Architectural Considerations for Type 2 PHY/FEC Scheme (Concatenated FEC) for 200G per Lane IMDD

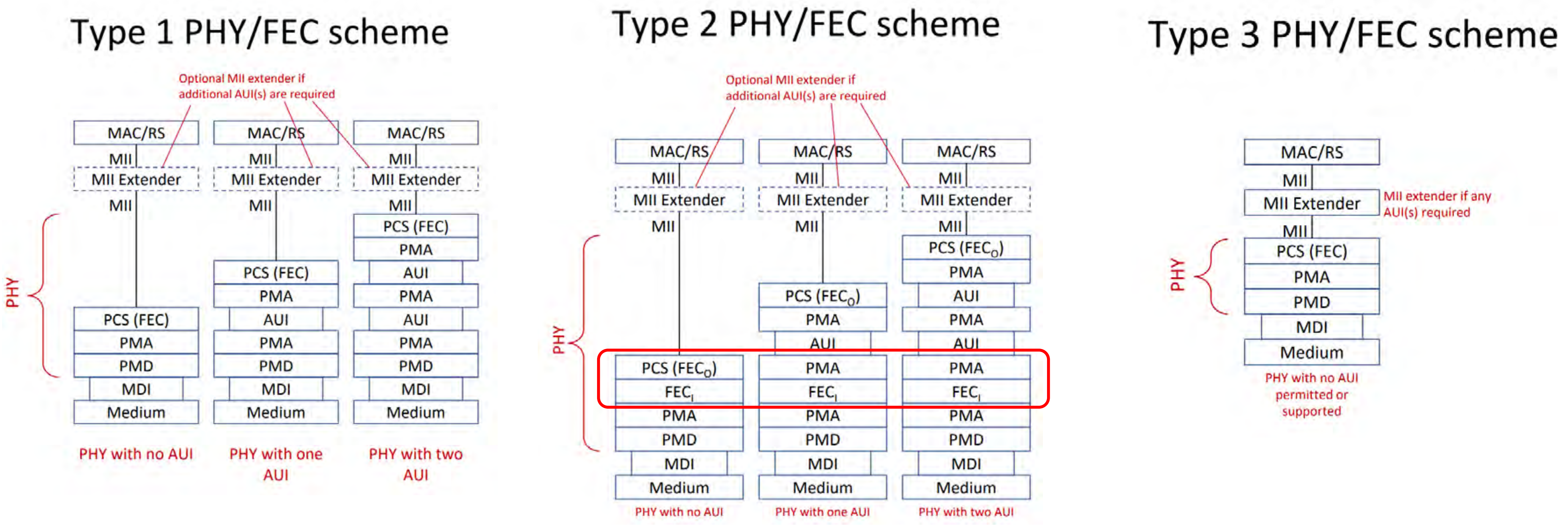
Xiang He, Huawei Technologies

Introduction

- Before we can develop a full baseline for Type 2 PHY/FEC, we need to reach consensus on the architecture first.
- The intention is to provide the architecture for all the Ethernet rates from 200GE to 1.6TE.
- The intention is to be inclusive of all proposals being considered.

Type1/2/3 PHY/FEC Schemes

- In brown_3dj_optx_adhoc_01a_230222, three types of PHY/FEC schemes were named and illustrated.
- The PMA below FEC_I is different from the BASE-R PMA, and requires dedicated clauses to describe the functions and service interfaces.
  - FEC_I is referred to as FEC_I, and PMA below FEC_I is referred to as PMA_I in this presentation.



List of Things to Consider

1. PHYs being addressed
2. PHY/FEC type
3. # of AUIs per PHY link
4. Assumed BER per AUI and burst error characteristics
5. PMD Link Burst Error Characteristics
6. Inner FEC Encode
7. Inner FEC pre-encoding interleaving characteristics
8. Post-encoding interleaving

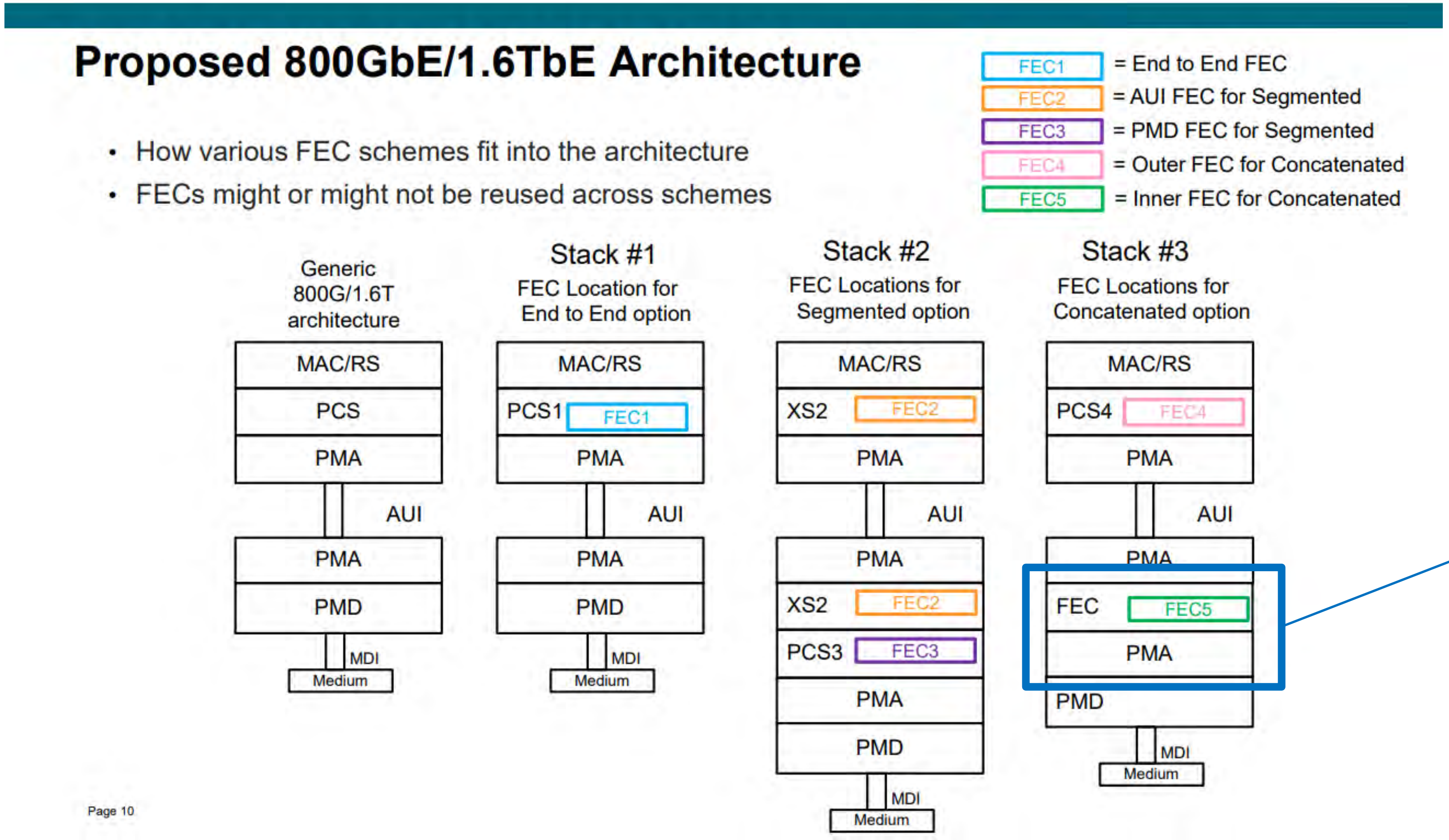
PHYs Being Addressed

Ethernet Rate	Assumed Signaling Rate	AUI	BP	Cu Cable	MMF 50m	MMF 100m	SMF 500m	SMF 2km	SMF 10km	SMF 40km
200 Gb/s	200 Gb/s	1 lane		1 pair			1 pair	1 pair		
400 Gb/s	100 Gb/s							4 pairs		
	200 Gb/s	2 lanes		2 pairs			2 pairs			
800 Gb/s	100 Gb/s	8 lanes	8 lanes	8 pairs	8 pairs	8 pairs	8 pairs	8 pairs		
	200 Gb/s	4 lanes		4 pairs			4 pairs	1) 4 pairs 2) 4 λ's		
	200 Gb/s (TBD)								*Single SMF 4 λ's (TBD)*	
	800 Gb/s (TBD)								*Single SMF 1 λ (TBD)*	*Single SMF 1 λ (TBD)*
1.6 Tb/s	100 Gb/s	16 lanes								
	200 Gb/s	8 lanes		8 pairs			8 pairs	8 pairs		

- Assuming that a concatenated inner FEC is required, this may apply to all PHYs highlighted.
- Two AUI segments each side can be supported if the BER for each is below 5E-5.
- One AUI segment with higher BER (<1E-4) can be allowed on each side.

Fit Into the Adopted Architecture

- This proposal fits within the adopted 802.3dj logic architecture.



gustlin_3df_01a_220517

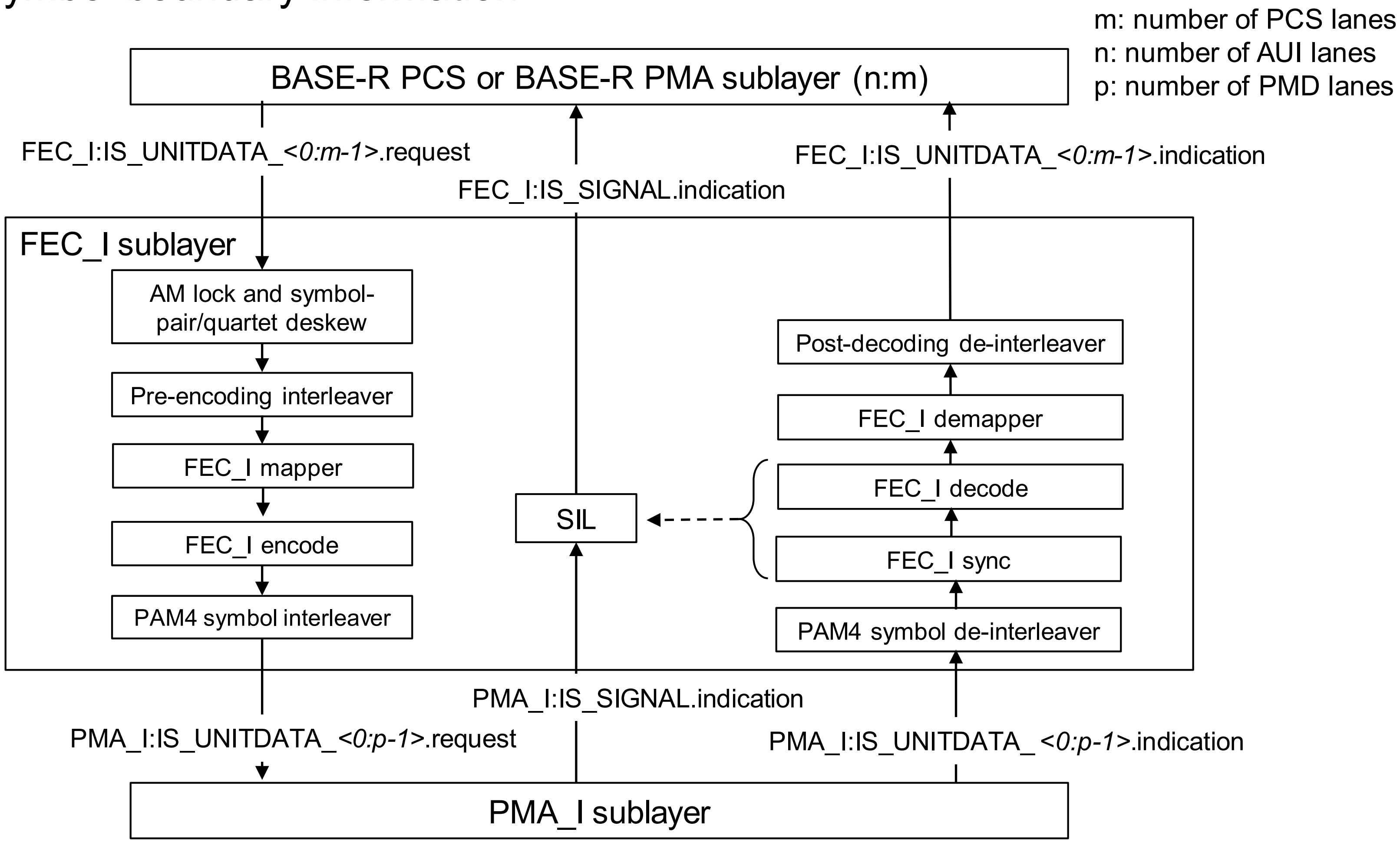
Interesting sublayers of this presentation

New Clauses and Subclauses

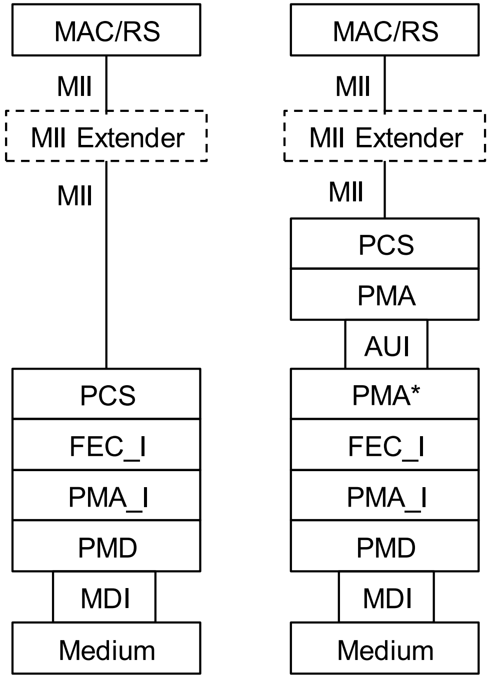
- Overview
  - Scope of inner FEC (FEC_I) and PMA_I sublayer, type 200GBASE-DR1/FR1, 400GBASE-DR2, 800GBASE-DR4/DR4-2/FR4/LR4 and 1.6TBASE-DR8/DR8-2
  - Relationship of FEC_I and PMA_I sublayers to other standards
  - Inter-sublayer interfaces
  - Functional block diagram
- FEC_I (Inner FEC) sublayer
  - Transmit: pre-encoding (convolutional) interleaver, FEC_I encode and post-encoding (PAM4 symbol) interleaver
  - Receive: pre-decoding (PAM4 symbol) de-interleaver, FEC_I sync, FEC_I decode and post-decoding de-interleaver
  - Bypass of pre-encoding interleaver
  - FEC_I degrade monitoring
- PMA_I sublayer
  - Overview
  - Service interface
  - Functions within the PMA, including soft-decision information for FEC_I decoding.
- Detailed functions and state diagrams
- Delay constraints

Transmit and Receive Flow of FEC_I Sublayer

- Rely on BASE-R PMA FEC-symbol-pair muxing discussions for 200G/lane PMDs.
- The “AM lock and symbol-pair/quartet deskew” function is required if BASE-R PMA does not provide symbol boundary information.



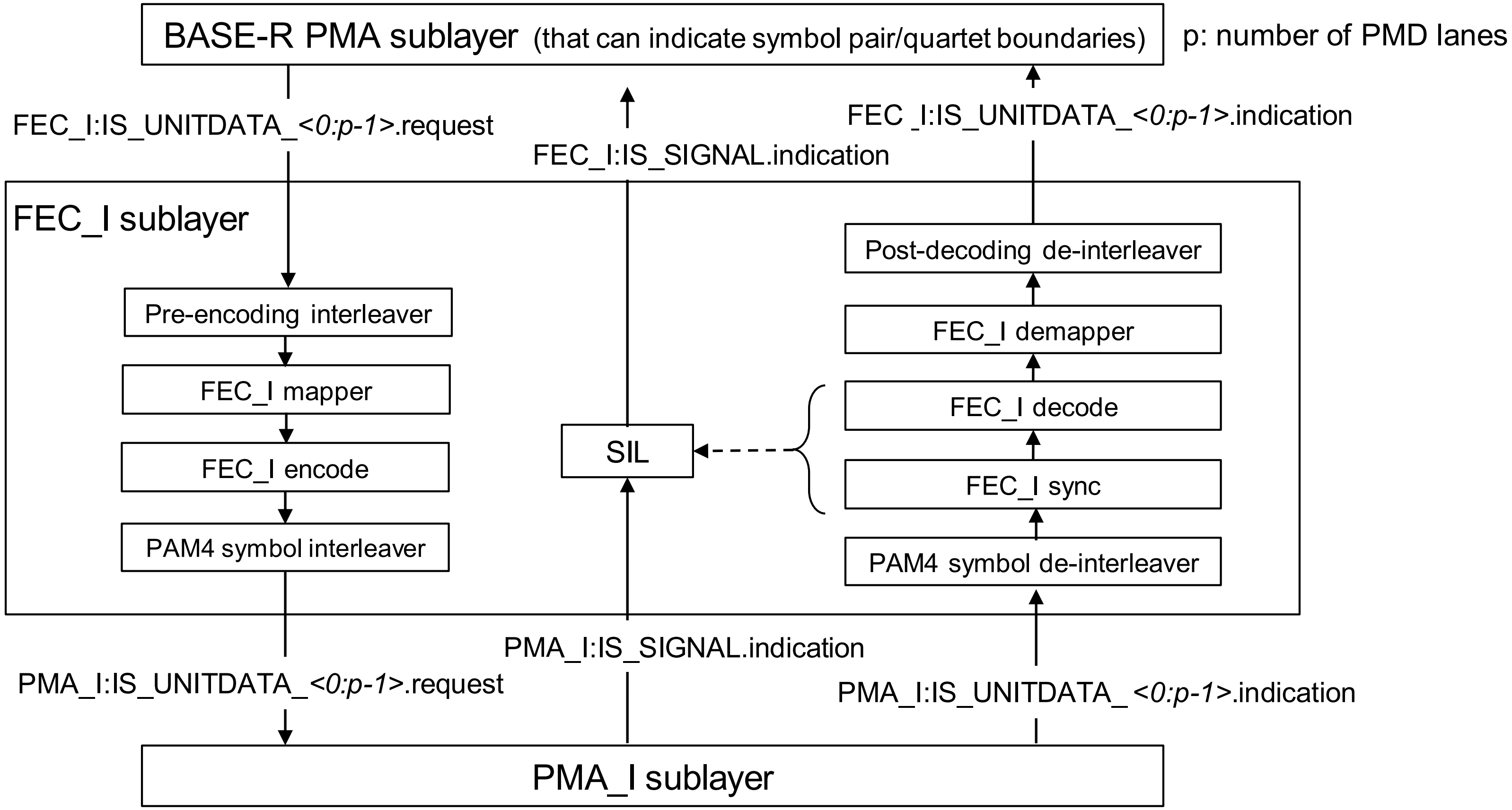
Example stacks



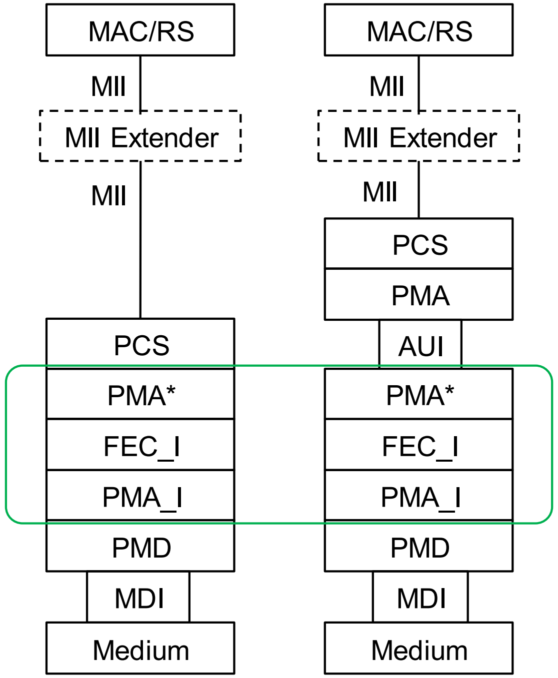
* This BASE-R PMA is bit-muxing PMA

Transmit and Receive Flow of FEC_I Sublayer (alternate)

- Rely on BASE-R PMA FEC-symbol-pair muxing discussions for 200G/lane PMDs.
- The BASE-R PMA indicates the symbol-pair/quartet boundary, or transmit symbols in 20b/40b groups.



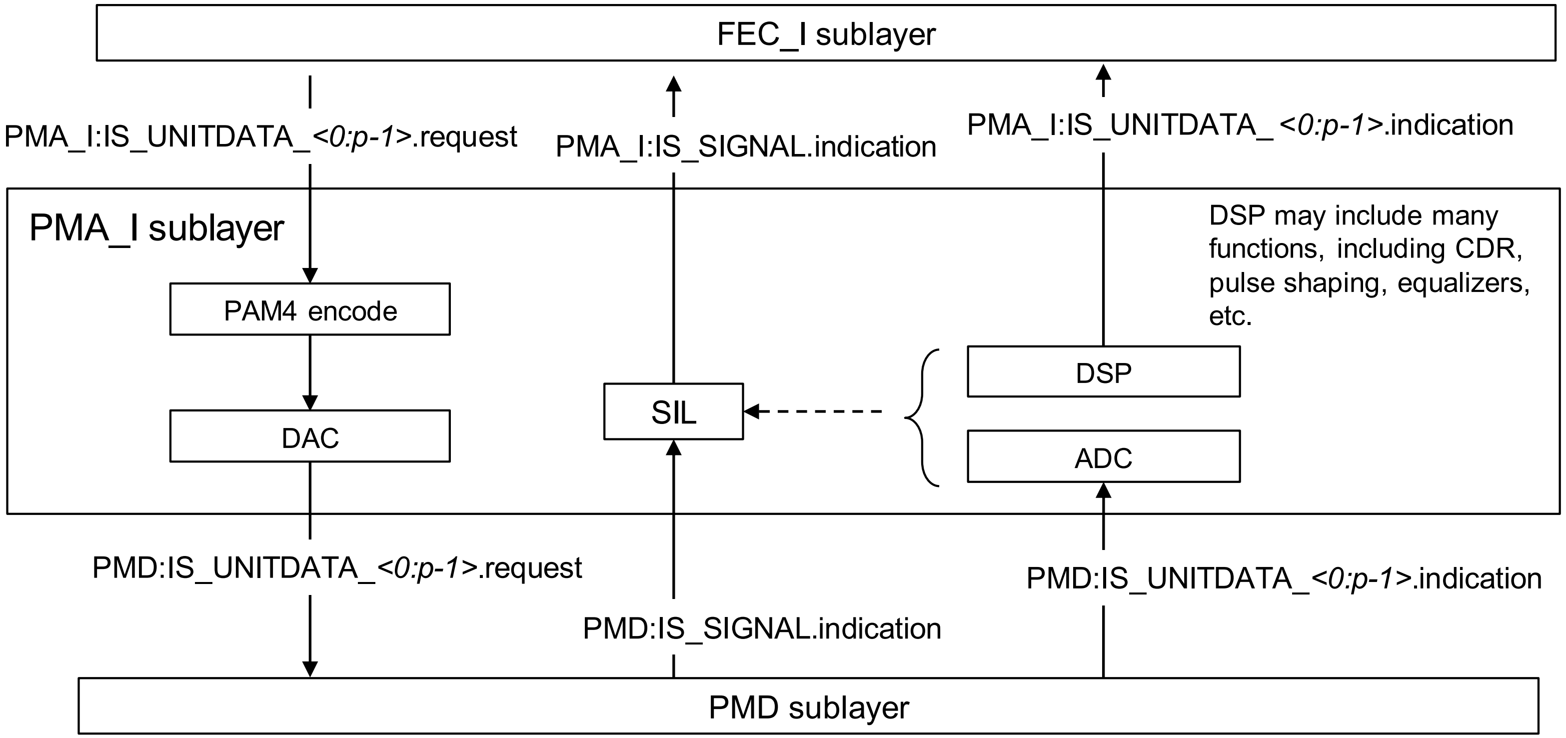
Example stacks



*This BASE-R PMA is the new PMA discussed in ran_3dj_01_2303.

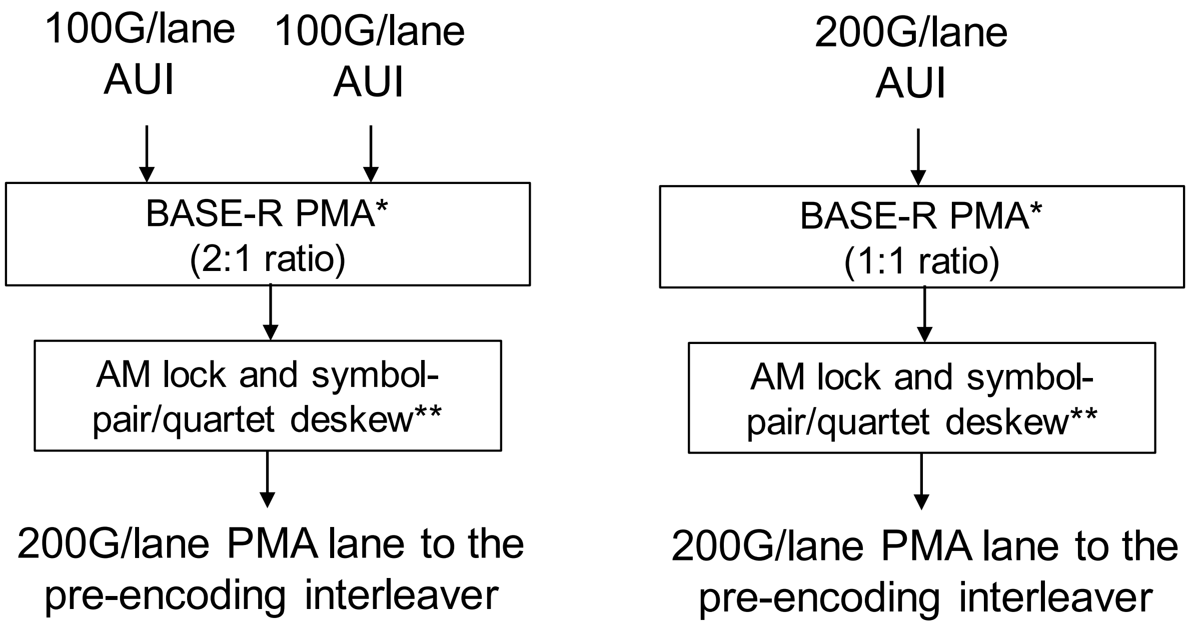
Transmit and Receive Flow of PMA_I Sublayer

- The PMA service interface is provided to allow the inner FEC sublayer to transfer information to and from the PMD sublayer.
- The PMA_I:IS_UNITDATA.indication primitive defines the transfer of a FEC_I codeword from the PMA_I to the FEC_I sublayer via the (rx_symbol) parameter.
  - The rx_symbol parameter conveys the sampled PAM4 symbols, and the resolution is implementation dependent.



Transmit Functions – AM lock and symbol-pair/quartet deskew

- Data obtained from PMA shall be aligned to symbol-pair (20b) boundary for 200 GbE and 400 GbE, or symbol-quartet (40b) boundary for 800 GbE and 1.6 TbE.
  - There is no need to perform full PCS lane deskew.
- It is recommended to include this function in the BASE-R PMA, and making the FEC_I sublayer generic through all Ethernet rates with 200G/lane optical PMDs.

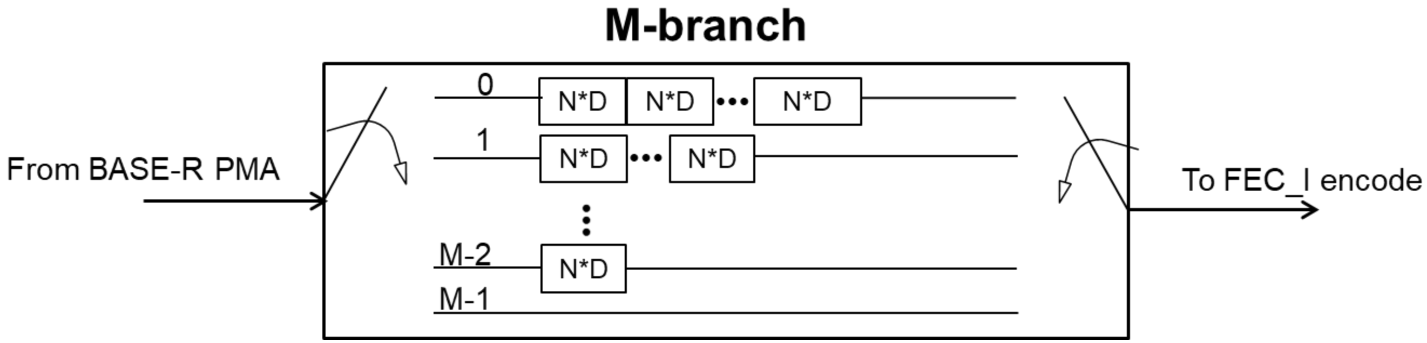


* See ran_3dj_01_2303

** Not needed if pre-encoding interleaver is bypassed

Transmit Functions – Pre-encoding interleaver

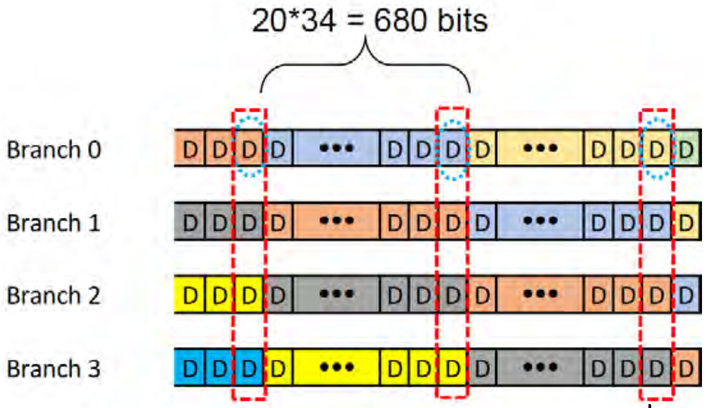
- The pre-encoding interleaver is a convolutional interleaver which could have a lower latency than a block interleaver with the same interleaving depth.
  - It contains M parallel delay lines (branches) with decreased delays from branch 0 to M-1.
  - Data sequence from the BASE-R PMA lane is distributed in fixed-size blocks to the M branches sequentially in a round-robin fashion.
  - The number M, N and D are code dependent.



- The pre-coding interleaver should be excluded for DR/DR-2 links.
  - Preferred to be PMD dependent. It can also be transmitter controlled.
  - For DR/DR-2 links, data from BASE-R PMA can be directly encoded by FEC_I.

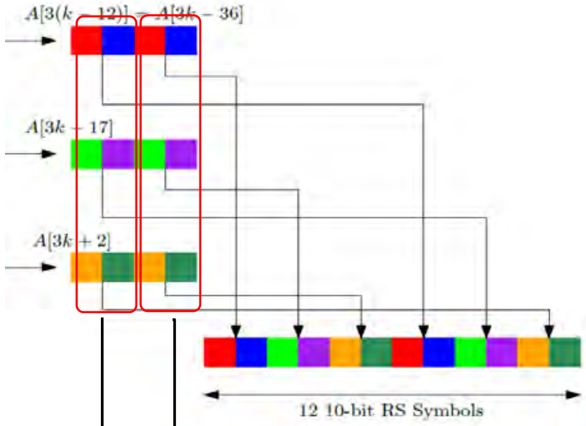
Transmit Functions – FEC_I Mapping

- Data mapping into FEC_I payloads should be defined based on whether pre-encoding interleaver is used.
  - Based on convolutional interleaver design, mapping may be different. Existing proposals have given clear mapping methods.
  - If pre-encoding interleaver is used, FEC_I payload should be aligned to symbol-pair/quartet boundarie.



he_3dj_01a_230206

One codeword



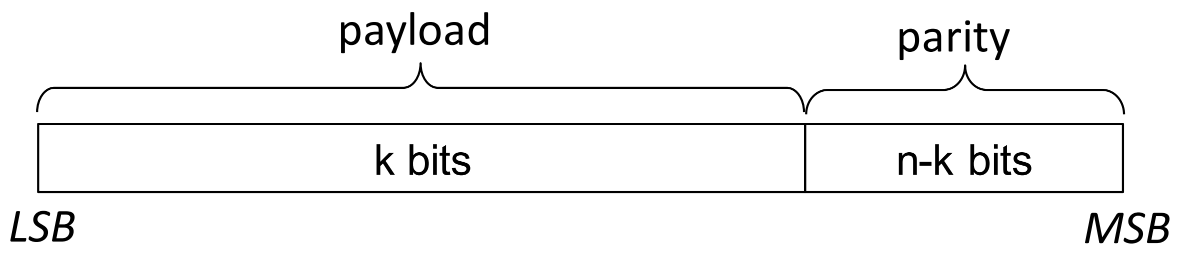
One codeword

farhood_3dj_01a_230206

- If convolutional interleaver is excluded, the bit stream can be encoded directly.
- Padding bits, if needed, can be inserted before encoding as FEC_I payloads.

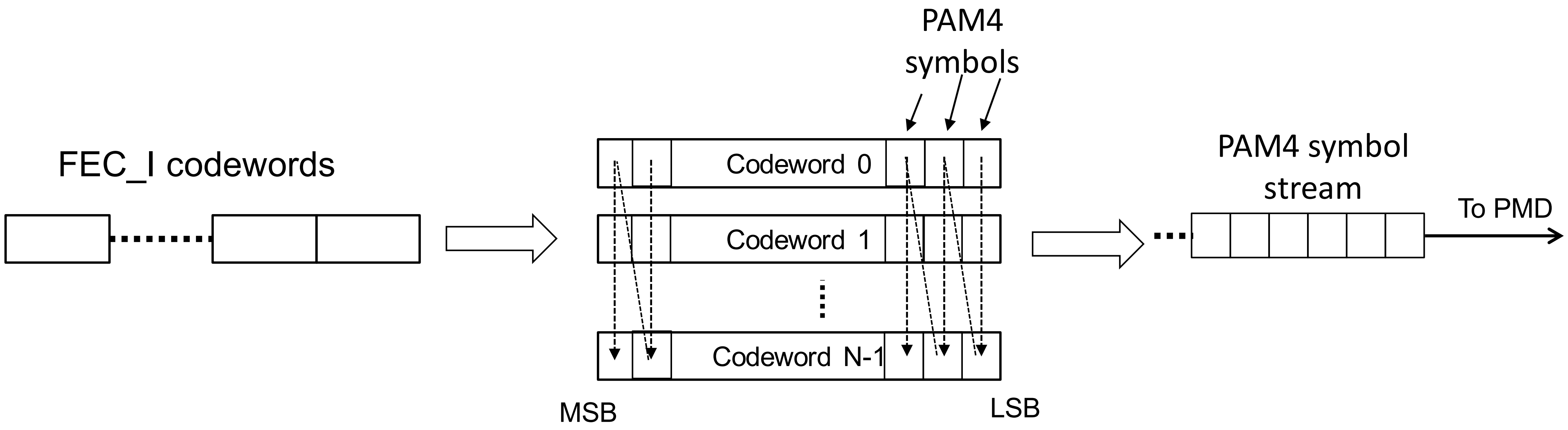
Transmit Functions – FEC_I Encode

- Different encoding methods have been proposed.
  - BCH polynomial as proposed in he_3df_01_221005, and in back up slide.
    - For 8-bit parity calculation, we could either use an 8th order polynomial as a primitive code, or use a 7th order poly times a (x+1) term as an extended code.
  - The XOR(MSB/LSB) method as proposed in bliss_3df_01b_2211.
  - The Hamming generation matrix with XOR(MSB/LSB) as proposed in farhood_3dj_01a_230206.
    - As proposed, there is not enough information for implementation.



Transmit Functions – Post-encoding PAM4 symbol interleaver

- The PAM4 symbol interleaver (aka channel interleaver) can help light bursts on PMD.
  - Simulation result has been provided in back up slide #27.
  - It can be deleted if later determined to be unnecessary based on optical track discussions on 200G/lane IMDD PMDs.
  - If not required, this function can be deleted and FEC_I codewords are directly mapped to PAM4 symbols.

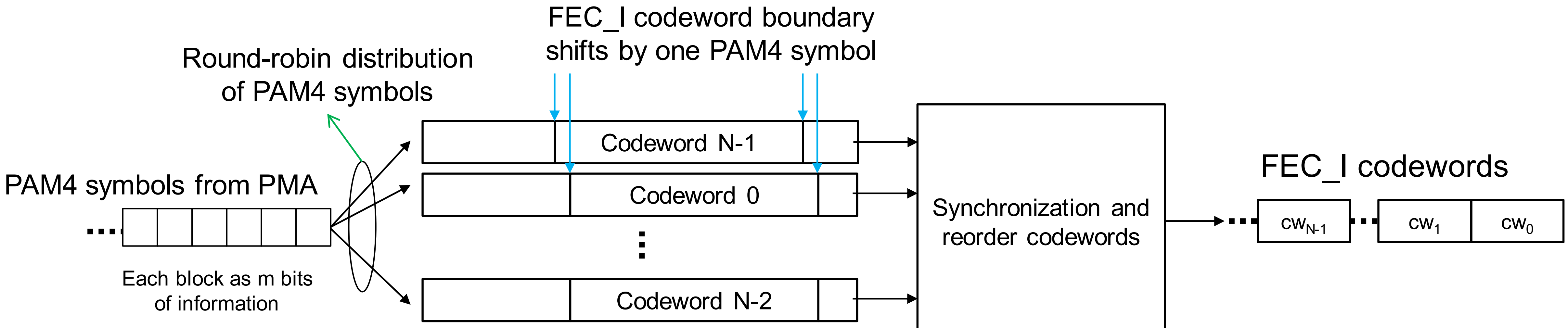


Receive Functions – Soft information signaling

- Each PAM4 symbol is sampled into an implementation dependent format, with more than 2 bits of resolution for each PAM4 unit interval.
- Each sample is transferred to the FEC_I sublayer through the PMA service interface.
  - Soft-decoding is required to achieve the PMD BER threshold.
  - Implementation can have the freedom to reduce the sample resolution or disable the soft-decoding to save power and latency, if it finds the BER is low enough.

Receive Functions – pre-decoding de-interleaving and FEC_I sync

- PAM4 de-interleaving can be performed arbitrarily, leaving the synchronization and reorder function to find the FEC_I codeword boundaries and orders.
- Each row can use self-sync method as shown in slide #26.
  - After each row of codewords are synchronized, the row where the boundary shifts one symbol ahead is the leading codeword for each group of N interleaved codewords.
- Synchronization can also be obtained by using alignment markers when padding is used.



PAM4 symbol de-interleave to N lanes of codeword streams.
The order of codewords is intentionally shown out of order.

Receive Functions – FEC_I decode

- Decoding of FEC_I is implementation dependent.
  - Using soft-decision or hard-decision is also implementation dependent and does not affect interoperation, but will result different BER thresholds.
  - BER thresholds shall be given explicitly with AUI BER taken into account. Slide #25 in back up gives an example.

Receive Functions – FEC_I demapping

- Once decoded, the demapper restores the FEC_I payload data into multiple branches for the convolutional de-interleaver.
- It is the reverse function of FEC_I mapping.
  - Paddings, if used, can be removed here.

Receive Functions – de-interleaver

- The convolutional de-interleaver shall perform the reverse function of the interleaver and produces data sequence as it was sent out of the BASE-R PMA.
- When the pre-encoding interleaver (convolutional interleaver) is excluded, the de-interleaver is also excluded.
- The synchronized FEC_I codewords can guarantee a successful de-interleaving.

FEC_I Degrade Monitoring

- Counters can be used to monitor the codeword error ratio of FEC_I for a given period of time.
  - Detailed usage can be further discussed.
- The propagation of FEC_I degrade signals is implementation dependent.

Summary

- This presentation illustrates the concatenated FEC may be fit into the 802.3 architecture.
- A complete baseline should include all transmit and receive functions.
- Leveraging the symbol-pair muxing PMA work may simplify the FEC_I sublayer.

Thank you

Back up slides

PMD BER Threshold Considering AUI

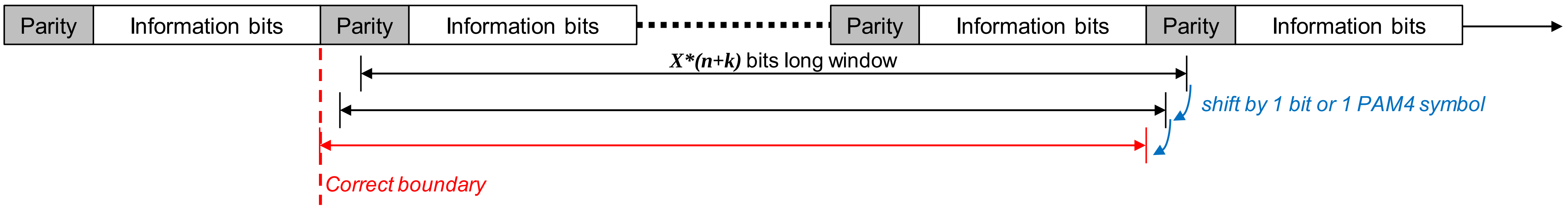
- Up to 2 segments of AUI on each side, not including MII Extenders, shall be supported.
- The combined effect of FEC_I and FEC_O results in the target frame loss ratio (FLR) for the PHY.
  - AUI BER threshold will affect the PMD BER allowed.
  - BER threshold listed below are updated data based on he_3dj_01a_230206.pdf and he_3df_01_2211.pdf.

AUI BER (each segment)	PMD (w/ Convo. Int.)	PMD (w/o Convo. Int.)
1E-5	4.4E-3*	3.1E-3*
5E-5	3.5E-3*	2.4E-3*

*Assuming the error statistics are sufficiently random. If the error statistics are not sufficiently random, the BER allowed shall be lower.

Receive Functions – FEC_I self-sync

- Follows Firecode methodology.
- Steps:
  1. **Search and Test:** Check N codewords, see if at least n of them are correct.
     – More preferably, we can try all possible positions, check N codewords for each position, and pick the position that has the most correct codewords. This may require less iterations.
  2. **Validate:** See in the following P codewords, if at least p codewords are also good.
     – If so, sync established. If not, go back to step 1.
     – If the number N in step 1 is large enough, step 2 may not be needed.
  3. **Monitor and Drop:** When there are m codewords with errors in the following M codewords.
     – Same methodology as hi_ser.



Effect of PAM4 Symbol Interleaver

- Following table lists BER threshold for BCH(144,136) with 8:1 post-encoding PAM4 symbol interleaver.
- The latency of 8:1 PAM4 interleaver is about ~5ns. The FEC_I decoding latency is about ~10ns.

AUI (Fixed total BER)		Optical PMD					Coding Gain Improvement, dBe
"a"	4x AUI Total BER	1-tap DFE value[b]	w/ 8:1 PAM4 symbol interleaver		w/o 8:1 PAM4 symbol interleaver		
			SNR, dBe	BER[c]	SNR, dBe	BER[c]	
0.5	4E-5 (4x1E-5)	--	14.99	4.50E-03	14.99	4.50E-03	--
		0.28	15.15	4.38E-03	15.31	3.81E-03	0.16
		0.5	15.93	3.07E-03	16.52	1.64E-03	0.59
0.75[a]	4E-5 (4x1E-5)	--	15.01	4.43E-03	15.01	4.43E-03	--
		0.28	15.16	4.34E-03	15.33	3.75E-03	0.17
		0.5	15.94	3.04E-03	16.53	1.62E-03	0.59
0.5	2E-4 (4x5E-5)	--	15.16	3.93E-03	15.16	3.93E-03	--
		0.28	15.30	3.85E-03	15.49	3.25E-03	0.19
		0.5	16.08	2.64E-03	16.78	1.21E-03	0.70
0.75[a]	2E-4 (4x5E-5)	--	15.27	3.55E-03	15.27	3.55E-03	--
		0.28	15.41	3.49E-03	15.61	2.91E-03	0.20
		0.5	16.19	2.35E-03	16.97	9.63E-04	0.78

a. Precoding is turned on.

b. 1-tap DFE is used to simulate error propagation instead of using error propagation probability "a" value. Tap value of 0.28 is equivalent to a = 0.1, and tap value of 0.5 is equivalent to a = 0.375.

c. The BER values includes additional errors due to bursts and the effect of precoding.