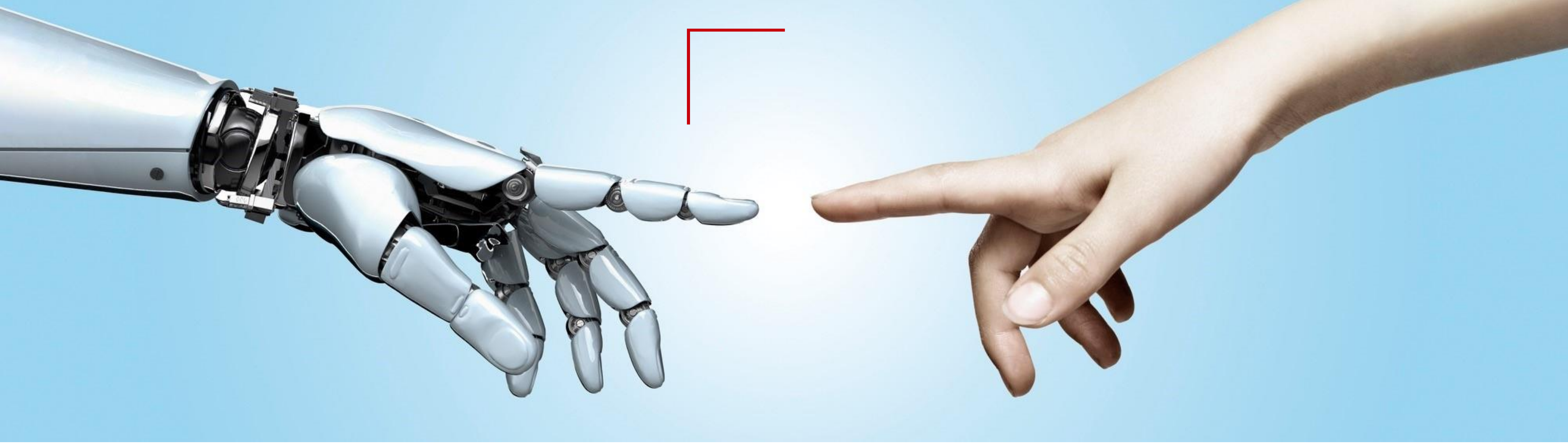
FEC Performance for 200 Gb/s per Lane Optical PHY and Interoperating



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Introduction: 200 Gb/s per Lane PHY

- Various objectives based on 200 Gb/s per lane technology have been adopted in P802.3df/dj for 800G/1.6TbE, including C2C/C2M AUIs, CR/KR electrical PMDs, IM-DD(PAM4) optical PMDs, and potential coherent (16QAM) PMDs.
- In wang_3df_01b_220928, FEC performance for 200 Gb/s per lane electrical PHYs was analyzed based on single-part link model with RS(544,514).
  - 4X codeword interleave has slightly worse FEC performance than 2X in some scenarios, due to the additional FLR penalty.
  - No significant FEC performance difference between 2:1 bit and symbol multiplexing at worst case.

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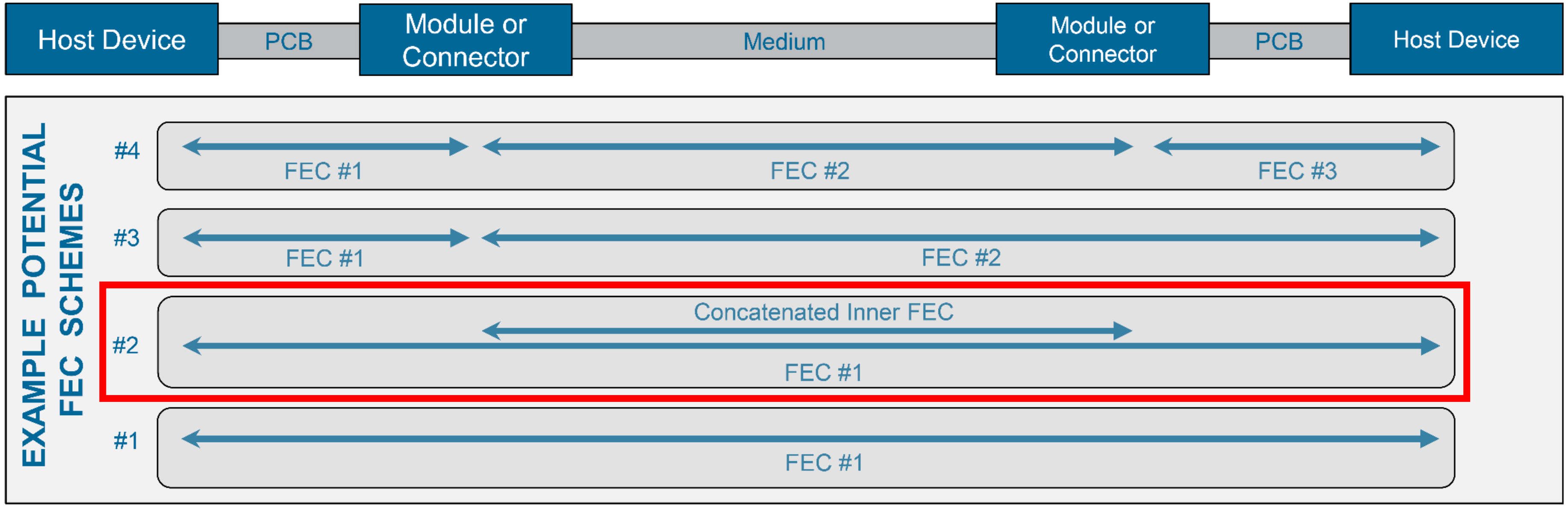
Motivation

- To investigate FEC performance for 200 Gb/s per lane based **multi-part** link model, such as DR/FR PMDs.
  - Multi-part link: multiple analyzed instances (AUIs and optical PHY) between interoperating host devices.
  - Focusing on concatenated scheme: soft-decision BCH inner code protects optical PHY only.



https://www.ieee802.org/3/B400G/public/21_1028/B400G_overview_c_211028.pdf

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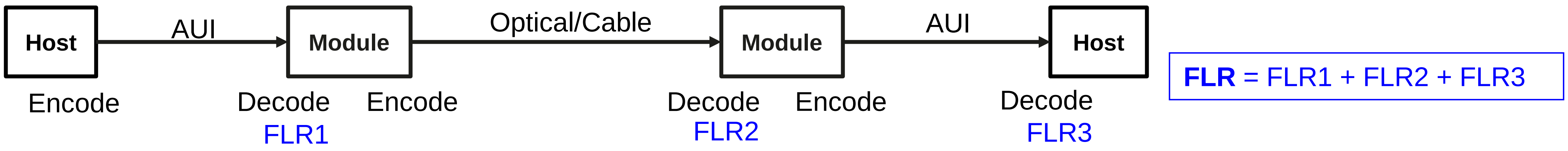
FLR Evaluation for Different FEC Schemes

- End-to-end FEC requires both AUI and optical PMD to be within the spec as defined in 802.3bs.
  - AUI BER shall be capped at 1E-5 for each segment.
  - Optical PMD pre-FEC BER target is 2.4E-4 (random error).

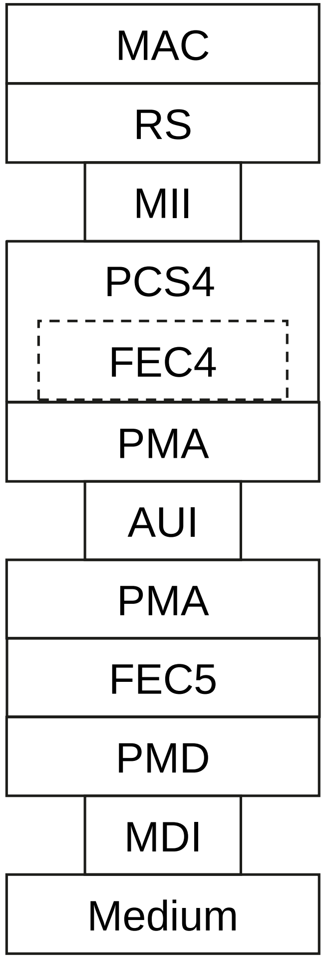
- Segmented FEC with RS(544,514) for each segment could result an elevated FLR



  - FEC error marking is required at each decode step for each FEC segment due to re-encode of data (he_b400g_01_210426, page 16).
  - Considering 3 FEC segments, the final FLR could be at least 3x as specified in the objective if keeping post-FEC BER@1E-13.

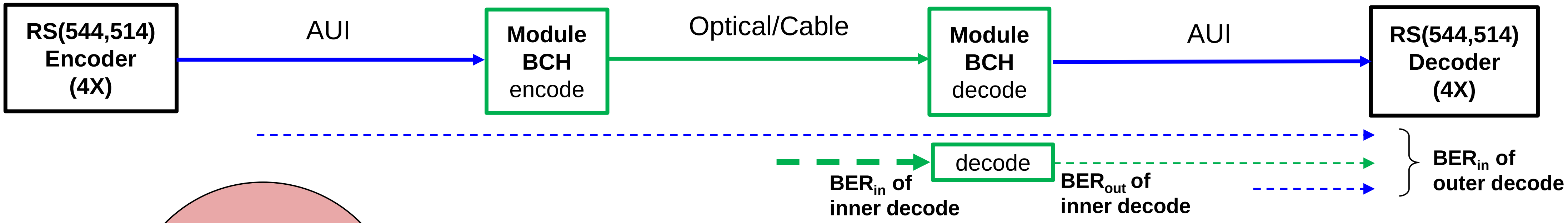
- Concatenated FEC on multi-part link allows higher optical PMD without increasing FLR.
  - Error marking is only performed once in the host device when RS(544,514) is decoded (he_b400g_01_210426, page 16).
  - If AUI BER is kept at 1E-5, the pre-FEC BER for optical PMD can be ~ 3E-3.
  - If pre-FEC BER for optical PMD is 2.4E-3, 5E-5 AUI BER (each AUI segment) can be tolerated.

Assumptions for Multi-Part Link FEC Performance



- FEC Scheme: Concatenated.
- Outer code: RS(544,514)
  - 4 codewords interleave
    - Both 802.3df D1.0 PCS (32 lanes) and 4-way RS interleave (8 lanes) are considered.
    - Bit or symbol multiplexing in PMA to form 200 Gb/s per physical lane from 2 PMA lanes.
- Inner code:
  - BCH(144,136), soft-decision decode as in page 6-7 of he_3df_01a_220308.
- AUIs: burst error model with 1-tap DFE introduced error propagation.
  - a = 0.5, 0.6 and 0.75 are analyzed as they are the worst cases.
  - Precoding on for a ≥ 0.6.
- Optical PHY: Random error model, same as 50 and 100 Gb/s per lane in 200/400GbE.

Mathematical Calculation for FEC Performance in Multi-Part Link



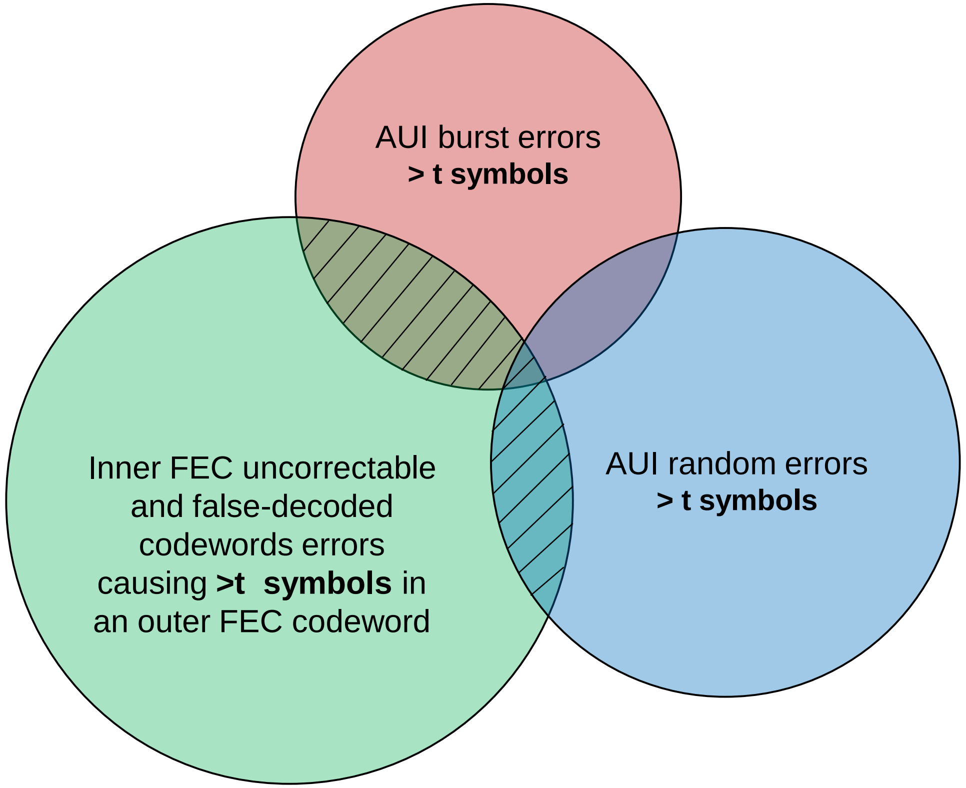


*Figure for illustration only, not to show the actual ratio.

- AUI burst + random errors induced uncorrectable RS codeword ratio has been studied in 802.3bs.
  - anslow_3bs_03_0915, wang_t_3bs_01_0514, etc.
- Error distribution in the output of inner code is not random, but appears to be clusters of errors in uncorrectable and false-decoded codewords.
  - bliss_3df_01a_220517, he_3df_01a_220308.
  - When soft-decision decoding is used, it is difficult to quantify the error distribution in RS codewords.
- New method shall be developed to evaluate the outer RS code uncorrectable codeword ratio (UCR).
  - Statistics of minimum independent data groups comprised of inner codeword errors and AUI errors can be used to evaluate the UCR for the outer RS FEC.

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Theoretical Analysis of Concatenated Code Performance (Green circle in page 6)

Assumptions: Outer code: 4-way interleaved RS(544,514); Inner code: BCH(144,136).

- Separate the 4×RS(544,514) codewords to 32 groups of 5×BCH(144,136) codewords.
  - Each group of 5x inner BCH codewords consists of 68×10-bits RS symbols.
  - Errors in each group of BCH codewords are independent from other groups.
  - Errors in each group are not random because of the non-Gaussian error distribution of BCH decoder output.
- Use $P(E_i)$ as the probability of a group of 5× BCH codewords containing E_i number of errors. We can express the uncorrectable codeword ratio (UCR) of the outer RS code as below:

$$\text{UCR caused by inner BCH} = \sum_{\substack{0 \le \mathrm{E}_i \le 68 \\ 15 < \sum_{i=1}^{32} \mathrm{E}_i \le 544}} \prod_{i=1}^{32} P(\mathrm{E}_i) \qquad \text{where } 0 \le E_i \le 68$$

- $P(E_i)$ can be obtained by simulation on a large number (>1E+9) of BCH codewords in a short period of time.

Theoretical Analysis of Concatenated Code Performance (Including AUI Burst Errors)

- When burst errors on AUIs are included, the previous model can be extended to larger blocks based on the interleaving scheme.
  - Assuming 4×RS(544,514) codewords interleaved to 4*n lanes (32 or 8).
  - Assuming inner BCH encode is performed on 200G/lane data streams.
  - The minimum independent data group would be based on the 4 inner codeword streams (800GbE).
    - Errors in each group are not random because of the non-Gaussian error distribution of BCH decoder output **AND** AUI bursts.
    - Errors in each group are independent from other groups.
  - The formula can be re-written as below:

$$\text{UCR} = \sum_{\substack{0 \leq \text{E}_i \leq 136 \\ 15 < \sum_{i=1}^{4} \text{E}_i \leq 544}} \prod_{i=1}^{4} P(\text{E}_i) \qquad \text{where } 0 \leq E_i \leq 136$$

  - $P(E_i)$ can then be obtained by simulation on a large number of independent data groups.

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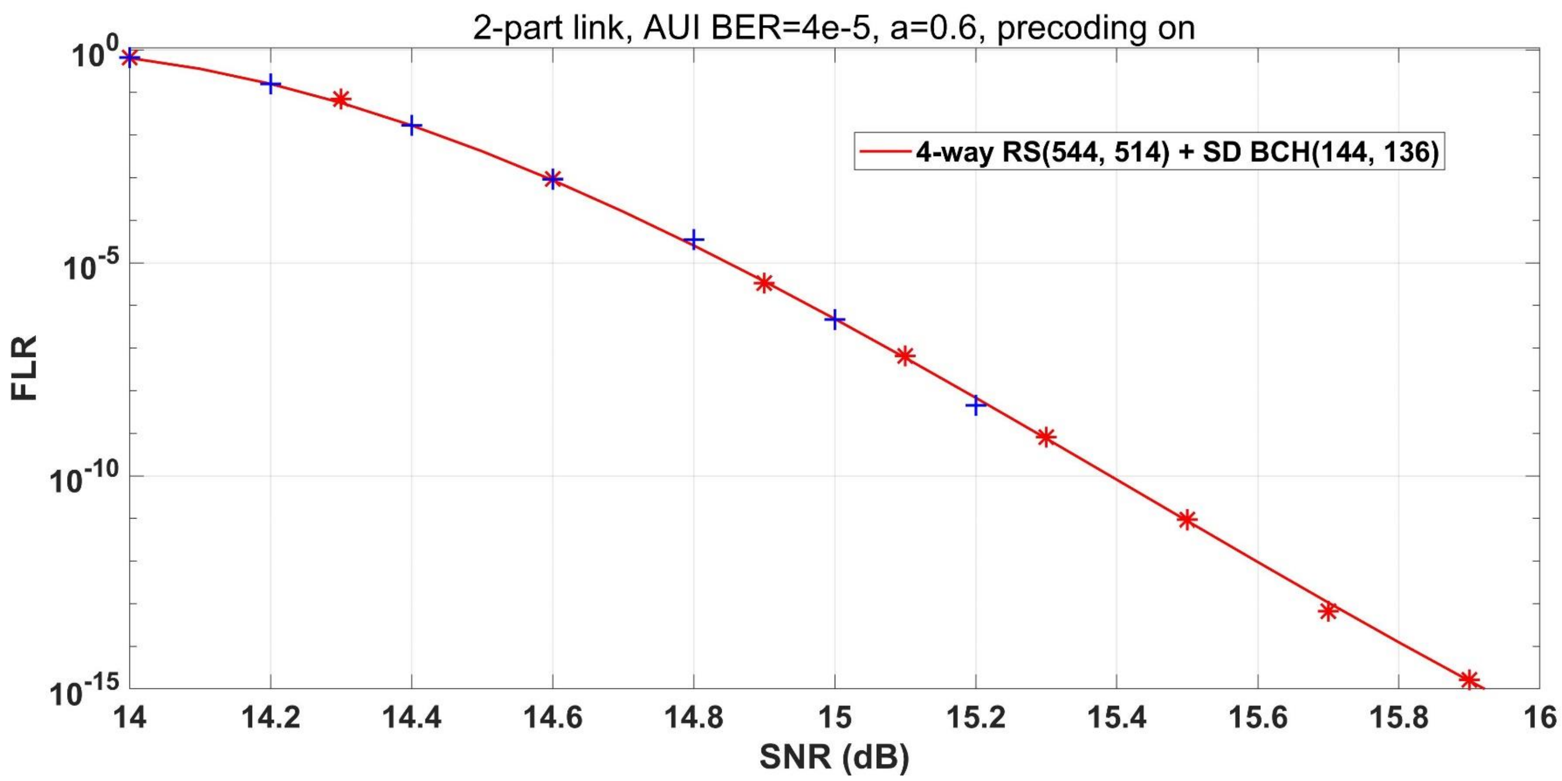
Verification of Theoretical Analysis

- Monte Carlo simulation results show excellent match to the calculated results.
- Time required to evaluate concatenated code with burst errors on AUI can be significantly reduced.



* Calculated based on model in previous pages.

+ Monte Carlo simulation based on the overall concatenated code.

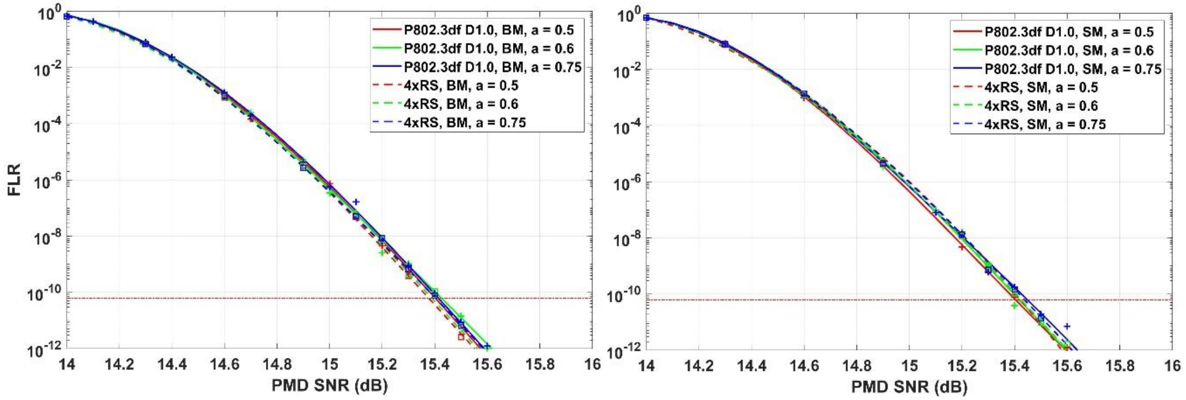
Concatenated Code Performance: P802.3df PCS vs 4xRS Interleave

- Simulation PCS/PMA setup:

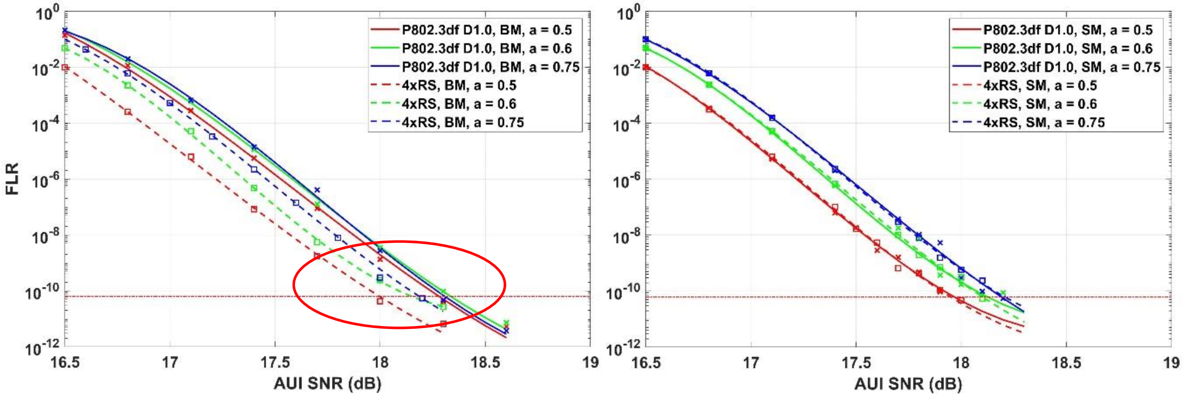
	# of PCS Lanes	PCS to PMA lane muxing	100G/lane to 200G/lane muxing
P802.3df D1.0 BM	32	32:8 bit mux	8:4 **bit mux**
P802.3df D1.0 SM	32	32:8 symbol mux	8:4 **symbol mux**
4xRS BM	8	8:8 symbol streams	8:4 **bit mux**
4xRS SM	8	8:8 symbol streams	8:4 **symbol mux**

- Two sets of comparisons were performed.
  - Sweeping the optical PMD SNR (random errors), with fixed AUI BER with different burst levels;
  - Sweeping the AUI SNR with different burst levels, with fixed optical PMD SNR/BER (random errors).
- 4x RS interleaving with 8 lanes has better performance in terms of AUI burst tolerance in the right two figures.

Fixed AUI BER@1E-5 for each segment



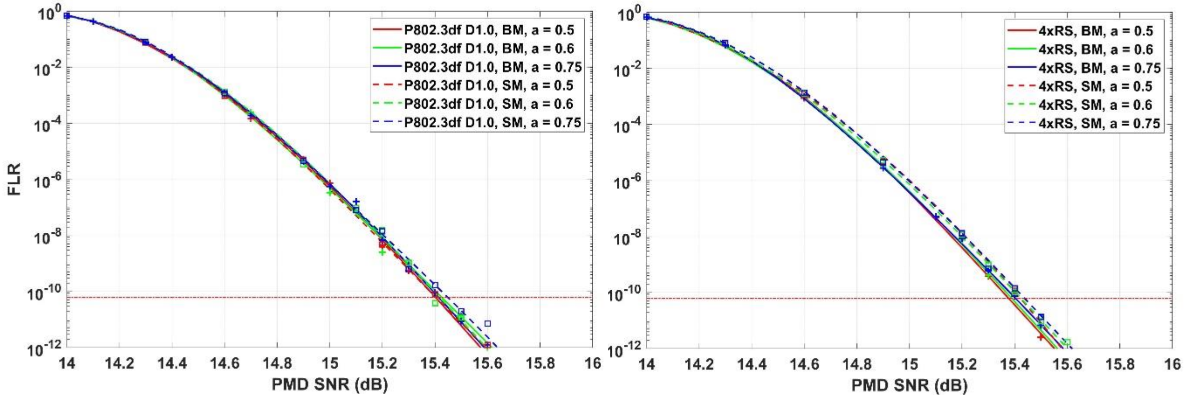
Fixed Optical BER@2.4E-3



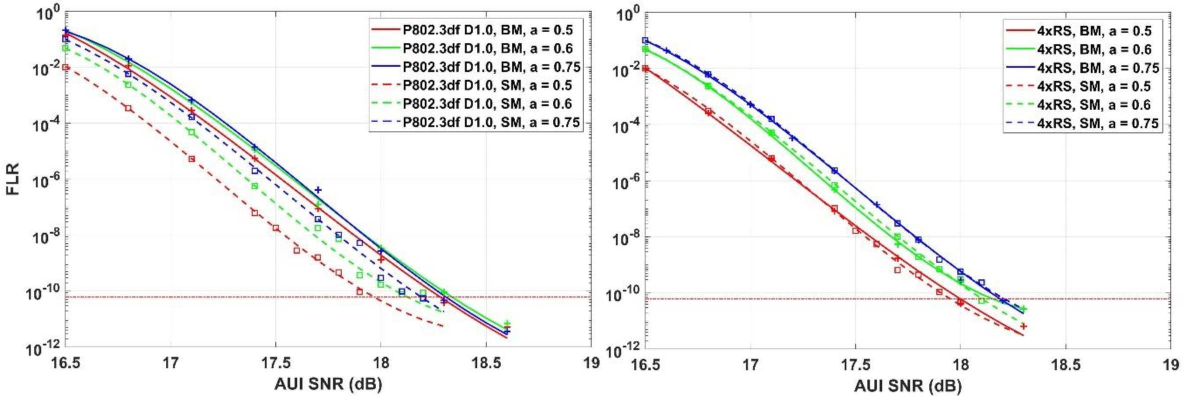
Concatenated Code Performance: Bit Mux vs Symbol Mux

- To compare the performance between bit mux and symbol mux for each PCS/PMA setup, the same sets of data were plotted differently.
- 4 RS codewords interleaving could well cover 4E-5 total AUI BER with bursts.
  - Not much difference can be seen between bit mux and symbol mux if total AUI BER is fixed at 4E-5.
- Using 8 PCS lanes could allow more errors on the AUI.
  - Symbol mux could help for 32 PCS lanes muxing to 8 PMA lanes.
  - There is no clear advantage for symbol mux if 8 PCS lane is used and the muxing ratio is 2:1.

Fixed AUI BER@1E-5 for each segment



Fixed Optical BER@2.4E-3



FEC Performance Results to Meet BER/FLR Objective

- The required SNR and DER at the slicer input, and the corresponding BER values at input of FEC decode to meet FLRs equivalent (6.2E-11) to that of a BER of 1E-13 are:

	AUI (Fixed total BER)			Optical PMD			AUI (Total BER)			Optical PMD (Fixed SNR)		
	SNR	DER	BER*	SNR	DER	BER	SNR	DER	BER*	SNR	DER	BER
a	**P802.3df D1.0, 32:8 bit mux + 8:4 bit mux**						**P802.3df D1.0, 32:8 bit mux + 8:4 bit mux**					
0.5	19.12	4.0E-5	4.0E-5	15.405	6.31E-03	3.16E-03	18.28	1.83E-04	1.83E-04	15.70	4.8E-3	2.4E-3
0.6**				15.425	6.20E-03	3.10E-03	18.34	1.65E-04	1.65E-04			
0.75**				15.415	6.26E-03	3.13E-03	18.31	1.74E-04	1.74E-04			
a	**P802.3df D1.0, 32:8 symbol mux + 8:4 symbol mux**						**P802.3df D1.0, 32:8 symbol mux + 8:4 symbol mux**					
0.5	19.12	4.0E-5	4.0E-5	15.405	6.31E-03	3.16E-03	17.97	3.00E-04	3.00E-04	15.70	4.8E-3	2.4E-3
0.6**				15.42	6.23E-03	3.12E-03	18.12	2.37E-04	2.37E-04			
0.75**				15.45	6.06E-03	3.03E-03	18.19	2.12E-04	2.12E-04			
a	**4xRS, 8:8 + 8:4 bit mux**						**4xRS, 8:8 + 8:4 bit mux**					
0.5	19.12	4.0E-5	4.0E-5	15.38	6.45E-03	3.23E-03	18.00	2.86E-04	2.86E-04	15.70	4.8E-3	2.4E-3
0.6**				15.39	6.40E-03	3.20E-03	18.15	2.26E-04	2.26E-04			
0.75**				15.405	6.31E-03	3.16E-03	18.19	2.12E-04	2.12E-04			
a	**4xRS, 8:8 + 8:4 symbol mux**						**4xRS, 8:8 + 8:4 symbol mux**					
0.5	19.12	4.0E-5	4.0E-5	15.420	6.23E-03	3.12E-03	17.95	3.09E-04	3.09E-04	15.70	4.8E-3	2.4E-3
0.6**				15.425	6.20E-03	3.10E-03	18.10	2.45E-04	2.45E-04			
0.75**				15.44	6.12E-03	3.06E-03	18.20	2.08E-04	2.08E-04			

* These values are the BER including the additional errors due to the bursts and effect of precoding. The values have been multiplied by 2.
** Precoding is turned on for a = 0.6 and 0.75.

Summary

- Mathematical model to evaluate the performance of concatenated code is introduced.
- The PCS/PMA multiplexing scheme will influence the concatenated FEC capability for multi-part link with burst errors.
    - 4× codewords interleave can provide excellent burst tolerance for AUI.
    - Symbol mux outperforms bit mux if there are 32 PCS lanes.
    - No significant FEC performance difference between 2:1 bit and symbol multiplexing for 800 GbE with 8 PCS lanes and 1.6 TbE with 16 PCS lanes.
    - More work is underway for 200G/lane AUIs.

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Thank You!

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