

Analysis of High Efficiency Coding Scheme for PAM3 Based Physical Link

Xinyuan Wang*

*Strategy and Business Development Dept., Huawei Technology Co., Ltd., Beijing, China

wangxinyuan@huawei.com

Abstract— Three-level pulse-amplitude-modulation (PAM3), is adopted in IEEE 802.3bp 1000BASE-T1 physical layer device (PHY) with 3 bits-2 trits (3B2T) line coding, universal serial bus 4 version 2.0 (USB4 V2) and JESD239.01 graphics double data rate 7 SGRAM standard (GDDR7) with 11 bits-7 trits (11B7T) coding scheme. For higher physical link rate, 11B7T coding has higher bandwidth efficiency advantage with in general to ask Reed-Solomon forward error correction (RS FEC) to improve post-FEC bit-error-ratio (BER) performance and reliability, especially in scenarios of prone to burst error introduced by decision feedback equalizer (DFE). In this article, optimized 11B7T coding schemes based on partitioned three grouped 3B2T and leftover 2 bits-1 trit, and related RS FEC are analysed for PAM3 based physical link. Furthermore, these 11B7T scheme methodology can evolve to non-integer-power-of-two PAM/QAM, such as PAM6 with 18 bits-7 senary symbols based on partition to three grouped 5 bits-2 senary symbols and leftover 3 bits-1 senary symbol coding application or PAM3 with 19 bits-12 trits based on partition to six grouped 3 bits-2 trits and leftover 1 bit to reach ~99.9% efficiency.

Keywords— BER, Constellation, FEC, Gray-Coding, PAM3

I. INTRODUCTION

IEEE 802.3bp 1000BASE-T1 PHY had ratified 3B2T with Gray coding based PAM3 as line code operating at 1 Gb/s over a single twisted pair for automotive and industry interconnection application in September 2016 [1]. The Universal Serial Bus 4 (USB4®) specification version 2.0 had released in October 2022, doubling the rate from USB4 V1 at 20 Gb/s to 40 Gb/s per lane with line coding from non-return-to-zero (NRZ) to PAM3 [2]. Analysis on achieved pre-FEC BER at ~1E-8 and post-FEC BER at >1E-19 of specified USB cable link is performed [3]. One of 11B7T coding scheme, based on partitioned three grouped 3B2T scheme and leftover 2 bits-1 trit, is defined in this USB4 V2 specification to improve coding efficiency from 94.6% of 3B2T to 99.1% resulting in 25.6G Baud per lane. GDDR7 defines another 11B7T scheme operating on single-end signaling parallel bus to connect memory controller and memory device [4]. In this article, three high efficiency 11B7T coding schemes based on four partitioned groups are investigated.

NRZ, PAM4 and its related RS FEC have been extensively studied and adopted in high rate Ethernet since 10, 25 Gb/s per lane with NRZ to 50, 100, 200 Gb/s per lane with PAM4. PAM3 has advantage for the specified physical link, such as

IEEE 802.3bp and USB4 V2 with balance on baud rate and link reach. The research and analysis on overall FEC performance and reliability of PAM3 based PHY link, are fewer, especially for high efficiency coding 11B7T. Some work focuses on “The Encoding Schemes and Test Sequences of PAM3” and “Performance Analysis: In Comparison to NRZ and PAM4” excluding FEC, physical link and its error behaviors to evaluate overall post-FEC BER performance from a point-to-point PHY link communication perspective [5].

The post-FEC BER objective is related to observable number of error bits or frames within a set period, which is influenced by logic layer, including FEC and CRC algorithm, encoding, etc. USB4 V2 defines RS(504, 480, 12, 11) FEC and CRC32 working together for 40 Gb/s per lane PAM3 based link to improve post-FEC BER with better than 1E-19 [3].

For PAM3, as each symbol presents $\log_2 3 \approx 1.5849625$ bits, which will require a coding mechanism to map multi-bits binary sequence to multi-symbols ternary sequence to approach ~100% coding efficiency to lower required bandwidth. One of 2D-PAM3 coding, aka 3B2T, uses two consecutive PAM3 symbols T1 and T0 to assign 3 bits binary B[2:0], with 1 redundant constellation point. The efficiency of 3B2T is $\frac{3}{2 \times 1.5849625} \approx 94.6\%$. Another most popular 7D-PAM3 coding, denoted as 11B7T, based on partition 11 bits sequence to three grouped 3B2T and leftover 2 bits sequence coding can achieve much higher efficiency $\sim \frac{11}{7 \times 1.5849625} \approx 99.1\%$ to lower bandwidth required comparing to 2D-PAM3.

To utilize PAM3 in PHY communication, the coded PAM3 symbol will traverse over transmitter, physical medium link, and receiver as present in Figure 1. In general, continuous time linear equalization (CTLE) is an acceptable architecture for the lower-speed electrical SerDes link (e.g., ~5 Gb/s) or optical link having moderate amounts of inter-symbol interference (ISI). CTLE offers low power and has been proven to be satisfactory for these applications, which is therefore evaluated with the assumption that only random errors exist in additive white gaussian noise (AWGN) channel. For higher rate per lane, PAM3 operating on lossy link with significant amount of ISI and crosstalk will require DFE, which is resilient to noise enhancement penalty. The drawbacks of the DFE are that it is prone to have correlated errors due to error propagation, which is if the previous PAM3 symbol detection is in error, it will potential cause the current symbol to be further detected in error

to lead burst error to increase symbol error ratio (SER). SER and resulted BER can be corrected by RS FEC and detected by CRC32 at receiver side in IEEE 802.3bp and USB4 V2 specification.

Section II describes 11B7T coding including two optimized schemes beyond definition in USB4 V2. Section III introduces the random and DFE introduced burst error model of PAM3 based physical link with the three-coding scheme, followed by post-FEC BER theoretical analysis and a Monte Carlo simulation model is built. Section IV presents the simulation results from post-FEC perspective. Section V summaries.

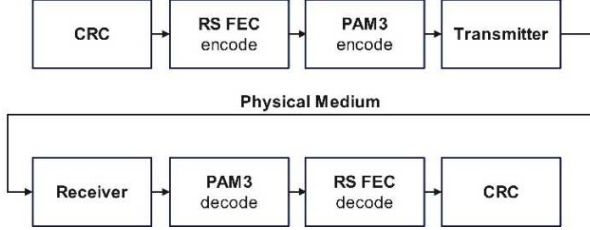


Figure 1. Link Model of a typical PAM3 based PHY

II. HIGH EFFICIENCY CODING OF PAM3

A. USB4 V2 11B7T

USB4 V2 defines one of 11B7T scheme mapping 11 bits binary sequence, using “0” and “1” representing signal of one bit, with $2^{11}=2048$ patterns to 7 trits, aka PAM3 symbols, using “0”, “1” and “2” representing signal of one PAM3 symbol, with $3^7=2187$ patterns through the following step.

First, partitioning 11 bits binary sequence to four groups, first group A with B[10:9] for 2 bits-1 trit(2B1T), second group B with B[8:6] for 3B2T(B), third group C with B[5:3] for 3B2T(C), fourth group D with B[2:0] for 3B2T(D), and partitioning 7 trits ternary sequence T[6:0] as four groups, T[6], T[5:4], T[3:2] and T[1:0] [2]. Within each 3B2T group do encoding according to Figure 2(a) with one redundant constellation point in the centre for each 3B2T group. This redundant constellation point {1,1} acts as special identifier to identify different coding branch. Second, mapping 2 PAM3 symbols T[1:0] of each grouped 3B2T to 6 ternary sequence T[5:0], such as T[5:4], T[3:2] and T[1:0] one-to-one correspondence by 3B2T(B), 3B2T(C) and 3B2T(D) if B[10:9] of first group 2B1T has the 2 bits sequence “00,01, or 10”. Furthermore, mapping B[10:9] to T[6] as in Figure 2(b). Encoding and decoding of 3B2T scheme is fully reused for each grouped 3B2T(B), (C) and (D) to minimize coding complexity. This first encoding branch maps $8 \times 8 \times 8 \times 3 = 1536$ bit sequence patterns to portion of 7 ternary sequence patterns.

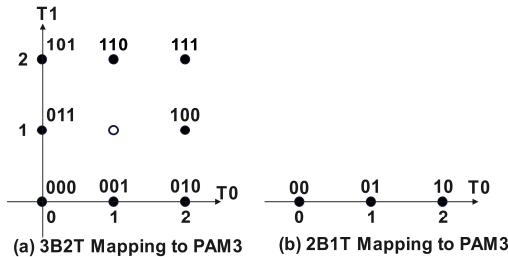


Figure 2. 3B2T and 2B1T constellation when B[10:9]= “00,01, or 10” of USB4 V2 11B7T

Second, if B[10:9] of first group 2B1T has the 2 bits sequence “11” observed, additional reshuffling of encoded 3B2T groups B, C, and D mapping to ternary sequence as in Table 1, the special identifier {1,1} at either T[5:4], T[3:2] or T[1:0] represents that B[10:9] has “11” pattern. When receiver detects “111” ternary sequence at T[6:4], it shall replace T[6:4] with “210” ternary sequence to decode for improving performance. This second encode branch maps $8 \times 8 \times 8 \times 1 = 512$ bit sequence patterns to part of 7 ternary sequence patterns, then total 2048 patterns of 11 bits binary sequence map to partial 7 ternary sequence finally.

TABLE 1. MAPPING TO 7 TRITS TERNARY SEQUENCE WHEN B[10:9]= “11” OF USB4 V2 11B7T

3B2T 7 Trits	B[8:6] of 3B2T(B)							
	000	001	010	011	100	101	110	111
T[6]	0	1	2	0	1	2	0	2
T[5:4]	2 Trits of 3B2T(C)			2 Trits of 3B2T(C)			11	11
T[3:2]	2 Trits of 3B2T(D)			11	11	11	2 Trits of 3B2T(C)	
T[1:0]	11	11	11	2 Trits of 3B2T(D)			2 Trits of 3B2T(D)	

B. Gray-coding 11B7T

As no Gray coding considered, 3B2T presented in Figure 2(a) has hamming distance at 2 for some of adjacent PAM3 constellation points. For example, 3 bits = “000” coding to T[1:0] = “00” compares to 3 bits = “011” coding to T[1:0] = “10”. This will result in degraded BER after PAM3 decode at receiver side. Similar issue exists at 2B1T presented in Figure 2(b).

Gray coding based 3B2T scheme is defined in IEEE 802.3bp and presented in Figure 3(a), and similar Gray coding based 2B1T is presented in Figure 3(b).

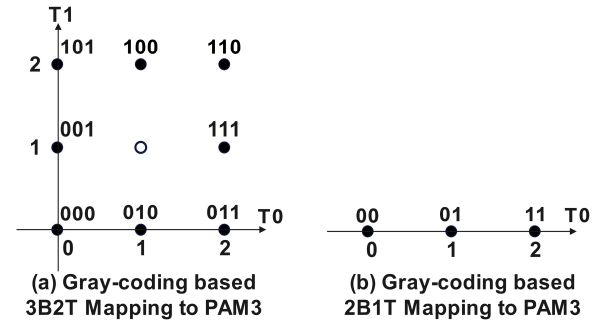


Figure 3. Gray-coding based 3B2T and 2B1T constellation

A new 11B7T scheme is proposed, denoted with “Gray-coding 11B7T” to distinguish with above mentioned “USB4 V2 11B7T”, which reuses the same partition of 11 bits and 7 trits to 4 groups, A, B, C, and D as USB4 V2. The difference of this scheme is to replace 3B2T and 2B1T coding as in Figure 3. Further revision is using the special identifier {1,1} to represent both of B[10:9]= “10” and the value—“0”, “1” and “2”—of encoded T1 of 3B2T(B) mapped to T[5:4], T[3:2] and T[1:0] respectively, mapping encoded T0 of 3B2T(B) to T[6]. This “Gray-coding 11B7T” is presented in Table 2.

TABLE 2. GRAY-CODING 11B7T OF 7D-PAM3

B[10:9]	B[8:6]	B[5:3]	B[2:0]
1 st branch: B[10:9] of 2B1T = "00, 01, 11"			
1st Group, A 2B1T	2nd Group, B 3B2T(B)	3rd Group, C 3B2T(C)	4th Group, D 3B2T(D)
T[6]	T[5:4]	T[3:2]	T[1:0]
2 nd branch: B[10:9] of 2B1T = "10" branch, Special Identifier = {1,1}			
3B2T(B) B[8:6]/T0	3B2T(B) B[8:6]/T1={2}	3B2T(C) B[5:3]	3B2T(D) B[2:1]
3B2T(B) B[8:6]/T0	3B2T(C) B[5:3]	3B2T(B) B[8:6]/T1={1}	3B2T(D) B[2:1]
3B2T(B) B[8:6]/T0	3B2T(C) B[5:3]	3B2T(D) B[2:1]	3B2T(B) B[8:6]/T1={0}

C. Right-trapezoid 11B7T

Decoding of above 11B7T schemes should detect special identifier at T[5:4], T[3:2] or T[1:0] as first step, which is {1,1} for "Gray-coding 11B7T" and "USB4 V2 11B7T", to judge either encode branch, first or second in Table 2, then further decoding. For example of "Gray-coding 11B7T", if no special identifier {1,1} is received at either one of T[5:4], T[3:2] or T[1:0], then decoding based on Figure 3(b) from received PAM3 symbol at T[6] to get B[10:9], and decode T[5:0] to get B[8:6], B[5:3], and B[2:0] respectively based on Figure 3(a). As PAM3 symbol error has opportunity to happen at receiver side due to noise, ISI and burst error by DFE, PAM3 constellation point at receiver side may be different from its original point at transmitter side and is most likely to change to another adjacent constellation point. For example, special identifier {1,1} has four adjacent constellation points {1,0}, {0,1}, {1,2}, {2,1}. Assuming equal error probability only for one constellation point to adjacent constellation point at receiver side, the special identifier {1,1} has four opportunity to be mis-detected to either one of the four adjacent constellation points, this will lead to much worse BER as 11B7T decoder has more opportunity to select different branch rather than original encoded branch at transmitter side. So, a "Right-trapezoid 11B7T" is presented, which includes right-trapezoid 3B2T in Figure 4(a) and Gray coding based 2B1T, and has same partitioning and mapping scheme as Table 2.

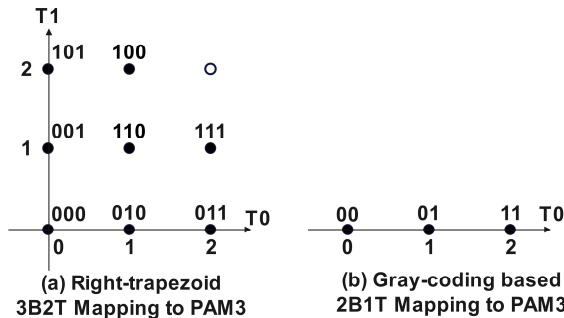


Figure 4. Right-trapezoid 3B2T and Gray-coding based 2B1T constellation

The right-trapezoid 3B2T selects constellation point at corner as special identifier, such as {2,2} in Figure 4(a). Other

alternative points are {2,0}, {0,2} and {0,0}. These special identifiers have two adjacent constellation points rather than 4 of "Gray-coding 11B7T" scheme to lower opportunity for decoder selecting wrong branch, and still keep hamming distance at 1 for most of adjacent PAM3 constellations points.

III. ERROR MODEL AND FEC FOR 11B7T PAM3 PHY LINK

For pulse-amplitude-modulation, assuming an AWGN channel for random error only at first, the SNR, SER and BER are expressed as equation (1), (2), (3) and Figure 5 for L=3 of PAM3 with {0, ± 2d} constellation points and standard deviation σ_n . "2d" is the minimum distance between adjacent symbols in the constellation.

$$\text{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}} = \frac{P_{\text{average}}}{\sigma_n^2} = \frac{L^2 - 1}{3} \frac{d^2}{\sigma_n^2} \quad (1)$$

$$\begin{aligned} \text{SER} &= \frac{2(L-1)}{L} Q\left(\frac{d}{\sigma_n}\right) = \frac{L-1}{L} \text{erfc}\left(\frac{d}{\sqrt{2}\sigma_n}\right) \\ &= \frac{L-1}{L} \text{erfc}\left(\sqrt{\frac{3\text{SNR}}{2(L^2-1)}}\right) \end{aligned} \quad (2)$$

$$\begin{aligned} \text{BER} &= \frac{1}{\log_2 L} \text{SER} = \frac{2(L-1)}{L \log_2 L} Q\left(\frac{d}{\sigma_n}\right) \\ &= \frac{L-1}{L \log_2 L} \text{erfc}\left(\sqrt{\frac{3\text{SNR}}{2(L^2-1)}}\right) \end{aligned} \quad (3)$$

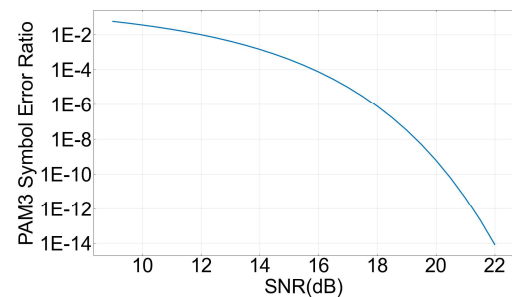


Figure 5. PAM3 SER vs SNR(dB)

Second, due to mentioned random error and DFE introduced error propagation, the probability of getting an error in the current symbol following a previous symbol in error by DFE is expressed as “a” with burst error size equal 2. This symbol error propagation probability “a” is calculated based on 1-Tap DFE model in equation (4) and Figure 6, which h_1/h_0 is the ratio of coefficient of the 1-Tap DFE [6]. For PAM3 signaling in this article, the worst-case error propagation “a” is 0.6667 for h_1/h_0 equal 1.

$$a = \frac{L-1}{L} \left[Q\left(\frac{d + 2(h_1/h_0)d}{\sigma_n}\right) + Q\left(\frac{d - 2(h_1/h_0)d}{\sigma_n}\right) \right] \\ = \frac{L-1}{2L} \left[\operatorname{erfc}\left((1 + 2(h_1/h_0)) \sqrt{\frac{3\text{SNR}}{2(L^2 - 1)}} \right) \right] \\ + \frac{L-1}{2L} \left[\operatorname{erfc}\left((1 - 2(h_1/h_0)) \sqrt{\frac{3\text{SNR}}{2(L^2 - 1)}} \right) \right] \quad (4)$$

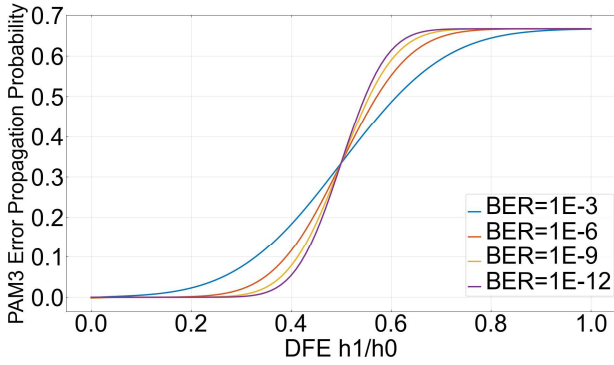


Figure 6. PAM3 symbol error propagation probability “a”

For FEC to correct error bit from noise channel, typical expression of a RS FEC code is $RS(n, k, t, m)$ where n is the codeword size in symbols with $n \leq 2^m - 1$, k is the information message length in symbols, t represents that any error combination up to t symbols per codeword can be corrected, and m defines the finite field $GF(2^m)$ for this code. The minimum hamming distance of this code is $n-k+1$.

For random error only, RS FEC(n, k, t, m) symbol error ratio (SER_{in}) and uncorrected codeword ratio (UCR) are present in equation (5) and (6). BER_{in} , or pre-FEC BER, is presented in equation (3).

$$SER_{in} = 1 - (1 - BER_{in})^m \quad (5)$$

$$UCR = \sum_{i=t+1}^n \binom{n}{i} (SER_{in}^i (1 - SER_{in})^{n-i}) \quad (6)$$

If 1-Tap DFE introduced burst error model is further included, UCR should add this factor based on “a” for any combination of errored RS FEC symbols number with great than t as in equation (7) [7], [7], where $P(e)$ denotes the probability of number of e FEC symbol errors.

$$UCR = \sum_{i=t+1}^n \binom{n}{i} SER_{in}^i (1 - SER_{in})^{n-i} \\ + \binom{n}{1} SER_{in}^1 (1 - SER_{in})^{n-1} P(t+1) \\ + \binom{n}{2} SER_{in}^2 (1 - SER_{in})^{n-2} \left(P\left(\frac{t+1}{2}\right) P\left(\frac{t+1}{2}\right) \right. \\ \left. + \binom{2}{1} P\left(\frac{t+1}{2} - 1\right) P\left(\frac{t+1}{2} + 1\right) \right. \\ \left. + \binom{2}{1} P\left(\frac{t+1}{2} - 2\right) P\left(\frac{t+1}{2} + 2\right) + \dots \right) \\ + \binom{n}{3} SER_{in}^3 (1 - SER_{in})^{n-3} \left(P\left(\frac{t+1}{3}\right) P\left(\frac{t+1}{3}\right) P\left(\frac{t+1}{3}\right) \right. \\ \left. + \binom{3}{1} P\left(\frac{t+1}{3} - 1\right) P\left(\frac{t+1}{3} + 1\right) P\left(\frac{t+1}{3}\right) \right. \\ \left. + \binom{3}{1} P\left(\frac{t+1}{3} - 2\right) P\left(\frac{t+1}{3} + 2\right) P\left(\frac{t+1}{3}\right) \right. \\ \left. + \dots \right) + \dots \\ + \binom{n}{t} SER_{in}^t (1 - SER_{in})^{n-t} \left(\binom{t}{1} P(1)^{t-1} P(2) \right. \\ \left. + \binom{t}{2} P(1)^{t-2} P(2)^2 + \dots \right) + \dots$$

$$P(1) = \frac{m-1}{m},$$

$$P(e) = \sum_{i=(e-2)m+1}^{(e-1)m} \frac{i - (e-2)m}{m} a^i (1-a) \\ + \sum_{i=(e-1)m+1}^{em-1} \frac{em-i}{m} a^i (1-a), \text{ for } e > 1 \quad (7)$$

Post-BER, or BER_{out} , of FEC decoder output is theoretical calculated for RS FEC by pre-FEC BER or BER_{in} from receiver side physical link in equation (8). UCR_i represents any combination of errored RS FEC symbols number i . As RS(504, 480, 12, 11) for PAM3 PHY from USB4 V2 specification, we use i with 13 RS FEC errored symbols within one codeword to calculate BER approximately as very low probability for more than 13.

$$BER_{out} \approx \frac{1}{m} \sum_{i=t+1}^n \frac{i}{n} UCR_i \approx \frac{t+1}{n \cdot m} UCR_{t+1} \quad (8)$$

These analytical equations, from 1 to 8, have been used to verify a Monte-Carlo simulation model which the physical link error achieves based on AWGN and 1-Tap DFE with error propagation probability “a”. Simulation based on this model is performed in the rest of this article to get more accuracy UCR and BER as including all $\geq t+1$ errored symbol within one codeword, and modelling DFE error propagation behaviour with real data sequence to terminate burst error.

To compare overall performance for these 11B7T coding schemes including USB4 V2, Gray-coding and Right-trapezoid based, RS(504, 480, 12, 11) is used in this simulation.

IV. FEC PERFORMANCE FOR 11B7T PAM3 BASED PHY

FEC performance is determined by random and burst error. The burst error introduced by 1-Tap DFE error propagation is simulated with error propagation probability “a”, which leads to a burst error length if current PAM3 symbol is false-detected due to AWGN and the burst ends when the following symbol is sampled correctly by a chance of “1 – a” or if the following PAM3 symbol already reaches its maximum or minimum signal level, say “+2d” or “-2d” respectively for PAM3 in this article, with error propagation further asking higher or lower signaling respectively. This article selects “a” with 0.6667 as long burst scenario and 0.15 as short burst scenario as in equation (4) and Figure 6 to simulate.

The achieved post-FEC BER and SNR by simulation is fitting and prediction by polynomial as in Figure 7 and Figure 8 for a=0.15 and 0.6667 respectively. Even considering fitting precision, “Right-trapezoid 11B7T” scheme still has best post-FEC BER, USB4 V2 11B7T scheme has worst post-FEC BER in both “a” at 0.6667 and 0.15 scenarios.

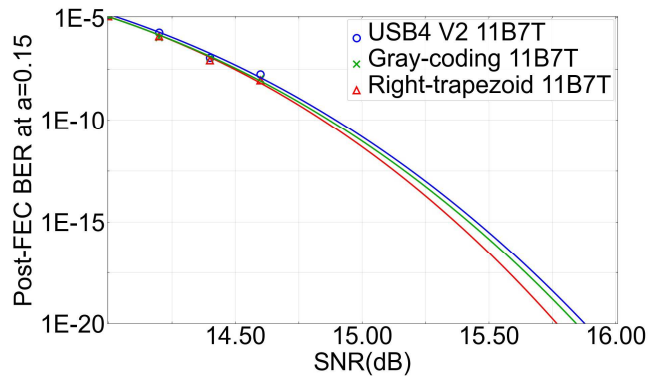


Figure 7. Post-FEC BER of 11B7T with RS(504, 480, 12, 11) for PAM3 based link at a=0.15

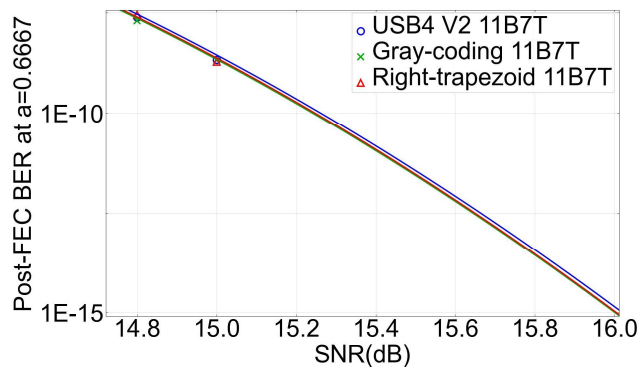


Figure 8. Post-FEC BER of 11B7T with RS(504, 480, 12, 11) for PAM3 based link at a=0.6667

Furthermore, for “Right-trapezoid 11B7T” from a=0.15 to a=0.667 for post-FEC BER at 1E-19 scenario, higher error propagation probability “a” will result in SNR penalty at ~0.55dB, equivalent to SER from 1.27E-4 to 4.8E-5. Restriction on “a”, or the ratio of coefficient h_1/h_0 is efficiency

measure to improve post-FEC performance for this PAM3 based physical link.

V. CONCLUSION

For PAM3 based PHY, high efficiency coding 11B7T has advantage to reach ~99.1% bandwidth utilization than 3B2T used in IEEE 802.3bp. All of three 11B7T coding schemes, defined in USB4 V2, Gray-coding and Right-trapezoid based in this article, partitioning 11B7T to four group to reuse 3B2T and allocating redundant constellation point as special identifier will lower circuit implementation complexity of 11B7T encoding and decoding. These 11B7T coding based PAM3 link work together with RS FEC to deal with both AWGN and DFE introduced burst error. From theoretical analysis and simulation, right-trapezoid based 11B7T scheme has better post-FEC BER than the other two schemes. The right-trapezoid based 11B7T scheme methodology and analysis can further evolve to non-integer-power-of-two PAM/QAM, such as PAM6 with 18 bits-7 senary symbols coding based on partitioning to three grouped 5 bits-2 senary symbols and one 3 bits-1 senary symbol coding application or PAM3 with 19 bits-12 trits based on partition to six grouped 3 bits-2 trits and leftover 1 bit to reach ~99.9% efficiency.

REFERENCES

- [1] IEEE standard for Ethernet, clause 97, physical coding sublayer (PCS), Physical medium attachment (PMA) sublayer, and baseband medium, type 100BASE-T1, IEEE Std 802.3bp™ -2016
- [2] Universal serial bus 4 (USB4®) specification version 2.0, October 2022
- [3] USB 80G PHY layer analysis, USB-IF Electrical Workgroup, <https://www.usb.org/sites/default/files/USB%2080G%20PHY%20backgroud.pdf>
- [4] JEDEC standard: graphics double data rate 7 SGRAM standard, JESD239.01 February 2024
- [5] S.S. Chen, F. Paulis, D.R. Stauffer and B. Holden, "Interconnection technologies for integrated circuits and flexible electronics, chapter 9, PAM3: history, algorithm, and performance comparison to NRZ and PAM4", Springer, 2024
- [6] C. Papadias and M. Rupp, "Performance Analysis of Unbiased Finite-Length DFE Receivers ", November 1998
- [7] A. Pete, " FEC performance on multi-part links", https://www.ieee802.org/3/bs/public/14_11/anslow_3bs_02_1114.pdf
- [8] T. Wang, Z. Wang, X. Wang, J. Sun and A. Ghiasi., "Analysis and Comparison of FEC Schemes for 200GbE and 400GbE", IEEE Communications Standards Magazine, pp.24-30, March 2017



Xinyuan Wang(M'20–SM'22), is a technical expert at Huawei Technologies for more than 10 years. His research work focuses on data communication network innovation, with special interests in Ethernet MAC/PHY technology. He is active in the IEEE 802.3 50 Gb/s, 200 Gb/s, 400 Gb/s, 800 Gb/s and 1.6T b/s Ethernet standard development, focusing on MAC/PCS/FEC/PMA architecture, algorithm, application in high speed physical interface and transceivers. He received his Master's degree in Electrical Engineering from Hebei University of Technology, China in 1998.