Proposal of Inner Code for 200 Gb/s per Lambda IM-DD Optical PMD

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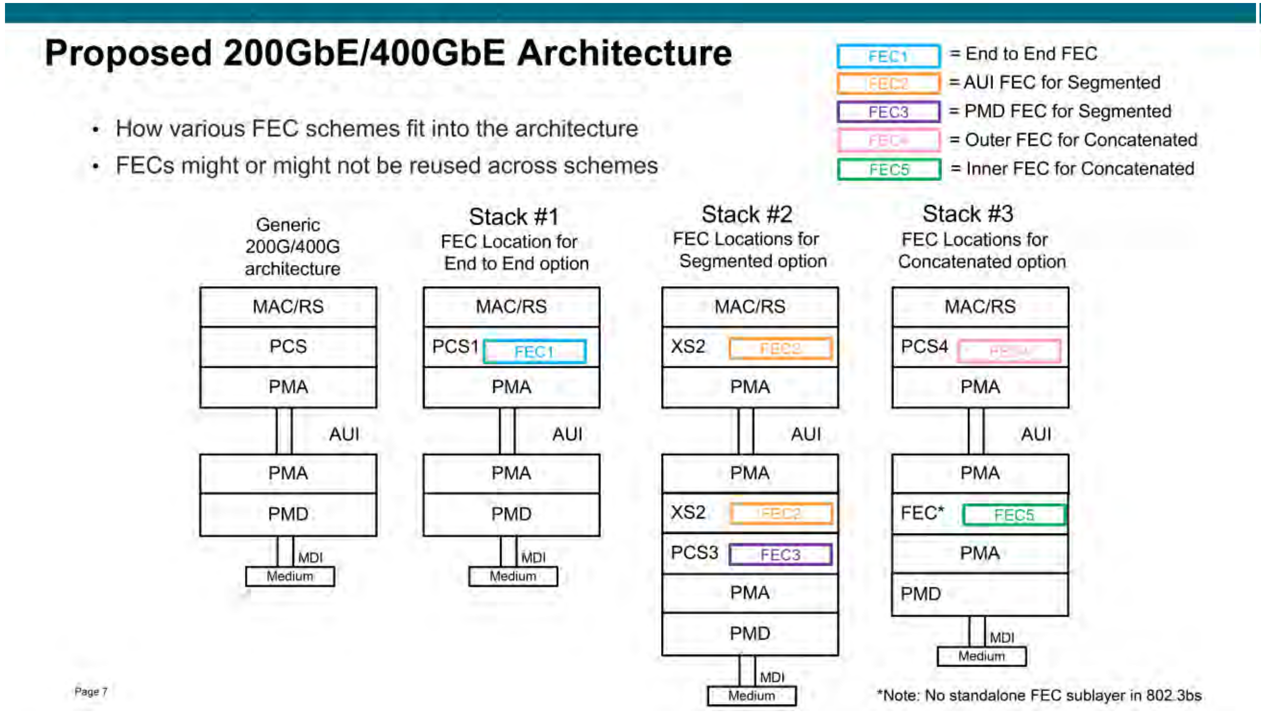
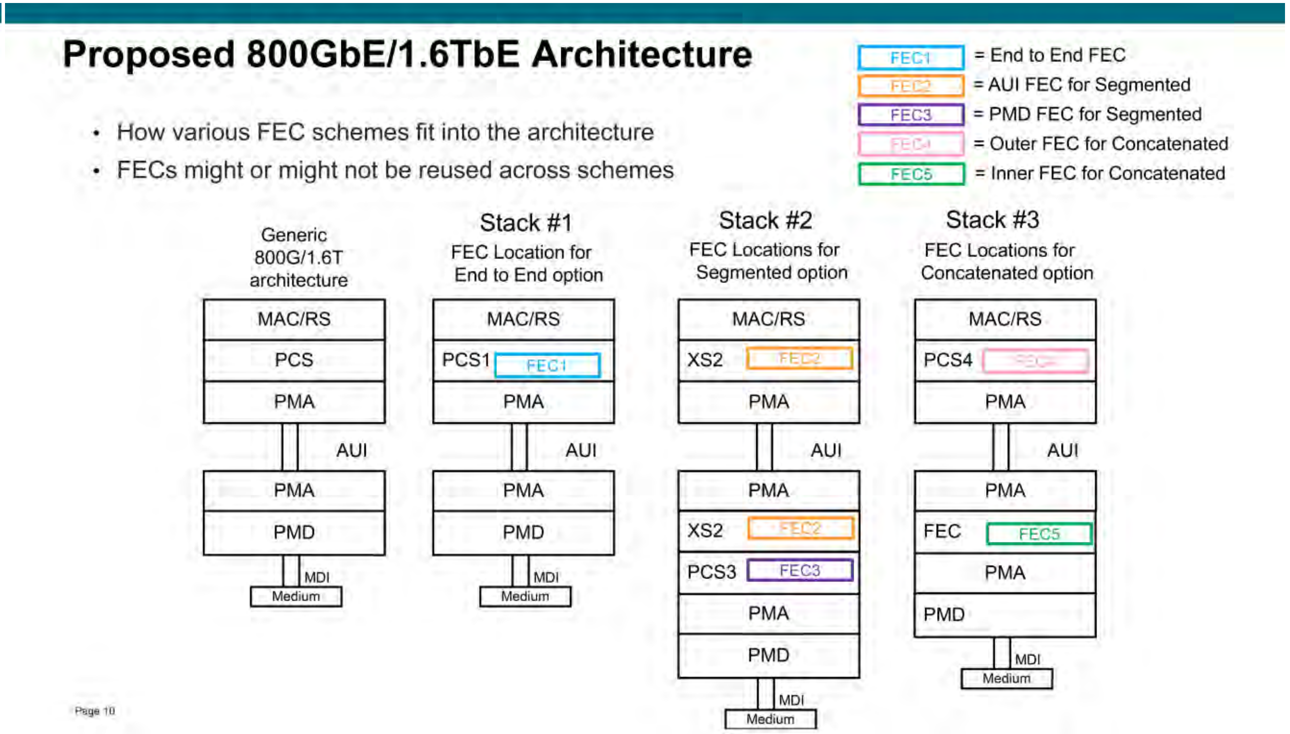
Motivation: Inner Code from Adopted Logic Baseline

- Adopted logic layer baseline includes stack #3 for concatenated scheme.
- In Gustlin_3df_01_2211XX, RS(544,514) is proposed for FEC1/2/4.
- FEC5, inner code, is proposed in this contribution based on KP4 RS(544,514) as the outer code.
  - Concatenated inner code does not preclude segmented KP4 if/as needed by 200G AUI





https://www.ieee802.org/3/df/public/22_05/22_0517/gustlin_3df_01a_220517.pdf

Soft-Decision Concatenated* Inner Codes for Higher Coding Gain

- Soft-decoded Inner concatenated codes with KP4 outer code are the only proposals with high net coding gain, and low area, power, and latency
  - An extra dB or two of operating link margin, over that provided by end-to-end KP4 RS(544,514) FEC, would be helpful in enabling a robust and diverse optical component roadmap

- Several soft-decision BCH/Hamming codes have been proposed that relax pre-FEC BER of 200 Gb/s per lane PAM4 optical PMD from ~2.4e-4 (KP4 alone) to the range of ~[2e-3 to 4.8e-3]
  - A. 15/16 rate Extended Hamming(128,120) in patra_3df_01__2207, bliss_3df_01c_220517
  - B. 17/18 rate Hamming (BCH) (144,136) in he_3df_01_221005
  - C. 17/19 rate Hamming (BCH) (76,68) further shortened from BCH(144,136) in he_3df_01_221005
  - D. 17/18 rate Extended Hamming code with coding properties of binary (76,68), constructed as a shortened (128,120), but which protect as a binary (144,136) code per bliss_3df_01_220929
    - XOR(MSB,LSB) of the 68 message PAM4 symbols reduces the inner code ‘message’ to 68 bits

***Note**: Concatenated coding is flexible in allowing both an end-to-end as well as segmented approach

Inner Code Rates: 15/16, 17/18, or 17/19

- 5.88% overhead from rate 17/18 code choice is advantageous
  - Avoids further line bit rate increases and their associated losses and costs
  - Keeps the simple historic Xtal references

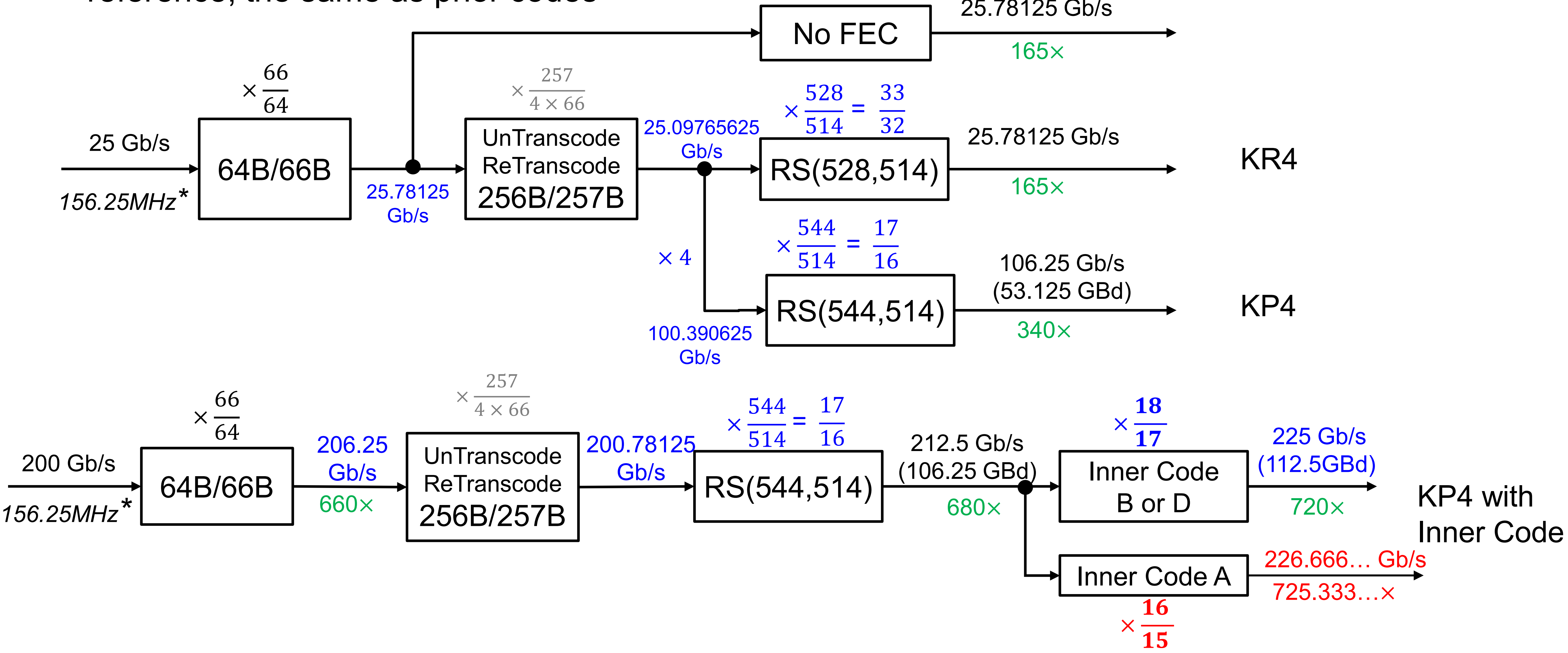
Code Option	Inner code	Code Rate	Codeword effective n *bits*	Message effective k *bits*	Baud Rate (GBd)	Bit Rate (Gb/s)	Multiple of 156.25MHz	BER_in for KP4 threshold*
A	Extended Hamming (128,120)	15/16	128	120	113.333 …	226.666 …	~725.333 …	5.5e-3
B	BCH(144,136)	17/18	144	136	112.5	225	720	5.0e-3
C	Shortened BCH(76,68) from BCH(144,136)	17/19	76	68	118.75	237.5	760	8.2e-3
D	Extended Hamming (128,120) shortened to (76,68) with XOR of message PAM-4 bits	17/18	144	136	112.5	225	720	5.0e-3

*Simulated with maximum likelihood decoding

*Line bit error rate input to Soft Hamming Decoder to achieve <3.2e-4 before and <1e-13 after KP4 decoding for AWGN w/ sufficient interleaving

Inner Code Rate and Prior Ethernet Rates

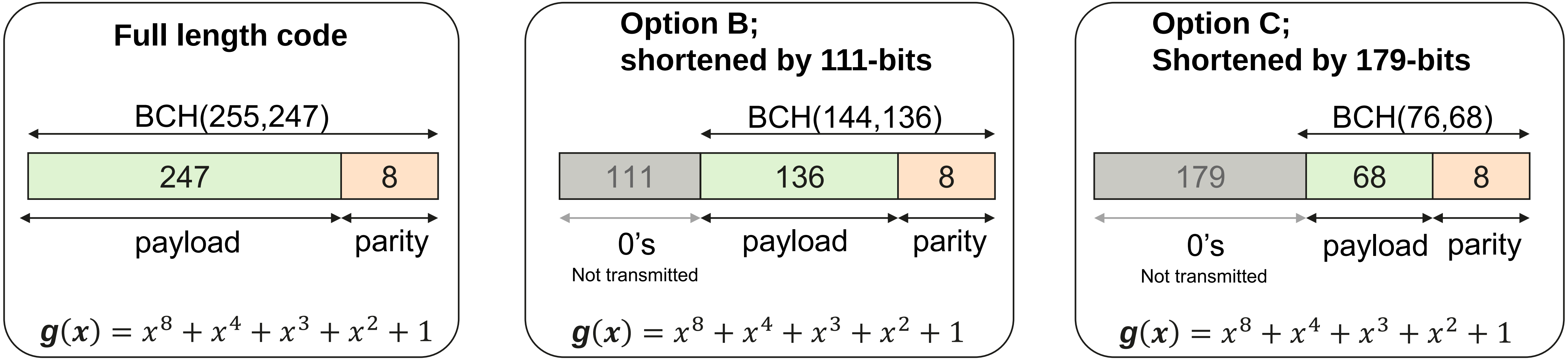
- The inner code rate choice of 17/18 gives Baud rate an integer multiple of the 156.25MHz Xtal reference, the same as prior codes



*Example Xtal frequency. Other frequencies like 312.5MHz are also popular in new Ethernet transceiver designs.

Inner Code **Options B&C**: BCH(144,136) and (76,68)

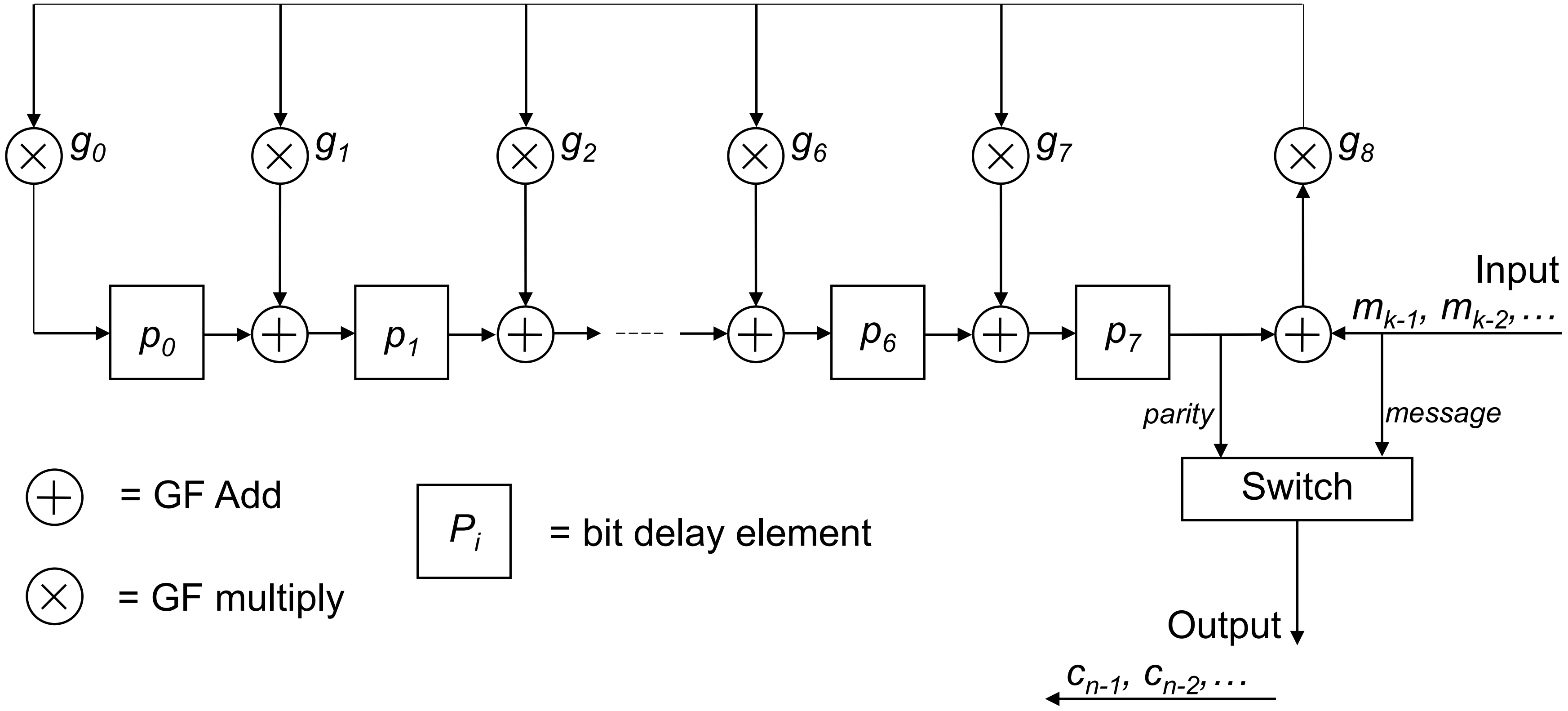
- In he_3df_01_221005, constructing a narrow-sense binary primitive BCH code with t = 1.
  - Shorten the m = 8 primitive BCH(255,247), by prefixing to the message bits a sequence of 0s.
    - E.g., we can use primitive polynomial $x^8 + x^4 + x^3 + x^2 + 1$ ("implicit + 1" notation 0x8E) to construct the code.
    - There are many other primitive polynomials with degree of 8: 0x95, 0xAF, 0xB1, 0xB2, 0xB4, 0xE1, 0xF3, ...
    - The zero prefix sequence is not transmitted and is only used to calculate the parity of the primitive code.



Generator polynomial unchanged.

Inner Code **Option B**: BCH(144,136) Encoder Functional Model

- For $g(x) = x^8 + x^4 + x^3 + x^2 + 1$ of BCH(144,136), the 9 coefficient are 100011101, MSB on the left.
- The parity calculation shall produce the same result as the shift register implementation below in the similar form as in 119.2.4.4 for RS encoder and 115.2.3.3, 115.2.4.3.2 for BCH encoder.
- The outputs of the delay elements are initialized to zero prior to the computation of the parity for a given message.



Inner Code **Option D**: 17/18 rate extended Hamming code using a code shortened from (128,120) to (76,68)

136 bits payload | 8 bits parity

68 PAM-4 symbols payload | 4 PAM-4 symbols parity

Physically on the line. Rate is 136/144 = 17/18

- XOR(MSB,LSB) reduces the code payload from 68 Bauds to 68 bits
- The code format is binary (76,68), which can be a shortened extended Hamming (128,120) code

68 bits ‘code’ payload | 8 bits parity

- Decoding the shortened code points to the PAM-4 symbols to ‘correct’, which is unambiguous and essentially lossless compared to pointing to ‘bits’

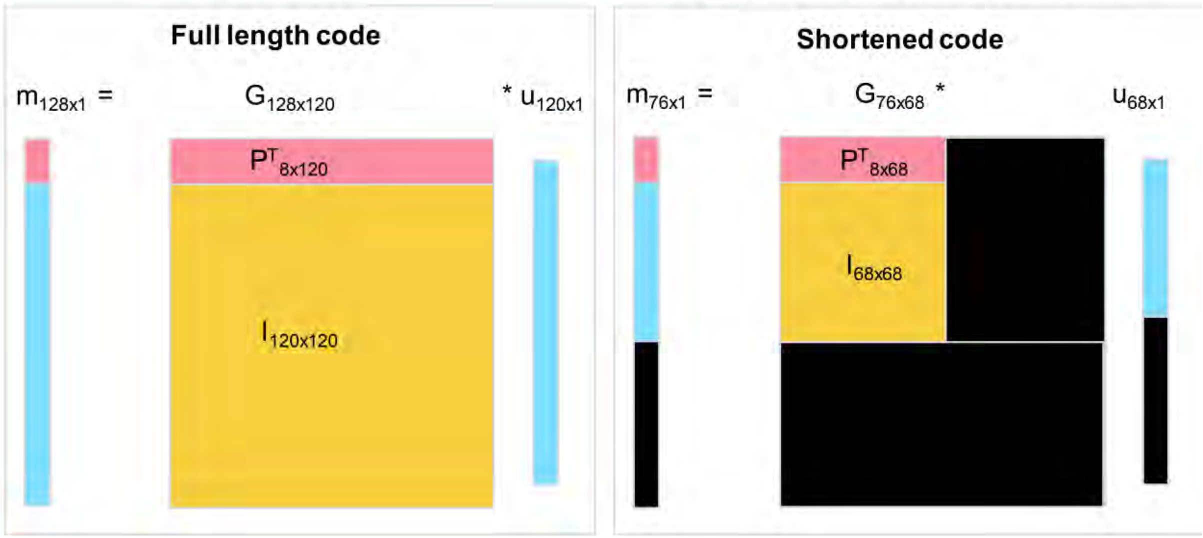
https://www.ieee802.org/3/df/public/22_10/22_1005/bliss_3df_01_220929.pdf

Inner Code **Option D**: 17/18 rate extended Hamming code using a code shortened from (128,120) to (76,68)

- The proposed code, like all systematic codes, is simple to 'shorten'.
- Message bits not used can conceptually be filled with zeros.
- Received bits not used likewise can be zeroed out.
- Which makes clear the components of G and of H that can be deleted.
- The 52 right side columns of G and the bottom 52 rows of G are deleted.
- Similarly, the 52 right side columns of H are deleted.

Shortening the (128,120) code to binary (76,68); G

- The 52 right side columns and 52 bottom rows of G are deleted



Shortening the (128,120) code to binary (76,68); H

- The 52 right side columns of H are deleted

Proposal

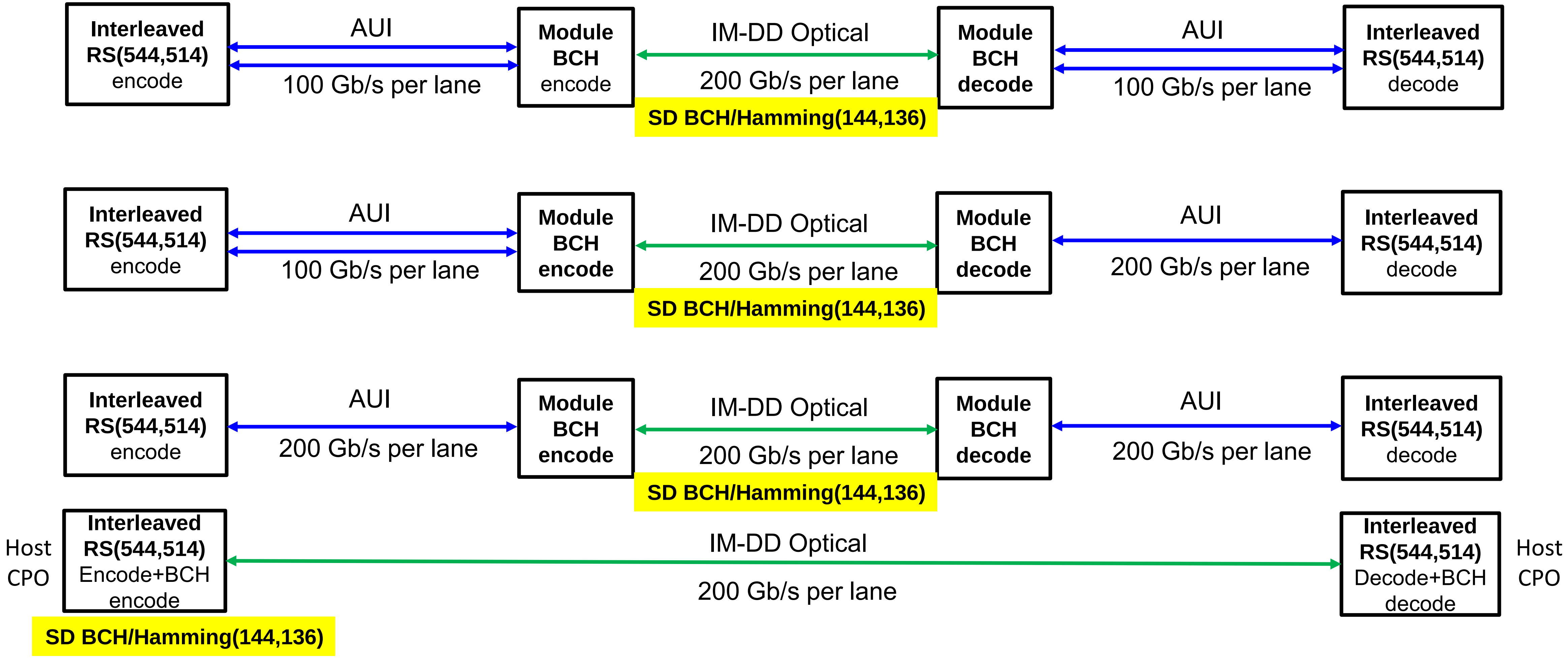
- Adopt a soft-decoded 17/18 rate BCH/Hamming code as the inner code of a concatenated code for 200G IM-DD optical PMDs
  - With effective (n,k) of (144,136)
  - With outer code KP4 RS(544,514)
  - Interleaving and multiplexing details can be performed in the optical PMD, with details TBD
- Benefit to the Task Force:
  - Narrows down FEC discussion to accelerate choosing a suitable inner code and format
  - Allows for an end-to-end as well as segmented approach allowing KP4 terminate/regenerate mode if required

Future Work for 200G Optical

- Define inner code exactly
  - Code rate and code parameters fixed
  - Codeword generating method: E.g., matrix of option D, or polynomial of option B, etc.
- Define overall format
  - Define Mapping / Distribution of PCS lanes to 200G lanes
  - Define Interleaving in 200G lanes
- Support forward looking development, especially for next generation 200G AUI
  - Pre-FEC BER targets for optical link for a range of future AUI performances
  - Develop segment/link quality metrics to aid user monitoring

Attractive and Challenging Application Example

- Using RS(544,514) at host ASIC as outer code for both AUIs and optical with soft-decision BCH/Hamming rate 17/18 effective (144,136) for optical
  - Lower area, power and latency for overall system
  - Consider breakout or next-generation 200/400GbE



Summary

- Adopt soft-decision BCH/Hamming at 225 Gbit/sec with the code rate of 17/18 as the inner concatenated code.
  - BCH(144,136) as in slides #7-10 are two example codes to be considered
  - Target input BER of <4.5e-3 from optical PMD
- RS(544,514) as the outer code to construct the concatenated code.
- Help the Task Force focus on 200 Gb/s per lane IM-DD optical and 200 Gb/s AUI PMDs discussions.

Thanks!