Adaptive Data-Transition Decision Feedback Equalizer for Serial Links

Yue Li and Fei Yuan

***Abstract*—Data-state decision feedback equalizers (DFEs) suffer from a fundamental drawback of deteriorating vertical eye-opening when consecutive 1s or 0s are present in data. To combat this, a new data-transition adaptive DFE termed data-transition DFE is proposed. We show that data-transition DFE does not reduce vertical eye-opening whereas data-state DFE shrinks vertical eye-opening when consecutive 1s or 0s are present. We further show for the high-frequency components of data, data-transition DFE is capable of increasing vertical eye-opening. Although data-state DFE is also capable of increasing vertical eye-opening for the high-frequency components of data, this is at the expense of sacrificing vertical eye-opening for the low-frequency components of data. The stronger the DFE action, the severer the reduction of the vertical eye-opening of the low-frequency components of data. The optimal tap of data-state DFE occurs when the vertical eye-opening of the low-frequency components of data is the same as that of the high-frequency components of data. Moreover, we show that data-transition DFE not only offers a unity signal transfer function at low frequencies where most of the energy of data is located but also provides first-order shaping on the difference between the desired and equalized data. Both give rise large vertical eye-opening. The theoretical findings are validated using the simulation results of two serial links, one with data-state DFE with loop-unrolling and the other with the data-transition DFE designed in TSMC 65 nm CMOS technology.**

***Index Terms*—Serial links, decision feedback equalizer (DFE), data-state DFE, data-transition DFE.**

I. Introduction

The data rate of serial links is limited by inter-symbol interference (ISI) arising from channel impairments with finite bandwidth, impedance mismatch, and crosstalk the most critical [1], [2]. Combating ISI by means of channel equalization is most effective and economical. Decision feedback equalization that eliminates post-cursor induced ISI by minimizing the power of the difference between desired and equalized data symbols is perhaps the most effective, robust, and widely used nonlinear post-equalization technique [3]. Fig.1 shows the configuration of a conventional DFE with 2PAM signaling. Minimizing the power of the difference between equalized data symbol $w(n)$ and desired data symbol $d(n)$ is used to guide the search for optimal tap coefficients $c(l)$, $l = 1, 2, ..., L$. The estimated post-cursors of past data are subtracted from current data symbol to remove the impact of the post cursors. Since the DFE use the output of the slicer, e.g. data as the steering signal of the current-steer configured DFE tap, we term it *data-state* DFE.

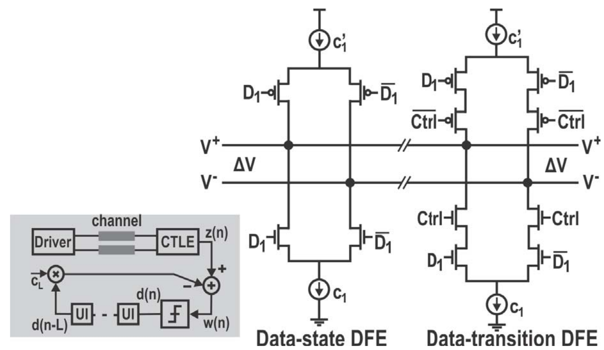

Fig. 1: Simplified schematic of data-state DFE and data-transition DFE.

Data-state DFE suffers from the following fundamental drawback : DFE taps are activated all the time by the output of the slicers regardless of incoming data. If the output of the slicer is 1, e.g., data$[n] = 1$, data-state DFE will subtract DFE taps from the current data symbol in order to remove the effect of the post-cursors of previous data symbols on the current one. This is desirable only if the next data is 0. If the next data is also 1, no reduction in data symbol should occur so as to retain a large vertical eye-opening. Data-DFE, however, will reduce vertical eye-opening by subtracting estimated post-cursors from the current data symbol, resulting in smaller eye-opening subsequently a deteriorating bit error rate (BER). It is necessary to disable DFE if consecutive 1s or 0s are encountered in data. One might argue that data conveyed to channels are typically DC-balanced via encoding. A train of 1s or 0s, however, do exist even though statistically the number of 1s and that of 0s tends to equal.

In this paper, we propose a new data-transition dependent decision feedback equalization algorithm hereafter referred to as *data-transition* DFE. The proposed data-transition DFE uses the state transition rather than state of data to determine whether a DFE operation should be launched or not . Specifically, no DFE action will be taken should a data transition is absent. DFE is initiated only when a data transition is detected. We show in both time and frequency domains that the proposed data-transition DFE indeed outperform conventional data-state DFE. We begin with the presentation of data-transition DFE.

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II. Data Transition Dependent DFE

A. Time-Domain Analysis

In this section, we use a time-domain approach to demonstrate that the proposed data-transition DFE outperforms conventional data-state DFE. Let $z(n)$ be the current data at the far end of the channel and $\Delta v = v^{+} - v^{-}$ be the output of the CTLE (continuous-time linear equalizer) preceding the DFE. The data-state DFE shown in Fig. 1) will increase Δv if a data transition occurs and reduce Δv if a data transition is absent[1] Equalized data can be written as

$$w(n) = z(n) - \sum_{l=1}^{L} c(l) \cdot d(n-l), \qquad (1)$$

where $c(l)$ is the coefficient of the lth DFE tap and $d(n-l)$ is the lth past decision of the slicer. To simplify analysis, let us consider DFE with only one tap. The DFE tap will be subtracted from the current data $z(n)$ if the previous decision of the slicer, $d(n-1)$, is 1, or added to $z(n)$ if the previous decision of the slicer is -1. If a data transition occurs at current time n, the equalized voltage Δv will be increased. However, if incoming data are a train of 1s or 0s, Δv will be reduced by data-state DFE even though no action should be taken by the DFE. To solve this problem, one can add control logic to disable DFE when no data transition is detected, as shown in Fig. 1. Defining controlling signal

$$\text{Ctrl} = \frac{1}{2} \cdot \left[\frac{d(n-l)}{d(n-l+1)} - 1 \right], \qquad (2)$$

we have

$$d(n-l+1) \cdot \text{Ctrl} = \begin{cases} +1 & 1 \to 0 \text{ transition}, \\ -1 & 0 \to 1 \text{ transition}, \\ 0 & \text{no transition}. \end{cases} \qquad (3)$$

To simplify presentation, factor $^{1}/_{2}$ in (2) is absorbed in tap coefficient $c(l)$. The equalized data with data-transition DFE can be written as

$$\begin{aligned} w(n) &= z(n) - \sum_{l=1}^{L} c(l) \cdot d(n-l+1) \cdot \text{Ctrl} \\ &= z(n) - \sum_{l=1}^{L} c(l) \cdot \left[d(n-l) - d(n-l+1) \right]. \end{aligned} \qquad (4)$$

It is seen that the proposed data-transition DFE will function the same way as data-DFE does only if a data transition exists (Ctrl = 1) and take no action if no data transition is detected (Ctrl = 0). The voltage of equalized data in this case will continue to climb thereby improving vertical eye opening.

To verify the operation of the data-transition DFE, two 5 Gbps (giga-bits-per-second) serial links, one with data-state DFE and the other with data-transition DFE, are designed in TSMC 65 nm 1.2 CMOS technology and analyzed using Spectre with BSIM4 device models. The channel consists of 3 backplane traces and 2 connection points with an overall channel length of 66 cm and a 30 dB loss at 100 Gbps [2]. Two identical channels are cascaded in order to have more channel loss so as to better test the proposed DFE. Fig.2 shows the response of the channel to a 1.2V pulse of pulse width 200 ps. At 5 GHz baud rate frequency, channel loss is approximately -25 dB.

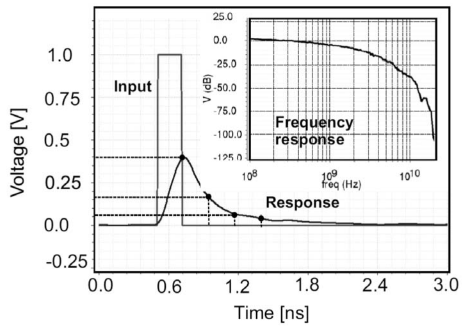

Fig. 2: Time and frequency responses of the channel.

Fig.3 compares the waveform of equalized data with data-state DFE and data-transition DFE with different DFE tap strengths. It is seen data-transition DFE tracks the output of CTLE closely when a set of consecutive 1s are encountered. For high-frequency components, data-transition DFE is capable of increasing vertical eye-opening. Although data-state DFE is also capable of increasing vertical eye-opening for high-frequency components, this is at the expense of sacrificing vertical eye-opening for low-frequency components. Also observed is that the stronger the DFE action, e.g., larger DFE taps, the severer the reduction of the vertical eye-opening of low-frequency components. The preceding observation is significant as it nullifies two common perceptions : (i) Vertical eye-opening is dominated by the high-frequency components of data, and (ii) the stronger the DFE action, the larger the vertical eye-opening. Fig.3 shows that the optimal tap of data-state DFE occurs when the vertical eye-opening of the low-frequency components of data is the same as that of high-frequency components of data.

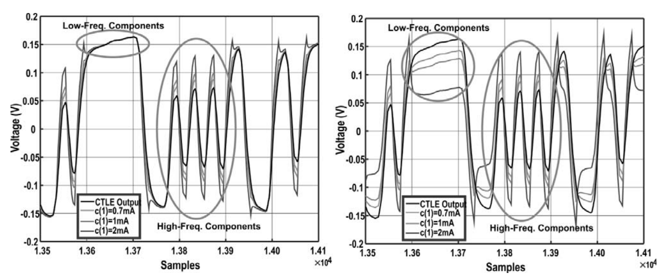

Fig. 3: Waveforms of equalized data with various DFE tap values. Left : Data-transition DFE. Right : Data-state DFE

Fig.4 compares the eye diagram of equalized data with data-state and data-transition DFE. It is seen that data-transition

[1].

[2] P. Patel and B. Barnett, "Experimental Test Fixture S-parameters 100 Gb/s Backplane Study Group," IBM Corporation. http://www.ieee802.org/3/100GCU/public/channel.html.

DFE increases vertical eye-opening while keeping signal boundaries intact. Data-state DFE also increases vertical eye-opening at the expense of reduced signal boundaries. The vertical eye-opening with data-transition DFE continues to improve with the increase in DFE strength while that with data-state DFE initially improves with stronger DFE but deteriorates when DFE is overly strong.

B. Frequency-Domain Analysis

In this section, we examine the proposed data-transition DFE in frequency domain. To assist analysis, let us define error signal $e(n)$ as the difference between the equalized and desired data, e.g., $e(n) = d(n) - z(n)$. Again only one DFE tap is considered. Write (1) and (4) with $L = 1$ in z-domain

$$W(z) = Z(z) - c(1) \cdot Z(z)z^{-1} - c(1) \cdot E(z)z^{-1}, \tag{5}$$

$$\begin{aligned} W(z) = \quad & Z(z) - c(1) \cdot Z(z)z^{-1} + c(1) \cdot Z(z) \\ & -c(1) \cdot E(z)z^{-1} + c(1) \cdot E(z). \end{aligned} \tag{6}$$

Defining signal transfer function STF $= W(s)/Z(s)$ and error transfer function ETF $= W(s)/E(s)$, we have

$$\begin{aligned} &\text{STF}_{DS} = 1 - c(1)e^{-j\omega T_s} \\ &\text{ETF}_{DS} = -c(1)e^{-j\omega T_s}, \\ &\text{STF}_{DT} = 1 + c(1) - c(1)e^{-j\omega T_s} \\ &\text{ETF}_{DT} = c(1) \cdot \left[1 - c(1)e^{-j\omega T_s}\right], \end{aligned} \tag{7}$$

where subscripts DS and DT specify data-state DFE and data-transition DFE, respectively. Since we are only interested in the behavior of data links at low frequencies where most of the energy of NRZ (non-return-to-zero) data is located, $\omega \ll 2\pi/T_s$ holds. Eqs. (7) can be simplified to

$$\begin{aligned} &\text{STF}_{DS} \approx 1 - c(1) + c(1) \cdot j\omega T_s, \\ &|\text{ETF}_{DS}| = c1, \\ &\text{STF}_{DT} \approx 1 + c(1) \cdot j\omega T_s, \\ &\text{ETF}_{DT} \approx c(1) \cdot j\omega T_s. \end{aligned} \tag{8}$$

Fig.5 compares the STF and ETF of data-state and data-transition DFE with $c(1) = 0.5$ and $c(1) = 0.7$. It is seen that data-transition DFE has a constant low-frequency gain while data-state DFE has a tap-dependent low-frequency gain. Also observed is that the low-frequency gain of data-transition DFE is 1 while that of data-state DFE is less than 1. Since most of the energy of NRZ data is concentrated at low frequencies, data-transition DFE outperforms data-state DFE by preserving more data energy subsequently a larger vertical eye opening. Also observed is the significantly lower error transfer function of data-transition DFE at low frequencies. It is interesting to note that the error transfer function of data-transition DFE exhibits first-order noise-shaping, similar to that in a first-order $\Delta\Sigma$ modulator. The reduced error transfer function of data-transition DFE at low frequencies allows equalized data to be more close to the desired thereby yielding large vertical eye-opening.

III. Loop-Unrolling for Data-Transition DFE

It was shown in (1) and (4) that data-transition DFE needs the knowledge of both the current and previous outputs of the slicer in order to determine data transition state. Since the current data state is not known at the time of executing DFE, loop-unrolling that performs data DFE by considering all possible states of current data, e.g. 0 and 1, becomes a natural choice for realizing the proposed data-transition DFE. Fig.6 shows the loop-unrolling scheme specifically tailored for data-transition DFE. In addition to data-state DFE with loop-unrolling shown in the top-left block, an additional branch for Ctrl=0 is added to provide another slicer decision when no data transition is detected. The outputs of the slicers, A and B, which are associated with Ctrl=1 and $\overline{\text{CLK}}$, are used to generate select signal Ctrl of the second 2-to-1 multiplexer, which selects the output of data-DFE with loop-rolling when a data transition exists or the output of the added branch when no data transition is detected.

Unlike DFE without loop-unrolling, equalized data are the input of the only slicer in the DFE. For DFE with loop-unrolling, regardless whether it is data-DFE or data-transition DFE, the location of equalized data changes between the input of the slicers [3]. Fig.7 shows equalized signals A, B, and C. It is seen that data-transition DFE selects from signals A, B and C whereas data-state DFE only selects from signals A and B.

Fig.8 plots the eye diagram of the serial links with data-state DFE with loop-unrolling and with data-transition DFE. Since both DFEs have loop-unrolling, the equalized data of signals A and B for data-state DFE with loop-unrolling and the equalized data of signals A, B, and C for data-transition DFE are combined in MATLAB so that complete eye diagrams can be obtained. It is seen that the vertical eye-opening of the equalized data of the link with data-transition DFE is significantly larger as compared with that with data-state DFE.

IV. Conclusions

A new data-transition DFE that overcomes the drawbacks of data-state DFE was presented. The time-domain analysis showed that data-transition DFE tracks the output of CTLE closely when a set of consecutive 1s or 0s are encountered in data. For high-frequency components of data, data-transition DFE is capable of increasing vertical eye-opening without sacrificing vertical eye-opening for the low-frequency components of data. Although data-state DFE is also capable of increasing vertical eye-opening for high-frequency components, this is at the expense of reduced vertical eye-opening for the low-frequency components of data. The stronger the DFE action, the severer the reduction of the vertical eye-opening of low-frequency components. These findings nullify two common perceptions : Vertical eye-opening is dominated by the high-frequency components of data, and the stronger the DFE action the larger the vertical eye-opening. The optimal tap of data-state DFE occurs when the vertical eye-opening of the low-frequency components of data is the same as that of high-

[3] In conventional DFE with loop-unrolling, the location of equalized data changes between slicers 1 and 2. In the proposed data-transition DFE, the location of equalized data changes among slicers 1, 2, and 3.

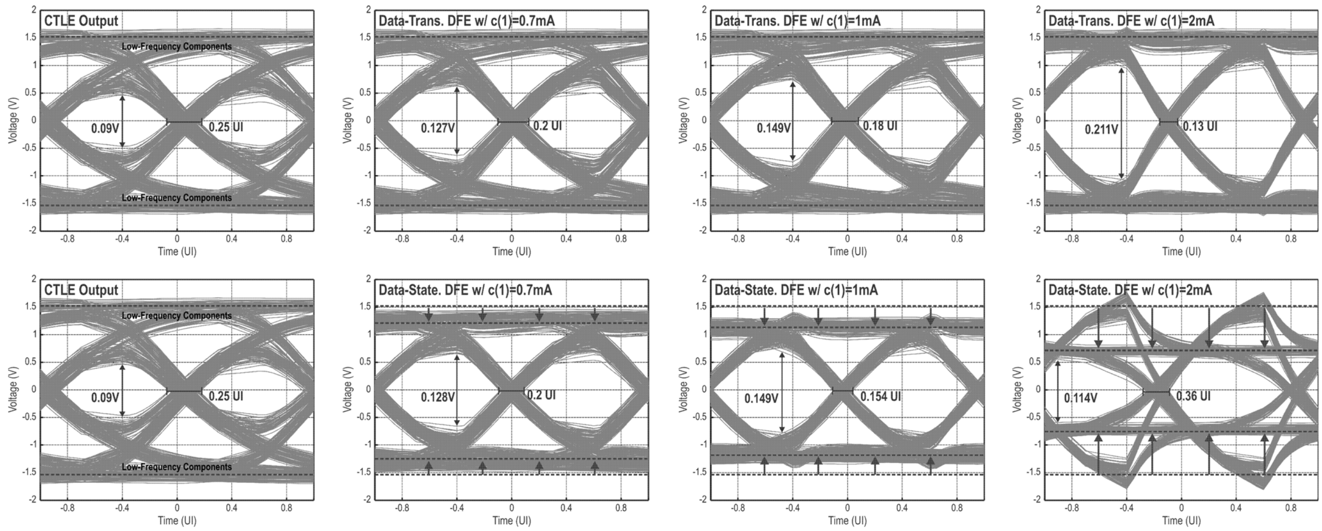

Fig. 4: Eye diagram of equalized data with 3 tap values. Top: Data-transition DFE. Bottom: Data-state DFE.

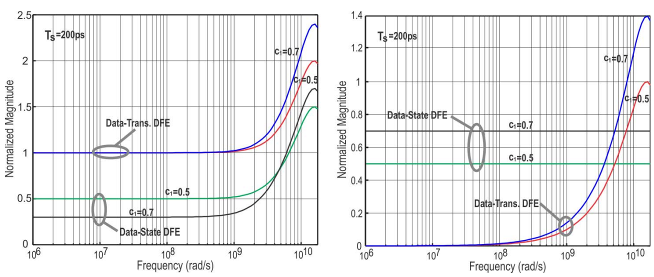

Fig. 5: STF (left) and ETF (right) magnitudes of DFE with $c(1) = 0.5$ and 0.7.

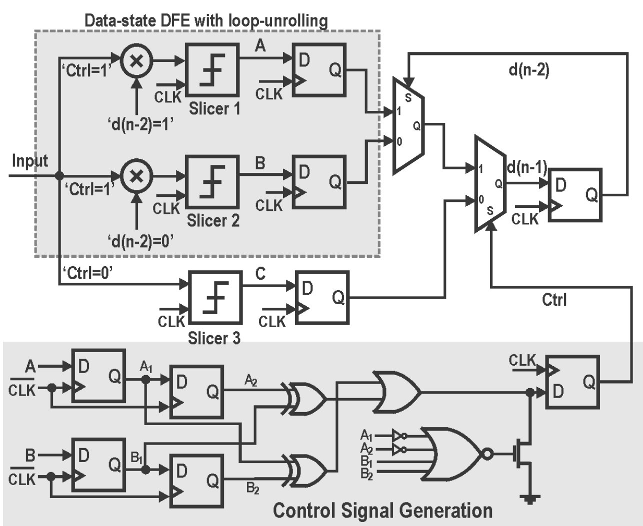

Fig. 6: Loop-unrolling for data-transition DFE.

frequency components of data. We further showed that data-transition DFE not only offers a unity signal transfer function at low frequencies where most of the energy of data is located but also provides first-order shaping on the difference between the desired and equalized data. Both result in large vertical

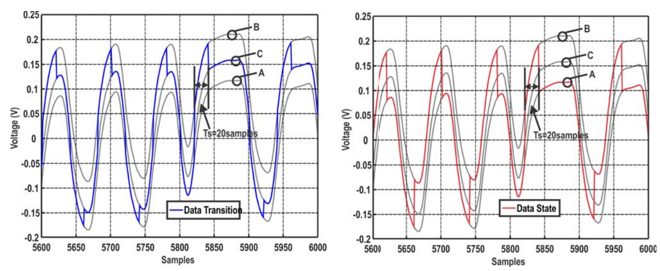

Fig. 7: Equalized signal with proposed loop-unrolling.

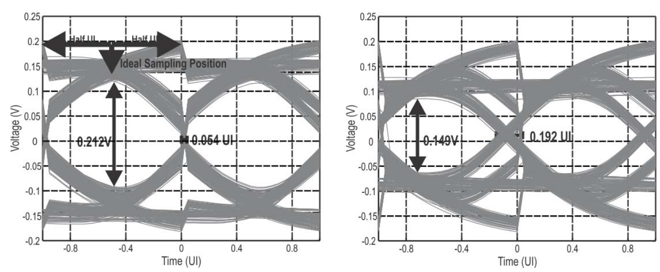

Fig. 8: Eye diagram. Left : data-transition DFE. Right : Data-state DFE.

eye-opening. The theoretical findings were validated using the simulation results of two serial links, one with data-state DFE with loop-unrolling and the other with the data-transition DFE.

References

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