Application of Generalized THP for Arbitrary PAM Level Design in Short-Reach IM/DD Signalling

Nobuhiko Kikuchi and Riu Hirai

Research & Development Group, Hitachi Ltd.
1-280 Higashi-Koigakubo, Kokubunji, Tokyo 185-8601, Japan, nobuhiko.kikuchi.ca@hitachi.com

Abstract *We introduce the concept of generalized-THP with arbitrary PAM level design for modulator non-linearity compensation and geometrical shaping of IM/DD THP-PAM signals, and show its effectiveness to lower BER floor by half an order of magnitude in 40-GBaud PAM4 and 50-GBaud faster-than Nyquist PAM4 signalling.*

Introduction

Data traffic within and between data centres grows steeply, and spurs the needs for ultra high-speed short-reach optical fibre links, such as 400GbE and beyond. To realize 50- and 100-Gbit/s/Lambda IM/DD links[1][2][3] for 400GbE, PAM4 signalling is introduced, however, it has intrinsic performance issues compared with binary signals, such as eye-opening penalty of 4.8 dB, higher susceptibility to inter-symbol-interference from linear and non-linear (NL) degradation like, limited AD/DA bandwidth, saturation of RF and optical devices, and so on. Therefore, improvement of PAM transceiver performance and power budget is required, and the applications of various advanced signalling techniques such as DFE, MLSE, and Tomlinson-Harashima Precoding (THP)[4][5] have been proposed. Among them, THP has the advantages of less computational power and the absence of noise enhancement and error propagation, and its applications to QAM/PAM signals have been investigated so far [6][7][8][9][10].

One of the challenging issues of THP-PAM signalling is the NL compensation, typically originating from transmitter- (Tx-) side driver saturation and laser/modulator non-linear E/O conversion curves, since regular THP encoders assume equi-spaced PAM signals: The use of receiver-side digital NL compensation (NLC) like a Volttera-series feed-forward equalizer (FFE) is an effective counter measure, but it requires vast amount of computational power and is yet unavailable for practical transceivers. On the other hand, Tx-side NLC can be realized by simpler DSP, but its implementation faces the problem of the equi-spacing PAM levels. Some Tx-side NLC schemes are proposed so far, based on analytical introduction[11], Volterra-series[12] and LUT[13]. However, they still require not heavy but a bit complicated DSP, precise NL model or repeated study of equalizers, which may make their introduction not a simple task.

In this paper, we introduce the generalized THP (GTHP) [14], in which PAM/QAM signal constellation can be arbitrary chosen, in order to improve the BER performance of short-reach IM/DD THP-PAM signalling. Its first application is the Tx-side NLC by moving THP-PAM signal levels to cancel out electrical and optical NL level shift. It is the most primitive NLC with limited performance, but its implementation is simple and requires small circuit size and it is suited to short-reach transceivers with severe power limitation. The second application is the geometrical shaping (GS) of THP-PAM signals. The probabilistic shaping (PS) and GS of PAM/QAM signals are proposed mainly to improve sensitivity in optical pre-amplified QAM/PAM systems by lowering average signal power by optimizing the use of inefficient high power symbols[15][16]. We applied the GS concept to optical amplifier-less IM/DD THP-PAM systems, by considering the difference of probabilistic occurrence rate of extended THP-PAM levels. We experimentally show the effectiveness of GTHP in both applications and show that BER floors are lowered by roughly half an order in 40-GBaud PAM4 and 50-GBaud faster-than Nyqust (FTN) THP-PAM4 signalling.

Generalized THP-PAM signalling

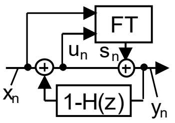
The operation of the conventional THP-PAM encoder in a transmitter is shown in Eq. 1,

$$y_n = \mathrm{mod}_{2N}\left(x_n + \left(1 - H(z)\right) \otimes y_n\right) \qquad (1)$$

$$z_n = \mathrm{mod}_{2N}\left(y'_n\right) \qquad (2)$$

where x_n is the input PAM-N sequence with the level spacings of 2, y_n is the encoded output, and H(z) is a linear channel response, mainly corresponds to the AD/DA bandwidth limitation in this paper. The amplitude of y_n is folded back by a Modulo (range 2N) function when it is overranged and thus coded into extended PAM signal with level M, typically M=6 or 8 for N=4. At the receiver, detected signal y'_n is input to the same Modulo function serving as a THP decoder to recover original PAM signal z_n~x_n as in Eq. 2.

In the case of GTHP, its extended signal levels and modulo range can be set to arbitrary values, which give the freedom of constellation design. Fig. 1(a) shows the configuration of our simplified GTHP encoder used in this paper, which utilize a folding table (FT) in Fig. 1(b) instead of the Modulo function. It stores the value of s_n indexed by x_n and the signal u_n which is the sum of x_n and the feedback signal from the THP loop. The output s_n is then added to u_n to fold back overrange signals: For example in N=4 case, lets assume the original PAM-4 signal levels as (L_3,L_2,L_1,L_0), which is the subset of the extended PAM-8 signal set (L_5,L_4,L_3,L_2,L_1,L_0,L_{-1},L_{-2})=(7,5.1,3.2,1.3,-0.6,-2.5,-4.5,-7), which is the one used in our 50-GBaud FTN-PAM4 signalling for NLC. The upper and lower folding boundaries Th^+ and Th^- are also arbitrary and typically set such as $Th^+=(L_3+L_4)/2$ and $Th^-=(L_0+L_{-1})/2$. If $x_n=L_3$ and u_n exceeds Th^+, $s_n=L_{-1}-L_3=-7.7$ is added to u_n to fold x_n down to L_{-1}. The FT in Fig. 1(b) covers only a single folding unlike fully cyclic Modulo function, but it is shown to be enough for the applications in this paper. The circuit size for GTHP is small enough compared to most digital NLCs, and requires no receiver-side knowledge or feedback study if is used for the compensation of fixed known impairments.



x_n	u_n: $>Th^+$	$<Th^-$	else
L_3	L_{-1}-L_3	-	0
L_2	L_{-2}-L_2	-	0
L_1	-	L_5-L_1	0
L_0	-	L_4-L_0	0

y_n	z_n
L_5	L_1
L_4	L_0
L_0~L_3	L_0~L_3
L_{-1}	L_3
L_{-2}	L_2

(a) GTHP Encoder (b) Folding table (c) Decoding table

Fig. 1: Schematic configuration of GTHP-PAM4 encoder, example folding table, and decoding table assuming extended PAM-8 signal (L_5,L_4,L_3,L_2,L_1,L_0,L_{-1},L_{-2}). Th^+ and Th^- are prefixed upper and lower folding boundaries.

To simplify decoding in the receiver, we firstly apply PAM-M signal decision, then a GTHP decoder to recover original PAM-N signal. If the received PAM-M signal is expected to be evenly spaced, the Modulo function can be used as the GTHP decoder, but if it is unevenly-spaced, for example, by the use of geometrical shaping, a simple defolding table as in Fig. 1(c) can be used as the decoder, which moves extended PAM-M levels back to the original position.

Experimental Setup

A schematic configuration of 40-GBaud THP- and 50-GBaud FTN zTHP-PAM-4 signalling experiments are shown in Fig. 2: In the Tx-side offline DSP, a PAM-N sequence is input to the GTHP encoder, where H(z) is approximated by a 3-tap FFE in 40-GBaud case for noise whitening, or a 22-tap FFE in 50-GBaud FTN case to represent sharp Rx-side 20-GHz cut off. The output signal is filtered by a raised cosine filter (Roll off factor: Ro=0.3), and re-sampling is performed. Then, it is passed to a 64-GSa/s 8-bit DA converter (3-dB bandwidth: 20 GHz) and the output signal drives a 1.5-μm electro-absorption (EA) modulator integrated laser (EML, Bw: 30 GHz) through a driver amplifier.

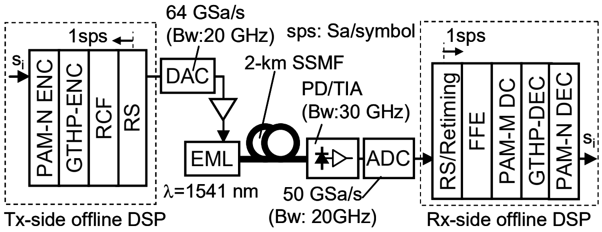
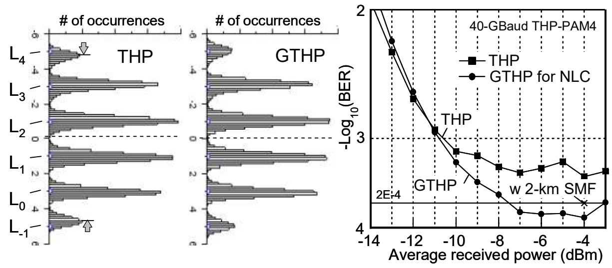


Fig. 2: Schematic configuration of 40-GBaud GTHP-PAM4 and 50-GBaud FTN GTHP-PAM4 signalling experiments. ENC: encoder, RCF: raised cosine filter, RS: re-sampling, DC: decision circuit, DEC: decoder.

The receiver has a pin-PD/TIA front end (3-dB bandwidth: 30 GHz) followed by an 8-bit AD converter with the sampling rate of 50 GSa/s with a rectangle anti-aliasing filter of 20-GHz bandwidth. In a Rx-side offline DSP, re-sampling, timing-recovery and an adaptive symbol-spaced 51-tap linear FFE are performed to the digitized received signal. And the PAM-M signal decision, GTHP decoding, PAM-N decoding are performed for bit error ratio (BER) calculation.

Non-Linear Compensation

Fig. 3(a) shows the experimentally received amplitude histograms of 40-GBaud THP-PAM signals: With conventional THP, the top and bottom levels (L_4 and L_{-1}) are shifted inside due to the saturation of the RF driver and EA modulator extinction curve. In the GTHP case, we tuned the extended PAM-6 set as (-5,-2.85,-0.95,0.95,2.85,5) to cancel non-linearity, and the received histogram becomes nearly equi-spaced.

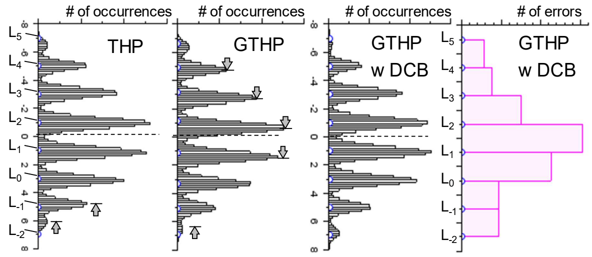


a) Amplitude histograms (b) BER characteristics

Fig. 3: Amplitude histograms and BER characteristics of experimentally received 40-GBaud PAM-4 transmission with conventional THP and GTHP for transceiver NLC.

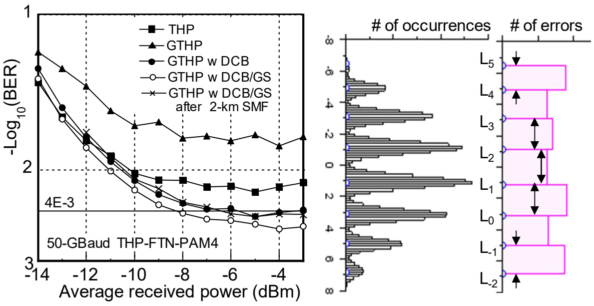
In Fig. 3(b), the use of GTHP is shown to be effective to lower the floors of a BER curve by about half an order of magnitude down to less than the KP-4 FEC threshold (BER=$2x10^{-4}$).

Next, Fig. 4 shows the experimentally received amplitude histograms of 50-GBaud FTN-THP-PAM signals, in which high-frequency zeros in H(z) converts PAM-4 to PAM-8 signal. With conventional THP, the bottom portion of the histogram (a) is strongly compressed by the extinction floor of the EA modulator. Fig. 4(b) shows the histogram with the application of GTHP using the extended PAM-8 signal (shown before) for NLC to counter the distortion in (a), but its symmetry is further degraded. This is found to be caused by the DC imbalance of the GTHP output signal when strong NLC is performed: In Fig. 4 case, the down-side folding of L_3 and L_2 occurs far frequent than that of the up-side folding of L_1 and L_0 due to the imbalance of folding boundaries (Th^+, TH^-)=(+3.5, -4.15). Therefore, we devise a DC balancing (DCB) technique by increasing TH^+ to +4.1 so that the DC component in GTHP output is canceled out, and the resultant histogram in Fig. 4(c) shows improved symmetry. This technique saves the need for an complicated external DC-bias control circuit to automatically keep the modulator bias point and simplifies the transmitter configuration.



(a) THP (b) GTHP w/o DCB (c) GTHP w DCB

Fig. 4: Received amplitude and error histograms of 50-GBaud FTN THP- and GTHP-PAM4 signals after linear FFE.



(a) BER performances (b) GTHP w DCB and GS

Fig. 5: BER performances and amplitude and error histograms of experimentally received 50-GBaud FTN-THP-PAM signals with conventional THP and GTHP with DCB and GS. DCB: DC balancing, GS: Geometrical shaping.

Fig. 5(a) shows the BER performances of THP (filled squares), GTHP (filed triangles), and GTHP with DCB (filled circles). Due to the higher BER floor of FTN signals, we assume the use of HD-FEC and It is shown that GTHP with DCB lowers the BER floor by 50 % to the HD-FEC threshold.

Geometrical Shaping of THP-PAM signal

The right hand side figure of Fig. 4(c) is the error histogram of the GTHP signal with DCB, which shows the numbers of the decision errors are higher at the center three eye openings of the PAM-8 signal; it is due to the THP nature of higher occurrence of center PAM levels as shown in amplitude histograms. It means that allocation of equi-spaced eye-openings is not optimal for THP-PAM signal. For further BER improvement, we applied the geometrical shaping (GS) to allocate a bit more spacing for center levels with higher occurrence and less for outer levels. The BER curve with GS is shown in Fig. 5 as open circles, in which GS reduces BER about 35 % and lowers the BER floor to less than HD-FEC threshold. The combined use of GTHP, DCB and GS shown to improve the BER floor by half an order of magnitude and the SNR about 1-dB at BER=10^{-2}. Transmissions over 2-km standard single-mode fiber (SMF) are also performed as crossed symbols in Fig. 5 (a) with slight penalties due to the fiber chromatic dispersion (~34 ps/nm @1.5 μm).

Conclusions

We propose the application of generalized THP for Tx-side device non-linearity compensation and geometrical shaping of THP-PAM signals in short-reach PAM signalling, and shows their effectiveness in BER improvement, which has the advantages of very simple configuration and small circuit size.

References

[1] X. Song *et al.*, IEEE 802.3 400 GbE SG, Interium Meeting, Jan. 2014.

[2] R. Hirai *et al.*, IEEE 802.3 400 GbE SG, Interium Meeting, Jan. 2014.

[3] N. Kikuchi *et al.*, OFC2015, paper Th3A.2.

[4] M. Tomlinson, Electronics Letters Vol.7, No.5, pp.138-139, 1971.

[5] H. Harashima *et al.*, IEEE Trans. Communication, Vol.20, No.4, pp.774-780, 1972..

[6] D. Chang *et al.*, OFC 2015, Los Angeles, CA, USA, Mar., 2015, paper Th3E.8.

[7] R. Rath *et al.*, IEEE Journal of Lightwave Technol., Vol. 35, No. 18, pp.3909-3917, 2017.

[8] K. Matsumoto *et al.*, OFC 2017, paper Th3D.7.

[9] N. Kikuchi *et al.*, OFC 2018, paper W1J.2.

[10] Q. Hu *et al*, ECOC2018, paper Th3F.6.

[11] N. Kikuchi *et al.*, ECOC 2018, paper Th.2.34.

[12] H. Xin *et al.*, Optics Express, Vol. 27, No. 14, Jul 2019, pp.19156-19167.

[13] N. Kikuchi *et al.*, ECOC 2020, paper We2D-6.

[14] R.F.H. Fischer, Precoding and Signal Shaping for Digital Transmission, John Wiley and Sons, Inc., New York, NY, USA, 2002.

[15] F. Buccali *et al.*, J. Lightwave Technol., Vol. 34, Issue 7, pp. 1599-1609, 2016.

[16] N. Stojanović *et al.*, IPC 2018, paper WF3.1.

[17] Z. He *et al.*, OECC/PSC 2019, paper TuB3-4.