Modulation, encoding, and error correction for 448 Gb/s per lane electrical links

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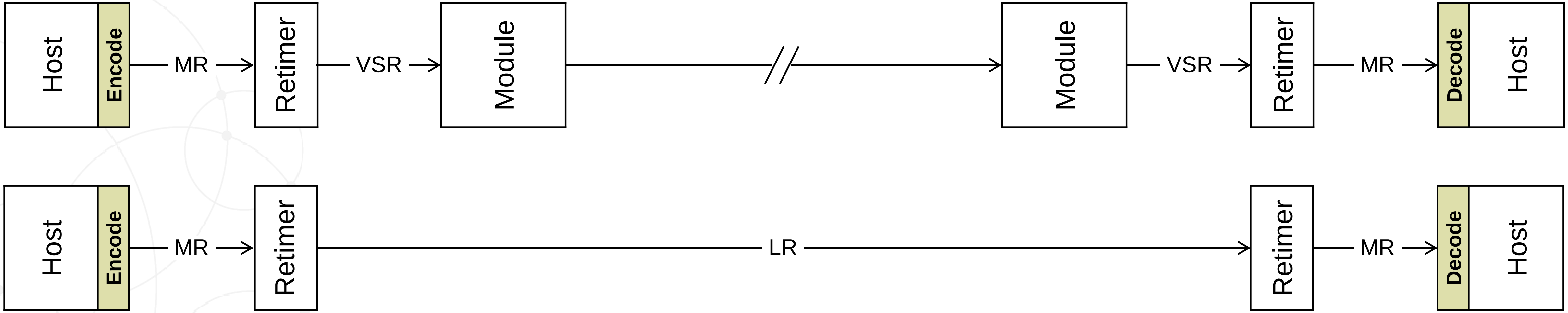
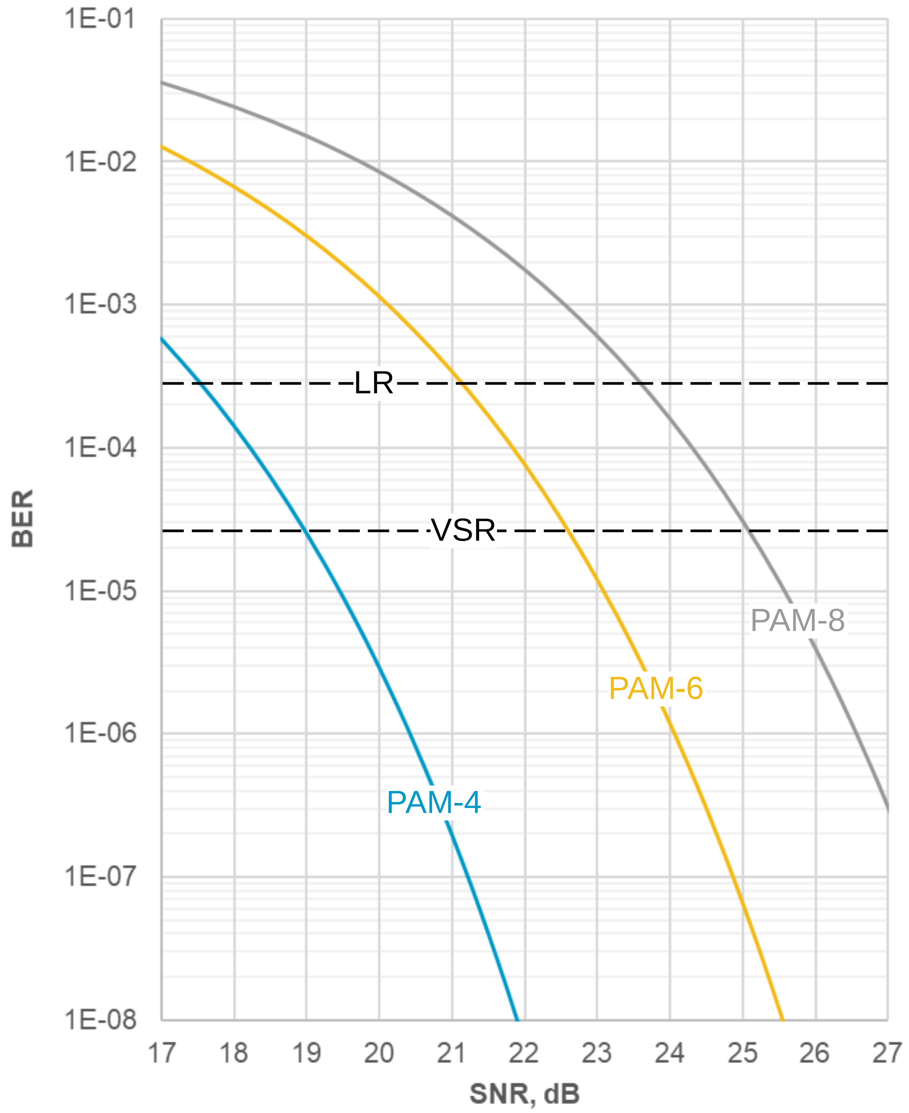
Introduction

- There is motivation to continue use of the established end-to-end Reed-Solomon encoding infrastructure
- However, 448 Gb/s per lane electrical links may not be able to support BERs that are consistent with the end-to-end error correction capability
- This presentation will examine tools to improve the performance of electrical links and support 448 Gb/s per lane within the established infrastructure



Challenges presented by 448 Gb/s per lane



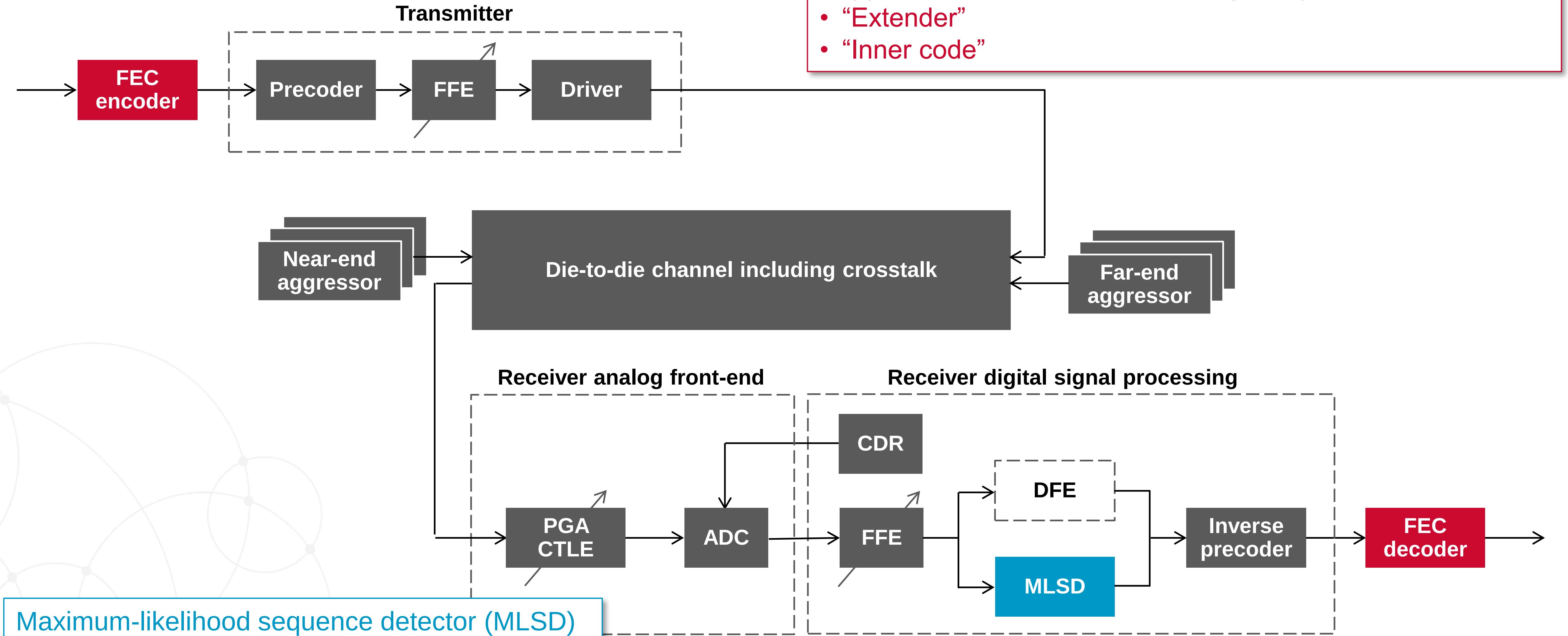
- Increase in BER due to...
- Channel and / or analog circuits not scaling with the increased signaling rate
- Channel and / or analog circuits not providing SNR improvement required for denser constellations

Modulation	**BER at SNR = 19 dB**	**Δ**	**SNR for BER = 2.4e−5**	**Δ**
PAM-4	2.4e−5	—	19	—
PAM-6	3e−3	125x	22.6	+3.6
PAM-8	1.5e−2	625x	25.1	+6.1

- Regardless of the choice of modulation, coding can be used to close an SNR gap

Some ways to close an SNR gap

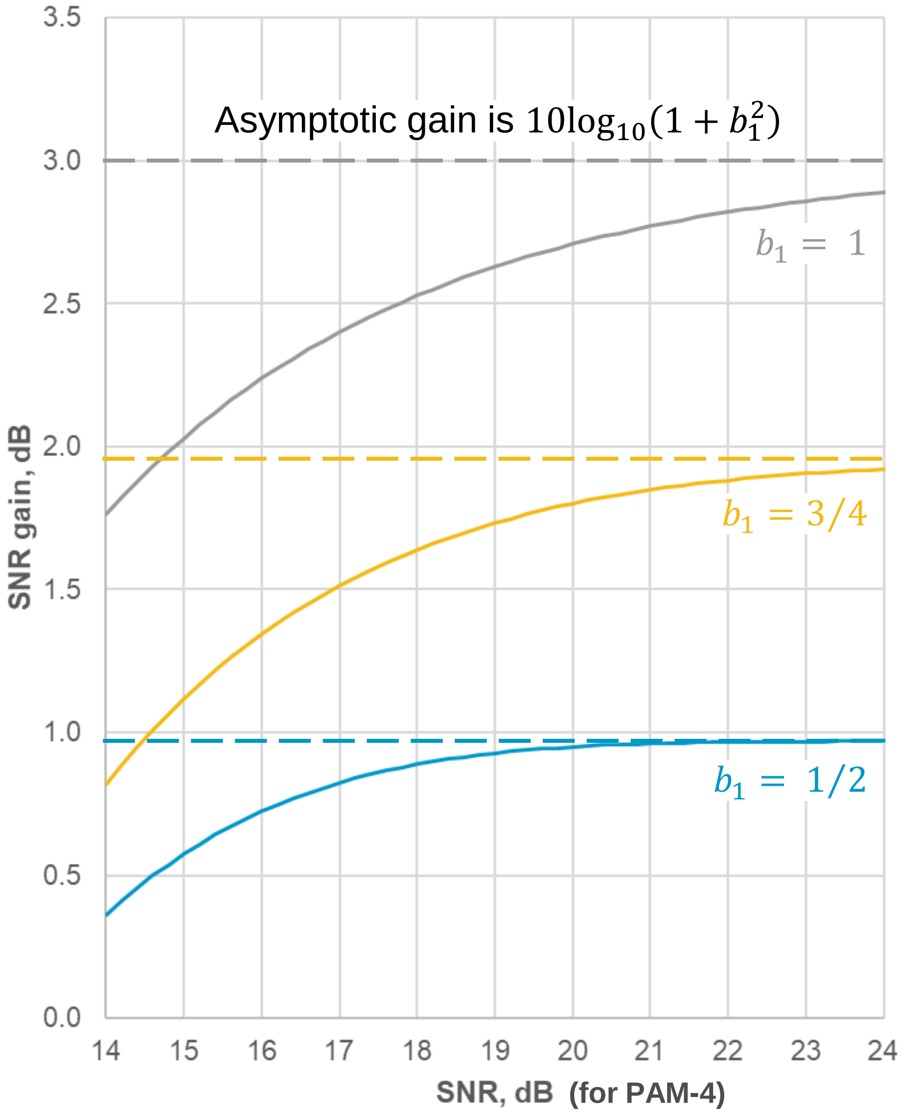
Supplement the error-correction capability of vulnerable links
- "Extender"
- "Inner code"



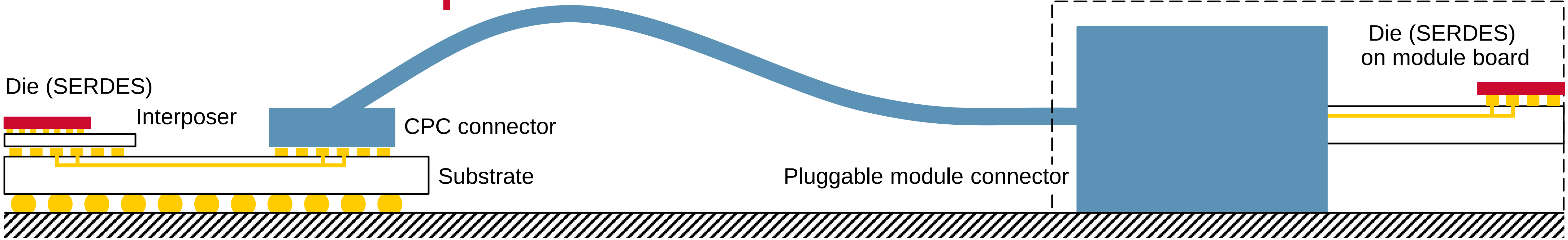
Maximum-likelihood sequence detector (MLSD)
- Already assumed for 224 Gb/s per lane LR
- Can be added for 448 Gb/s per lane VSR

Maximum-likelihood sequence detection (MLSD)

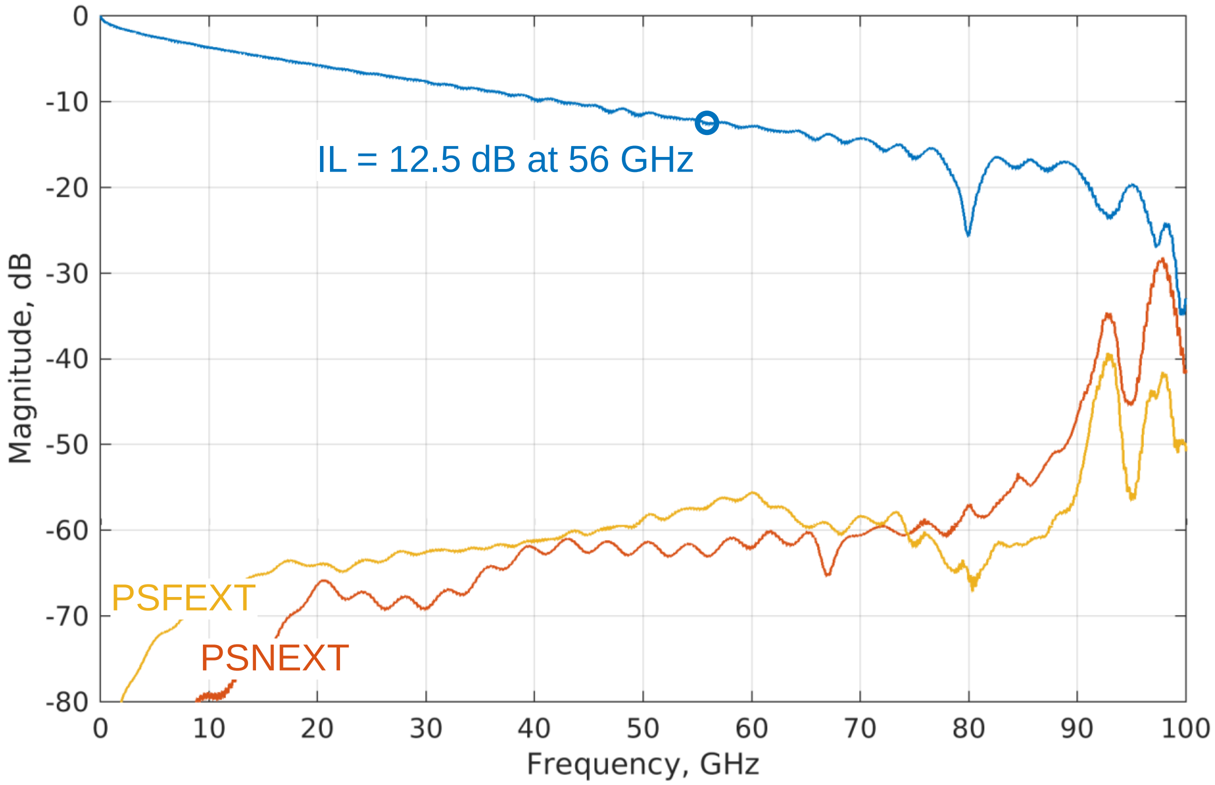
- Can be thought of like error correction
- SNR gain is related to the partial response
- The optimal partial response is channel-dependent
- SNR gain weakens as the input SNR get worse
- SNR gain weakens with denser constellations
- Can be used in conjunction with an inner code
- Use with soft-decision inner code adds complexity



VSR channel example



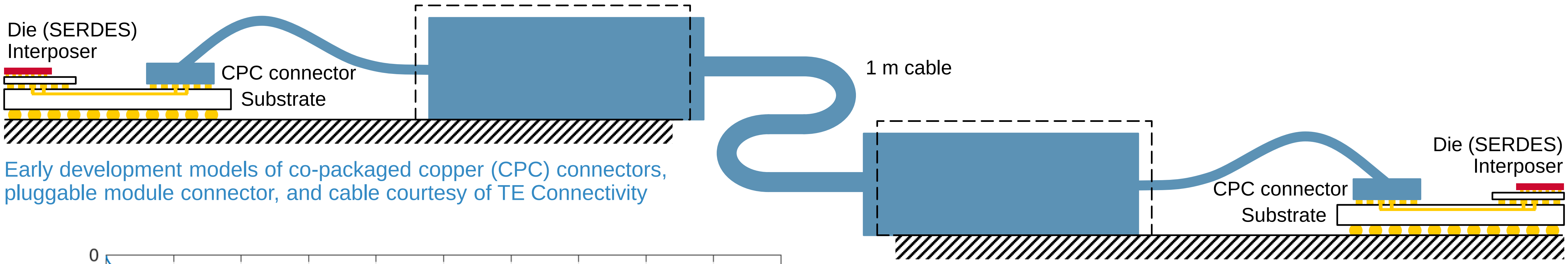
Early development models of co-packaged copper (CPC) connectors, pluggable module connector, and cable courtesy of TE Connectivity



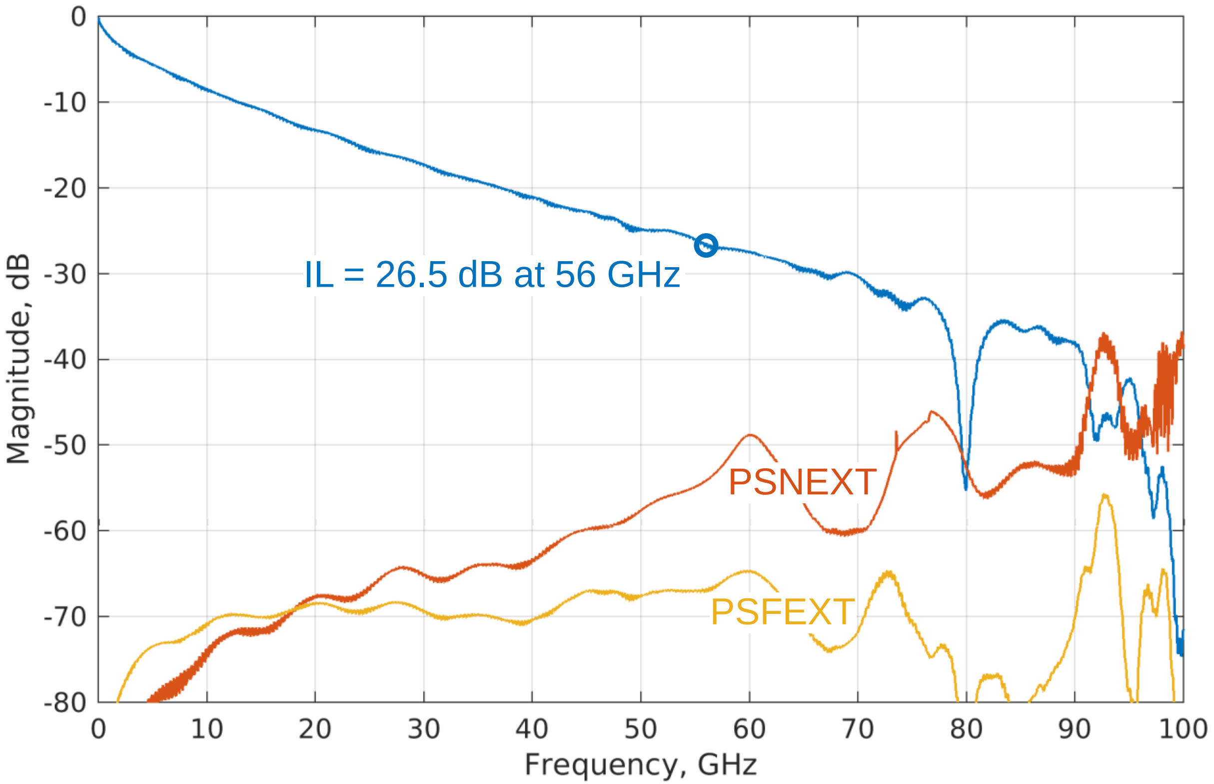
Data rate, Gb/s [1]	425	
Modulation	PAM-6	PAM-8
Signaling rate, GBd	170	142.5 [2]
Insertion loss, dB	17.3	14.9
BER including MLSD	1e−7	7.1e−6
Desired net coding gain, dB [3, 4]	0.9	2.4

[1] Includes standard RS(544,514) encoding but no inner code overhead.
[2] Nearest convenient multiple of a typical Ethernet reference clock.
[3] For 3 dB margin relative to BER = 2.4e−5.
[4] Net coding gain includes any performance penalties due to overhead.

1 m DAC channel example



Early development models of co-packaged copper (CPC) connectors, pluggable module connector, and cable courtesy of TE Connectivity

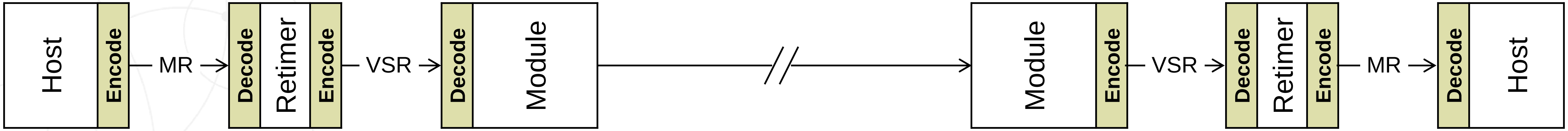


Data rate, Gb/s [1]	425	
Modulation	PAM-6	PAM-8
Signaling rate, GBd	170	142.5 [2]
Insertion loss, dB	36.6	32
BER including MLSD	1e−5	2.2e−5
Desired net coding gain, dB [3, 4]	1.2	1.4

[1] Includes standard RS(544,514) encoding but no inner code overhead.
[2] Nearest convenient multiple of a typical Ethernet reference clock.
[3] For 3 dB margin relative to BER = 2.76e−4.
[4] Net coding gain includes any performance penalties due to overhead.

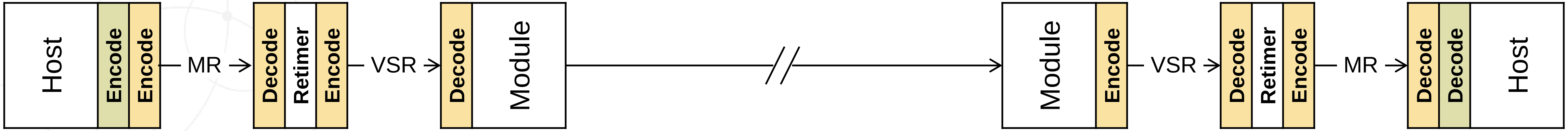
“Extenders”

- The receiver of each VSR (or MR) link decodes the Reed-Solomon codewords and corrects the errors
- The result is re-encoded for transmission over the next link (not necessarily with the same code)
- For “standard” Reed-Solomon encoding, this increases the BER allowance by an order of magnitude or effectively more than 1 dB of SNR gain
- The cost for doing this includes a stack up of decoding latencies



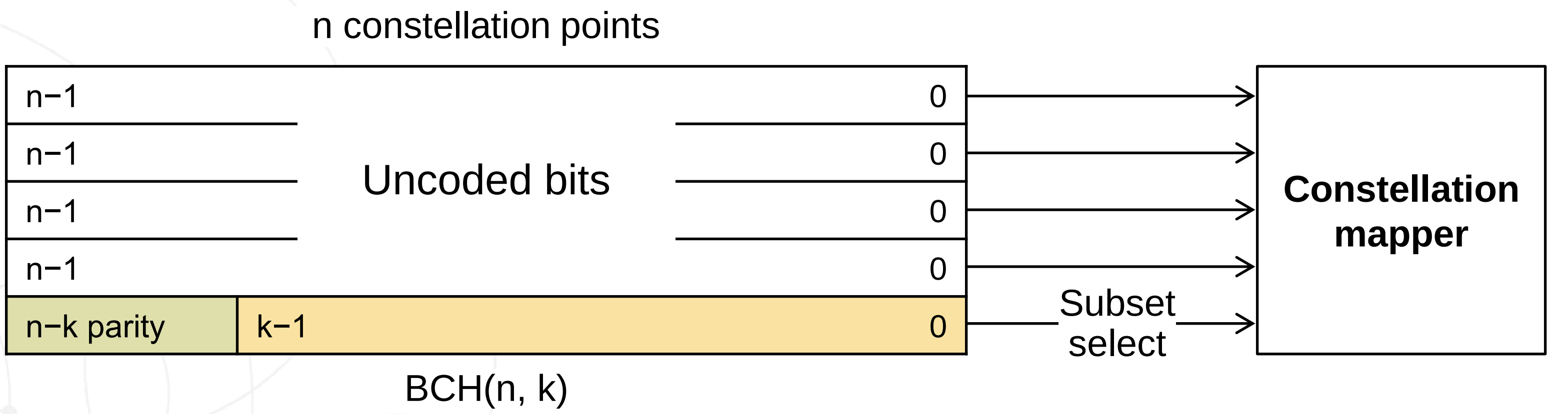
“Inner code”

- The error ratio is proportional to the distance between coded signals d_{min}
- Redundancy can be added at intermediate points in the link to increase d_{min}
- Secondary encoding with an **inner code**
- Decoding corrects errors and alleviates the burden on the outer code (in this case, Reed-Solomon)
- Trade-offs between SNR gain, overhead, complexity, and latency



Inner code examples for 2.5 information bits per symbol

- Constellation can be split into two subsets each with larger distance [1]
- Block code is used to protect the bits that indicate which subset was sent
- This dilutes the overhead of the block code over the coded and uncoded bits which reduces the required increase in signaling rate
- Well-documented hard- and soft-decision decoding algorithms can be applied
- Simpler decoding is preferrable for large-scale integration



n constellation points

n−1 0

n−1 0

n−1 0

n−1 0

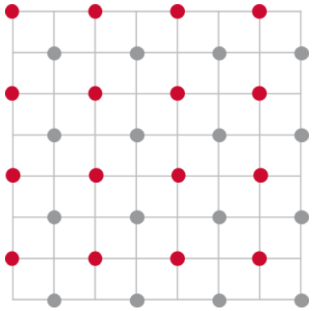
Uncoded bits

n−k parity | k−1 0

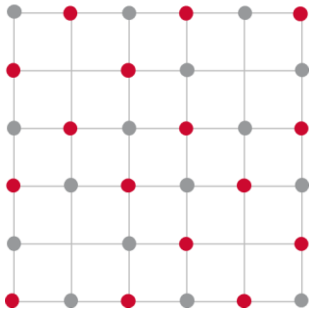
Subset select

Constellation mapper

BCH(n, k)



DSQ-32



PAM-6
framed cross

[1] C. Liu, “Performance Analysis at 400+Gbps Over Next-Generation VSR Channels”, Ethernet Alliance Technology Exploration Forum 2024

Predicted SNR gain for example codes

Code	Signaling rate[a], GBd	Overhead, %	Constellation	Decoding algorithm	SNR gain[b], dB
BCH(156,136) over GF(2^{10}), t = 2	172.5	1.47%	2D PAM-6	Hard decision	1.8
BCH(312,272) over GF(2^{10}), t = 4	175	2.94%	2D PAM-6	Hard decision	2.3
BCH(276,258) over GF(2^{9}), t = 2	172.5	1.47%	DSQ-32	Hard decision	2.0
BCH(280,240) over GF(2^{10}), t = 4	175	2.94%	DSQ-32	Hard decision	2.6

[a] Supports 425 Gb/s data rate.

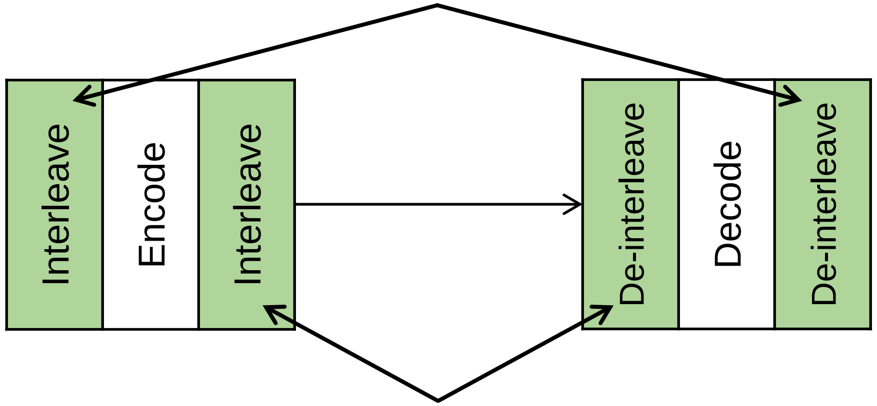
[b] Relative to uncoded PAM-6 symbol error ratio of 1e−4 for random errors (AWGN). Does not include rate penalty.

- Results are for 2.5 information bits per symbol
- Similar codes can be constructed for 2 or 3 information bits per symbol
- Similar trends are expected for 2 or 3 information bits per symbol
- Choose the appropriate solution based on the application requirements

Interleaving

- Performance is often evaluated with random errors
- It is usually the best performance
- Interleavers are used to spread out correlated errors to make them look more random
- This brings actual performance closer to predictions
- Convolutional interleavers are often chosen for lower end-to-end latency

Disperse errors from miscorrection of inner FEC codeword to avoid overwhelming the outer FEC decoder



Disperse “clumps” of errors that may occur on the channel to avoid overwhelming the inner FEC decoder

Summary and conclusions

- Challenges presented by 448 Gb/s per lane are likely to result in an SNR gap for certain applications
- SNR gaps can be closed using maximum-likelihood sequence detection and / or secondary encoding with an inner code
- Design of an inner code must identify the trade-offs between SNR gain, overhead, complexity, and latency that best fit the application requirements
- For loss- or bandwidth-limited channels, SNR gain of a code must account for the increase in the signaling rate required to support its overhead
- There are theoretical and practical limits to how much SNR gain can be realized