

Fig. 3 shows a conceptual illustration of the proposed BEE transceiver with comparisons to the conventional BCE and duobinary transceivers. Unlike the conventional BCE and duobinary signaling methods where the equalizations are done for bit-centers, the proposed BEE method is based on equalizing only the edges of data bits by adjusting LMS error derivation points. This proposed BEE method utilizes a TX pre-coding and decoding scheme that is similar to the differential encoder/decoder for a duobinary partial response channel. However, in the conventional duobinary signaling method, the differential sequence \( \{a_k\} \) is first converted into a duobinary sequence \( \{b_k\} \) before being transmitted, where \( c_k = \left( a_k + a_{k-1}\right) / 2 \). On the other hand, the proposed BEE method transmits \( \{b_k\} \) through the FIR filter and channel directly, and seeks to drive the received bit-edge data at the channel’s far-end to equal to the desired bit-edge data sequence \( \{s_k\} \). \( \{s_k\} \) is defined by

\[
x_k = \begin{cases} 
\pm 1 & \text{if } a_k = a_{k-1} \\
0 & \text{if } a_k \neq a_{k-1} 
\end{cases}
\]

With TX pre-coding, the received 3-level BEE signal to 2-level binary decoding depends only on the current received bit. No error propagation occurs. The BEE signal decoding is defined by

\[
h_k = \begin{cases} 
1 & \text{if } x_k = 0 \\
0 & \text{if } x_k = \pm 1
\end{cases}
\]

The proposed BEE eliminates the need for a “delay and add” duobinary filter that has a Z-transform of \( 1+z^{-1} \) as in the conventional duobinary transceiver [3], and is more compatible with the conventional BCE transceiver.

III. THE PROPOSED BIT-EDGE EQUALIZATION METHOD

Edge equalization can be used to minimize ISI at zero crossing transition edges. Based on different error derivation approaches, edge equalization falls into two categories: amplitude-optimized and phase-optimized. The amplitude-optimized edge equalization performs equalization by looking at the amplitudes of data that occur at the bit edges of a data signal and seeks to drive those associated error terms to zero [4], [8]-[9]. Phase-optimized edge equalization is a different way of thinking channel equalization by compensating for phase delay instead of amplitude attenuation. The difficulty in phase-optimized edge equalization is that the reference zero crossing points will shift in time with different data patterns and transmission rates. Therefore, complicated algorithms are required to achieve phase equalization [10], [11].

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B. Optimizing the Bit-Edge Equalizer

There are two basic processes involved in the receiver (RX) decision feedback adaptive filtering method: a filtering process and an adaptive process. The filtering process consists of computations of the output of a transversal filter produced by a set of tap inputs, and generates an estimation error by comparing this output to a desired response. The adaptive process performs automatic adjustments of the tap coefficients in accordance with the estimation error. Fig. 4 illustrates the adaptive filtering process used in the Matlab simulation.

In Fig. 4, \( u[k] \) is the distorted data at the channel’s far-end. \( n_d \) is a data delay relative to the bit center (BC) as shown in Fig. 2. \( u_d[k] \) is the delayed version of \( u[k] \). \( \tau \) is the delay operator, where \( \tau \) is equal to one symbol period for an SSF filter. The output of the SSF filter is given by:

\[
y[k] = \sum_{n=0}^{N-1} c_n[k] u[n - k],
\]

(3)

where \( k \) is the \( k \)th bit of the data sequence, \( N \) is the number of taps, and \( c_n \) are the tap coefficients. \( c_n \) are updated using an error convergence algorithm. For LMS criterion:

\[
c_n[k+1] = c_n[k] + \mu e[k] u[k],
\]

(4)

where \( \mu \) is the step size, \( u_d[k] = u[k - n_d] \), and \( e[k] \) is the error between the desired data \( x[k] \) and the actual filter output \( y[k] \), \( e[k] = x[k] - y[k] \). As the error is minimized, the tap coefficients are driven to their optimal values.

Using the proposed BEE method, \( n_d \) is adjusted around \( \pm0.5UI \) away from the bit center where \( n_d = 0 \). Therefore, when comparing the received sampling data to the desired bit-edge data \( \{x_n\} \), the error information is modified. This modified error information in turn updates the tap coefficients and optimizes the filter output.

In determining the optimal sampling phase for BEE, \( n_d \) is iteratively adjusted based on the peak of the iteratively computed equalized pulse response. Theoretically, when the equalized pulse response is symmetric, \( n_d \) is optimized. However, such an optimization criteria of \( n_d \) needs intolerably large iteration times. Moreover, in real implementation, the resolution of phase interpolation is constrained by the hardware. Therefore, in this work, the iteration points are limited to 16 per symbol period. Once the optimal BEE coefficients are obtained, a conventional SSF filter can be used as TX pre-emphasis for bit-edge equalization.

IV. SIMULATION RESULTS AND DISCUSSIONS

For the purpose of demonstration, the Tyco 34-inch FR4 backplane [13] was used as the transmission channel. A normalized 1Vpp PRBS 2\(^{11} - 1 \) data sequence was transmitted at 10Gbps through the backplane channel. A conventional 5-post-tap SSF filter was applied as transmitter pre-emphasis. Simulations have been performed using the proposed BEE method, the symbol-spaced BCE method, and the conventional duobinary signaling method [3], respectively. A Matlab script based on [13] has been generated and used to obtain the optimal filter tap coefficients. These equalization methods being compared are all based on pulse amplitude modulation.

A. The Effect of Sampling Points on Optimal Eye Opening

Fig. 5 shows the eye diagrams of the received data at the channel’s far-end using the proposed BEE method with adjustments of \( n_d \). In Fig. 5(a), \( n_d = 0.5UI \). The SSF filter samples at ideal bit edges. In Fig. 5(b)-(d), the data sequence is evenly left shifted by \( \frac{1}{16} \) unit interval (UI) for each step, and in Fig. 5(e)-(g), the data sequence is evenly right shifted by \( \frac{1}{16} \) unit interval (UI) for each step. Fig. 6 shows the convergence of the error square accordingly. It is interesting to note that when time shifting a data sequence out of the bit-edge time margin, the bit-edge eyes are closed while the bit-center eyes are opened as shown in Fig. 5(c) and (d), which results in big convergence errors as shown in Fig. 6(c) and (d).

Fig. 5 illustrates that when \( n_d = \frac{7}{16}UI \), the channel far-end bit-edge eye opening is optimized. Further increasing \( n_d \) could enlarge the bit-edge eye width with a significant reduction in percentage of the bit-edge eye height. This shifting of \( n_d \) verifies that at a high data rate, the optimal bit-center sampling points are shifted from the centers of bit time periods.

Figure 4. LMS adaptive filtering with modified SSF

Figure 5. Channel far-end eye diagrams using the proposed bit-edge equalization with \( n_d \) adjustment

(a) \( n_d = 8/16UI \) (b) \( n_d = 7/16UI \) (c) \( n_d = 6/16UI \) (d) \( n_d = 5/16UI \)

(e) \( n_d = 9/16UI \) (f) \( n_d = 10/16UI \) (g) \( n_d = 11/16UI \)
applying these different methods.

C. A Comparison of Channel Frequency Response and Filter Tap Values

Fig. 11 shows the channel frequency response with TX pre-
emphasis using the described methods. The plots in Fig. 11 demonstrate that using the proposed BEE method needs the least high-frequency boost, which can also be represented by the filter tap coefficients as shown in Fig. 12. The normalized tap values are also listed in Table I. Since the proposed bit-edge equalization needs the least high-frequency boost, it allows the use of the smallest sum of absolute tap values. Therefore, when applied to the TX pre-emphasis FIR filter, the proposed BEE is the least peak-power constrained, which is extremely important in low-voltage CMOS implementation.

V. CONCLUSIONS

An improved BEE method based on equalizing only the edges of data bits with adjustment of LMS error derivation points has been presented. In this work, a typical Tyco 34-inch FR4 backplane channel was used as the comparison benchmark. With TX pre-coding, a 5-post-tap conventional SSF filter was applied as TX pre-emphasis for bit-edge equalization. The simulation results verify that at a 10Gbps data rate, due to the sever channel group delay distortion, the received data eyes are no longer peaked at bit centers and the eye diagrams are no longer symmetric, which results in the optimal bit-center and bit-edge sampling points being shifted. With TX pre-coding and pre-emphasis, the channel near-end data spectrum using the proposed BEE has the most DC and low frequency content compared to those using either the bit-center equalization or the conventional duobinary signaling method. At the channel’s far-end, the received data spectrum using the proposed BEE is least attenuated by the channel and needs the least high-frequency boost. Therefore, the proposed BEE is expected to have the largest SNR if the peak power remains the same. In addition, since the proposed BEE needs the least high-frequency boost, which implies a minimal amplification of crosstalk, the proposed BEE method is expected to be more immune to crosstalk than the conventional BCE and duobinary methods.

The simulation results also demonstrate that using the proposed BEE method, the channel far-end bit-edge eye height is enlarged by approximately 57.1% with an 8.4% reduction in eye width compared to the bit-center eye when using the conventional BCE method. In addition, the bit-edge eye height using the proposed BEE method is enlarged by approximately 76% with an 11.2% reduction in eye width compared to the eye height and width when using the duobinary signaling method. Hence, the proposed BEE method is more suitable for relatively high-loss channels, whereas the duobinary signaling method might be a candidate when channel group delay distortion is a main concern.

REFERENCES