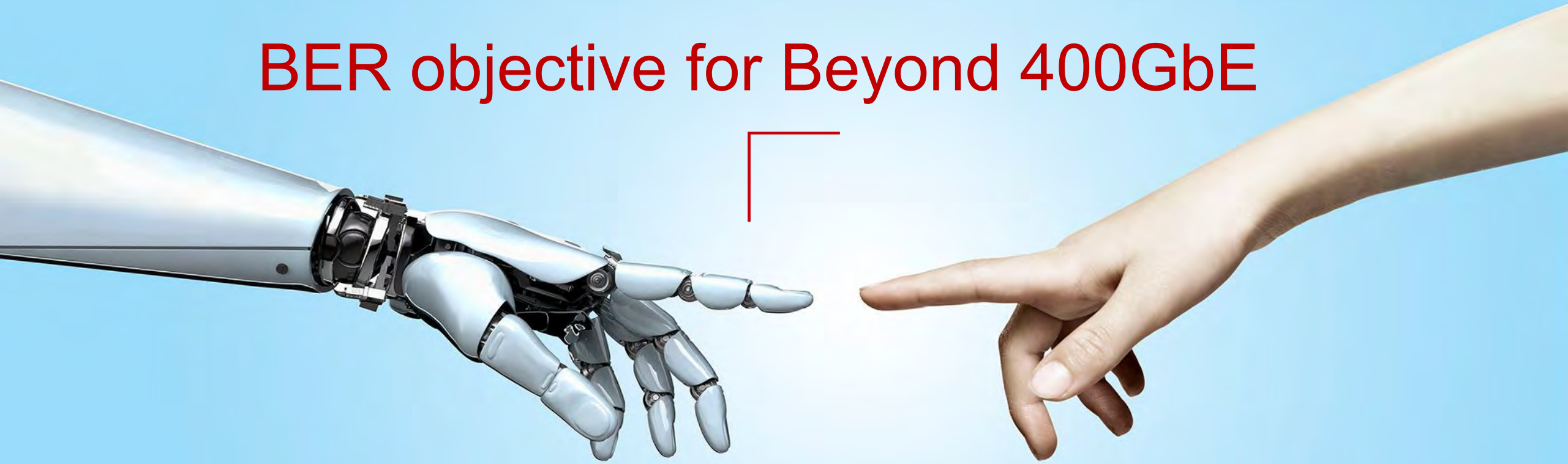
BER objective for Beyond 400GbE



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BER objective of previous IEEE 802.3 Ethernet standard

- In dambrosia_b400g_01_210118 :

"Apple Pie" Objectives Wording

	802.3ba	802.3bs	802.3by	802.3cd
Support full-duplex operation only	✓	✓	✓	✓
1. Preserve the 802.3 / Ethernet frame format utilizing the 802.3 MAC	✓			
2. Preserve the Ethernet frame format utilizing the Ethernet MAC		✓	✓	✓
1. Preserve minimum and maximum FrameSize of current 802.3 standard	✓			
2. Preserve minimum and maximum FrameSize of current Ethernet standard		✓		
3. Preserve minimum and maximum FrameSize of current IEEE 802.3 standard			✓	✓
Provide appropriate support for OTN	✓	✓	✓	✓
1. Specify optional Energy Efficient Ethernet (EEE) capability	n/a	✓		
2. Support optional Energy-Efficient Ethernet operation			✓	✓
1. Support a BER better than or equal to 10-12 at the MAC/PLS service interface	✓			
2. Support a BER of better than or equal to 10-13 at the MAC/PLS service interface (or the frame loss ratio equivalent)		✓		
3. Support a BER of beLer than or equal to 10-12 at the MAC/PLS service interface (or the frame loss ratio equivalent)			✓	
4. Support a BER of better than or equal to 10-12 at the MAC/PLS service interface (or the frame loss ratio equivalent) for 50 Gb/s and 100 Gb/s operation				✓
5. Support a BER of better than or equal to 10-13 at the MAC/PLS service interface (or the frame loss ratio equivalent) for 200 Gb/s operation				✓

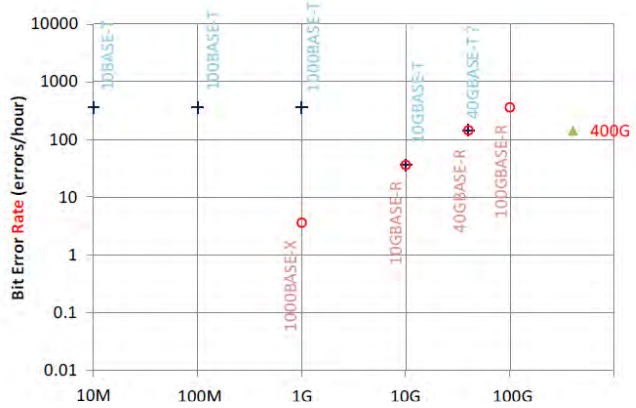
Observation – wording of objectives tends to improve with successive iterations

Revisit BER discussion at 802.3bs Study Group for 400GbE

- In ofelt_400_01_0713:
  - Minimum BER objective proposal:1E-15
  - Better BER objective proposal:1E-17
- In anslow_400_01_0913: Analyzed BER target from "Bit Error Rate" perspective
  - "Setting the BER target to be 1E-13 would be 144 errors an hour which is the same rate as 40GbE".
- Based on anslow_400_02_1113: the study group agreed on 1E-13 as the BER objective for 400GbE with or without FEC for PMDs.

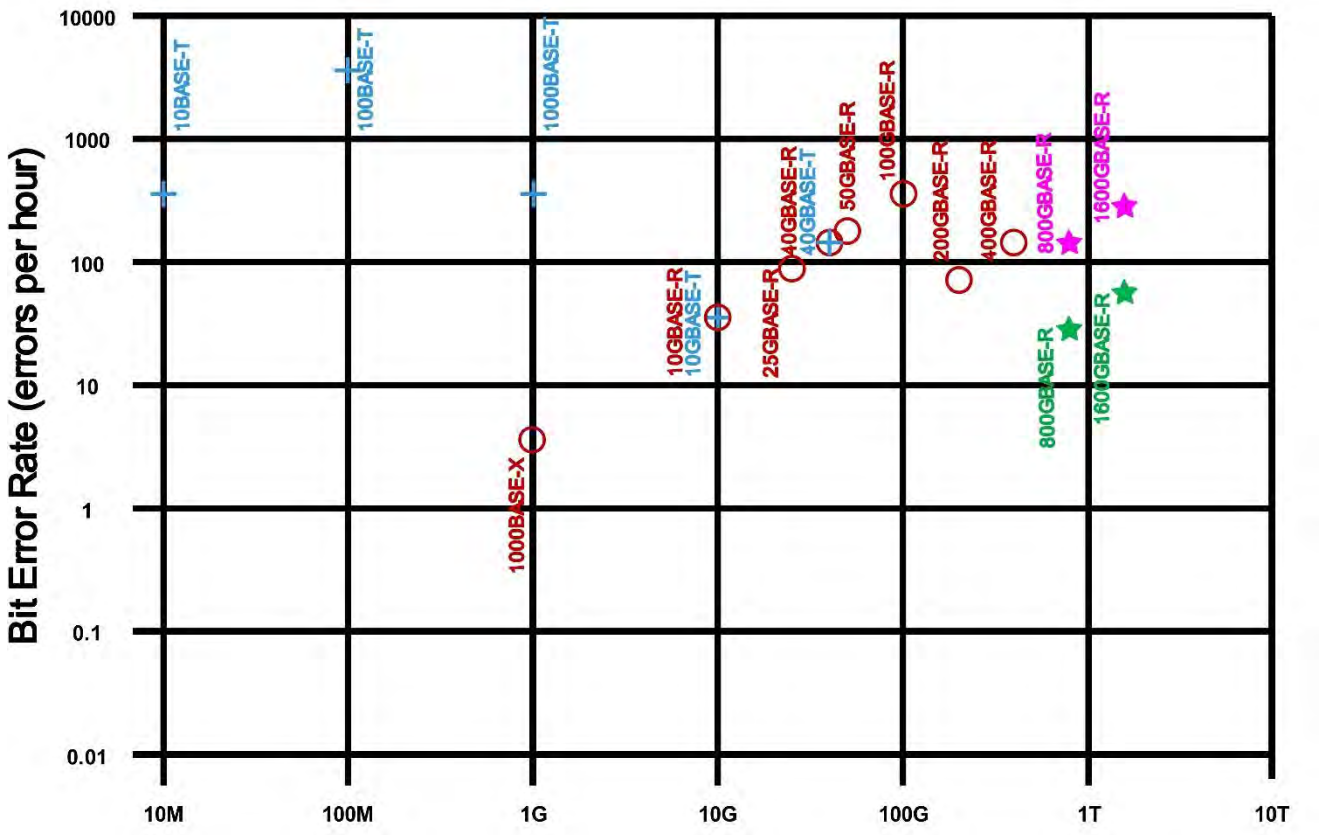
Since we cannot decide that all PHYs will use FEC in the Study Group phase the error performance objective should be set so as to not burden any non-FEC PHYs with costly measurements:

Support a BER of better than or equal to 10^{-13} at the MAC/PLS service interface [in the consensus objective format which results from anslow_400_01_1113]



Using Bit Error Rate to consider B400GbE BER objective

- 1E-14 BER objective for 800GbE and 1.6TbE looks like to be a straight forward evolution.
  - At least better than 25/50/200/400GbE with less errors from system perspective



Ethernet Rate	BER Objective	Bit Error Rate (Errors/Hour)
10BASE-T	1.00E-08	360
100BASE-T	1.00E-08	3600
1000BASE-T	1.00E-10	360
1000BASE-X	1.00E-12	3.6
10GBASE-R	1.00E-12	36
10GBASE-T	1.00E-12	36
25GBASE-R	1.00E-12	90
40GBASE-R	1.00E-12	144
40GBASE-T	1.00E-12	144
50GBASE-R	1.00E-12	180
100GBASE-R	1.00E-12	360
200GBASE-R	1.00E-13	72
400GBASE-R	1.00E-13	144
800GBASE-R	5.00E-14	144
1600GBASE-R	5.00E-14	288
800GBASE-R	1.00E-14	28.8
1600GBASE-R	1.00E-14	57.6

From Pete Anslow: BER measurement times

To obtain a reasonable estimate of the BER when the PHY is making some errors it is necessary to measure at least 10 errors. The time taken to do this at a BER of 1E-14 is:

Rate	Time
800G	20.8 minutes
1.6T	10.4 minutes

If the PHY does not make any errors then using Equation 9-11 from ITU-T G.Sup39:

$$n = \frac{\log(1-C)}{\log(1-P_E)}$$

Where:

- n is the required number of error free bits
- C is the confidence level (e.g., 0.95 for 95% confidence)
- P_E is the BER requirement (e.g., 10^{-12})

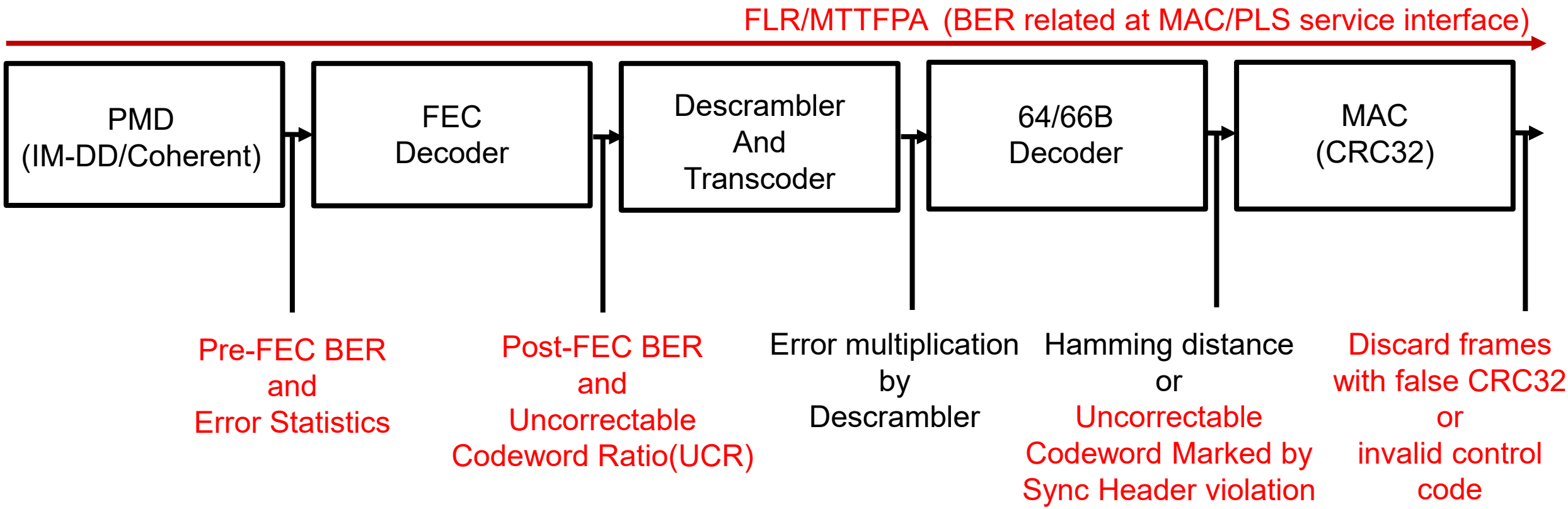
Then the time taken for 95% confidence that the BER is below the requirement is:

Rate	Time
800G	6.2 minutes
1.6T	3.1 minutes

Trade off needed for B400GbE BER objective

- Better BER objective, 1E-15, or lower?
  - End users expect error free, not considering cost or feasibility.
  - Large chassis and system with more Ethernet links will require lower bit error rate.
  - Longer test time – 10x longer time at 208/104 minutes if lowering BER from 1E-14 to 1E-15 for 800GbE/1.6TbE respectively.
  - Longer test time – 100x longer time at 2080/1040 minutes if lowering BER from 1E-14 to 1E-16 for 800GbE/1.6TbE respectively, .
- Is 1E-14 BER objective acceptable?
  - MTTFPA and retransmission risk
  - Feasibility from technical and economic perspective
  - Shorter test time

BER objective from Ethernet architecture perspective



- Assuming 800G/1.6TbE reuse 200/400GbE Descrambler, Transcoder, 64/66B Decoder, there will be no impact to CRC32 capability to drop invalid frames.
  - FEC capability (UCR and error marking) is the main contributor to meet MTTFPA.

Calculating MTTFPA from BER objective

- The mean time to false packet acceptance (MTTFPA) is the key parameter for Ethernet standard, which requires only one false frame acceptance could occur within the age of the universe (AOU: about 13.8 Billion years).
- Calculating MTTFPA of Beyond 400GbE with mandatory FEC to protect both AUI and PMD
  - Pre-FEC BER from AUI or PMD will be improved by FEC to post-FEC BER, with majority of the post FEC errors in uncorrectable FEC codewords marked and discarded.
    - Post-FEC BER can be linked to BER/FLR objective at MAC/PLS.
  - Mark uncorrectable FEC codewords by corrupting the corresponding 64/66B sync headers.
  - Input error distribution to FEC decoder is random (uncorrelated).
  - The error distribution in uncorrectable codewords at the output of the FEC decoder is similar to its input.
  - Choose the worst Ethernet frame length.
  - Discard MAC frames missing their /S/ or /T/ control codes or containing invalid control codes.
  - Discard MAC frames with a false CRC32.
  - The probability of a MAC frame with errors having a matching CRC32 is no more than 2^{-32}.

Calculating MTTFPA for BER objective (Cont'd)

- This leads to MTTFPA calculation:

$$\mathrm{BER_{out}} = \sum_{i=t+1}^{n} \frac{i}{n} UCR_i \approx \frac{t+1}{n*m} * UCR$$

$$\mathrm{UMR} \approx (2^m - 1)^{-(d-t-1)} \binom{n-d+t}{t}$$

$$\mathrm{MTTFPA} > \frac{N * T_{bit}}{UCR * UMR * (1 + \frac{N}{k})} * 2^{32}$$

$\mathrm{BER_{out}}$:	Post-FEC BER.
UCR:	Uncorrectable Codeword Ratio (Related to Pre-FEC BER).
UMR:	UnMarked uncorrectable codeword Ratio.
T_{bit}:	Bit time.
t:	FEC error correction capability.
d:	Number of erroneous symbols in a codeword.
n:	FEC codeword size in symbols.
m:	Galois Field index.
k:	Number of message bits in a FEC codeword.
N:	Ethernet MAC frame size in bits.

Note:
1. The calculation is based on RS FEC.
2. For UMR calculation method please refer to cideciyan_01_0112.pdf.

- Post-FEC BER is directly related to the FEC capability and pre-FEC BER.
- The key contributor to MTTFPA is input error to FEC decoder from AUI or PMD, which can be evaluated based on different FEC approach, End to End, Concatenated or Segment by Segment.

FEC approaches to support proposed BER objective

FEC Approach #	FEC Algorithm Example*	Pre-FEC BER (Rough estimated)	Net Coding Gain (Assume 1E-14 BER Objective)	Optical PMD Reach Example*
A End to End	RS(544,514) (Hard Decision)	~2.2E-4	~6.6 dB	50m-500m
B Concatenated	Outer code: RS(544,514) (Hard Decision) Inner code: BCH,t=1 or 2 (Soft/Hard Decision)	~2E-3 ~1E-3	~8.4 dB ~7.7 dB	50m-2km+
C Segment by Segment	CFEC and/or Product Code	~1E-2	~10.4dB	10km+

***: For generic observation, FEC approaches are independent to PMD solution, IM-DD/Coherent and different reach example**

AUI interface evolution to support proposed BER objective

- In 802.3bs/ck project, RS(544,514) FEC protects both AUI and Optical PMDs
  - 0.2dB from 6.4dB of RS(544,514) to correct errors from AUI
  - 1E-5 BER for 50Gb/s and 100Gb/s per AUI lane in Annex 120E.1.1/120G.1.1
  - MTTFPA is satisfied at 1E-13 BER objective of 400GbE
- In Beyond 400GbE project
  - FEC should protect both AUI and Optical PMDs
  - 212.5/225Gb/s per lane AUI BER target needs to be further investigated.
    - 1E-5,1E-4 or better?

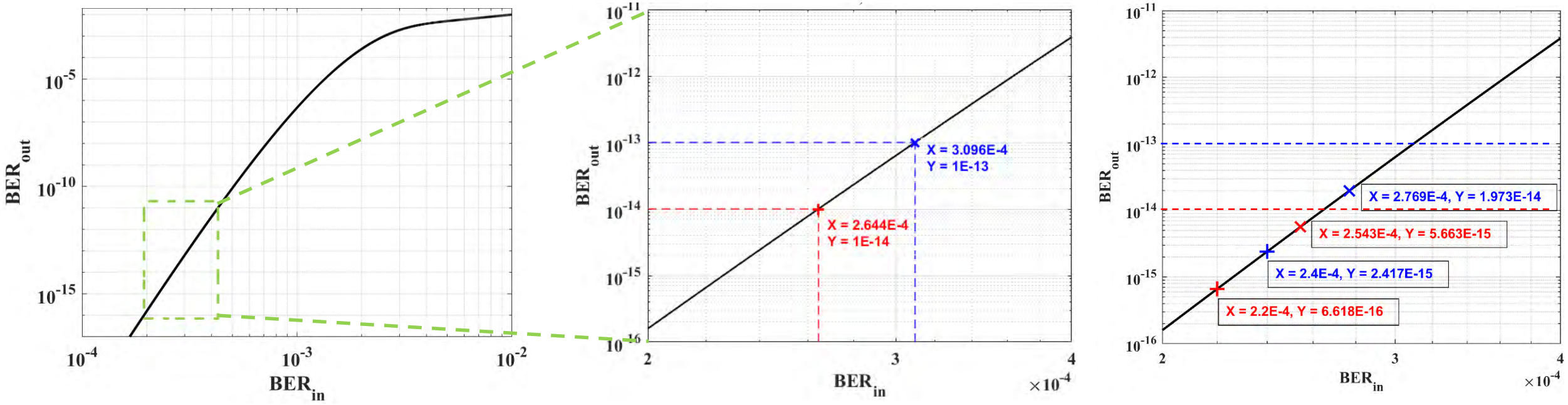
Using E2E RS(544,514) FEC as an example to get target BER objective

- Reuse 802.3bs methodology to analyze BER target and FEC requirement

RS(544,514)

Apply to one-part link

Apply to two-part link
(AUI + Optical)

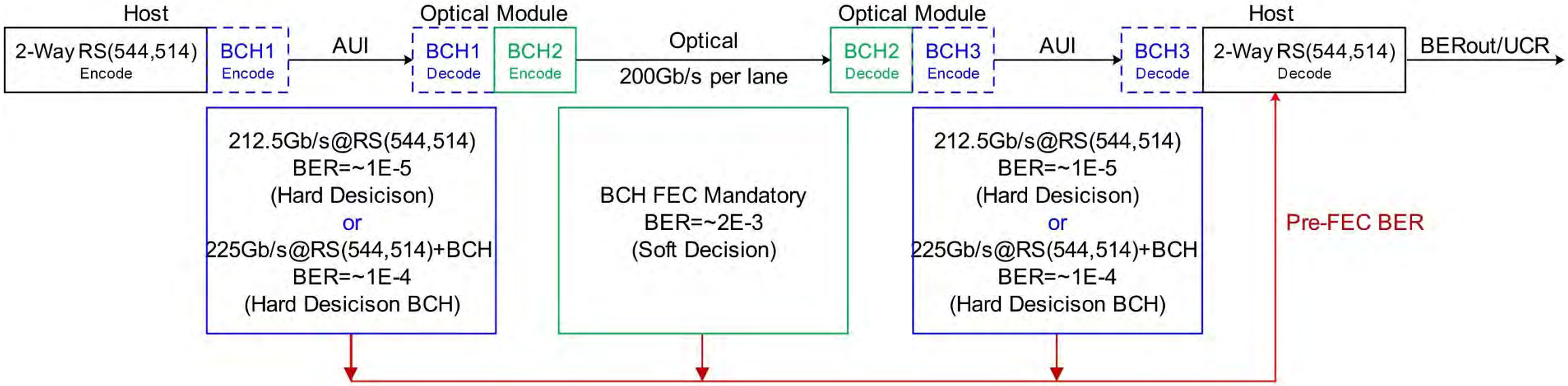


- For 1E-13 BER objective of 802.3bs/ck, 2.4E-4 for optical link with 1E-5 for 50Gb/s and 100Gb/s AUI.
- For 1E-14 BER objective of B400GbE, 2.2E-4 for optical link with 1E-5 for 100Gb/s AUI.

More detailed information, please refer to anslow_3bs_03_0915

Using Concatenated FEC as an example to get target BER objective

- For AUI bit rate, 212.5Gb/s(4X) with RS(544,514) FEC operating at or below BER of 1E-5 is the straight forward evolution from 53.125Gb/s (1X) and 106.25Gb/s(2X) per AUI lane as in Annex 120E.1.1/120G.1.1.
- If the BER target of 1E-5 is challenging for 200G per lane AUI, a short BCH FEC can be added for additional error correction capability, with only 1.6/2.4ns latency (assuming 1.25GHz clock) and low cost, bumping the bit rate of AUI lane up to 225Gb/s.



For capability and latency of soft/hard decision concatenated FEC, please refer to wang_b400g_01_210208

Summary

- Propose to consider the following BER objective for 800G/1.6TbE:
  - Support a BER of better than or equal to 10^{-14} at the MAC/PLS service interface (or the frame loss ratio equivalent)
- PHY/AUI and FEC can be further studied during Task Force period to meet the BER objective and ensure the MTTFPA target.

Thank you