Modulation and FEC Considerations for 400GPL Electrical Links

802.3 400GPL Study Group Electronic Interim

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Modulation Design under Different Hardware Constraints for Electrical Links

Average-Power Constraint

- Power consumption
- Thermal budget

Relevant metric:

$$\mathrm{SNR} = \frac{E_s}{N_0}$$

Goal:

- Maximize information rate for a given average transmit power
- Favor energy-efficient constellations

Which constraint is dominant, and which constellation does it suggest?

Peak-Power Constraint

- Amplifier saturation
- DAC output swing

Relevant metric:

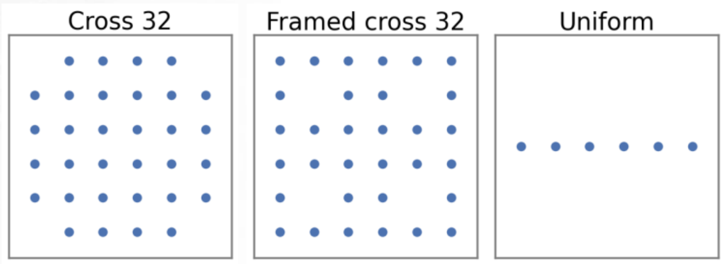
$$\text{Peak-slot SNR} = \frac{E_{max,slot}}{N_0}$$

Goal:

- Maximize information rate for a given signal swing
- Favor constellations that utilize the available amplitude range efficiently

Case study: PAM6-Derived Constellations

- Cross 32/Framed Cross 32/Uniform



Methodology: Mutual Information Comparison

Average-Power View (MI vs SNR)

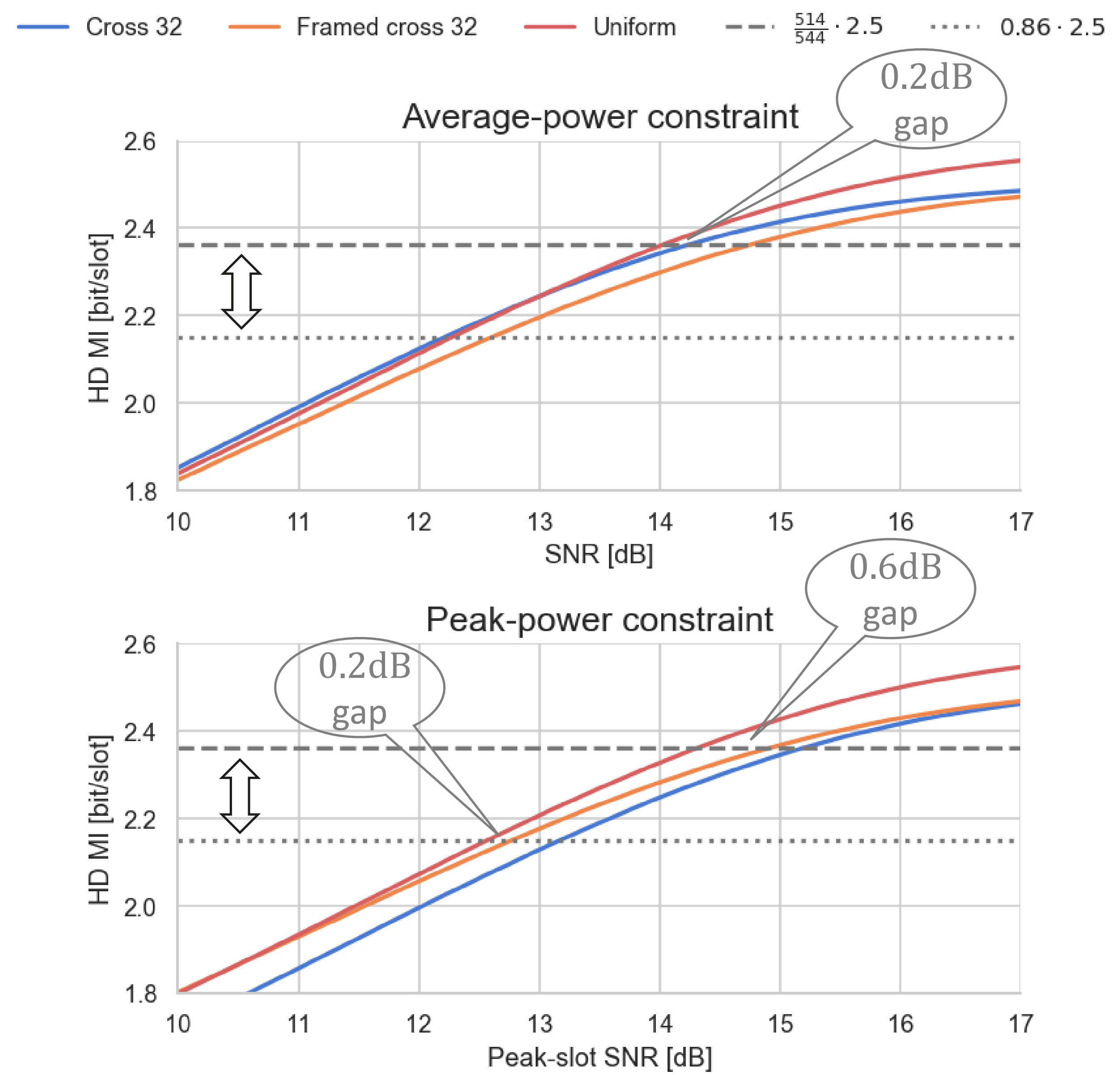
- Both Cross 32 and uniform achieve the highest mutual information for a given average SNR

Peak-Power View (MI vs Peak-Slot SNR)

- Uniform provides the most attractive operating point near the target rate
- Framed Cross 32 becomes interesting for lower rates

The preferred modulation format depends on the dominant hardware constraint and the target spectral efficiency

At which spectral efficiency will we operate?



FEC Overhead Considerations

Motivation

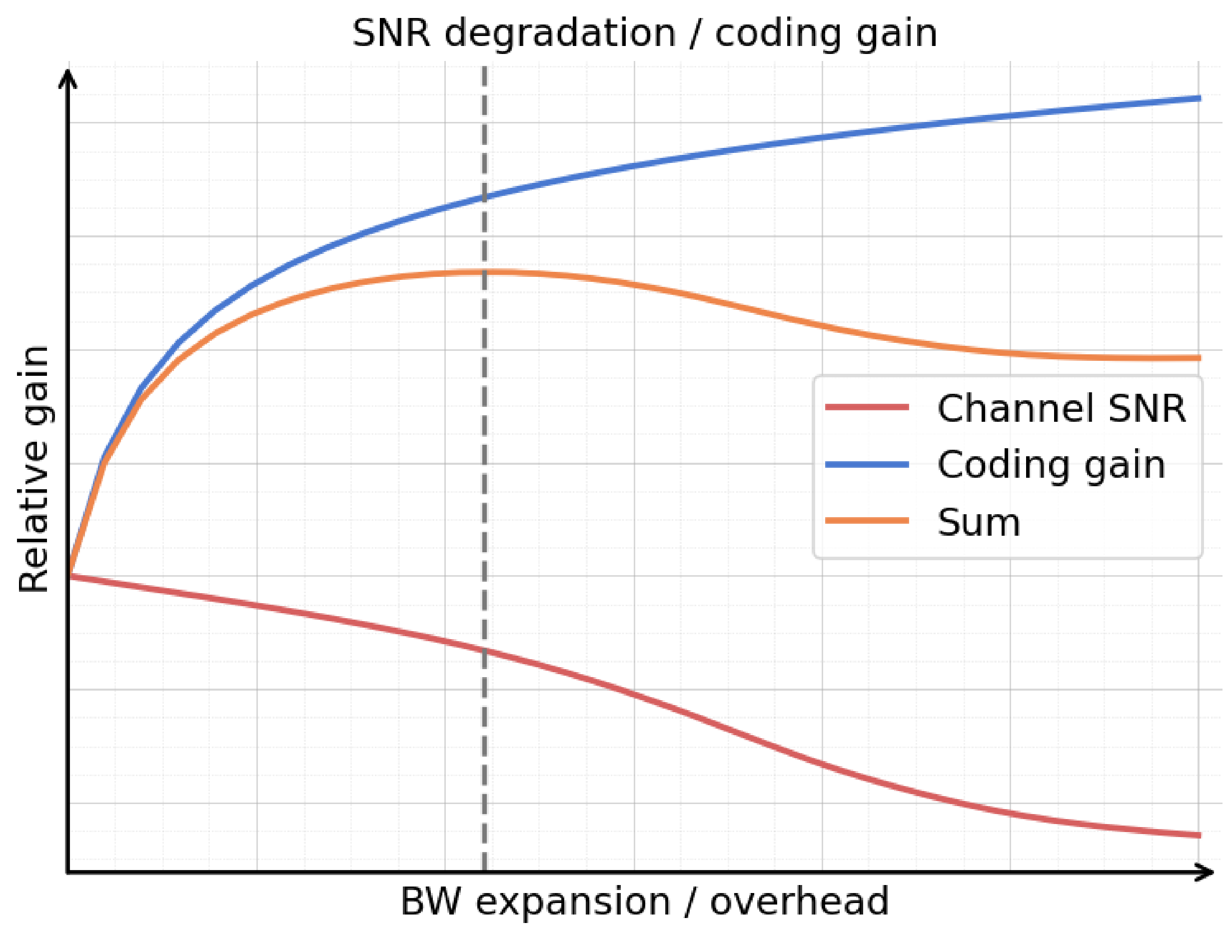
- Additional FEC overhead provides increased coding gain (benefit).
- Additional FEC overhead also increases occupied bandwidth, resulting in an effective SNR penalty (cost)

System design therefore involves a cost-benefit tradeoff

- Bandwidth expansion and coding gain should be evaluated jointly

Case study

- PAM6 signaling



How can the performance-optimal FEC overhead be determined?

Abstracted Channel Model

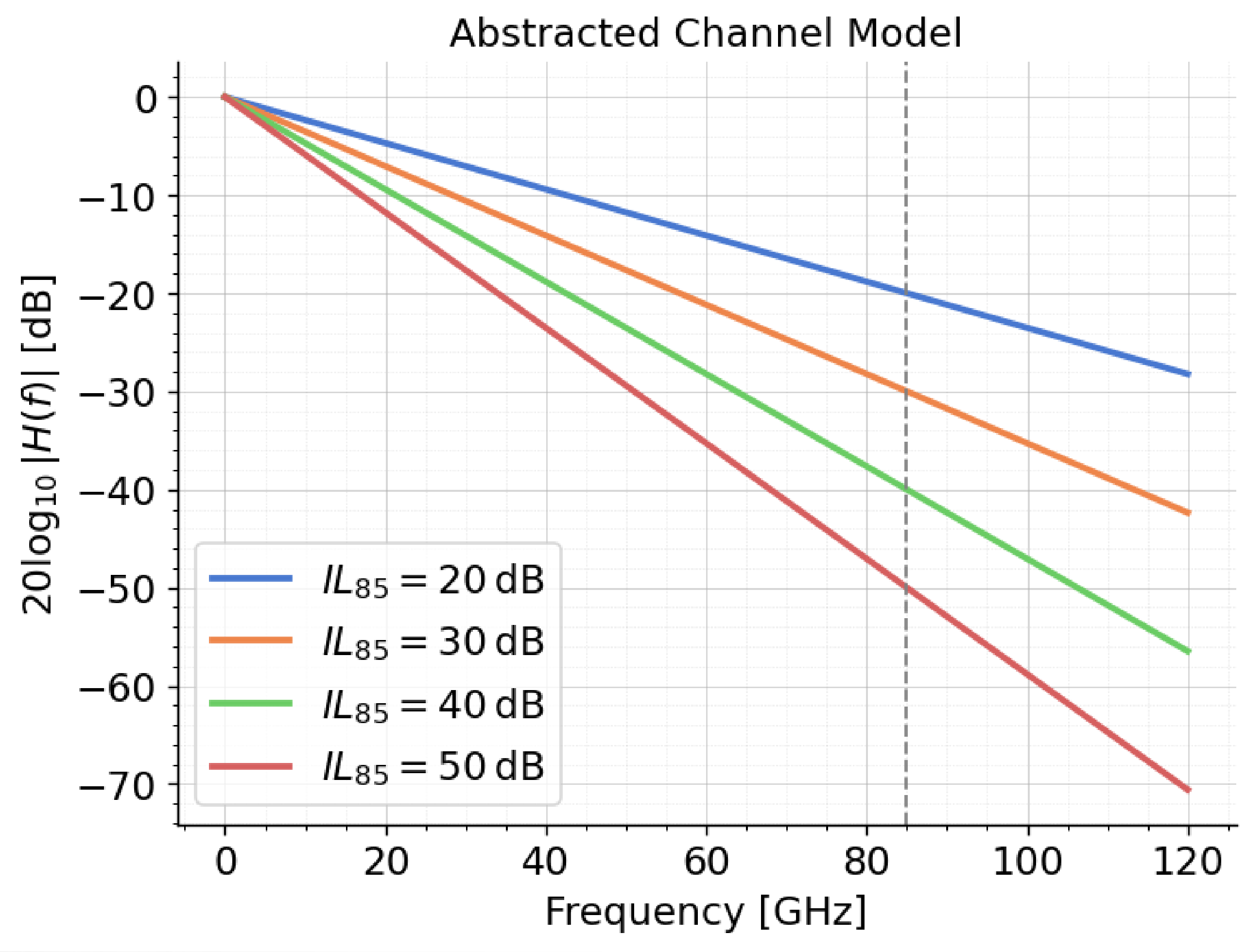
Simple one-parameter model

- The channel magnitude response follows a linear roll-off in the logarithmic domain
- Channel severity is characterized by the insertion loss at 85 GHz (IL_{85})

$$20\log_{10}|H(f)| = -IL_{85} \cdot \frac{f}{85\ GHz}$$

- Sweeping IL_{85} captures a range of channel conditions

The model is intended to capture first-order trends rather than predict implementation-specific performance



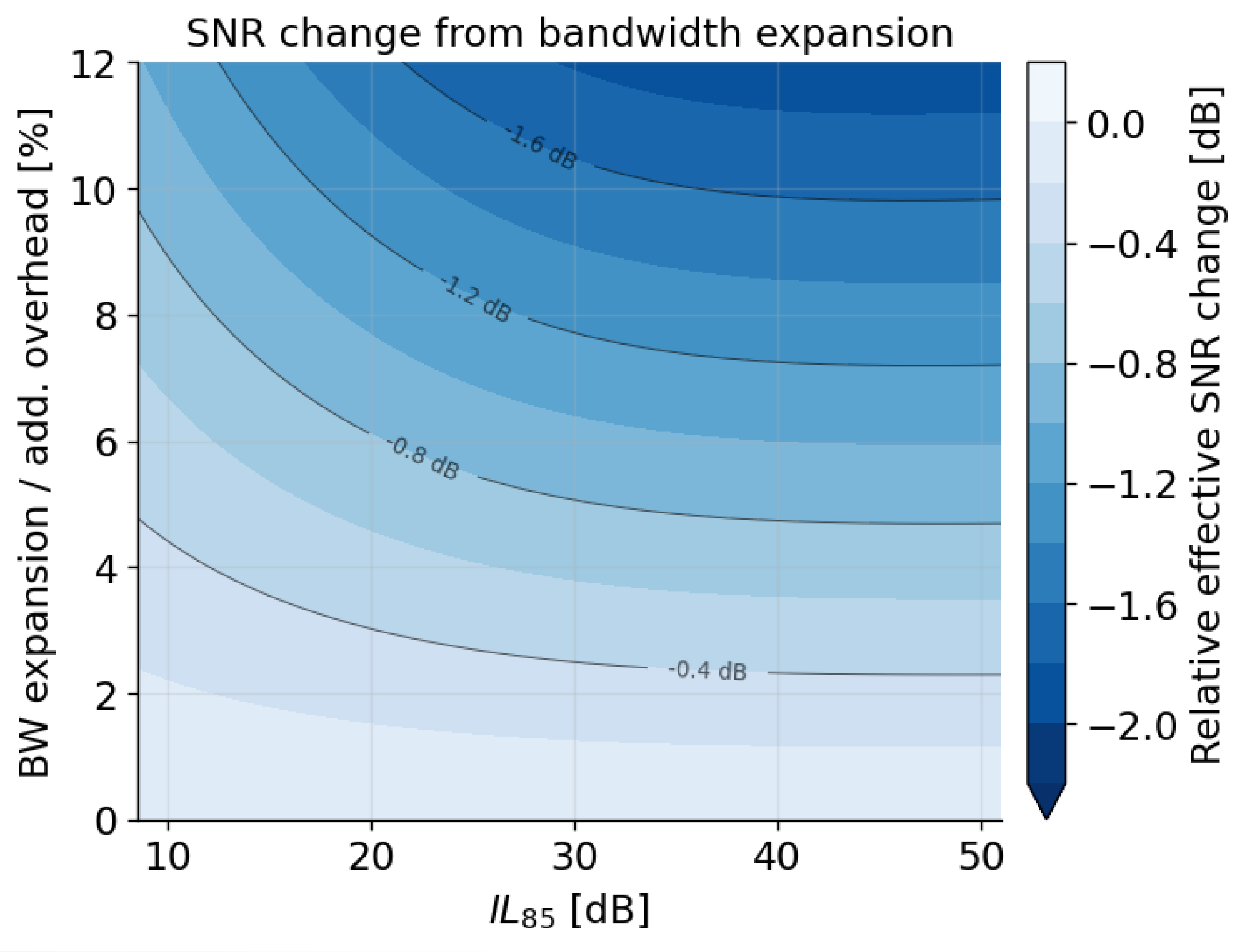
Impact of Bandwidth Expansion on Channel SNR

Setup

- Reference bandwidth of 85GHz
- The SNR degradation is estimated using the Salz approximation [1].

Notes

- Additional FEC overhead increases the occupied channel bandwidth
- The SNR degradation depends on both the **channel loss profile** and the **bandwidth expansion**



[1] J. Salz, "Optimum Mean-Square Decision Feedback Equalization", Bell Syst. Tech. J., vol. 52, no. 8, pp. 1341–1373, Oct. 1973.

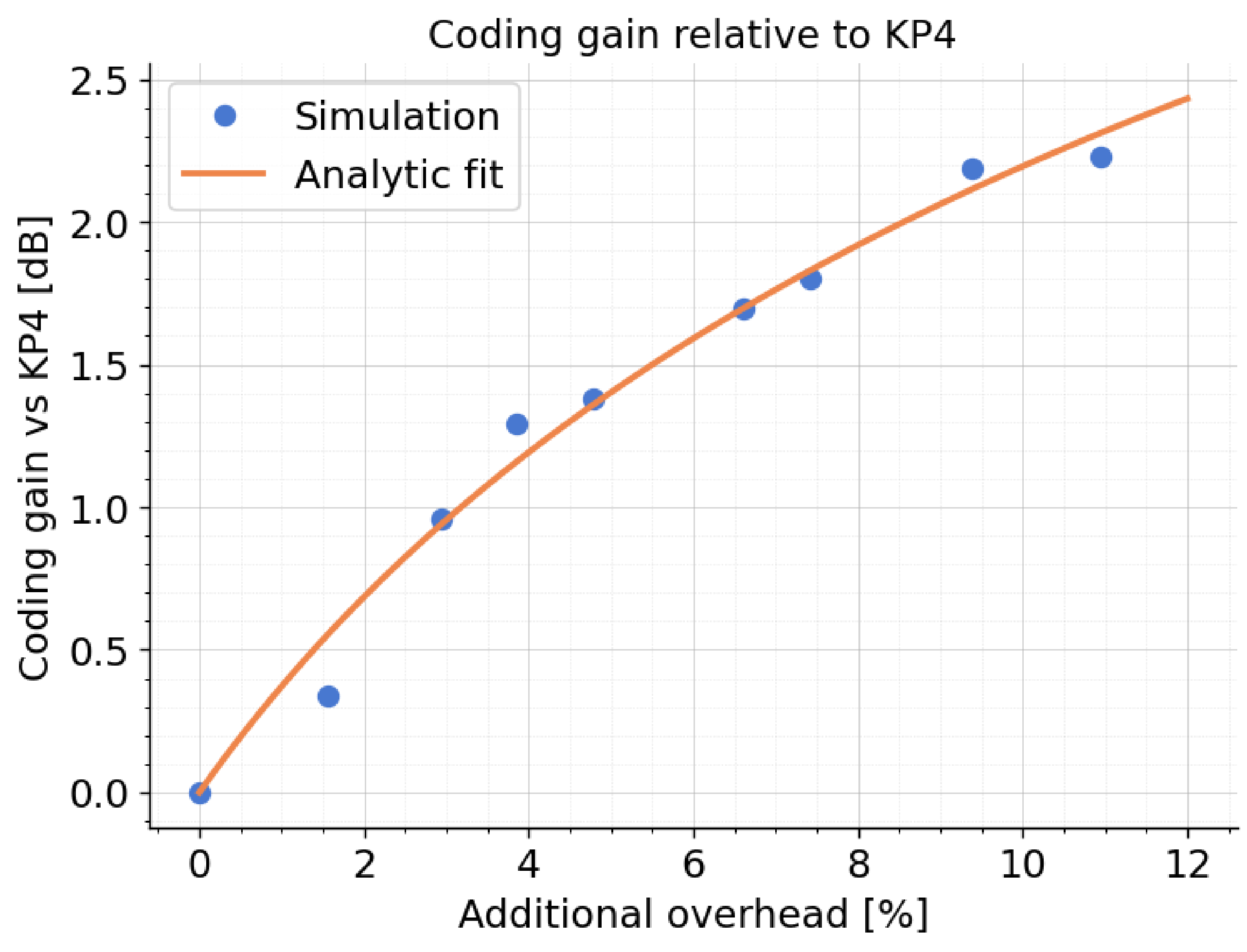
Coding Gain Model

FEC overhead provides coding gain

- Coding gains were obtained from link-level simulations of PAM6 employing KP4 outer FEC and **hard-decision** BCH inner FEC
- A smooth analytic fit is used to interpolate between simulated overhead points
- It serves as an **illustrative case study** based on one representative FEC architecture

Notes

- The coding gain is measured relative to the KP4-only baseline
- Additional overhead denotes the inner-FEC overhead beyond KP4



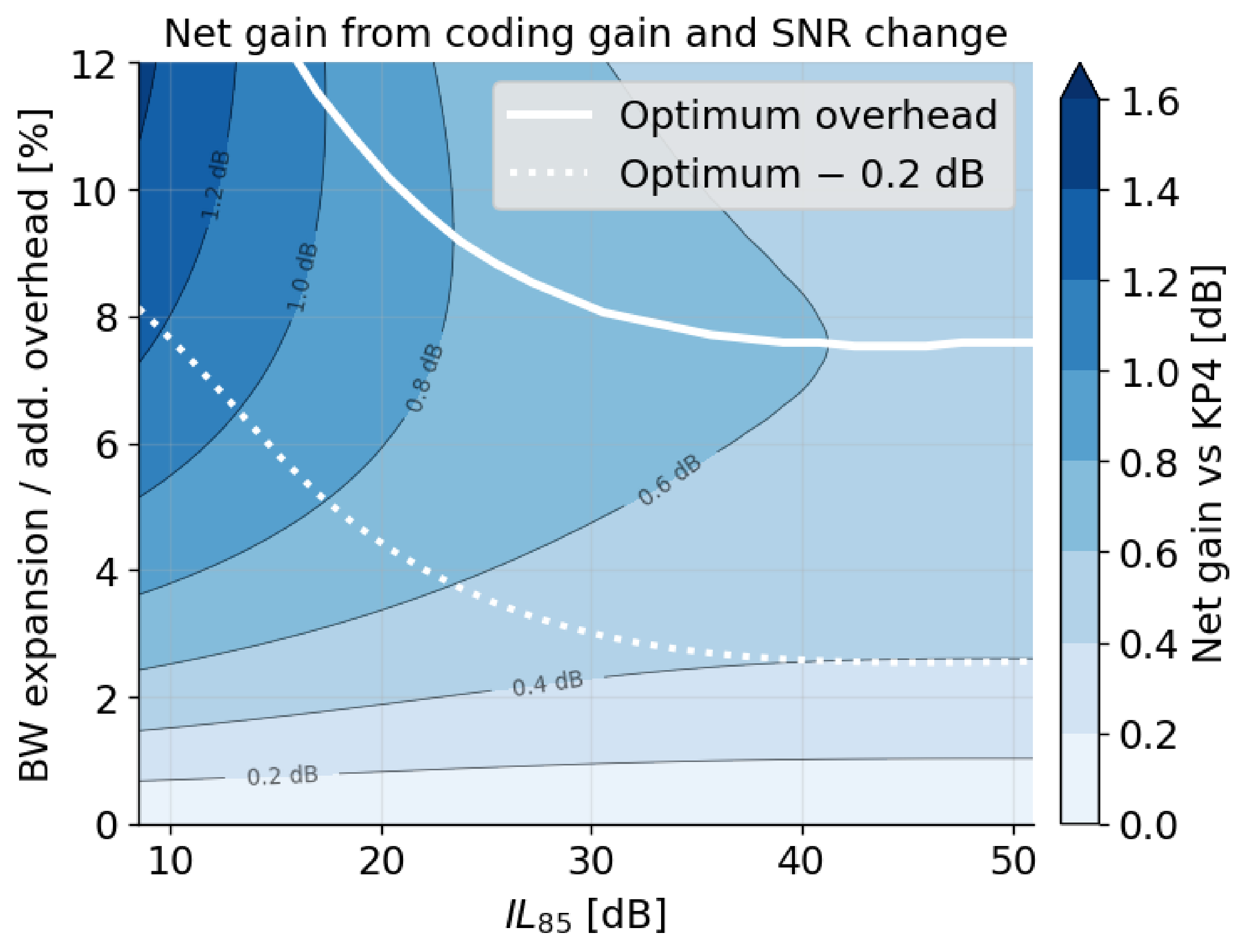
Net Link Gain

The coding gain and channel-induced SNR decrease are combined

- The optimum inner code overhead maximizes the net gain for a given channel

Observations

- The model-based optimum overhead decreases as channel loss increases
- The performance surface is relatively flat: several overhead values operate close to optimum
- Performance appears relatively insensitive to the precise overhead value



400GPL Channels Reported to Date

No.	Link Type / Extent	Length [cm]	IL @ 85 GHz [dB]	Contribution	Year
1	C2C CPC_EBW single twinax	12– 50	5 – 13	gore_e4ai_01a_250529	2025
2	C2M CPC-C 25 mm pkg + 400 mm	~43	~22	kocsis_e4ai_01_250327	2025
3	C2M CPC-B 25 mm pkg + 400 mm	~43	~25	kocsis_e4ai_01_250327	2025
4	CR/DAC	~160	~29	tracy_e4ai_01a_250430	2025
5	NPC	75– 125	31 – 36	he_e4ai_01_251023	2025
6	**CPC assembly**	**~160**	**~25**	**OIF 2026.263.01**	**2026**
7	Vendor channels w/ breakout PCB	N/A	22 – 29	OIF 2026.228.01	2026
8	Customer ref. channel	N/A	50	OIF 2026.258.01	2026

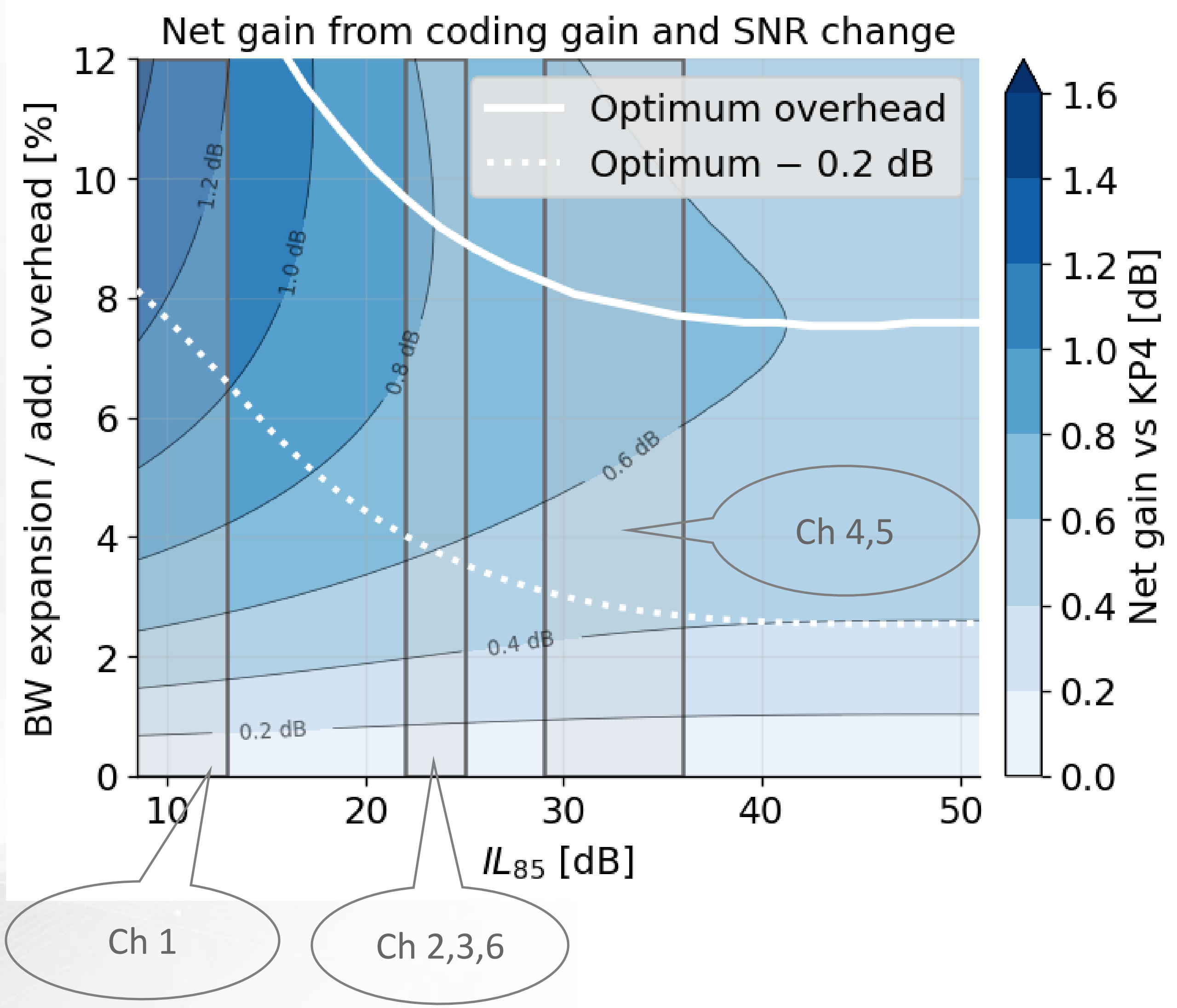
Illustrative Overheads for 400GPL Channels

Recent channel examples correspond primarily to IL_{85} between 22 dB and 29 dB
when mapped onto the abstracted channel model

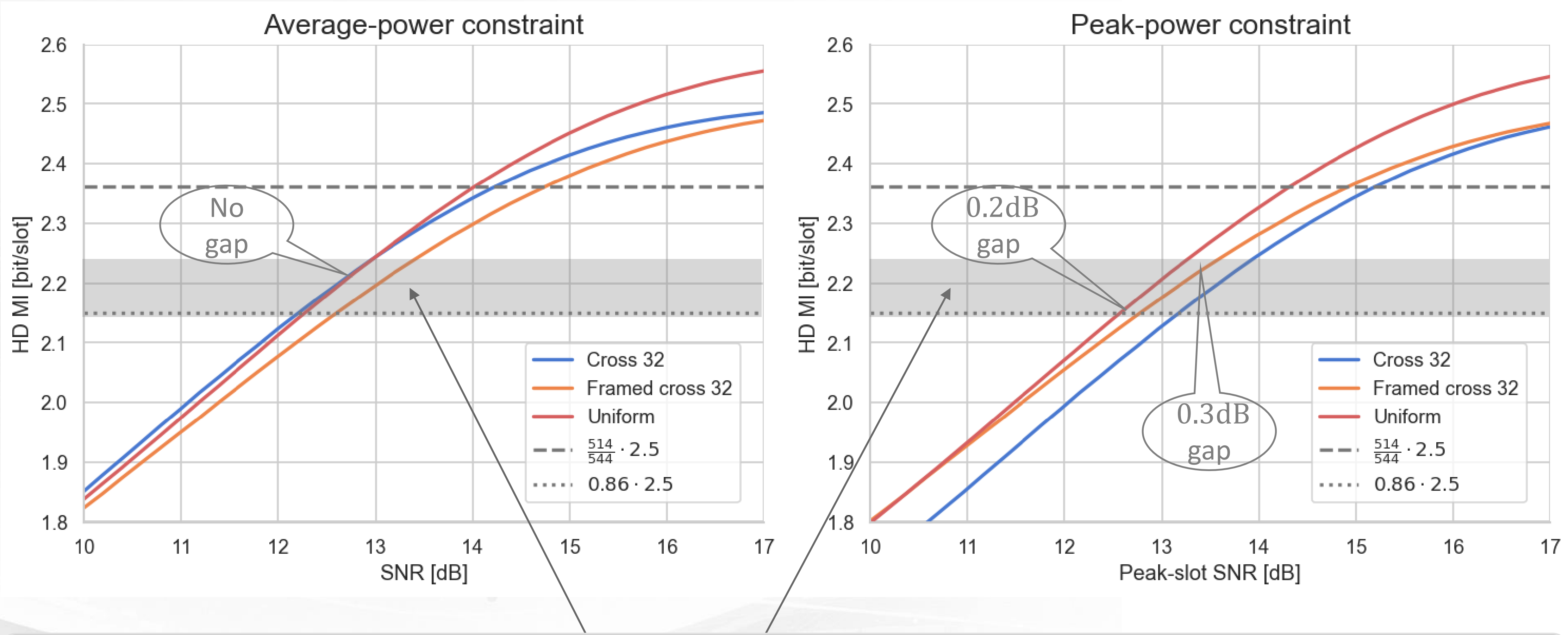
Observations:

- **Short** links may operate without an inner code at a penalty of approximately 1.4 dB
- **Starting at $IL_{85} \approx 22$ dB** channels with predicted optimum overheads around 9–10%
- **Starting at $IL_{85} \approx 29$ dB** channels with overheads around 8% or lower

Continued improvements in packaging and interconnect technologies are expected to further reduce insertion loss



Target Spectral-Efficiency Region



The analysis identifies the relevant operating region, which determines the preferred modulation format

Key Findings

The relative attractiveness of modulation formats depends

- On the dominant hardware constraint
- On the target spectral efficiency (overhead)

Increasing FEC overhead introduces a trade-off between coding gain and bandwidth expansion

- The model predicts decreasing favorable overhead with increasing channel loss
- Representative 400GPL channels suggest modest additional inner-FEC overheads (9% or less)
- Performance appears relatively insensitive to the precise overhead value

Under the assumptions considered

- Uniform PAM6 provides the highest theoretical MI under the assumptions considered
- Yet, 2D constellations remain attractive alternatives

These results illustrate a methodology for evaluating modulation and FEC trade-offs

Thank you