Various Convolutional Interleaver Options for Inner FEC Code (128,120)

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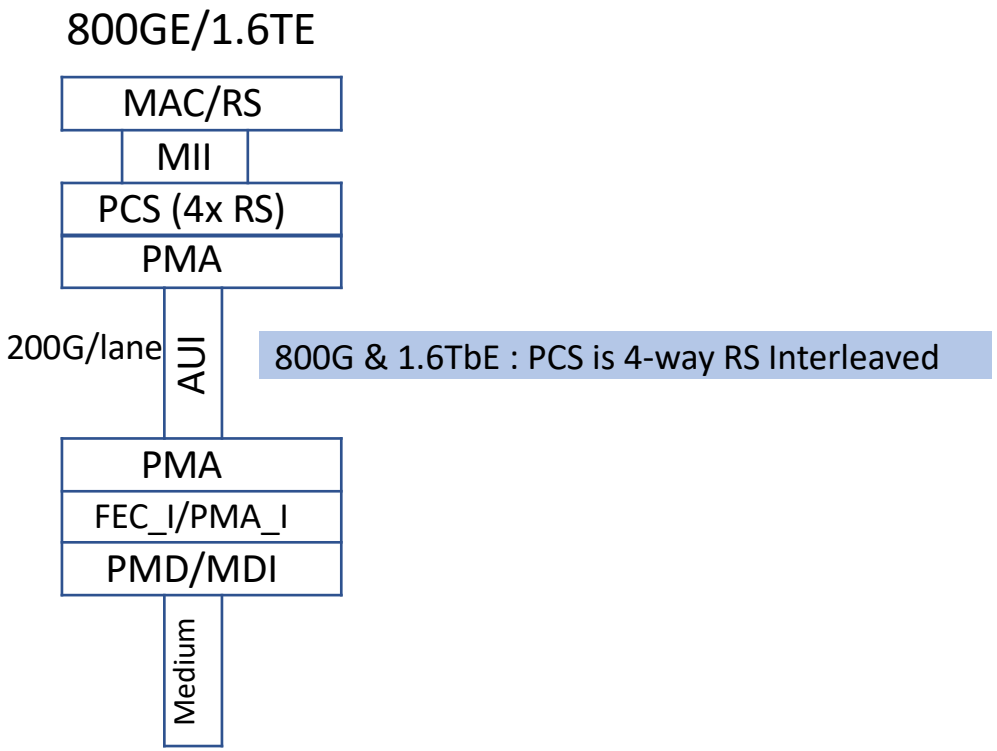
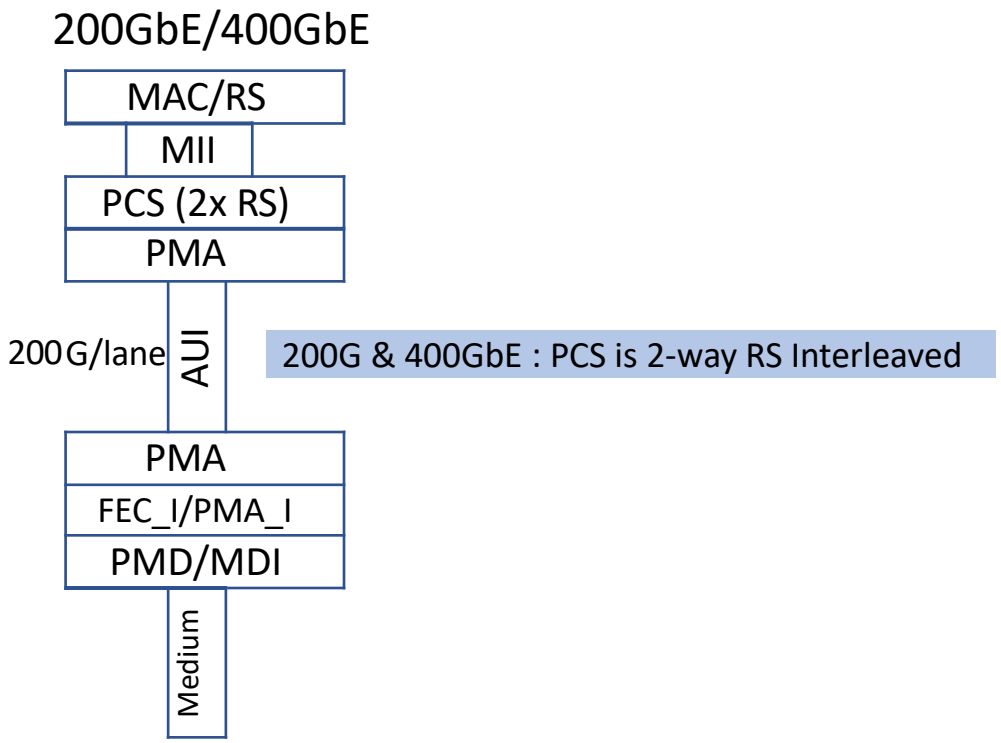
Goal of this Presentation

This presentation describes the end-to-end latency & coding gain trade offs associated with various Convolutional Interleaver depth with inner code (128,120) for 200GbE, 400GbE, 800GbE & 1.6TbE MAC configurations.

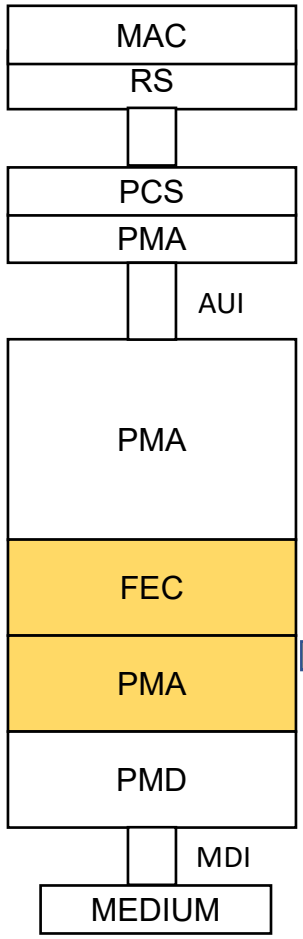
Recap of 200G/400G/800G/1.6T PCS FEC Interleaving Status





- As defined in IEEE:
  - 200G & 400GbE is 2 way Interleaved. 800GbE & 1.6TbE is 4-way RS interleaved per 200G/Lane PMD
  - 200G & 400GbE is 2 way Interleaved. 800GbE is 2 way Interleaved per 100G/lane PMD
  - 1.6TbE is 4-way RS Interleaved based on 100G/lane PMD

Recap of Inner FEC Architecture & Work in Progress

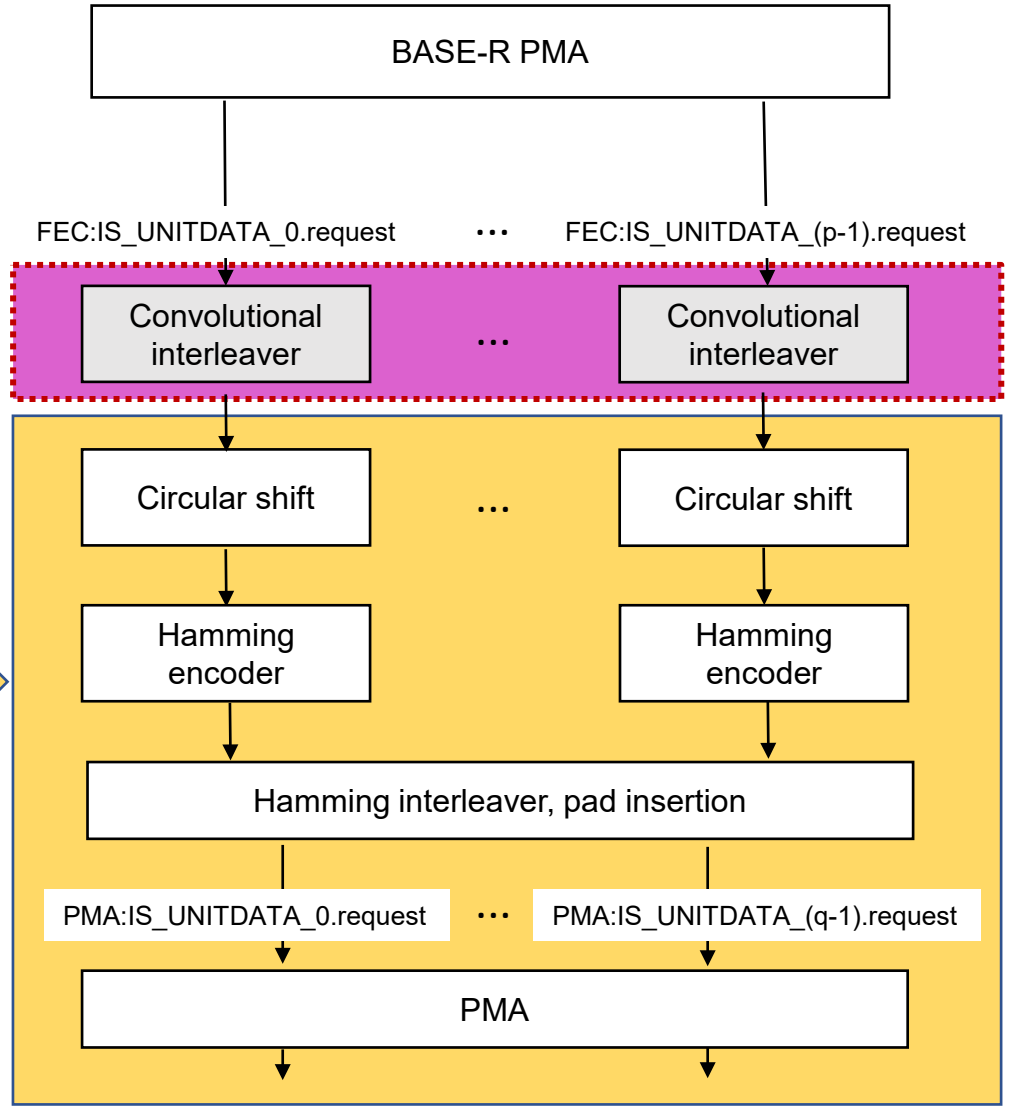


Type 2 scheme

Work in Progress:

- Rate of Convolutional Interleaver for 200G/400G/800GbE
- Inner FEC sublayer for 1.6TbE

* Most of the Inner Code FEC sublayer is adopted except few blocks



Recap of PCS/XS (RS-FEC) Latency & Inner Code FEC (128,120) Latency

- **An example of RS FEC Latency for 200G/400G/800G/1.6TbE**
  - Core clock 1 GHz
  - 3 clock cycles for encoder (3ns)
  - codewords are corrected in parallel
  - 31 clocks cycles for correction (31ns)
  - 3 clock cycles for decoder miscellaneous (3ns)
  - 4 x 5440 bit-times for 800G (25.6ns) and 1.6T (12.8ns) for codeword storage
  - 2 x 5440 bit-times for 200G (51.2ns) and 400G (25.6ns) for codeword storage
- **Total:**
  - 200GE: 3 + 3 + 31 + 51.2 = 88.2ns
  - 400GE: 3 + 3 + 31 + 25.6 = 62.6ns
  - 800GE: 3 + 3 + 31 + 25.6 = 62.6ns
  - 1.6TE: 3 + 3 + 31 + 12.8 = 49.8ns

- **An example of Inner Code Encoder & Decoder Latency**
  - 1 GHz core clock
  - BCH Encoder/Decoder
    - 2 clock cycles for encoder (2ns)
    - 128 * 8 bit-times for the decoder BCH codeword de-interleaver (4.52ns)
    - 15 clock cycles for decoder error correction (15ns)
    - 2 clock cycles for decoder miscellaneous (2ns)
    - **Total:**
      - 2 + 4.52 + 15 + 2 = 23.5ns

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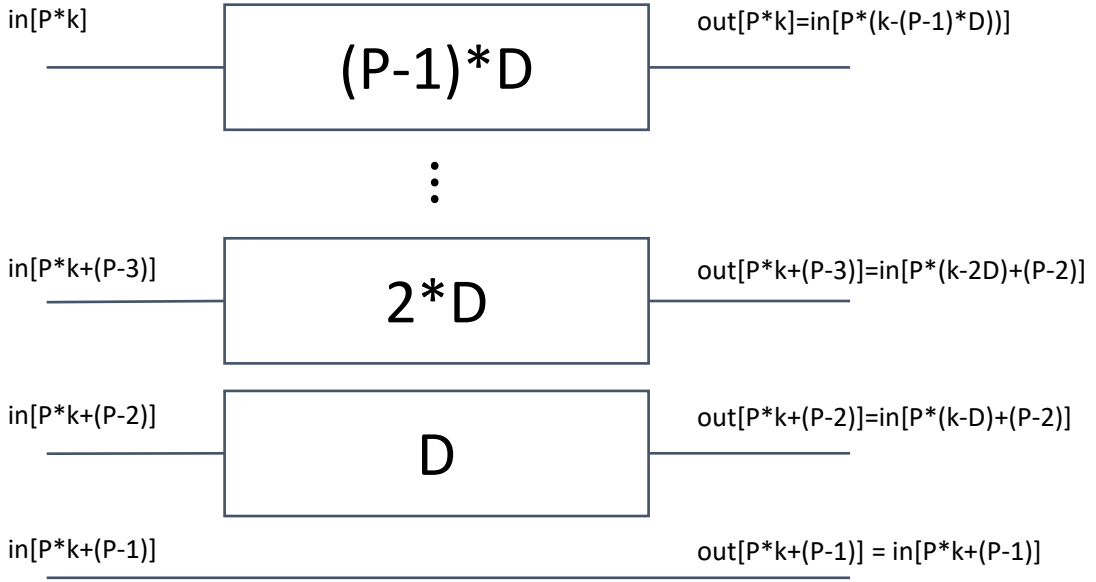
Generic Representation of Parametrized Per-Lane *Convolutional Interleaver*

- Convolutional Interleaver is defined per PCS lane
- Parameters for the per-lane Convolutional Interleaver
  - W: Number of KP4 RS codewords in each “word”
  - P: Number of sub-lanes of Interleaver
  - D: Number of “word” delays
  - k : Time index
  - in[k]: Input “word” at time index k
  - out[k]: Output “word” at time index k

W-symbol words at Interleaver input are round-robin distributed to P sub-lanes



W-symbol words from P sub-lanes are round-robin multiplexed to Interleaver output

Convolutional Interleaver + Inner Code (128,120) Latency for 200G per Lane PMD

Client Type	Convolutional Interleaver	Parameters for Interleaver	FEC	Decoder Input BER	Latency
1.6TBASE-R (4 way interleaved)	12-way Convolutional Interleaver	W=4,P=3,D=12	KP4 + Inner code(128,120)	~4.8E-3 (alpha=0.75)	~27ns
800GBASE-R (4 way interleaved)		W=4,P=3,D=6			~54ns
400GBASE-R (2 way interleaved)		W =2,P =6,D =6			~135ns
200GBASE-R (2 way interleaved)		W =2,P =6,D =12			~271ns

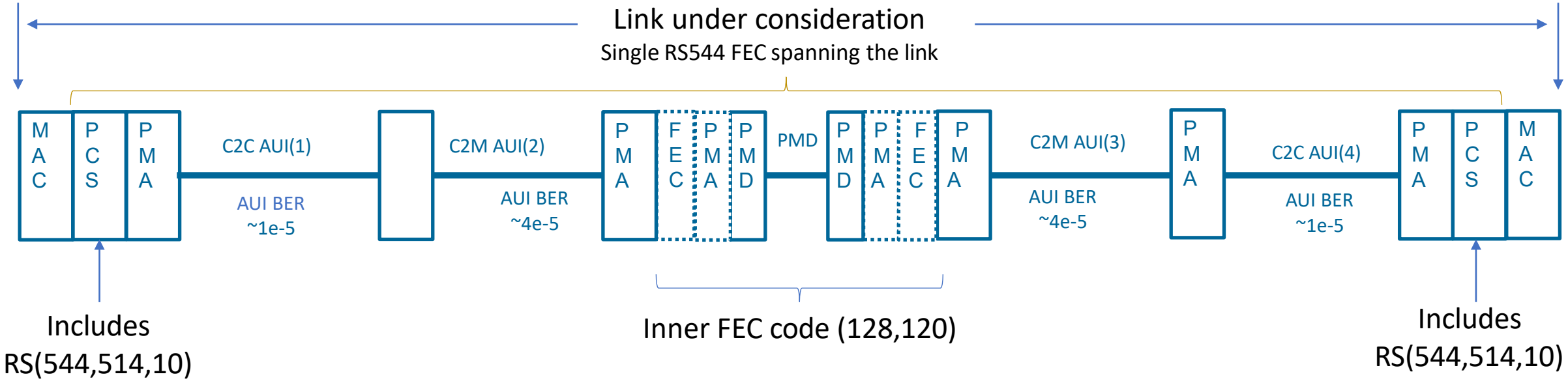
Client Type	Convolutional Interleaver	Parameters for Interleaver	FEC	Decoder Input BER	Latency
1.6TBASE-R (4 way interleaved)	6-way Convolutional Interleaver	W=6,P=2,D=12	KP4 + Inner code(128,120)	~3.6e-3 (alpha=0.75)	~13ns
800GBASE-R (4 way interleaved)		W=6,P=2,D=6			~27ns
400GBASE-R (2 way interleaved)		W =4,P =3,D =6			~54ns
200GBASE-R (2 way interleaved)		W =4,P =3,D =12			~110ns

AUI/PMD BER budgeting

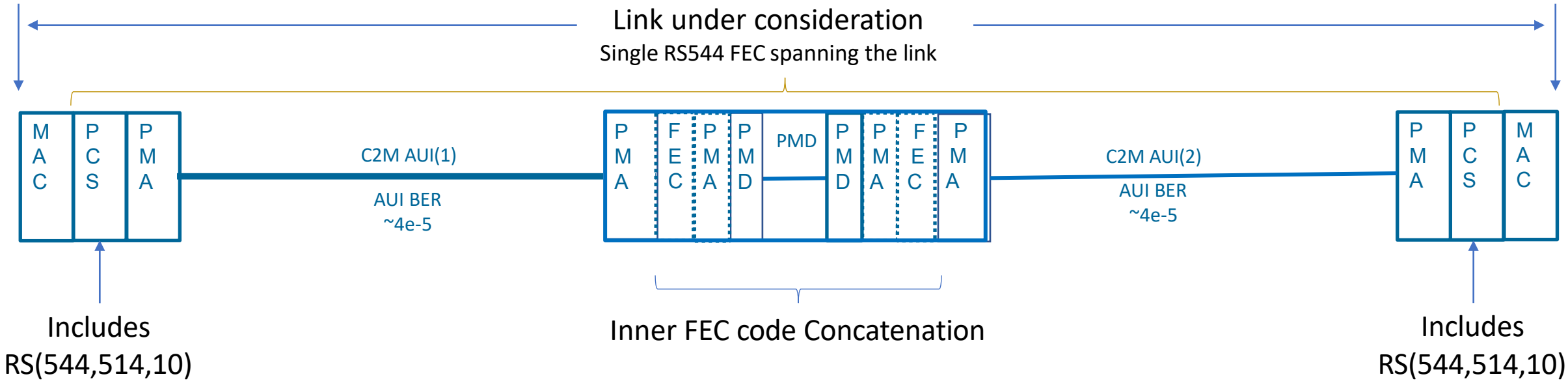
- In the following pages, we go over multiple FEC implementation schemes including protection of the AUI and PMD solely through the concatenated code scheme as well as the so called “extender” type ideas where the KP FEC is terminated and regenerated at each AUI point to decouple the PMD from the AUI

- When using a non-extended architecture, we then assume a 2 segment AUI (2xC2M) as well as a 4 segment AUI (2xC2M+2xC2C)

- To make the analysis simple, and to avoid getting into the EXACT BER allocation for each AUI segment, when the architecture does not use extender, we assume a **total of 1e-4** measured AUI BER for **aggregate** of ALL AUI errors. For example, we propose per AUI measured error of **4e-5 for each segment of C2M AUI** and **1e-5 for each segment of C2C AUI**



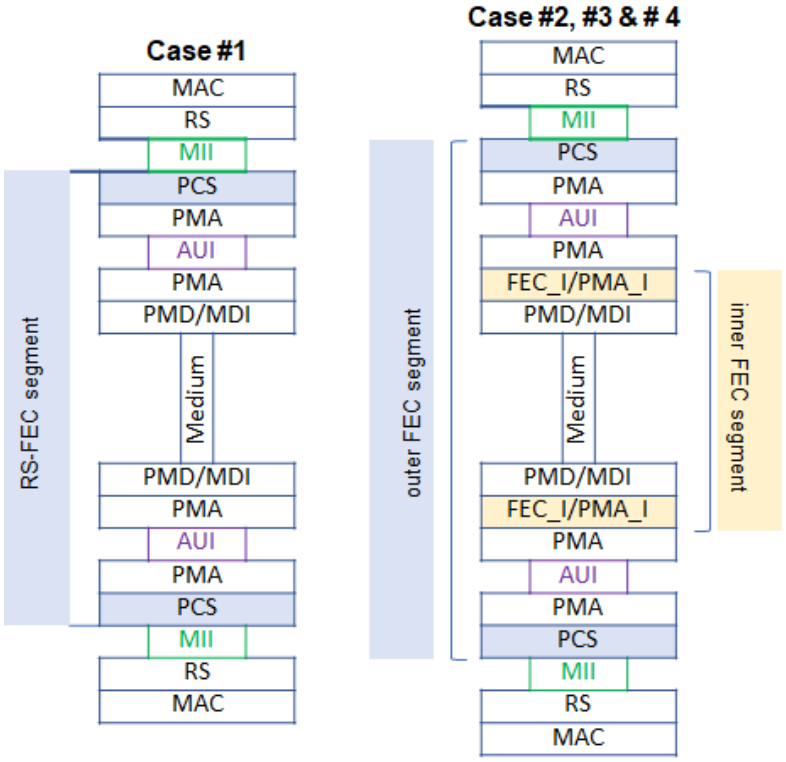
Two AUI Segments Based Link with No Extender



- No extender sublayers in this link
- Current assumption: Each C2M AUI must maintain a *measured* BER of ~4e-5
- For optical PMD BER : DFE Alpha of 0.75 with pre-coder enabled is assumed to represent the worst case Burst error events
- The combination of the C2M AUI and PMD link BERs is analyzed in the following slides

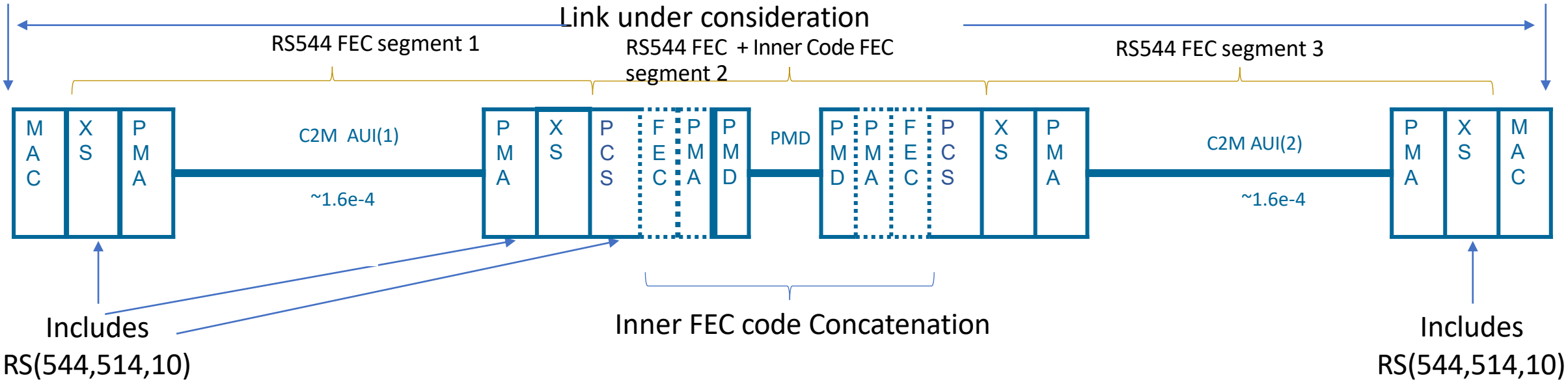
MAC-link Latency with no extenders – BER vs Coding gain Trade off

Case #1: Type 1 with end-to- end RS FEC ONLY	1.6T	800G	400G	200G	Per AUI BER	PMD BER 800G/1.6T	PMD BER 200G/400G
PCS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
Total (ns)	**49.8**	**62.6**	**62.6**	**88.2**	**~1E-5**	**~2.6E-4**	**~2.4E-4**
Case #2: Type 2 with Inner FEC ONLY without any CI	**1.6T**	**800G**	**400G**	**200G**			
PCS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
FEC_I: interleaver/deinterleaver	0.0	0.0	0.0	0.0			
FEC_I: encoder/decoder	23.5	23.5	23.5	23.5			
Total (ns)	**73.3**	**86.1**	**86.1**	**111.7**	**~5E-5**	**~3.1E-3**	**~2E-3**
Case #3: Type 2 with Inner FEC & 6-way Convolutional Interleaver	**1.6T**	**800G**	**400G**	**200G**			
PCS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
FEC_I: interleaver/deinterleaver	11.4	25	56	110			
FEC_I: encoder/decoder	23.5	23.5	23.5	23.5			
Total (ns)	**84.7**	**111.1**	**142.1**	**221.7**	**~5E-5**	**~3.7E-3**	**~3.5E-3**
Case #4: Type 2 with Inner FEC & 12-way Convolutional Interleaver	**1.6T**	**800G**	**400G**	**200G**			
PCS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
FEC_I: interleaver/deinterleaver	25.6	56	140	280			
FEC_I: encoder/decoder	23.5	23.5	23.5	23.5			
Total (ns)	**98.9**	**142.1**	**226.1**	**391.7**	**~5E-5**	**~4.6E-3**	**~4.4E-3**



- 800G/1.6TbE – PCS is 4-way RS Interleaved and 200/400G is 2-way RS Interleaved
- BER numbers are with alpha = 0.75 – representing Worst case BER conditions

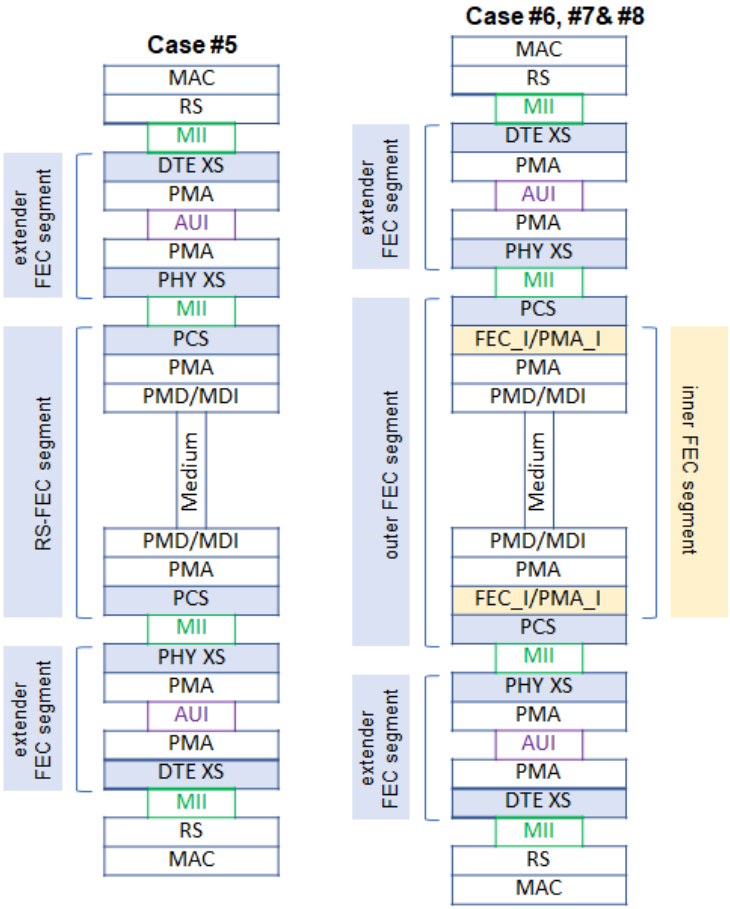
Two AUI Segments Based Link with Extenders



- Extender sublayer is present in all C2M Link segments
- Current assumption: Each AUI must maintain a *measured* BER of ~1.6e-4 belonging to each segment of AUI for 2-way KP interleaved (Worst case)
- For optical PMD BER : DFE Alpha of 0.75 with pre-coder enabled is assumed to represent the worst case Burst error events
- The combination of the AUI and PMD link BERs is analyzed in the following slides

MAC-link Latency with Extenders – AUI BER Vs PMD BER Trade Off

Case #5: Type 1, extender at each end	1.6T	800G	400G	200G	Per AUI BER	PMD BER 800G/1.6T	PMD BER 200G/400G
XS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
PCS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
XS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
Total	**149.4**	**187.8**	**187.8**	**264.6**	**~2.6E-4**	**~2.6E-4**	**~2.6E-4**
Case #6: Type 2 with Inner FEC but no CI & extender at each end	**1.6T**	**800G**	**400G**	**200G**			
XS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
PCS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
FEC_I: interleaver/deinterleaver	0.0	0.0	0.0	0.0			
FEC_I: encoder/decoder	23.5	23.5	23.5	23.5			
XS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
Total	**172.9**	**211.3**	**211.3**	**288.1**	**~2.6E-4**	**~3.5E-3**	**~2.3E-3**
Case #7: Type 2 with Inner FEC & 6-way CI & extender at each end	**1.6T**	**800G**	**400G**	**200G**			
XS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
PCS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
FEC_I: interleaver/deinterleaver	11.4	25	56	110			
FEC_I: encoder/decoder	23.5	23.5	23.5	23.5			
XS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
Total	**184.3**	**236.3**	**267.3**	**398.1**	**~2.6E-4**	**~3.9E-3**	**~3.9E-3**
Case #8: Type 2 with Inner FEC & 12 -way CI & extender at each end	**1.6T**	**800G**	**400G**	**200G**			
XS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
PCS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
FEC_I: interleaver/deinterleaver	25	56	140	280			
FEC_I: encoder/decoder	23.5	23.5	23.5	23.5			
XS: RS FEC encoder/decoder	49.8	62.6	62.6	88.2			
Total	**197.9**	**267.3**	**351.3**	**568.1**	**~2.6E-4**	**4.8E-3**	**4.8E-3**



MAC-Link Latency, Summary and Observations

With the Inner code FEC, Majority of the MAC link segments can be covered without Extender

No Extender Case	MAC Link with No Extender			
	1.6T Latency	800G Latency	400G Latency	200G Latency
Case #1: Type 1 – End to End RS FEC	49.8ns,	62.6ns	62.6ns	88.2ns
Case #2: Type 2 – With Inner FEC code but without any Convolutional Interleaver	73.3ns	86.1ns	86.1ns	111.7ns
Case #3: Type 2 - With Inner FEC code and with 6-way Convolutional Interleaver	86.3ns	113.1ns	140.1ns	221.7ns
Case #4: Type 2 - With Inner FEC code and with 12- way Convolutional Interleaver	98.9ns	142.1ns	226.1ns	391.7ns
Legend | Blue: < 100 ns | Green: 100 ns to 200 ns | Yellow: 200 ns to 300 ns | Red: > 300 ns |				

No Extender Case	MAC Link with No Extender			
	1.6T/800G PMD BER	400G/200G PMD BER	C2C BER	C2M BER
Case #1: Type 1 – End to End RS FEC	~2.6e-4	~2.4e-4	~1e-5	~1e-5
Case #2: Type 2 – With Inner FEC code but without any Convolutional Interleaver	~3.1e-3	~2e-3	~1e-5	~4e-5
Case #3: Type 2 - With Inner FEC code and with 6-way Convolutional Interleaver	~3.7e-3	~3.5e-3		
Case #4: Type 2 - With Inner FEC code and with 12- way Convolutional Interleaver	~4.6e-3	~4.4e-3		

Extender Case	MAC Link with Extender			
	1.6T Latency	800G Latency	400G Latency	200G Latency
Case #1: Type 1 – Segmented RS FEC	149.4ns	187.8ns	187.8ns	264.6ns
Case #2: Type 2 – With Inner FEC code but without any Convolutional Interleaver	172.9ns	211.3ns	211.3ns	288.1ns
Case #3: Type 2 - With Inner FEC code and with 6-way Convolutional Interleaver	185.9ns	238.3ns	265.3ns	398.1ns
Case #4: Type 2 - With Inner FEC code and with 12- way Convolutional Interleaver	199.9ns	265.3ns	346.3ns	559.1ns
Legend | Green: 100 ns to 200 ns | Yellow: 200 ns to 300 ns | Red: > 300 ns |				

Extender Case	MAC Link with Extender			
	1.6T/800G PMD BER	400G/200G PMD BER	C2C BER	C2M BER
Case #1: Type 1 – Extender RS FEC	~2.6e-4	~2.6e-4	~2.6e-4	~2.6e-4
Case #2: Type 2 – With Inner FEC code but without any Convolutional Interleaver	~3.5e-3	~2.3e-3		
Case #3: Type 2 - With Inner FEC code and with 6-way Convolutional Interleaver	~3.9e-3	~3.9e-3		
Case #4: Type 2 - With Inner FEC code and with 12- way Convolutional Interleaver	~4.8e-3	~4.8e-3		

- **Turning off Extender has a significant latency advantage**
- **Inner code coding gain can be leveraged to relax the AUI BER for MAC Link without Extender Case**
- **All the BER limit described in this table represent Worse case BER with DFE alpha 0.75 to represent Burst error events**

Inner code can reduce latency and improve PMD error tolerance

No Extender Case	MAC Link with No Extender			
	1.6T Latency	800G Latency	400G Latency	200G Latency
Case #1: Type 1 – End to End RS FEC	49.8ns,	62.6ns	62.6ns	88.2ns
Case #2: Type 2 – With Inner FEC code but without any Convolutional Interleaver	73.3ns	86.1ns	86.1ns	111.7ns
Case #3: Type 2 - With Inner FEC code and with 6-way Convolutional Interleaver	86.3ns	113.1ns	140.1ns	221.7ns
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Legend | Blue: < 100 ns | Green: 100 ns to 200 ns | Yellow: 200 ns to 300 ns | Red: > 300 ns |				

No Extender Case	MAC Link with No Extender			
	1.6T/800G PMD BER	400G/200G PMD BER	C2C BER	C2M BER
Case #1: Type 1 – End to End RS FEC	~2.6e-4	~2.4e-4	~1e-5	~1e-5
Case #2: Type 2 – With Inner FEC code but without any Convolutional Interleaver	~3.1e-3	~2e-3		
Case #3: Type 2 - With Inner FEC code and with 6-way Convolutional Interleaver	~3.7e-3	~3.5e-3	~1e-5	~4e-5
Case #4: Type 2 - With Inner FEC code and with 12- way Convolutional Interleaver	~4.6e-3	~4.4e-3		

Extender Case	MAC Link with Extender			
	1.6T Latency	800G Latency	400G Latency	200G Latency
Case #1: Type 1 – Segmented RS FEC	149.4ns	187.8ns	187.8ns	264.6ns
Case #2: Type 2 – With Inner FEC code but without any Convolutional Interleaver	172.9ns	211.3ns	211.3ns	288.1ns
Case #3: Type 2 - With Inner FEC code and with 6-way Convolutional Interleaver	185.9ns	238.3ns	265.3ns	398.1ns
Case #4: Type 2 - With Inner FEC code and with 12- way Convolutional Interleaver	199.9ns	265.3ns	346.3ns	559.1ns
Legend | Green: 100 ns to 200 ns | Yellow: 200 ns to 300 ns | Red: > 300 ns |				

Extender Case	MAC Link with Extender			
	1.6T/800G PMD BER	400G/200G PMD BER	C2C BER	C2M BER
Case #1: Type 1 – Extender RS FEC	~2.6e-4	~2.6e-4		
Case #2: Type 2 – With Inner FEC code but without any Convolutional Interleaver	~3.5e-3	~2.3e-3		
Case #3: Type 2 - With Inner FEC code and with 6-way Convolutional Interleaver	~3.9e-3	~3.9e-3	~2.6e-4	~2.6e-4
Case #4: Type 2 - With Inner FEC code and with 12- way Convolutional Interleaver	~4.8e-3	~4.8e-3		

Summary

- MAC link latency with and without Extender cases are analyzed with various Convolutional Interleaver depth of Inner code FEC (128,120).
- For Latency sensitive application – Recommendation is to bypass the Convolutional Interleaver.
- 6-way or 12-way Convolutional Interleaver should be used for stringent Optical PMD segments.

Thanks !