

Transition-limited pulse-amplitude modulation technique for high-speed wireline communication systems

Eunji Song¹ | Seonghyun Park² | Jaeduk Han² 

¹Department of Nanoscale Semiconductor Engineering, Hanyang University, Seoul, Republic of Korea

²Department of Electronic Engineering, Hanyang University, Seoul, Republic of Korea

Correspondence

Jaeduk Han, Department of Electronic Engineering, Hanyang University, Seoul, Republic of Korea.

Email: jdhan@hanyang.ac.kr

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Abstract

This paper presents a transition-limited pulse-amplitude modulation (TLPAM) signaling method to enable a high data rate and robust wireline communications. TLPAM signaling addresses the impact of high intersymbol interference (ISI) ratios in conventional M -ary PAM signaling methods by limiting the maximum voltage transition level between adjacent symbols. The implementation of a TLPAM signaling encoder is realized by setting back the most significant bits (MSBs) in the queue. The correlation between TLPAM's maximum transition level, effective data rate, and eye width/height is analyzed with various channel loss parameters, followed by characterization and measurement results with a realistic channel setup. The analysis and experimental results reveal the effectiveness of the proposed TLPAM signaling scheme for achieving a high data rate with minimal interference.

KEYWORDS

effective data transfer rate, intersymbol interference, pulse-amplitude modulation, signal integrity, wireline communication

1 | INTRODUCTION

Because many data-driven applications require high-performance computing systems that are composed of multiple processors and large-capacity memories, the need for high-speed wireline communication systems has been growing increasingly to transmit and receive data between computing systems components. The four-level pulse amplitude modulation (PAM-4) method has been widely adopted [1, 2] in such communication systems to increase the data rate under finite channel bandwidth conditions. The PAM-4 signaling scheme transmits two bits of data per symbol using four voltage levels. This doubles the data rate compared with the conventional method, which is called binary or non-return-to-zero (NRZ), for the same baud rate. Although the PAM-4

signaling method enables data transmission at 56–112 Gb/s/lane in [2–8], continuing advances in computing technology require even higher data transmission rates [9, 10]. Therefore, it is expected that higher-order PAM methods such as PAM-8 and PAM-16 are needed for next-generation wireline communication systems [11]. However, as observed in the PAM-4 transceiver systems, multilevel signaling schemes suffer from a low signal-to-noise ratio because of the reduced signal levels [12, 13] as the maximum signal power is constrained, regardless of the signaling method. To make matters worse, the impact of intersymbol interference (ISI) on signal integrity is much higher in multilevel signaling than in conventional NRZ systems. Specifically, it is shown in [14] that the data rate of the M -ary PAM system is increased by $\log_2 M$ compared with NRZ, whereas the

ISI ratio, which is the ratio of the relative ISI to the signal size, is elevated by $M-1$. As a result, high-order PAM modulations result in reduced eye opening, increasing the bit-error ratio (BER). The increased BER poses challenges to the adoption of high-order PAMs in wireline communication systems. To address the signal quality degradation issue in high- M -ary PAM transceivers, this paper proposes a signaling technique called transition-limited PAM (TLPAM), which limits the maximum transition level of signals. TLPAM achieves a lower effective ISI ratio than the conventional PAM by limiting the maximum magnitude of signal changes that can occur at once, which can reduce the effective ISI ratio and achieve high data transmission rates with improved eye opening.

This paper is structured as follows: Section 2 introduces the TLPAM method and mathematically analyzes its differences from the conventional full-transition PAM method. Section 2.1 proposes an example encoding scheme to implement TLPAM. Section 2.2 analyzes the relationships between the maximum transition size and the eye opening characteristics of TLPAM for simple first-order channels. Sections 2.3 and 2.4 investigate the maximally achievable data rate using the Markov chain theory in TLPAM with various maximum transition levels. This section also describes simulations that verify the efficiency of the proposed TLPAM signaling. Section 3 demonstrates the measurement setup and results, using a realistic channel to characterize the eye opening improvements through experiments.

2 | TRANSITION-LIMITED PULSE AMPLITUDE MODULATION

Figure 1 shows the eye diagrams of various signaling schemes for the same baud rate, peak signal swing, and channel characteristic. As illustrated in Figures 1A,B,

increasing the order of PAM modulation enhances the data rate at the expense of degraded eye opening. It also shows that the top and bottom eyes are more affected by the high ISI ratio in PAM-8 than the center eye. This is because the worst-case ISI is injected by the full-scale transitions between the lowest and highest signal levels. However, if we apply the proposed TLPAM technique that limits the maximum transition level to 6, the significant signal shifts that produce the worst-case ISIs are removed, improving the top and bottom eye openings in both horizontal and vertical manners, as shown in Figure 1C for the case in which the maximum transition level is limited to 6.

2.1 | Implementation of a TLPAM signaling encoder

Although there would be various ways of implementing an encoder for the TLPAM signaling, this paper introduces one possible way of implementation, which is illustrated with its sample timing diagrams in Figure 2. The figure assumes that the encoder is followed by a 3:1 serializer. The encoder receives the raw input symbols and converts them to transition-limited ones by setting back their most-significant bits (MSB), which only pop out in valid conditions. To be specific, for each cycle, the encoder disassembles the raw input symbols and stores the MSB parts in the encoder's internal queues. Then, the encoder reads out from the queues with their read pointers ($rd_pointer$) and reconstructs the symbols for two cases: (1) the replaced MSBs are combined with the input second-significant bits and the least-significant bits (LSB) (r_data), and (2) the replaced MSBs are flipped and combined (f_data). Next, the encoder checks whether the recombined symbols can be transferred by computing the following parameters $TL_r[i]$ and $TL_f[i]$, which are the

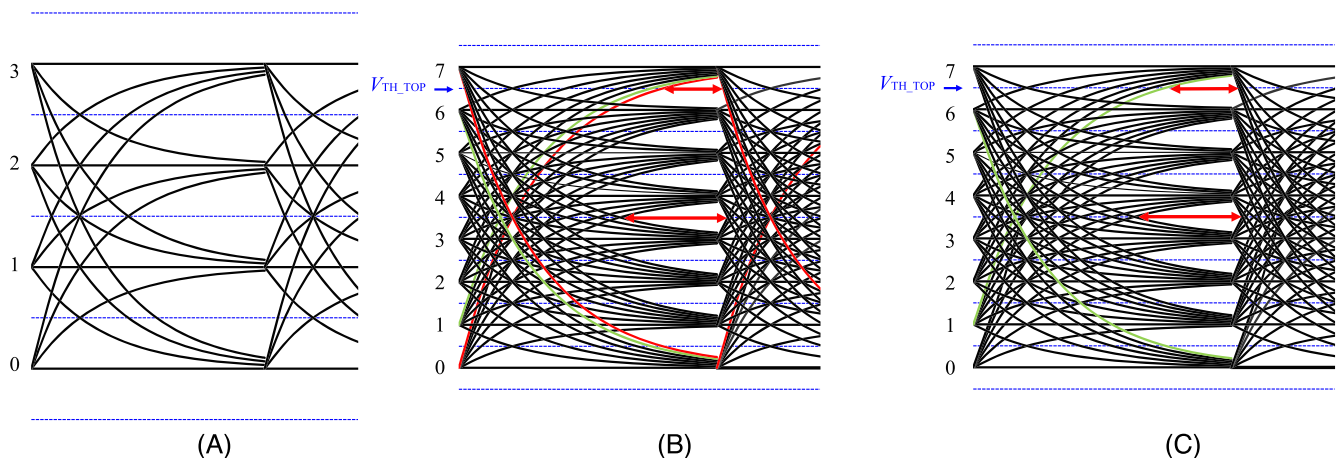


FIGURE 1 Comparison of eye diagrams of various signaling schemes: (A) conventional PAM-4; (B) conventional PAM-8; (C) transition-limited PAM-8 when the maximum transition level is 6

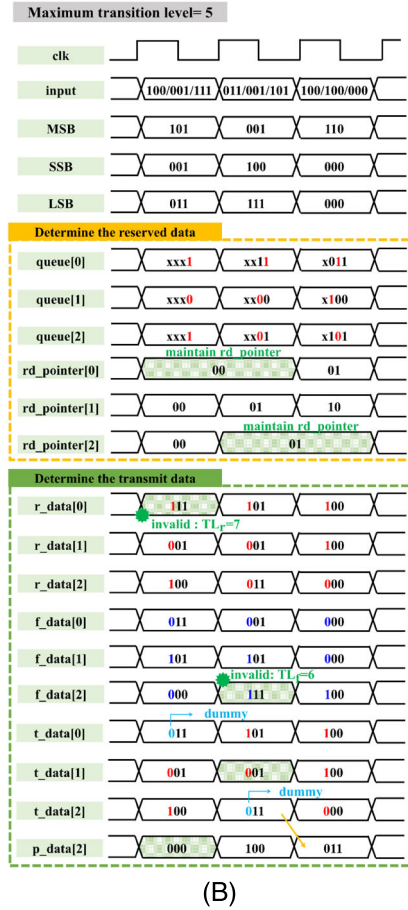
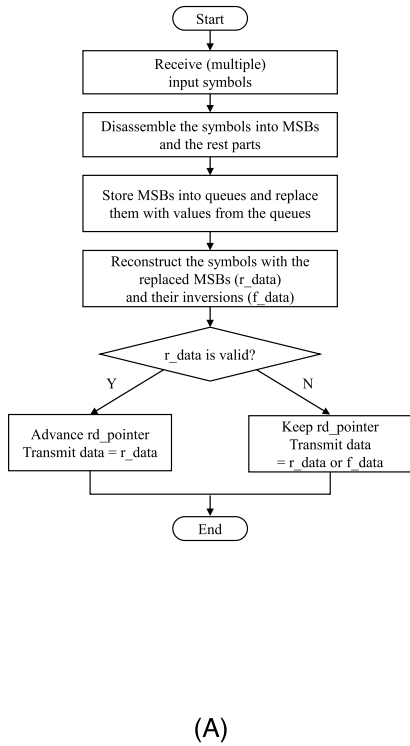


FIGURE 2 (A) A sample flowchart of the TLPAM encoder and (B) sample timing diagram of the TLPAM encoder for PAM-8 when the maximum transition level is 5

transition distances when the i th r_data and f_data are transmitted, respectively:

$$TL_r[i] = |r_data[i] - t_data[i-1]|, \quad (1)$$

$$TL_f[i] = |f_data[i] - t_data[i-1]|. \quad (2)$$

Here, t_data is the i th transmitted symbol, and $t_data[-1]$ indicates the last data in the previous cycle, which is the same as the p_data [2]. The proposed encoder determines that $r_data[i]$ is valid when both $TL_r[i]$ and $TL_f[i]$ are less than the maximum allowed transition level because this condition implies that there is a possibility of choosing between $r_data[i]$ and $f_data[i]$ (and send information) without breaking the transition-limitation constraint. In this condition, the encoder produces $r_data[i]$ as its output ($t_data[i]$) and advances its $rd_pointer$ by one step. Otherwise, the encoder transmits a dummy bit for the MSB of $t_data[i]$ by choosing either $r_data[i]$ or $f_data[i]$ based on the value of $TL_r[i]$ and $TL_f[i]$, such that $t_data[i]$ does not break the transition-limitation constraint. The value of the $rd_pointer$ does not advance in this case. In other words, the TLPAM encoder sets back the MSBs and transmits the data if the transition level is not above the maximum.

Because the value of $TL_r[i]$ and $TL_f[i]$ can be computed by observing the received symbols, the receiver can detect whether the received MSB is a dummy or not. To be specific, on the receive side, the TLPAM decoder flips the MSB and computes the distance from the previous symbol. If the computed distance is larger than the maximum transition level, the MSB is invalid and is removed.

2.2 | Impact of TLPAM signaling on signal integrity

The improvement in the eye opening can be quantified further by introducing a new metric called the eye width ratio (EWR). The EWR is defined by the ratio of the widths of the top eye openings when the proposed TLPAM technique is applied or not, as expressed here:

$$EWR = \frac{(\text{Top eye width with TLPAM})}{(\text{Top eye width without TLPAM})}. \quad (3)$$

The width of the top eye can be obtained by measuring the intersection between the horizontal line $V_{TH, TOP}$ at

$(M - 1 + M - 2)/2 = M - 3/2$ and the worst-case trajectory in the eye diagram, where M is the order of the PAM modulation applied.

If the maximum transition level allowed at once is denoted by N , the worst-case signal trajectories will be transitions from the startLvl to max (startLvl + N , $M - 1$), or from startLvl to min (startLvl - N , 0). As shown in Figure 1B,C, the top eye width is decided by the transitions from the level $(M - 1 - N)$ to $(M - 1)$ and from $(M - 1)$ to $(M - 1 - N)$. In that case, if the channel impulse response is given by $h(t)$ and the first-tap post-cursor dominates the ISI, and the approximate EWR is given by

$$\text{EWR} = \frac{T_{\text{sym}} + s^{-1}\left(\frac{0.5}{N}\right) - s^{-1}\left(\frac{N-0.5}{N}\right)}{T_{\text{sym}} + s^{-1}\left(\frac{0.5}{M-1}\right) - s^{-1}\left(\frac{M-1.5}{M-1}\right)}, \quad (4)$$

where T_{sym} is the symbol period and $s^{-1}(L)$ is the inverse function of the unit step response $s(t) = h(t) * u(t)$ that corresponds to the time instant when the step response reaches L , which is the transition level at once.

For example, if the channel response is approximated by a first-order system in which the time constant τ is located at T_{sym}/k , the transition trajectory from $(M - 1 - N)$ to $(M - 1)$ is given by

$$\begin{aligned} & (M - 1 - N) + (M - 1 - (M - 1 - N)) \left(1 - e^{-t/\tau}\right) \\ &= (M - 1) - N \cdot e^{-t/\tau}. \end{aligned} \quad (5)$$

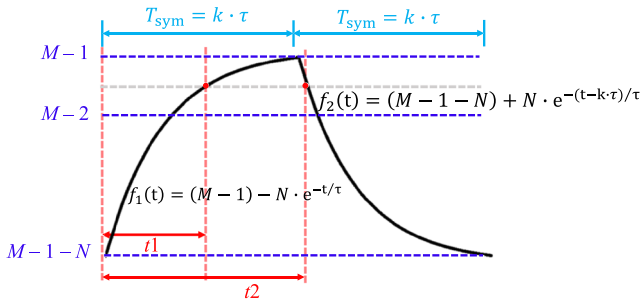


FIGURE 3 Signal trajectory related to the derivation of EWT in first-order systems

Figure 3 provides a graphical explanation of this derivation. Then, the time instant t_1 at which the two lines $V_{\text{TH, TOP}}$ and (5) intersect is obtained by

$$(M - 1) - N \cdot e^{-t_1/\tau} = \frac{(M - 1) + (M - 2)}{2} \quad (6)$$

which gives the value of t_1 as follows:

$$t_1 = \tau \ln(2N). \quad (7)$$

Similarly, the intersection of $M - 1$ and $M - 1 - N$ is given by the following:

$$t_2 = k \cdot \tau + \tau \ln\left(\frac{2N}{2N - 1}\right), \quad (8)$$

which gives the expression for the top eye width (EWT) as follows:

$$\text{EWT} = t_2 - t_1 = \tau(k - \ln(2N - 1)). \quad (9)$$

Because the width of the top eye in the conventional PAM can be obtained by substituting $M - 1$ for N , the EWR for the conventional PAM- M case is expressed as

$$\text{EWR} = \frac{k - \ln(2N - 1)}{k - \ln(2(M - 1) - 1)}, \quad (10)$$

which is also obtained from (4) by setting $s(t) = 1 - e^{-t/\tau}$ and $T_{\text{sym}} = k \cdot \tau$. From (10), it is shown that the EWR is enhanced by reducing the value of N .

Figure 4 shows eye diagrams of TLPAM signaling for various values of N when the value of k is set to 3. It can be seen that the horizontal opening of the top eye is 0.23 UI when N is 5, whereas the horizontal opening of the top is 0.19 UI for the conventional PAM-8 case. This means that the horizontal opening of the top eye is enhanced by 20%. The enhancement is 4% higher than the computation result from (10) because (10) is derived from the assumption that the ISI after the first-tap post-

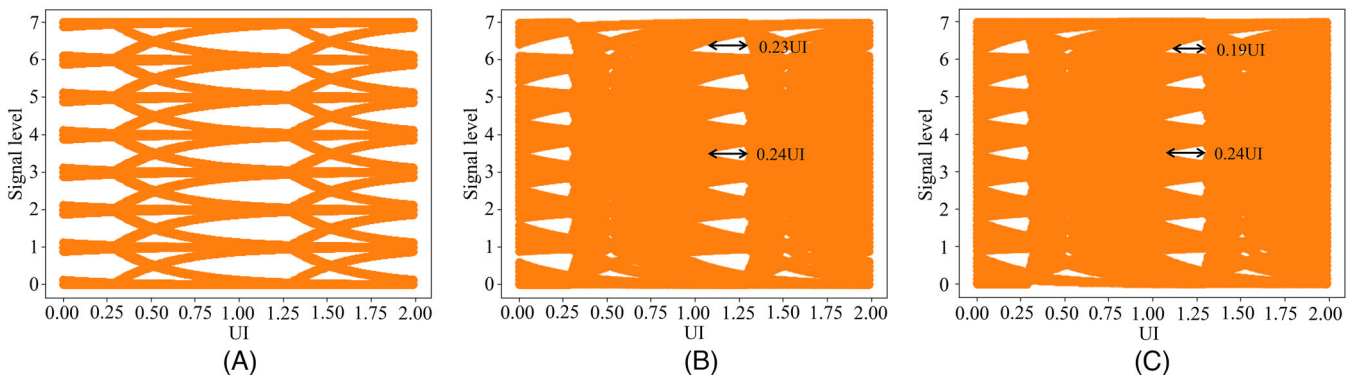


FIGURE 4 Simulated eye diagrams obtained by varying the maximum transition level in TLPAM-8 compared with the conventional PAM-8 scheme. (A) TLPAM-8 ($M = 8$, $N = 1$), (B) TLPAM-8 ($M = 8$, $N = 5$), (C) conventional PAM-8 ($M = 8$, $N = 7$)

cursor is negligible. This observation implies that the EWR and the effectiveness of TLPAM are enhanced as the channel loss increases.

The impact of the enhanced eye width on the BER can be estimated by computing the value of the Q function in the presence of the additive Gaussian jitter $\sigma_{j,rms}$, which is given by the following expression:

$$BER_{top,eye} = Q\left(\frac{EWT}{2\sigma_{j,rms}}\right). \quad (11)$$

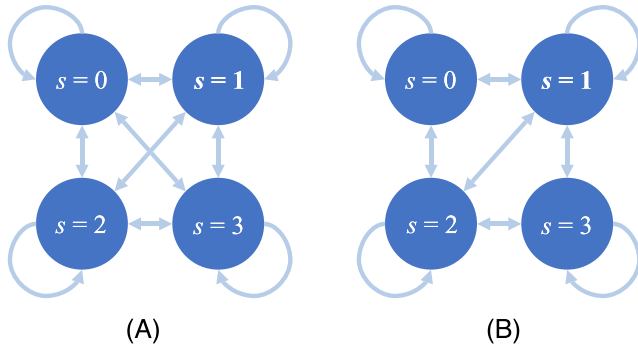


FIGURE 5 Markov chain models of (A) normal PAM-4 and (B) transition-limited PAM-4 ($N = 2$)

N	EWR ($k = 5$)	DRR	FOM
1	2.05	0.492	1.01
2	1.60	0.705	1.13
3	1.39	0.830	1.15
4	1.25	0.907	1.13
5	1.15	0.956	1.10
6	1.07	0.986	1.05
7	1.00	1.000	1.00

(A)

N	EWR ($k = 5$)	DRR	FOM
1	1.47	0.675	0.99
2	1.15	0.911	1.04
3	1.00	1.000	1.00

(B)

FIGURE 6 Comparison tables of EWR, DRR, and FOM for various maximum transition levels in (A) PAM-4 and (B) PAM-8

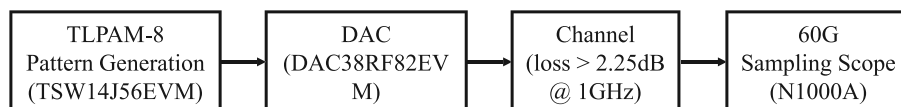


FIGURE 7 Measurement setup

In the case where $EWR > 1$, $BER_{top,eye}$ gets lower than the baseline, which corresponds to an improved BER.

2.3 | Analysis of effective data rates of TLPAM signaling

One issue related to the transition-limited signaling scheme is the reduction in the data rate for smaller N s, as the number of allowed transitions is reduced from M to N . The impact of the reduced transition levels on the data rate can be analyzed by Markov chains with M states. Figure 5 shows the Markov chain representations of a conventional PAM-4 ($M = 4$) and a TLPAM-4 with $N = 2$. The number of levels that are reachable in the s th state is denoted by T_s and is expressed as

$$T_s = 1 + \min(s, N) + \min(M - 1 - s, N) \quad (12)$$

where s indicates each signal level.

If we also define π_s as the probability of being in the s th state, then by the nature of the Markov chain, the following conditions constrain the value of π_s :

$$\sum_{s=0}^{M-1} \pi_s = 1, \quad (13)$$

$$\pi_s = \sum_{p=\max(0, s-N)}^{\min(s+N, M-1)} \pi_p \cdot p_{s,p}, \quad (14)$$

where $p_{s,p}$ is the probability of moving from the p th state to the s th state. If we assume a random distribution of symbols and equiprobable transitions, $p_{s,p}$ is given by the following expression:

$$p_{s,p} = \frac{1}{T_s}. \quad (15)$$

Combining (13) with (15) gives the expression for π_k :

$$\pi_s = \frac{T_s}{\sum_{i=0}^{M-1} T_i}. \quad (16)$$

Finally, the effective data rate is given by the multiplication of the original data rate without applying the transition-limiting technique to the data rate ratio, which is defined as the following:

$$\text{DRR} = \sum_{s=0}^{M-1} \pi_s \cdot \frac{\log_2 T_s}{\log_2 M}. \quad (17)$$

2.4 | Analysis of ISI improvement of TLPAM signaling

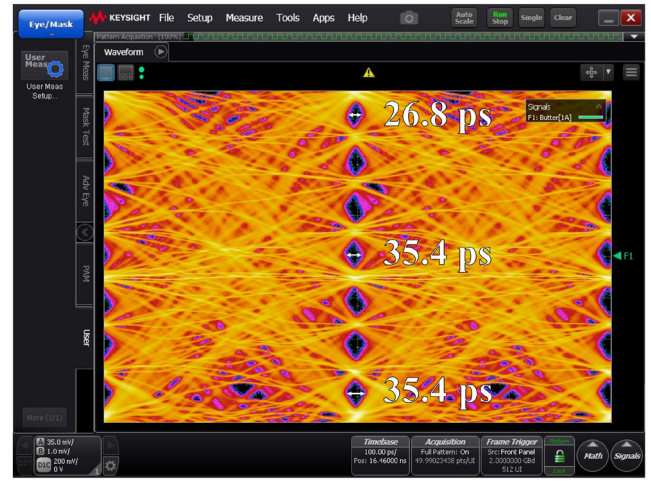
In order to elaborate on the impact of TLPAM on EWR and DRR, we defined that the efficiency of TLPAM was investigated by comparing the figure of merit (FOM) as follows:

$$\text{FOM} = \text{EWR} \cdot \text{DRR}. \quad (18)$$

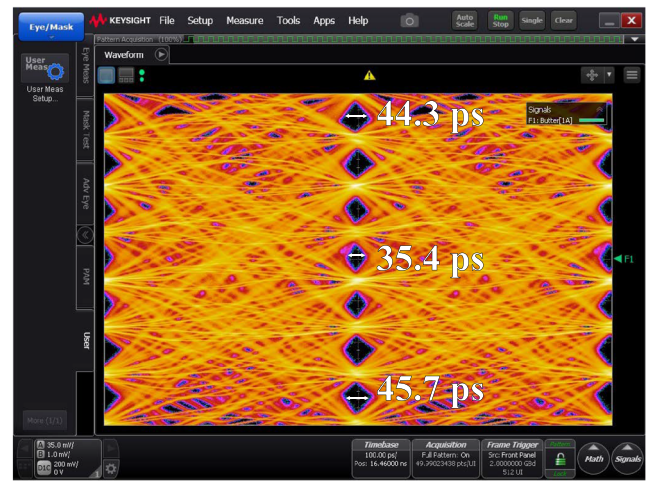
Figure 6 shows the comparison results of EWR, DRR, and FOM by varying the maximum transition level in PAM-4 and PAM-8. It should be noted that the fractional values of DRR require the use of elastic buffers and data flow control methods, on both the transmit and receive sides, to handle the variable data rate. In PAM-4 signaling, the FOM reaches its highest value when the maximum transition level is limited to 2, which is increased by 4% compared with the case when a full transition is allowed ($N = 3$). In the case of PAM-8, the FOM achieves 115% when $N = 3$. However, as shown in Section 2.2, the effective EWR is dependent on the channel response and baud rate. Therefore, the optimal N value is also dependent on the channel response and baud rate, and the benefit of the proposed TLPAM signaling is enhanced when the modulation complexity increases. It should also be noted that when the baud rate is increased to compensate for the reduced data rate, the optimal value of N would be higher than that provided in Figure 6. This aspect can be modeled by updating the value of $k = T_{\text{sym}}/\tau$ in the numerator part in (10) to model the increased data rate. For example, when $N = 5$ for PAM-8 signaling, the value of EWR becomes 1.06 when the baud rate is increased by 4.6%, whereas $\text{EWR} = 1.01$ for $N = 3$ when the baud rate is increased by 20%.

3 | MEASUREMENT RESULTS

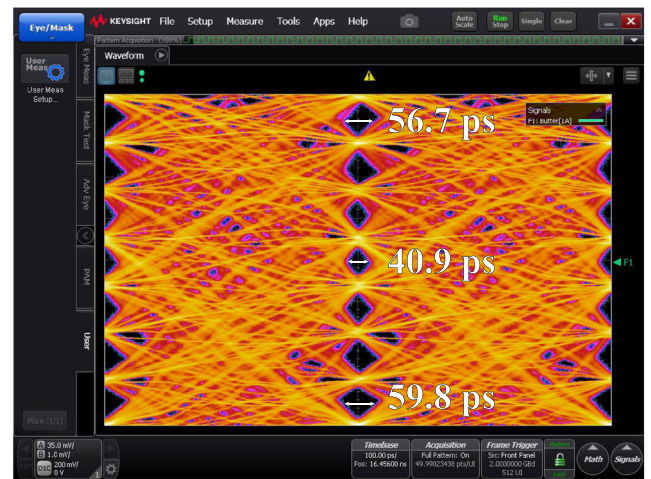
Although the FOM is useful for quickly investigating the effectiveness of the proposed TLPAM technique with simplifications, it does not reflect cases with more complicated channel characteristics. Therefore, to demonstrate the efficiency of TLPAM with a realistic channel, TLPAM-8 signals with various values of N were measured using the test setup illustrated in Figure 7. To



(A)



(B)



(C)

FIGURE 8 Measured PAM-8 eye diagrams obtained (A) when the conventional PAM-8 scheme is applied ($N = 7$), (B) when the TLPAM-8 scheme with $N = 6$ is applied, and (C) when the TLPAM-8 scheme with $N = 5$ is applied

produce the PAM-8 signals with the transition-limitation profiles, a pattern generation board TSW14J56EVM was used. The test patterns were generated from a sequence of random digital bits, which were converted to have pre-defined transition-limited profiles. The test patterns were then converted and transmitted using a high-speed digital-to-analog converter board DAC38RF82EVM and measured by a sampling oscilloscope.

Figure 8 shows the measured PAM-8 eye diagrams from the setup at the 6-Gb/s data rate. When the full transition was allowed (Figure 8A), the horizontal opening of the top eye was measured to be 26.8 ps, and the bottom eye opening was 35.4 ps. The center eye opening was 35.4 ps. When the value of N was set to 6, the top and bottom eye openings were enhanced by the transition-level limitation (65.3% for top and 29.1% for bottom), as shown in Figure 8B.

Figure 8C shows the measured PAM-8 eye diagram of the DAC transmitter at 6 Gb/s when the N value was 5. The eye openings were further enhanced, achieving a 56.7-ps opening for the top eye and 59.8 ps for the bottom eye. The center eye had a 40.9-ps opening. As shown in the measurement results, the eye openings were enhanced, with minimal penalties on the data rates (1.4% for $N = 6$ and 4.4% for $N = 5$).

4 | CONCLUSIONS

This paper describes an encoding scheme (TLPAM) for pulse-amplitude-modulated wireline communication systems to enable a high data rate and robust operation. The TLPAM signaling enhanced the eye openings by limiting the maximum voltage transition level between adjacent symbols. A TLPAM signaling encoder that used a setting-back method to control the MSBs was introduced. The correlations between the TLPAM's maximum transition level, horizontal and vertical openings of the top and bottom eyes, and effective ideal data rate were analyzed by mathematical analysis and simulation/measurement results. The analysis and experimental results revealed the effectiveness of the proposed TLPAM signaling scheme for achieving a high data rate with enhanced sampling margins.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

ORCID

Jaeduk Han  <https://orcid.org/0000-0002-2292-7670>

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AUTHOR BIOGRAPHIES



Eunji Song received her BS degree in electronic engineering from Hanyang University, Seoul, Republic of Korea, in 2021. She is currently pursuing her MS degree in nanoscale semiconductor engineering from Hanyang University, Seoul, Republic of Korea. Her current research interests include high-speed circuit design and design automation.



Seonghyun Park received her BS degree in electronic engineering from Hanyang University, Seoul, Republic of Korea, in 2022. She is currently pursuing her MS degree in electronic engineering from Hanyang University, Seoul, Republic of Korea.

Her current research interests include high-speed circuit design and design automation.



Jaeduk Han is an assistant professor of electronic engineering at Hanyang University, Seoul, Republic of Korea. He received his BS and MS degrees in electrical engineering from Seoul National University, Seoul, Republic of Korea, in 2007 and 2009, respectively. He received his PhD in electrical engineering and computer sciences from the University of California at Berkeley, CA, USA, in 2017. He has held various internships and full-time positions at TLI, Altera, Intel, Xilinx, and Apple, where he worked on digital, analog, and mixed-signal integrated circuit designs and design automation. His research interests include high-speed analog and mixed-signal (AMS) circuit design and automation.

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