FEC performance with PAM4 on multi-part links

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Introduction

The IEEE 802.3bs Task Force has adopted RS(544,514) FEC and the use of PAM4 with DFE for CDAUI-8.

This leads to a requirement for analysis of the effect of burst errors in the PAM4 electrical sub-links with RS(544,514) FEC

In analysing the performance of 400GbE FEC encoded links, two of the aspects that are considered here are:

- The interaction of burst errors due to decision feedback equalization (DFE) and dis-interleaving of bit-streams from higher rate lanes.
- Covering several sub-links with a single end-to-end FEC.

As per previous presentations, the analysis is performed using both Monte Carlo and analytical methods.

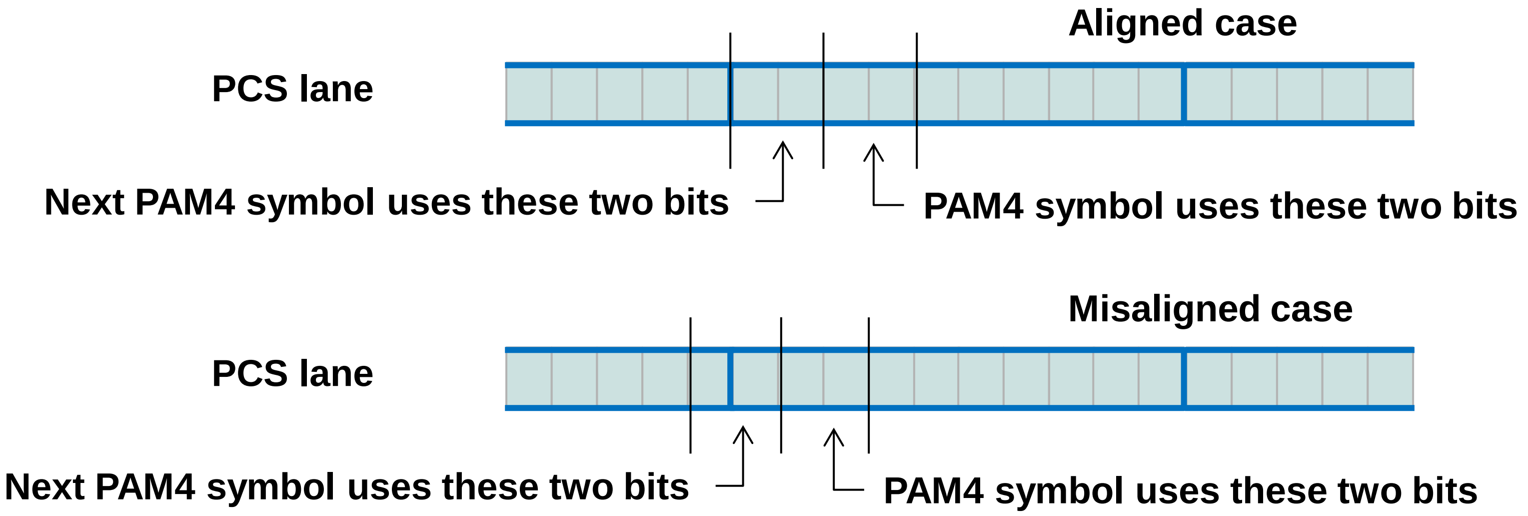
Signal structure

The PCS structure in gustlin_3bs_02a_0315 is assumed with 16 PCS lanes formed by striping in 10-bit blocks aligned with RS 10-bit symbols.

To start with, assume a 1 x 400G FEC architecture to allow lowest latency and cleanest solution for the long run (gustlin_3bs_02a_0315 page 13).

This also has the advantage of diluting the errors from the worst lane with 15 other lanes rather than with 3 other lanes for the 4 x 100G case.

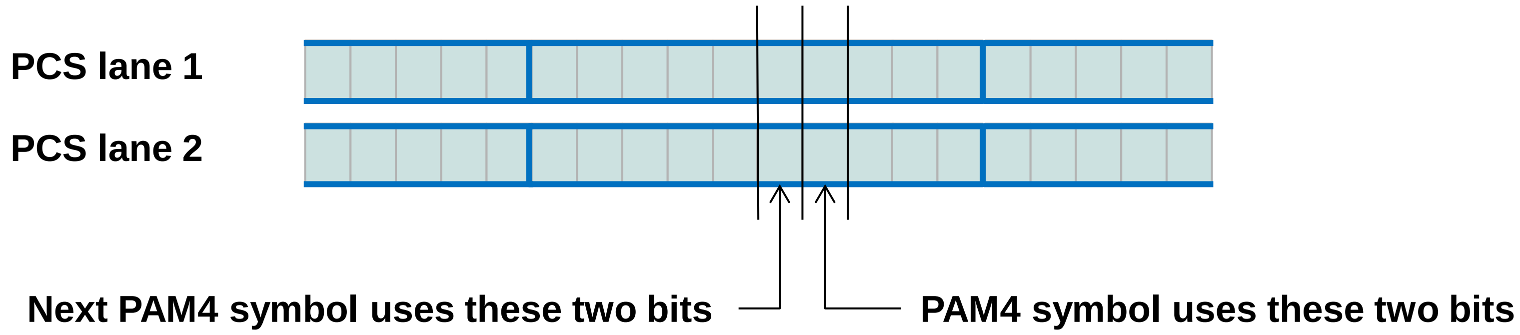
The simplest way to form the PAM4 symbols is to take two bits at a time from a single 26.5625 Gb/s PCS lane:



Interleaved case

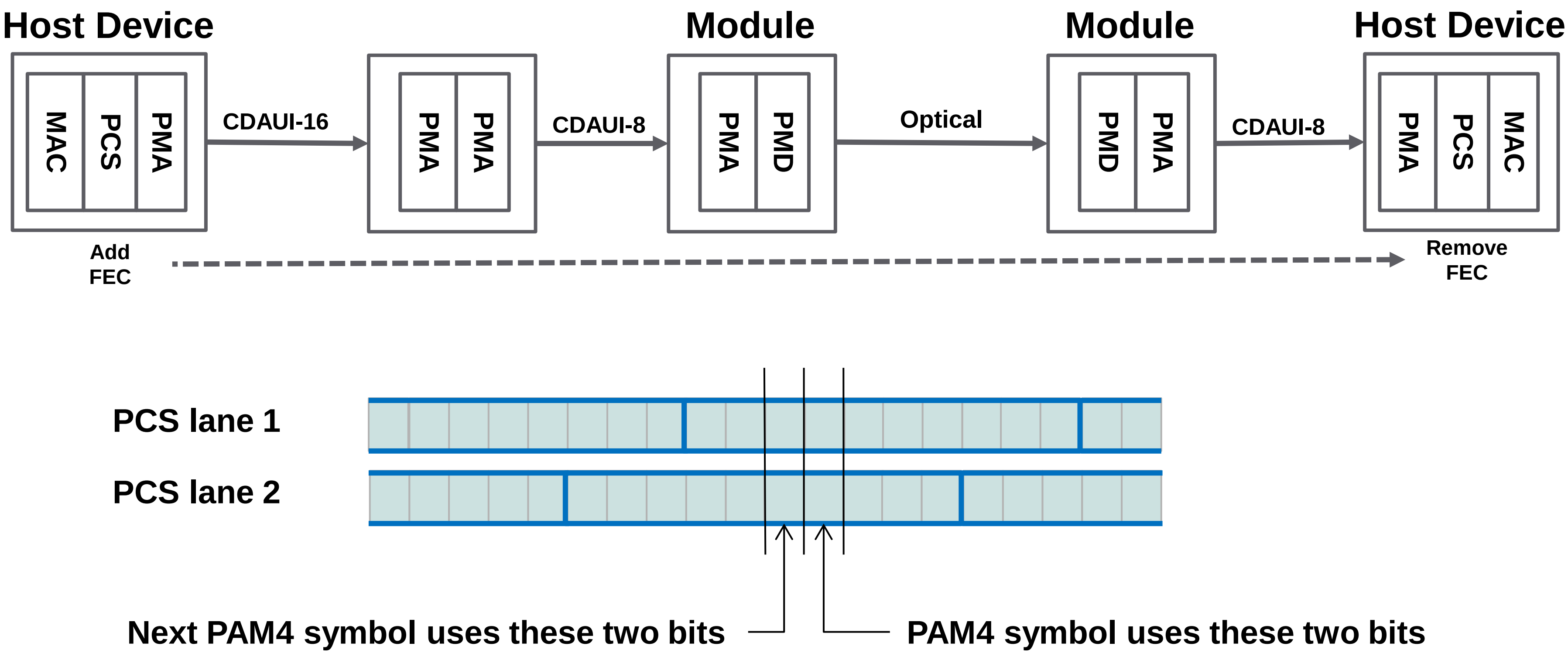
In the case where a pair of 25 Gb/s PCS lanes is used to form a 50 Gb/s PAM4 lane, if FEC symbol interleaving is used, then the performance will be as for the non-interleaved case on the previous slide.

For bit interleaving, the simplest way to form the PAM4 symbols is to take one bit from each of the two 26.5625 Gb/s PCS lanes (to start with, assume no skew between lanes):



Skew

For the multi-part link shown below, skew in the CDAUI-16 can cause an offset between the 10-bit FEC symbol boundaries in the two streams used to form the PAM4 symbols.

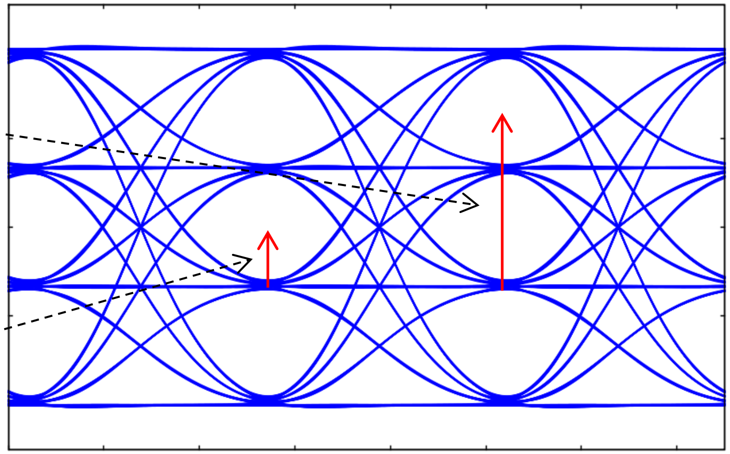


Gray coding

Assume the use of Gray coding (li_3bs_01a_0315 page 6, brown_3bs_01a_0315 page 6) as illustrated below:

Noise amplitude required for both bits to be in error

Noise amplitude required for 1 bit to be in error



If noise causes any of the 4 levels to be mistaken for an adjacent level, this causes one of the two bits to be in error.

If there is just enough Gaussian noise to cause a BER of 3.2E-4* due to single level errors, then the probability of that noise causing both bits to be in error is 6E-25.

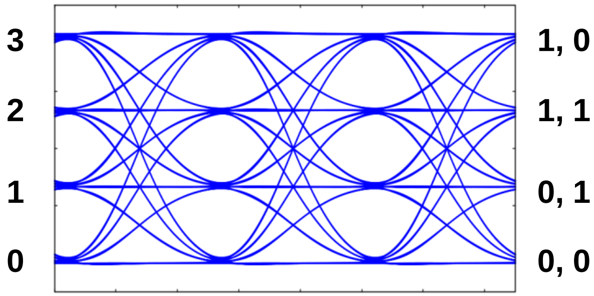
This analysis therefore assumes that only one of the two bits is in error.

* FLR = 6.2E-11 (equivalent to BER = 1E-13 with random errors) after RS(544,514) FEC

Burst error model 1

The NRZ burst analysis in anslow_3bs_02_1114 page 12 assumed that if a **bit** is in error, the worst case probability that the next **bit** is also in error is 0.5. If we assume for Gray coded PAM4 that an error in a particular symbol only causes the decision on the next symbol to move up or down one level, then the possibilities are:

Correct level	Received level		Error pattern	
	One up	One down	One up	One down
3	3	2	✓, ✓	✓, ✗
2	3	1	✓, ✗	✗, ✓
1	2	0	✗, ✓	✓, ✗
0	1	0	✓, ✗	✓, ✓



Since two of the eight possibilities result in both bits being correct, these states terminate the burst. Therefore for Gray coded PAM4, if a **symbol** is in error, the worst case probability that the next **symbol** is also in error is 0.75.

Burst error model 2

The second aspect of this table is that of the six possibilities giving bits in error, two have errors in the first bit while four have errors in the second bit.

Correct level	Received level		Error pattern	
	One up	One down	One up	One down
3	3	2	✓, ✓	✓, ✗
2	3	1	✓, ✗	✗, ✓
1	2	0	✗, ✓	✓, ✗
0	1	0	✓, ✗	✓, ✓

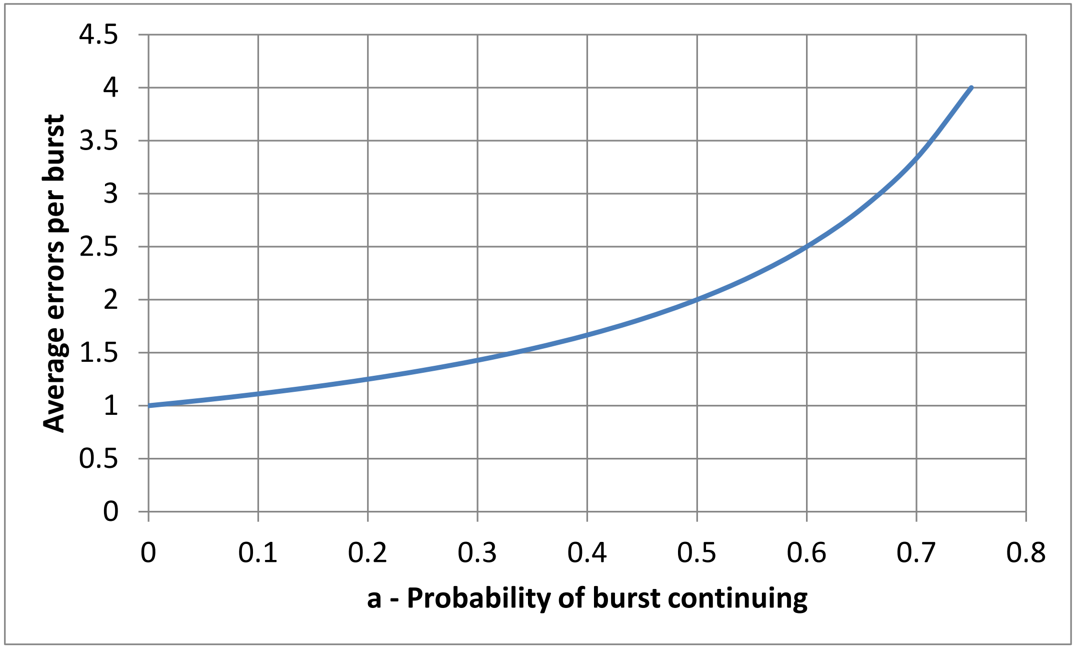
The analysis in the remainder of this contribution therefore assumes that if a given symbol is in error, the probability of a bit error in the first bit is 1/3 and in the second bit is 2/3.

Burst error model 3

The "SNR" shown on the X axis of the following results slides is related to the noise induced input BER via the following equation:

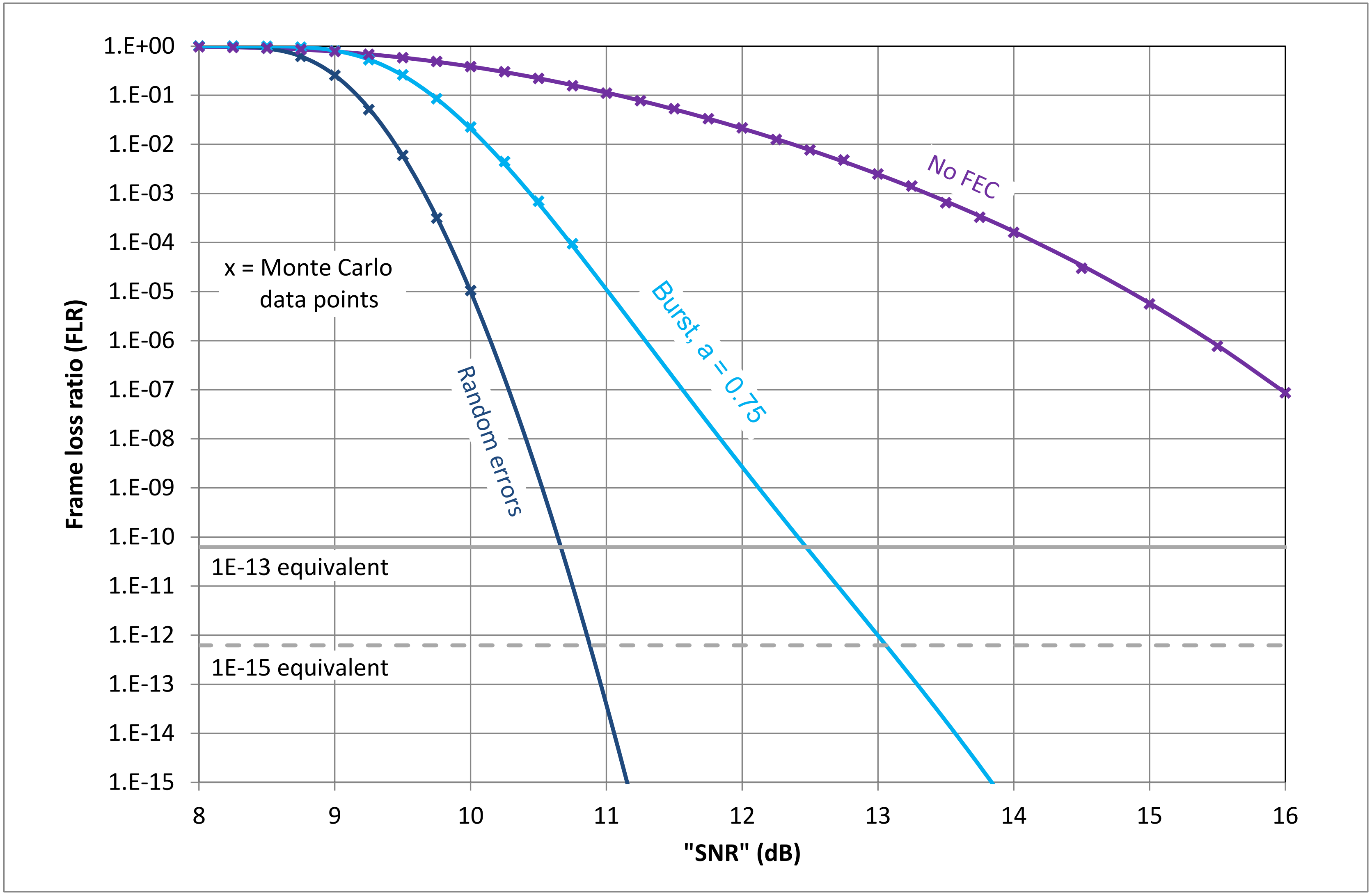
$$BER_{in} = \frac{1}{2} erfc\left(\sqrt{\frac{SNR}{2}} \right) \qquad (1)$$

Which does not include the additional errors due to the bursts. The average number of errors in a burst is related to the probability of the burst continuing "a" as shown below:

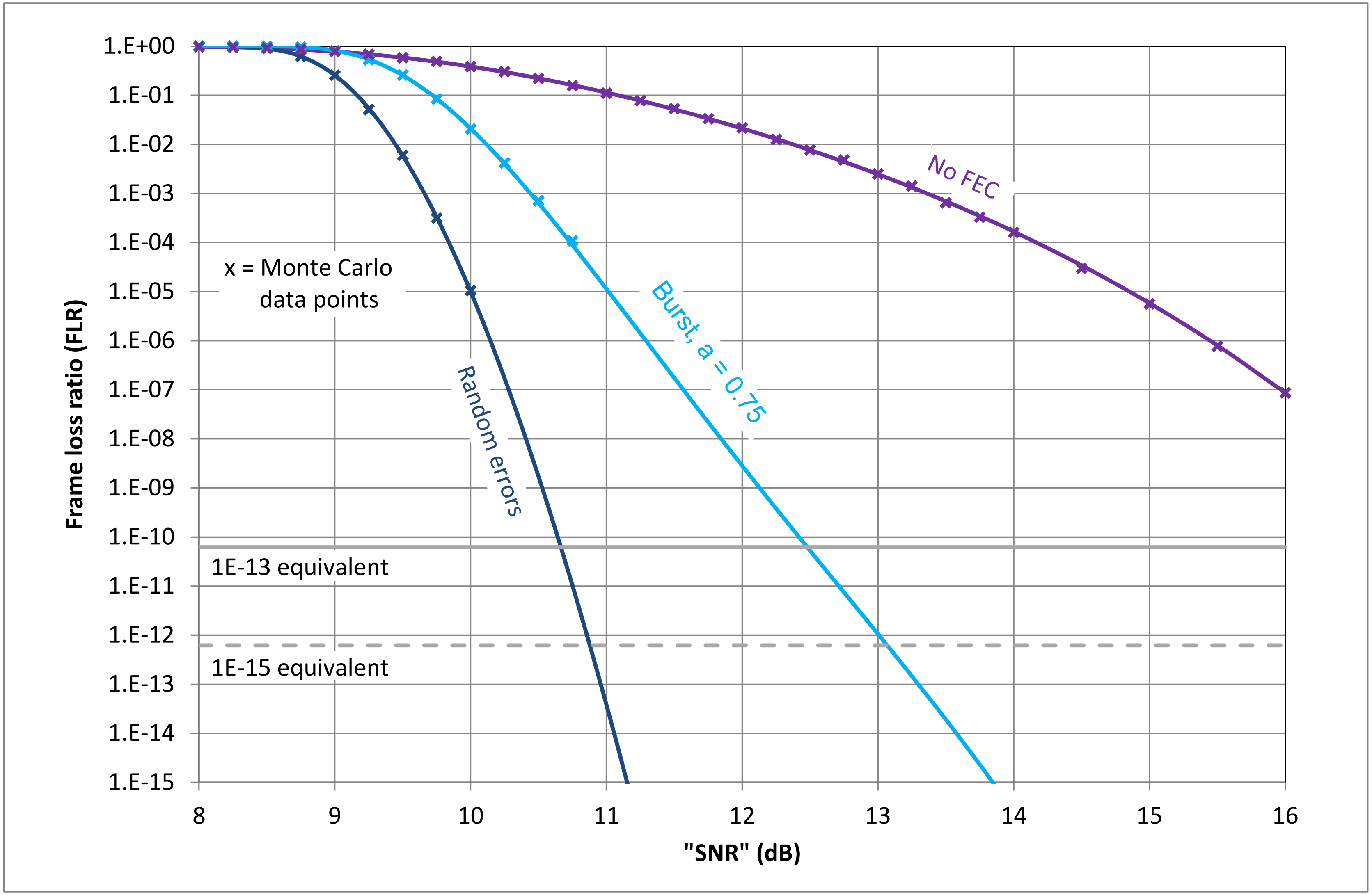


For a = 0.75, the BER_{in} including bursts is 4 x the BER_{in} due to noise.

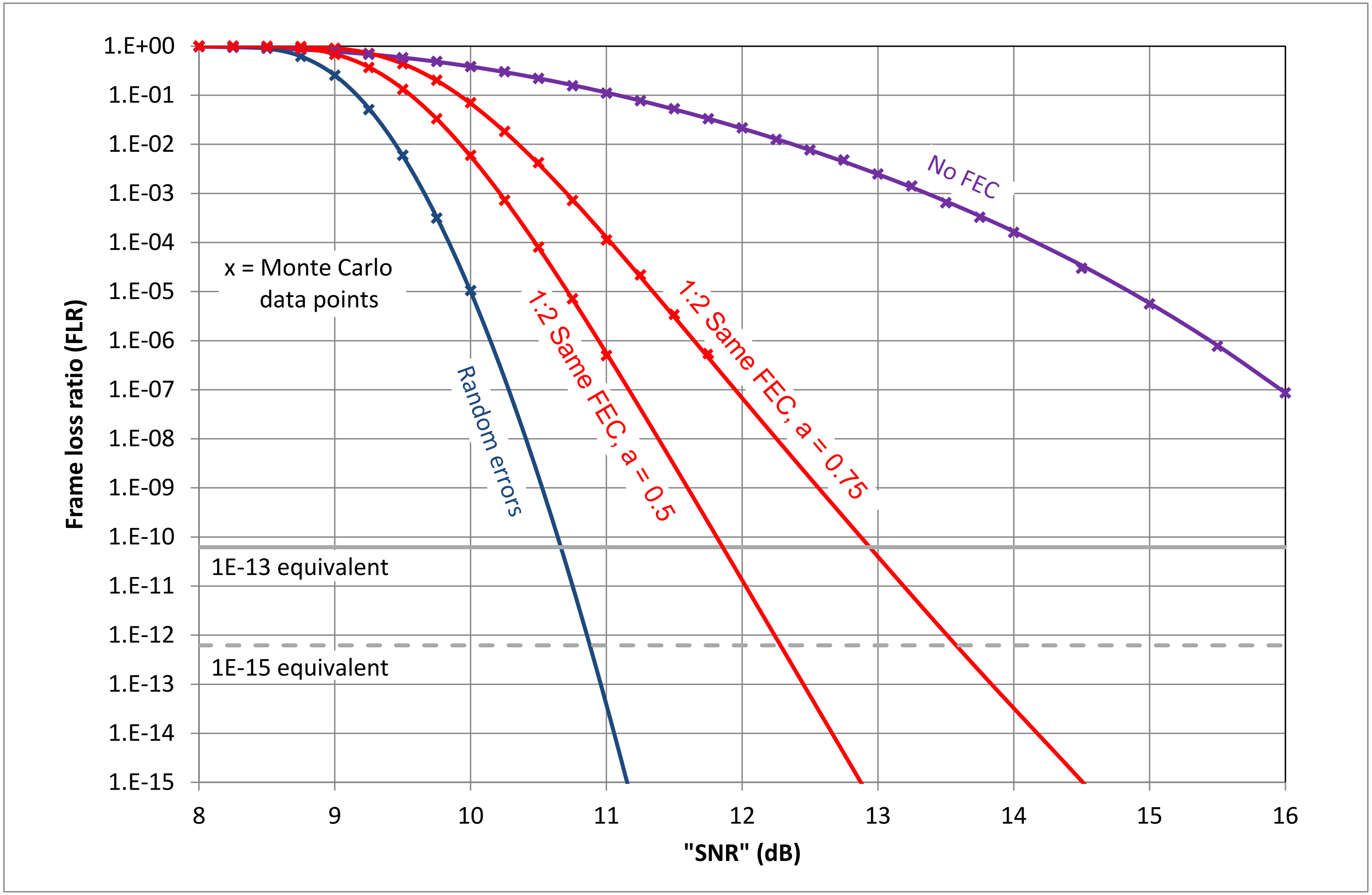
RS(544,514) no interleaving results (aligned)



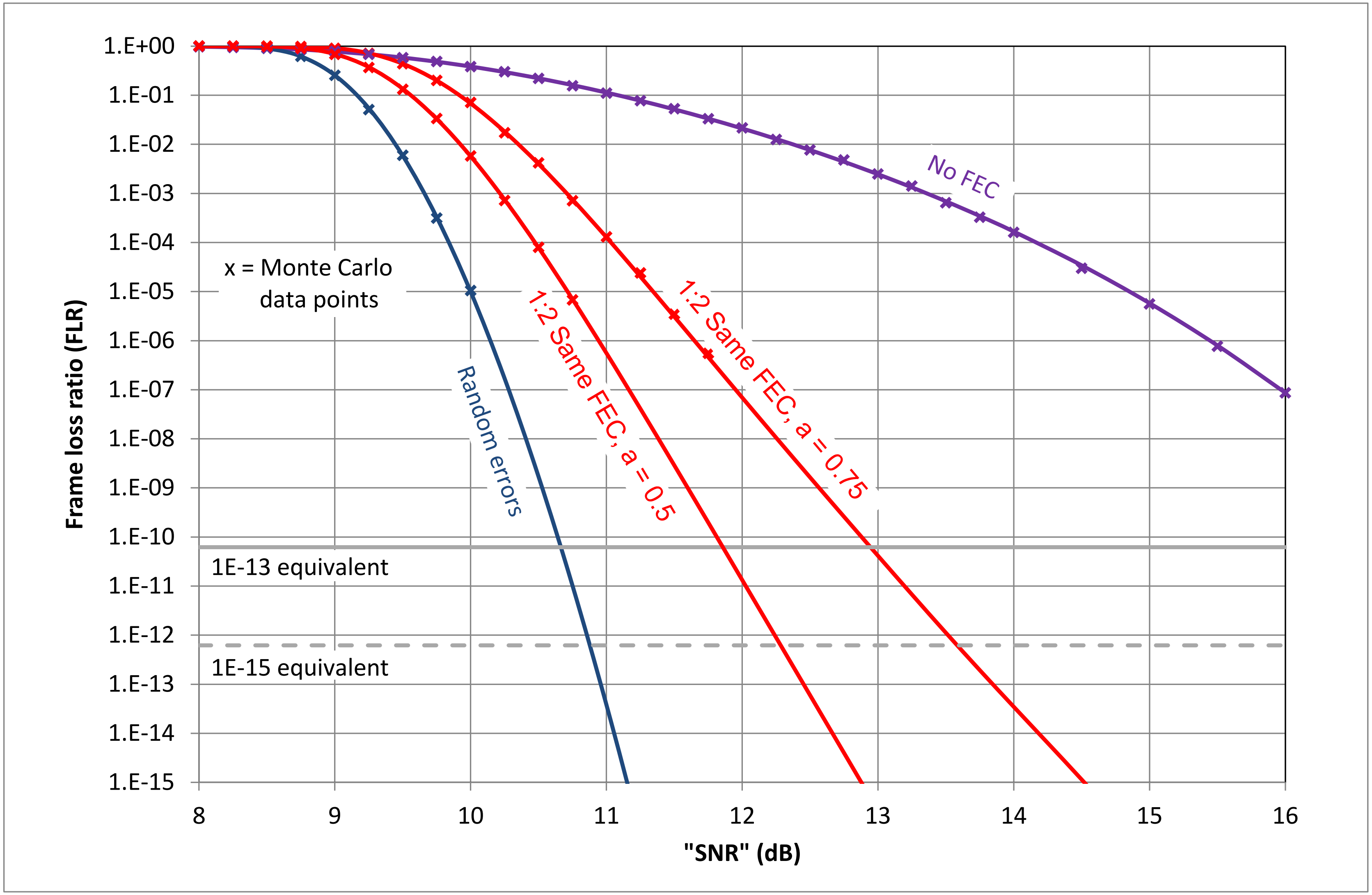
RS(544,514) no interleaving results (misaligned)



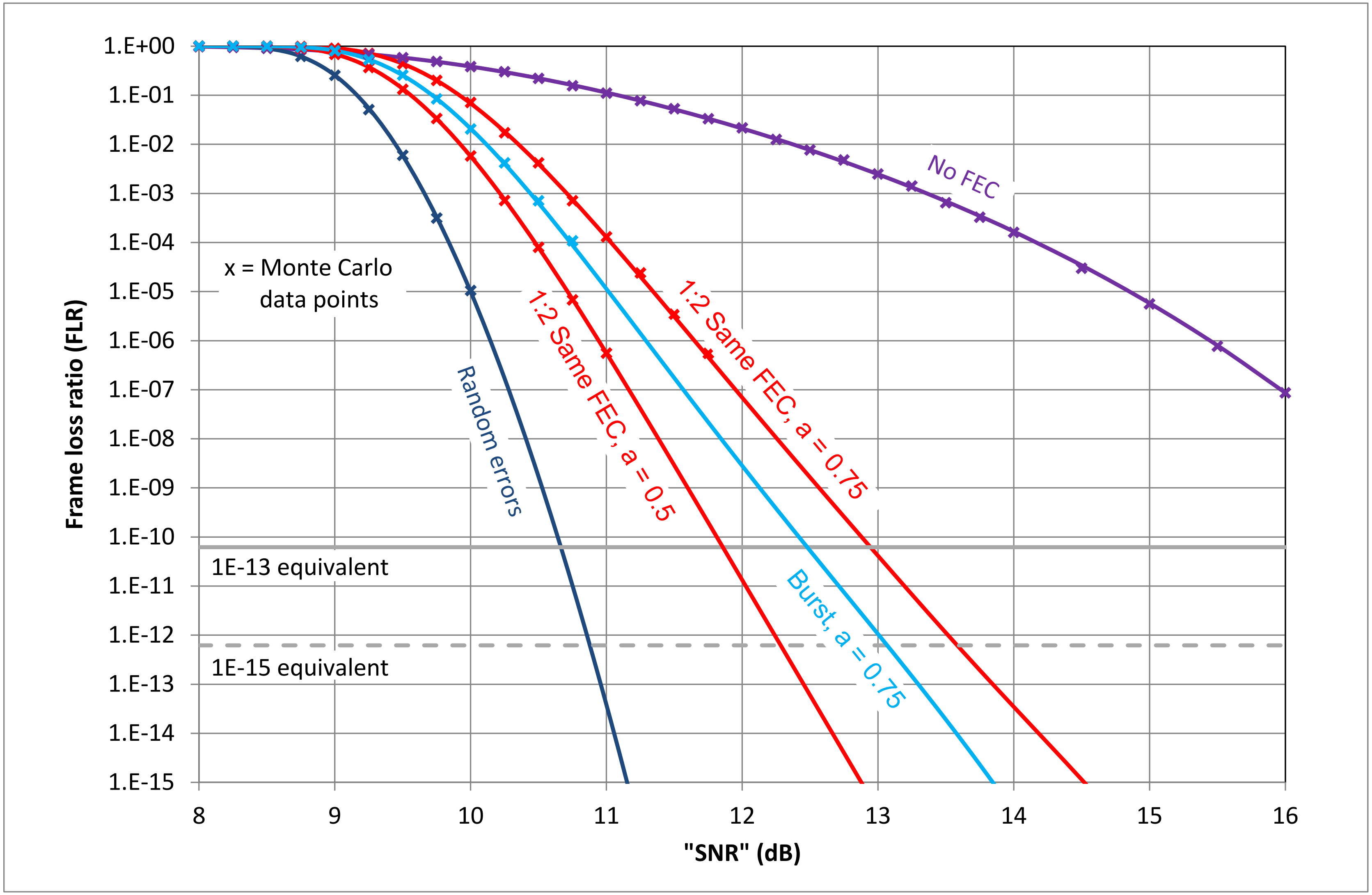
RS(544,514) 1:2 results (no skew)



RS(544,514) 1:2 results (with worst case skew)



RS(544,514) all results (skew and misaligned)



Results for RS(544,514) all gain used for PAM4

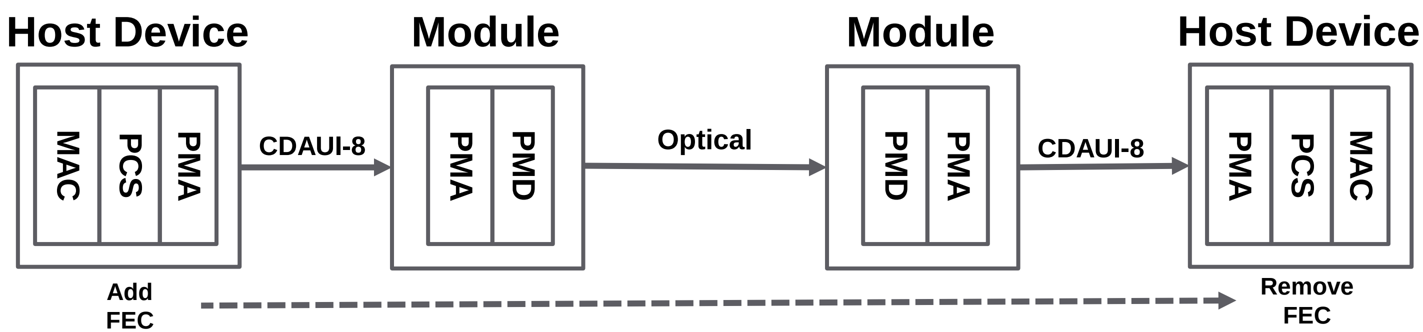
Just for reference (not what is proposed), from the curves shown on the previous slide, if all of the coding gain were to be used for the PAM4 link, the BERs at the FEC input required to give FLRs equivalent to that of a BER of 1E-13 and 1E-15 are:

	RS(544,514)	
	FLR = 6.2E-11	FLR = 6.2E-13
No FEC	1E-13	1E-15
1:2 Same FEC, a = 0.75 no skew	1.8E-5*	3.6E-6*
1:2 Same FEC, a = 0.75 worst skew	1.8E-5*	3.6E-6*
1:2 Same FEC, a = 0.5 no skew	3.9E-5*	9E-5*
1:2 Same FEC, a = 0.5 worst skew	3.9E-5*	9E-5*
a = 0.75 misaligned	5.2E-5*	1.3E-5*
a = 0.75 aligned	5.3E-5*	1.4E-5*
Random errors	3.2E-4	2.3E-4

Note – these values are the BER **including** the additional errors due to the bursts. To account for burst errors, the values marked with "*" have been multiplied by 4 when a = 0.75 and 2 when a = 0.5.

What about multi-part links with FEC?

If the FEC bytes are added at the source PCS layer and then the correction is applied only at the destination PCS layer as in:



Then the worst case input BER for the FEC decoder must be met by the concatenation of all of the sub-links.

In the case of CAUI-10 -> SR10 -> CAUI-10, the worst case BER for each of the sub-links is 1E-12 which is the same as the end-to-end requirement. This situation is tolerated on the basis that it is unlikely that all three sub-links will be at the worst case BER at the same time and if two of them were, then the end-to-end BER would still be 2E-12.

The results for multiple sub-links sharing the same RS(544,514) protection is shown on the next slide.

Multi-part link results

The BER of the electrical sub-links for a penalty of ~0.1 dB optical in the optical sub-link are shown in the table below.

Two alternative options for 1:2 are included: the first is for 0.1 dB optical penalty (but with little headroom for multiple electrical sub-links); the second is for 0.16 dB optical penalty (with adequate headroom for multiple electrical sub-links).

	RS(544,514) FLR = 6.2E-11			
	Electrical		Optical	
1:2 Same FEC, a = 0.75 worst skew	Burst	1.4E-6*	Random	2.4E-4
1:2 Same FEC, a = 0.75 worst skew	Burst	2.9E-6*	Random	2E-4
a = 0.75 misaligned	Burst	5.2E-6*	Random	2.4E-4
Random errors	Random	8.2E-5	Random	2.4E-4

Note – these values are the BER **including** the additional errors due to the bursts. To account for burst errors, the values marked with "*" have been multiplied by 4 when a = 0.75.

Conclusion

If the optical sub-link can accept an optical penalty of 0.16 dB (BER of 2E-4), then it seems viable to form PAM4 symbols in the electrical sub-links by simply taking 1 bit from each of two PCS lanes (assuming these are formed by striping in 10-bit blocks aligned with RS 10-bit symbols from a 1 x 400G FEC). Skew between the two PCS lanes does not affect the performance.

Thanks!