An Enhanced Eye-Opening PAM-4 with Encoding for Short-Reach Wireline Communication Systems

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2024 IEEE 67th International Midwest Symposium on Circuits and Systems (MWSCAS) | 979-8-3503-8717-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/MWSCAS60917.2024.10658934

***Abstract*—This paper presents a new encoding scheme for PAM-4 signaling with the aim of reducing the inter-symbol interference (ISI) caused due to the bandwidth limited channel. The proposed encoding converts any consecutive identical symbols (CIS) in the input data to an alternative transition, which helps to mitigate inter-symbol interference and results in wider eye opening at the receiver as compared to unencoded PAM-4. Performance of the proposed encoding is validated through transistor level simulations at 56Gb/s using two different pseudo random quaternary sequence (PRQS) data patterns across two communication channels (6dB and 9dB channel loss) in 16nm FinFET technology. Simulations show more than 2× improvement in the vertical and horizontal eye opening with the proposed encoding scheme.**

***Index Terms*—PAM-4, Encoding, Eye-opening, ISI**

I. Introduction

There is a growing demand for higher data rates in high-speed chip-to-chip wireline links in various virtual Reality (VR) and Augmented Reality (AR) devices [1], [2]. However, the physical distance of the wireline communication channel is not shrinking at the same rate at which the data rate is increasing, and this is mainly due to the physical limitation of the chip packaging and the augmented reality devices. Wireline links are low-bandwidth in nature. As a result, increasing the data rates through these links results in a higher inter-symbol interference (ISI), which results in higher bit error rate (BER). Therefore, as the demand for higher data rates continues to increase, maintaining signal integrity by reducing the ISI and minimizing power and BER are critical challenges in short reach wireline links [3].

PAM-4 modulation is a popular choice to achieve data rates at 56Gb/s and beyond. However, PAM-4 modulation is more sensitive to ISI as compared to the NRZ [4]. Therefore, PAM-4 requires more equalization scheme to achieve an open eye and low bit error rate at the receiver. Techniques such as feed-forward equalization (FFE) on the transmitter help to compensate for the channel loss. However, driving multiple output driver slices to implement the FFE makes the FFE energy inefficient [5]. Researchers have introduced innovative encoding techniques such as the full-transition avoidance (FTA) encoding scheme, which aims to reduce data transitions in PAM-4 that cause significant inter-symbol interference (ISI) [6]. However, challenges such as increased coding overhead (14%), less improvement in the middle eye (full transition avoidance is more effective in top and bottom eyes only), and low energy efficiency because of the use of pre-driver + 2-tap FFE equalizer are associated with the FTA approach. Researchers have also explored an interesting approach to do spectral shaping of the transmitted data by encoding the data to overcome the channel non-ideality [7]. However, due to the absence of any simulated or measured result in [7], which can validate ISI reduction in the received data, it is difficult to gauge the effectiveness of this approach.

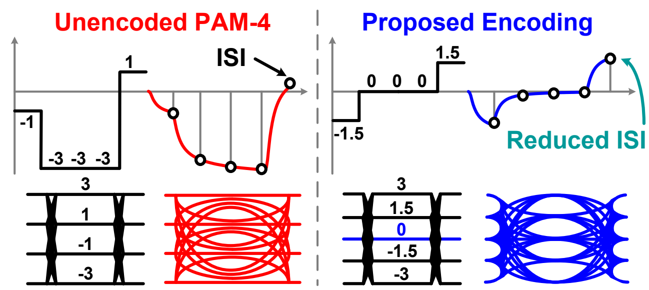

Fig. 1: Conceptual eye diagram of unencoded PAM-4 and proposed encoding when consecutive identical symbols are present in the data pattern.

In view of these limitations, this paper presents an encoding approach for PAM-4 data to compensate for the ISI and increase the eye-opening at the receiver. Fig. 1 conceptually illustrates the proposed approach. The proposed encoding scheme introduces an additional voltage in the middle of the transmitted data to avoid consecutive identical symbols (CISs), which results in more than 2× improvement in vertical and horizontal eye-opening. The following are the key contributions of this work:

- Mathematical analysis of the effect of consecutive identical symbols (CIS) on ISI.
- Introduce a new encoding scheme to reduce ISI in PAM-4 by avoiding CIS in the transmitted data.
- Validation of ISI reduction with the proposed encoding through transistor level simulation at 56Gb/s using 16nm FinFET technology node.

The rest of the paper is organized as follows. Section II analyzes the effect of consecutive identical symbols on ISI in PAM-4 modulation. Section III presents the proposed encoding approach along with its MATLAB simulation in both the time and frequency domains. Section IV presents circuit simulation results and Section V concludes this paper.

II. Inter-Symbol Interference in PAM-4 due to Consecutive Identical Symbols

The presence of consecutive identical symbols (CIS) in the unencoded PAM-4 modulation is one of the major causes of inter-symbol interference (ISI). To understand how the CIS results in ISI, let's assume for simplifying the analysis that the communication channel is a single pole dominant channel with a time constant τ. The transfer function of the communication channel in the time domain can be expressed as:

$$h(t) = \frac{1}{\tau} e^{-\frac{t}{\tau}} \tag{1}$$

The time domain response of this channel to a unit pulse with time duration of T_d $(u(t) - u(t - T_d))$ is expressed as:

$$y(t) = \left[1 - e^{-\frac{t}{\tau}}\right] u(t) - \left[1 - e^{-\frac{(t-T_d)}{\tau}}\right] u(t - T_d) \tag{2}$$

Let's consider that the PAM-4 data has 4 voltage levels {3V, 1V, -1V, -3V} corresponding to {11, 10, 01, 00} bits, respectively. Assuming PAM-4 data with no consecutive identical symbols (bits:"10,01,10,01,10,01") is transmitted through the channel (1) with the corresponding voltage levels (x_1: "1, -1, 1, -1, 1, -1"), then the voltage at the end of the data transition ($t = 6T_d$) is mathematically expressed as :

$$\begin{aligned} y_1(6T_d) = &-1 - e^{-\frac{6T_d}{\tau}} + 2e^{-\frac{5T_d}{\tau}} - 2e^{-\frac{4T_d}{\tau}} + 2e^{-\frac{3T_d}{\tau}} \\ &- 2e^{-\frac{2T_d}{\tau}} + 2e^{-\frac{T_d}{\tau}} \end{aligned} \tag{3}$$

In the next case, if the PAM-4 data with 3 consecutive symbols is transmitted (bits:"10,01,10,10,10,01") (x_2:"1, -1, 1, 1, 1, -1"), the voltage amplitude at the end of last transition $t = 6T_d$ is mathematically expressed:

$$y_2(6T_d) = -1 - e^{-\frac{6T_d}{\tau}} + 2e^{-\frac{5T_d}{\tau}} - 2e^{-\frac{4T_d}{\tau}} + 2e^{-\frac{T_d}{\tau}} \tag{4}$$

The transient response of the data at the channel output is shown in Fig. 2. Assuming the received data (y_1 and y_2) are sampled at the channel output at time $t = 6T_d$, the reduction in the vertical sampling margin for the received data at $t = 6T_d$ due to the presence of 3 CIS is mathematically expressed by subtracting (3) from (4):

$$|y_1(6T_d) - y_2(6T_d)| = 2 \times \left| e^{-\frac{3T_d}{\tau}} - e^{-\frac{2T_d}{\tau}} \right| \tag{5}$$

Furthermore, if the PAM-4 data with 5 consecutive symbols is transmitted (bits:"10,10,10,10,10,01") (x_3:"1, 1, 1, 1, 1, -1"), the voltage amplitude at the end of the last transition $t = 6T_d$ would be:

$$y_3(6T_d) = -1 - e^{-\frac{6T_d}{\tau}} + 2e^{-\frac{T_d}{\tau}} \tag{6}$$

Here, the reduction in the vertical sampling margin for the received data at $t = 6T_d$ due to the presence of 5 CIS is mathematically expressed by subtracting (3) from (6):

$$|y_1(6T_d) - y_3(6T_d)| = 2 \times \left| e^{-\frac{5T_d}{\tau}} - e^{-\frac{4T_d}{\tau}} + e^{-\frac{3T_d}{\tau}} - e^{-\frac{2T_d}{\tau}} \right| \tag{7}$$

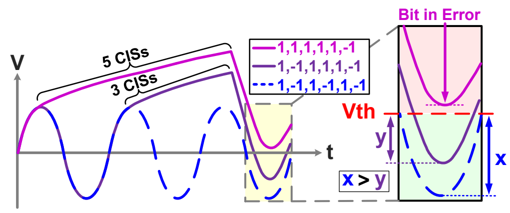

Fig. 2: Effect of CIS on ISI and reduction in the sampling margin.

Encoding Table

Case	x[n-1]	x[n]	x[n+1]	Last Transition of y	y[n]	Case	x[n-1]	x[n]	x[n+1]	Last Transition of y	y[n]
1	+3	+3	≠ +3	+1.5→0	0	**17**	-3	-3	≠ -3	-1.5→0	0
2	+3	+3	≠ +3	+3→0	+3	**18**	-3	-3	≠ -3	-3→0	-3
3	+3	+3	≠ +3	1.5↛0 & 3↛0	+1.5	**19**	-3	-3	≠ -3	-1.5↛0 & -3↛0	-1.5
4	+3	+3	+3	×	0	**20**	-3	-3	-3	×	0
5	+3	+1	×	+3→0	+1.5	**21**	-3	-1	×	-3→0	-1.5
6	+3	+1	×	+3↛0	0	**22**	-3	-1	×	-3↛0	0
7	+3	-3	×	×	-3	**23**	-3	+3	×	×	+3
8	+3	-1	×	×	-1.5	**24**	-3	+1	×	×	+1.5
9	+1	+1	≠ +1	+3→0	0	**25**	-1	-1	≠ -1	-3→0	0
10	+1	+1	≠ +1	+1.5→0	+1.5	**26**	-1	-1	≠ -1	-1.5→0	-1.5
11	+1	+1	≠ +1	1.5↛0 & 3↛0	+3	**27**	-1	-1	≠ -1	-1.5↛0 & -3↛0	-3
12	+1	+1	+1	×	0	**28**	-1	-1	-1	×	0
13	+1	+3	×	+1.5→0	+3	**29**	-1	-3	×	-1.5→0	-3
14	+1	+3	×	+1.5↛0	0	**30**	-1	-3	×	-1.5↛0	0
15	+1	-3	×	×	-3	**31**	-1	+3	×	×	+3
16	+1	-1	×	×	-1.5	**32**	-1	+1	×	×	+1.5

(a)

Decoding Table

Case	x[n]	Last Transition of x	Next Transition of x	y[n]	Case	x[n]	Last Transition of x	Next Transition of x	y[n]
1	0	+3→0	0→-3	+1	**9**	0	-3→0	0→+3	-1
2	0	+3→0	0→+1.5	+3	**10**	0	-3→0	0→-1.5	-3
3	+3	+1.5→+3	×	+1	**11**	-3	-1.5→-3	×	-1
4	+3	+1.5↛+3	×	+3	**12**	-3	-1.5↛-3	×	-3
5	0	+1.5→0	0→-1.5	+3	**13**	0	-1.5→0	0→+1.5	-3
6	0	+1.5→0	0→+3	+1	**14**	0	-1.5→0	0→-3	-1
7	+1.5	+3→+1.5	×	+3	**15**	-1.5	-3→-1.5	×	-3
8	+1.5	+3↛+1.5	×	+1	**16**	-1.5	-3↛-1.5	×	-1

(b)

Fig. 3: (a) Mapping table of the encoder, and (b) mapping table of the decoder.

It can be observed that (7) is greater than (5) :

$$|y_1(6T_d) - y_3(6T_d)| > |y_1(6T_d) - y_2(6T_d)| \tag{8}$$

The reduction in the vertical sampling margin is more when 5 CIS are present. Therefore, eliminating the CIS in the transmitted data will result in a bigger eye-opening.

III. Proposed Encoding Scheme

The proposed encoding aims to reduce ISI by eliminating the consecutive identical symbols from the PAM-4 data sequence. To achieve this objective, the proposed encoding adds an extra voltage level (0V) to create redundancy in the symbol space. It maps the PAM-4 data with 4 symbols to the new encoding with 5 symbols in such a way that consecutive identical symbols and other undesirable transitions are avoided thus reducing the ISI. Fig. 1 shows the transmitted eye diagram of the unencoded PAM-4 and the proposed encoding scheme. Assuming the PAM-4 voltage/symbol levels at the transmitter are $-3, -1, +1, +3$. These voltage levels will correspond to $-3, -1.5, +1.5, +3$, respectively in the proposed encoding (see Fig. 1). Additionally, one extra symbol at 0V is placed at the center of the proposed modulation.

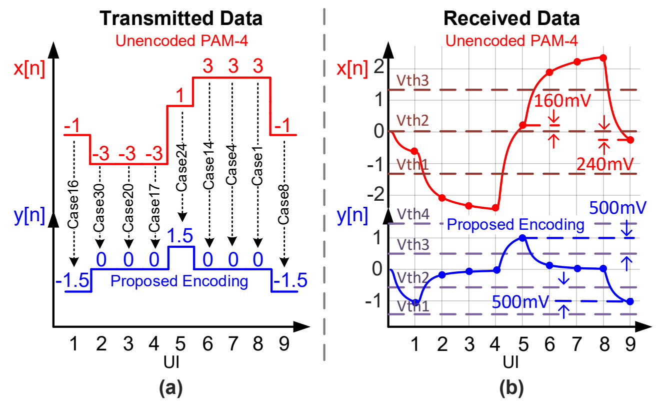

Fig. 4: (a) Encoding example, and (b) transient response at the channel output.

It is to be noted that the proposed encoding does not increase the transmitted peak-to-peak voltage. The addition of an extra voltage level at 0V reduces the SNR of the transmitted data by 2.5dB. However, based on the simulation results (Section IV) the reduction in the ISI with the proposed encoding at the far-end of the channel, outweighs the reduction of the SNR of the transmitted signal.

The proposed encoding converts any consecutive identical symbols present in the PAM-4 data to an alternative transition. Fig. 3 shows the mapping table of the proposed encoder and decoder. The y[n] is the output of the encoder and x[n-1], x[n], and x[n+1] are previous, present, and next input data, respectively. The term "Last Transition in y" refers to past transition in the output. Encoding of PAM-4 data with consecutive identical symbols is explained with the help of an example.

Example: Assuming the initial level of the PAM-4 data x[0]=1; in the first unit interval (UI), x[1]=-1 indicating a transition to a different polarity, as shown in Fig. 4(a). Based on case 16 in the encoding table (Fig. 3), the output y[1]=-1.5. In the second UI, x[1]=-1 and x[2]=-3, which indicates that the present symbol has the same polarity as the previous one. Cases 29 and 30 can be applied to this scenario. However, the last transition at the output (y) is not -1.5→0. Therefore, case 30 is used, and the output y[2]=0. In the third UI, x[2]=x[3]=x[4]=-3, based on case 30, 20 and 17, the y[2]=y[3]=y[4]=0. It can be noted that the consecutive identical symbols at the input are all encoded to 0V (common mode voltage), which does not result in ISI at the output. Based on the encoding table, the rest of the input data x[n] can be encoded to y[n].

A. *Time Domain Response of Proposed Encoding*

To visualize the ISI reduction with the proposed encoding, a time domain Matlab simulation of the previous example with unencoded PAM-4 and encoded data was performed. Data is transmitted through a communication channel with 6dB loss at the Nyquist frequency, and the results are shown in Fig. 4(b). Due to the presence of CIS in the unencoded data, the data at 5UI sufferers from severe ISI, and the vertical sampling margin for the data at 5UI is 160mV. In the case of encoded

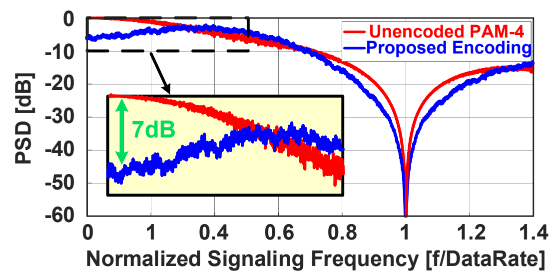

Fig. 5: Power spectrum density of unencoded PAM-4 and proposed encoding.

data output, the vertical sampling margin for the data at 5UI is 500mV (3.125× higher than the unencoded case).

Similarly, the presence of three +3 symbols in 6UI, 7UI, and 8UI results in higher ISI for the data in the 9UI in the unencoded PAM-4. The vertical sampling margin for the data at 9UI is 240mV. In the case of encoded data output, the vertical sampling margin for the data at 9UI is 500mV (2.08 times higher than unencoded case).

B. *Frequency Response of Proposed Encoding*

The equalizing characteristics of the proposed encoding method can be observed through the power spectral density (PSD) obtained from MATLAB simulations of both unencoded PAM-4 and the proposed encoding in PRQS-15 data, as shown in Fig. 5. In contrast to the unencoded PAM-4, the proposed encoding technique exhibits a 7dB lower PSD at low-frequency and a slightly higher PSD at the high-frequency. This reshaping of the PSD in the proposed encoding approach mimics the high-pass filtering characteristics of an equalizer, and it helps in mitigating the ISI.

IV. Simulation Results

To validate the effectiveness of the proposed encoding scheme and compare it with the unencoded PAM-4, two transmitters are designed and simulated in Cadence at 56Gb/s using 16nm FinFET technology. One transmitter supports unencoded PAM-4 modulation and the second transmitter supports the proposed encoding. The architecture and simulation setup of the proposed transmitter is shown in Fig. 6(a). Transient simulations are conducted using two distinct PRQS-15 patterns (PRQS-15v1 and PRQS-15v2) across two different channels with a channel loss of 6dB and 9dB, respectively, at 14GHz, as shown in Fig. 6(b). The PRQS-15v1 displays a limited number of transitions within the dataset. Consequently, the PRQS-15v1 pattern demonstrates reduced randomness. The PRQS-15v2

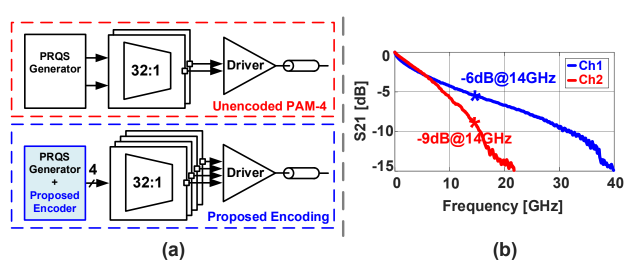

Fig. 6: (a) Transmitter architectures, and (b) measured channel response.

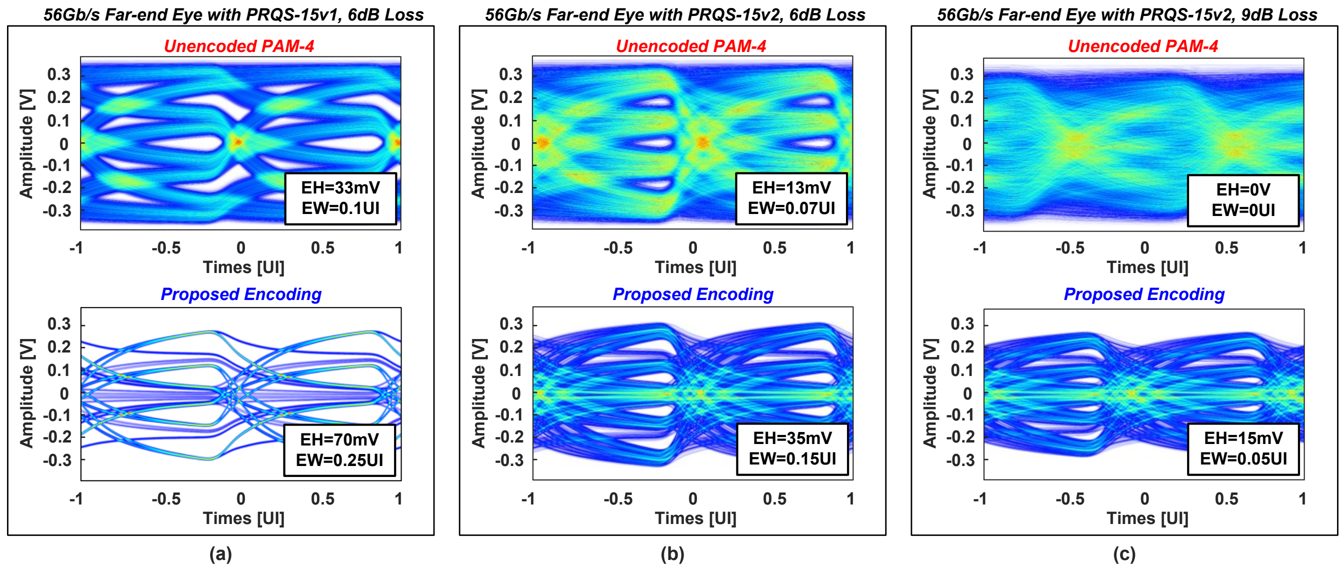

Fig. 7: Simulated far-end eye diagram at 56Gb/s of unencoded PAM-4 and proposed encoding for (a) PRQS-15v1 with 6dB loss, (b) PRQS-15v2 with 6dB loss, and (c) PRQS-15v2 with 9dB loss.

exhibits all possible data transitions, resulting in a higher level of randomness within the dataset. Fig. 7(a) shows the eye-diagrams in the receiver front-end using channel 1 with 6dB loss at 56Gb/s in PRQS-15v1. The maximum peak-to-peak swing of the transmitter output is 750mV. The minimum eye height (EH) and eye width (EW) at the receiver for unencoded PAM-4 are 33mV and 0.1UI respectively and for the proposed encoding are 70mV and 0.25UI, respectively. This shows more than 2× improvement in eye-opening in the proposed approach both vertical and horizontal dimensions.

Simulation results with the PRQS-15v2 dataset with 6dB loss in channel 1 are shown in Fig. 7(b). The minimum vertical eye and horizontal eye are 13mV and 0.07UI, respectively for the unencoded PAM-4, and 35mV and 0.15UI respectively, for the proposed encoding. The proposed encoding exhibits more than 2× eye height and width compared to unencoded PAM-4. Simulation results with channel 2 (9dB loss) in PRQS-15v2 are shown in Fig. 7(c). The unencoded PAM-4 eye is completely closed, whereas the eye is open in the proposed encoding with a minimum eye height of 15mV and an eye width of 0.05UI. Compared to PRQS-15v1 simulation results, a reduction in the eye opening with PRQS-15v2 data for both unencoded PAM-4 and the proposed encoding case is due to the higher randomness present in the PRQS-15v2 dataset. These simulation results demonstrate the equalizing ability of the proposed encoding to mitigate ISI and achieve more than 2× eye-opening as compared to the unencoded PAM-4.

V. Conclusion

A new encoding scheme for PAM-4 signaling is presented to reduce the inter-symbol interference (ISI). By introducing an additional symbol, the proposed encoder effectively reduces the impact of consecutive identical symbols (CIS) within the data stream, which results in a reduction in ISI. The power spectral density of the encoded data confirms the equalizing nature of the proposed encoding approach. The performance of the proposed encoding method is validated through transistor-level simulations at 56Gb/s in 16nm FinFET technology, demonstrating more than 2× improvement in vertical and horizontal eye openings using two different channel loss and data patterns.

Acknowledgment

This work was supported in part by the Center for Ubiquitous Connectivity (CUbiC), sponsored by the Semiconductor Research Corporation (SRC) and the Defense Advanced Research Projects Agency (DARPA) under the JUMP 2.0 program. We thank Intel for the PDK support, and Dr. Thinh Nguyen at Oregon State University for valuable discussions.

References

[1] M. Hekmat et al., "A 6Gb/s 3-tap FFE transmitter and 5-tap DFE receiver in 65nm/0.18μm CMOS for next-generation 8K displays," *2016 IEEE International Solid-State Circuits Conference (ISSCC)*, pp. 402–403, 2016.
[2] Y. Lee, Y. Choi, J. Song, S. Hwang, S.-G. Bae, J. Jun, and C. Kim, "12-Gb/s over four balanced lines utilizing NRZ braid clock signaling with no data overhead and spread transition Scheme for 8K UHD intra-panel interfaces," *IEEE Journal of Solid-State Circuits*, vol. 54, no. 2, pp. 463–475, 2019.
[3] K. McCollough, S. D. Huss, J. Vandersand, R. Smith, C. Moscone, and Q. O. Farooq, " A 480Gb/s/mm 1.7pJ/b short-reach wireline transceiver using single-ended NRZ for die-to-die applications," *2021 IEEE International Solid-State Circuits Conference (ISSCC)*, vol. 64, pp. 1–3, 2021.
[4] A. Tajalli et al., "A 1.02-pJ/b 20.83-Gb/s/Wire USR transceiver using CNRZ-5 in 16-nm FinFET," *IEEE Journal of Solid-State Circuits*, vol. 55, no. 4, pp. 1108–1123, 2020.
[5] Z. Wang et al., "An output bandwidth optimized 200-Gb/s PAM-4 100-Gb/s NRZ transmitter with 5-Tap FFE in 28-nm CMOS," *IEEE Journal of Solid-State Circuits*, vol. 57, no. 1, pp. 21–31, 2022.
[6] E. Song, J. Han, H. Seo, H. Kim, H. Im, and J. Han, "A 35-Gb/s PAM-4 transmitter with 7B4Q full-transition avoidance and area-efficient Gm-boosting techniques," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 71, no. 1, pp. 46–50, 2024.
[7] J. Cavers and R. Marchetto, "A new coding technique for spectral shaping of data," *IEEE Transactions on Communications*, vol. 40, no. 9, pp. 1418–1422, 1992.