PAM-6 with Channel Memory: Which Option Wins?

802.3 400GPL Study Group Electronic Interim

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August 20, 2026

PAM-6 Creates a Constellation–FEC Trade-off

Multiple PAM-6 options under discussion

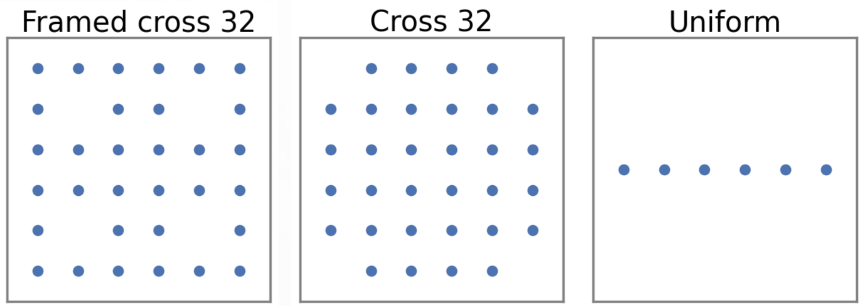
- 2D PAM-6: Framed Cross-32 or Cross-32 [1]
- Higher-dimensional constellations [2]
- Uniform PAM-6 as a benchmark

Uniform PAM-6 provides coding headroom

- 2D constellations: 2.5 bits/slot
- Uniform PAM-6: $\log_2 6 = 2.585$ bits/slot
- 3.4% gross-rate headroom for stronger FEC [3]

Swing-limited links

- Available amplitude is constrained by DAC/driver output swing



[1] Prinz et al., “PAM-6 Coded Modulation for IM/DD Channels with a Peak-Power Constraint”, ISTC 2021
[2] Xu et al., “400 Gb/s+ per Lane Transmission with PAM4, 6, 8,” IEEE 802.3 E4AI
[3] Shan and Zhang, “The 3% Inner FEC for PAM6 and PAM8,” OIF 2026.258.01

Which PAM-6 option requires less transmitter swing at the same net data rate?
How does the answer change with channel memory or precoding?

Unit-Tap-Energy $1 + \alpha D$ Channel Model

Effective channel after RX processing

- $S_{21}(f)$: physical channel response
- MMSE FIR: shortens the channel
- Noise whitening: produces nearly white noise

Unit energy channel response

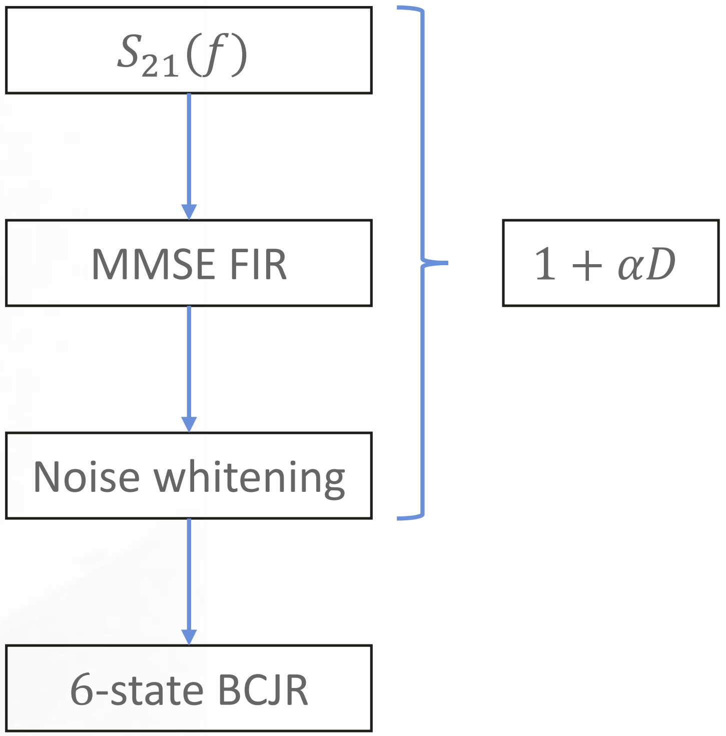
$$H_{\text{eff}}\left(e^{j\omega}\right) = G\,\frac{1+\alpha e^{-j\omega}}{\sqrt{1+\alpha^2}}$$

- G: absolute effective-channel gain
- $\alpha = h1/h_0$ determines the residual channel memory
- $\alpha = 0$: memoryless channel; larger α: stronger residual ISI

Simulations: $\boldsymbol{G = 1}$

$$y_i = \frac{u_i + \alpha u_{i-1}}{\sqrt{1+\alpha^2}} + n_i, \quad 0 \le \alpha \le 1$$

- $n_i \sim N(0, \sigma^2)$



Fixed tap energy separates memory from overall gain; absolute swing requires G and receiver-noise

α Sets the DC-to-Nyquist Loss Difference

At DC and Nyquist

$$|H_{\text{eff}}(0)| = G\,\frac{1+\alpha}{\sqrt{1+\alpha^2}}$$

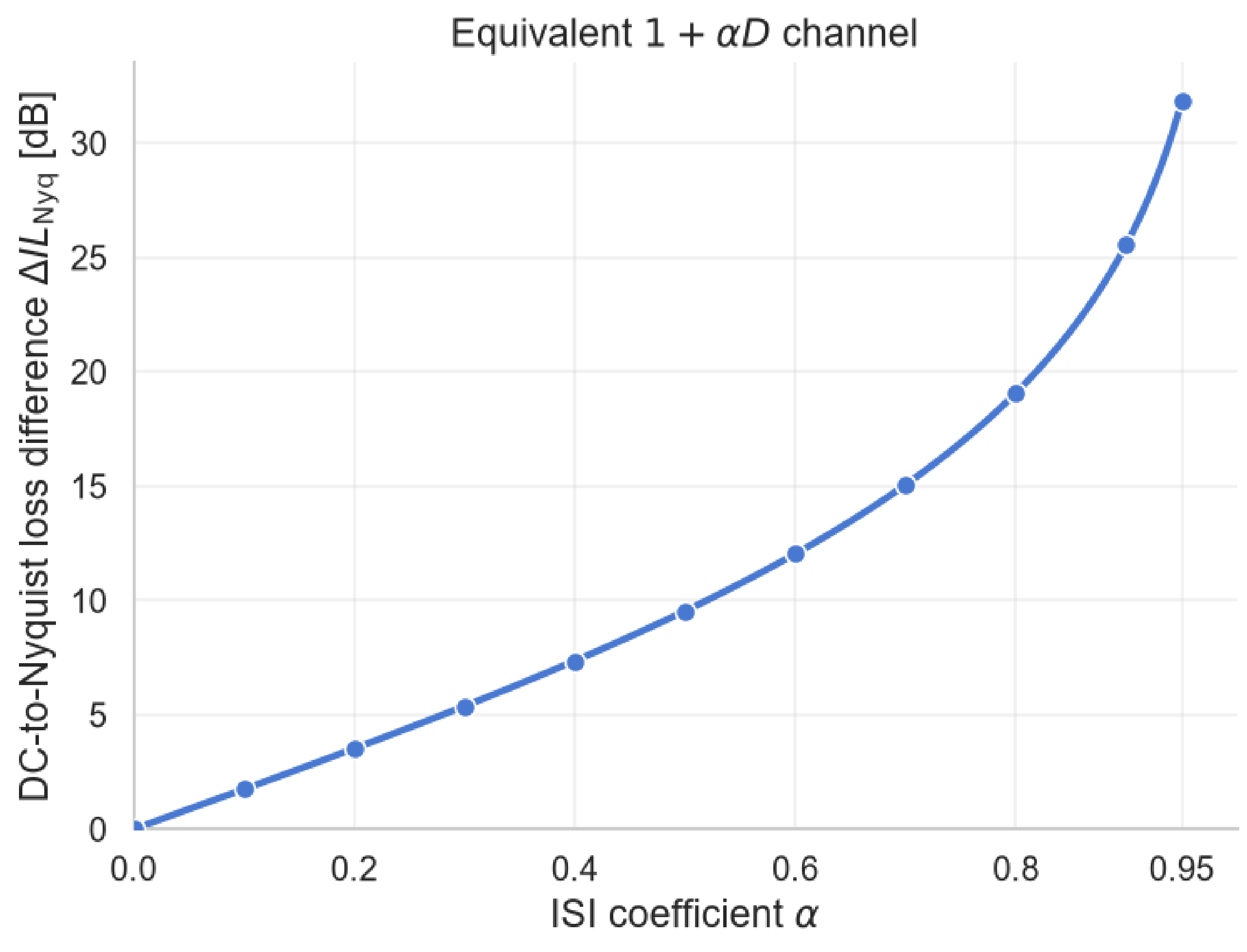
$$|H_{\text{eff}}(\pi)| = G\,\frac{1-\alpha}{\sqrt{1+\alpha^2}}$$

DC-to-Nyquist insertion-loss difference

$$\Delta IL_{\text{Nyq}} = 20\log_{10}\frac{1+\alpha}{1-\alpha}$$

Interpretation

- α determines the DC-to-Nyquist loss difference
- G determines the absolute effective-channel gain
- The relation applies to the effective channel, not directly to $S_{21}(f)$



AWGN Benchmark: Coding Headroom Favors Uniform PAM-6

Achievable information rate (AIR): rate supported at a given peak SNR (PSNR) by an asymptotically long code

From PSNR to input-referred swing $V_{\mathbf{pk}}$

$$\boxed{\mathrm{PSNR} = \frac{G^2}{2\sigma_{RX}^2} \cdot V_{\mathrm{pk}}^2}$$

with $\sigma_{RX} = \sigma \frac{V_{\mathrm{pk}} G}{u_{\mathrm{pk}}}$

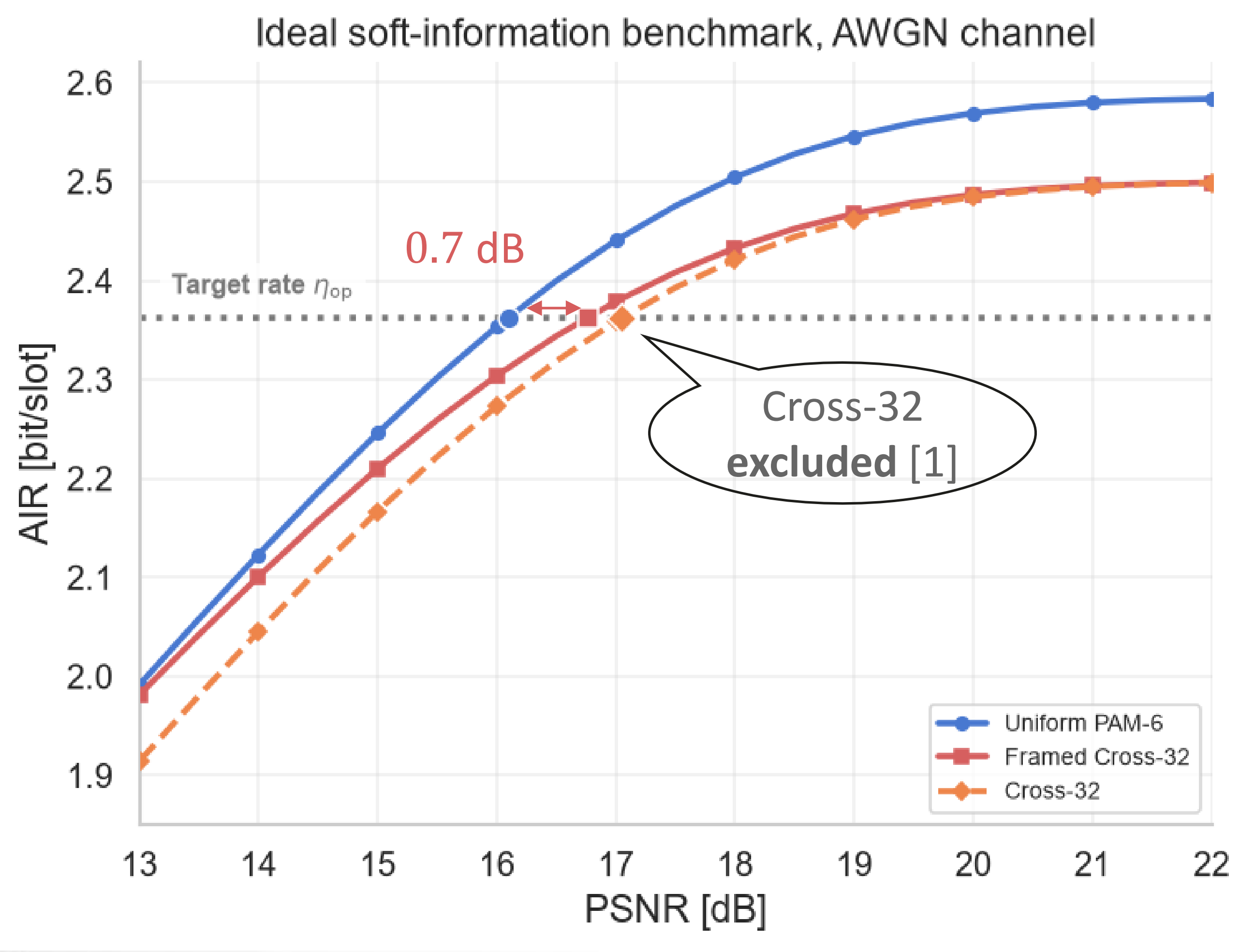
AIR operating point

- Spectral efficiency

$$\eta_{\mathrm{op}} = 2.5 \cdot \frac{514}{544} = 2.36 \text{ [bits/slot]}$$

- Corresponding required PSNR

$$\mathrm{PSNR}_{\mathrm{op}} = R_{\mathrm{AIR}}^{-1}(\eta_{\mathrm{op}})$$



[1] Matuz et al., "Modulation Design under Different Hardware Constraints for Electrical Links", IEEE 802.3 400GPL Study Group

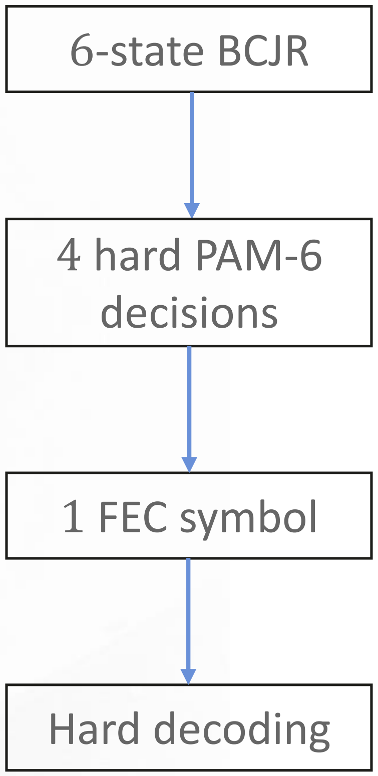
Practical FEC interface

Practical hard-symbol FEC interface

- KP4 uses 10-bit RS symbols
- An FEC-symbol error occurs if **any of the 10** bit decisions is wrong
- Decoding metric does **not distinguish** between 1,2,…,10 bit errors → potentially **suboptimal**
- Hard Hamming-metric decoding (BDD)

Combined FEC and modulation

- Framed Cross-32: four slots carry exactly 10 bits
- Uniform PAM-6: four slots represent ≈ 10.3 bits—currently an idealized interface



Without Precoding, the Ranking Reverses at High Memory

Setup

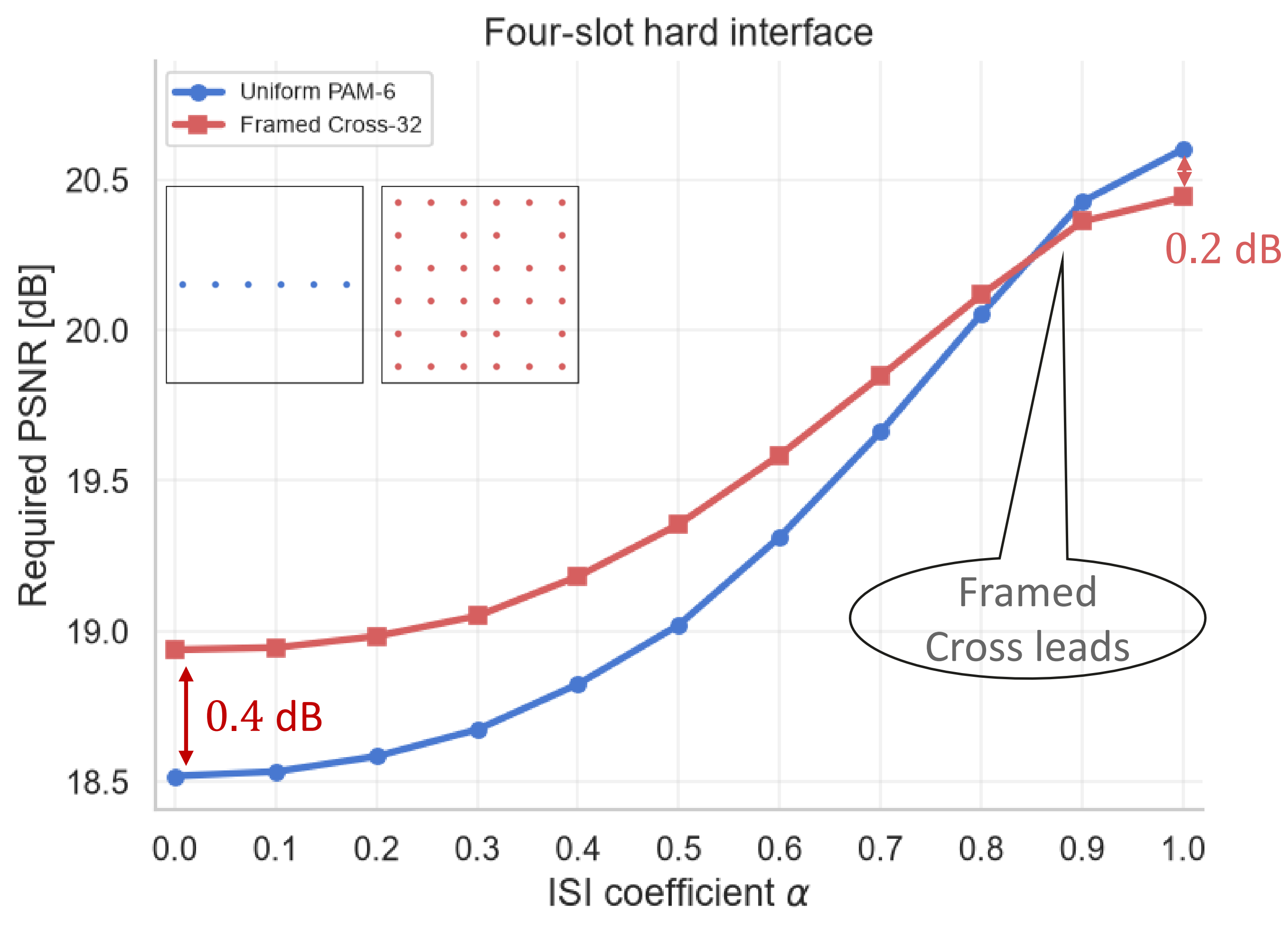
- BCJR produces hard PAM-6 decisions
- Four consecutive decisions form one FEC symbol
- All curves evaluated at the same net rate η_{op}

PSNR differences in dB equal swing differences

$$\Delta\mathrm{PSNR}_{A-B} = 20 \cdot \log_{10} \frac{V_A}{V_B} = \Delta V_{A-B}^{\mathrm{dB}}$$

Key results

- At $\alpha = 0$, Uniform requires approximately 0.4 dB less swing
- Uniform's advantage decreases as channel memory increases
- Framed Cross-32 becomes slightly better only at very high memory



With Precoding, Only Uniform Benefits at High Memory

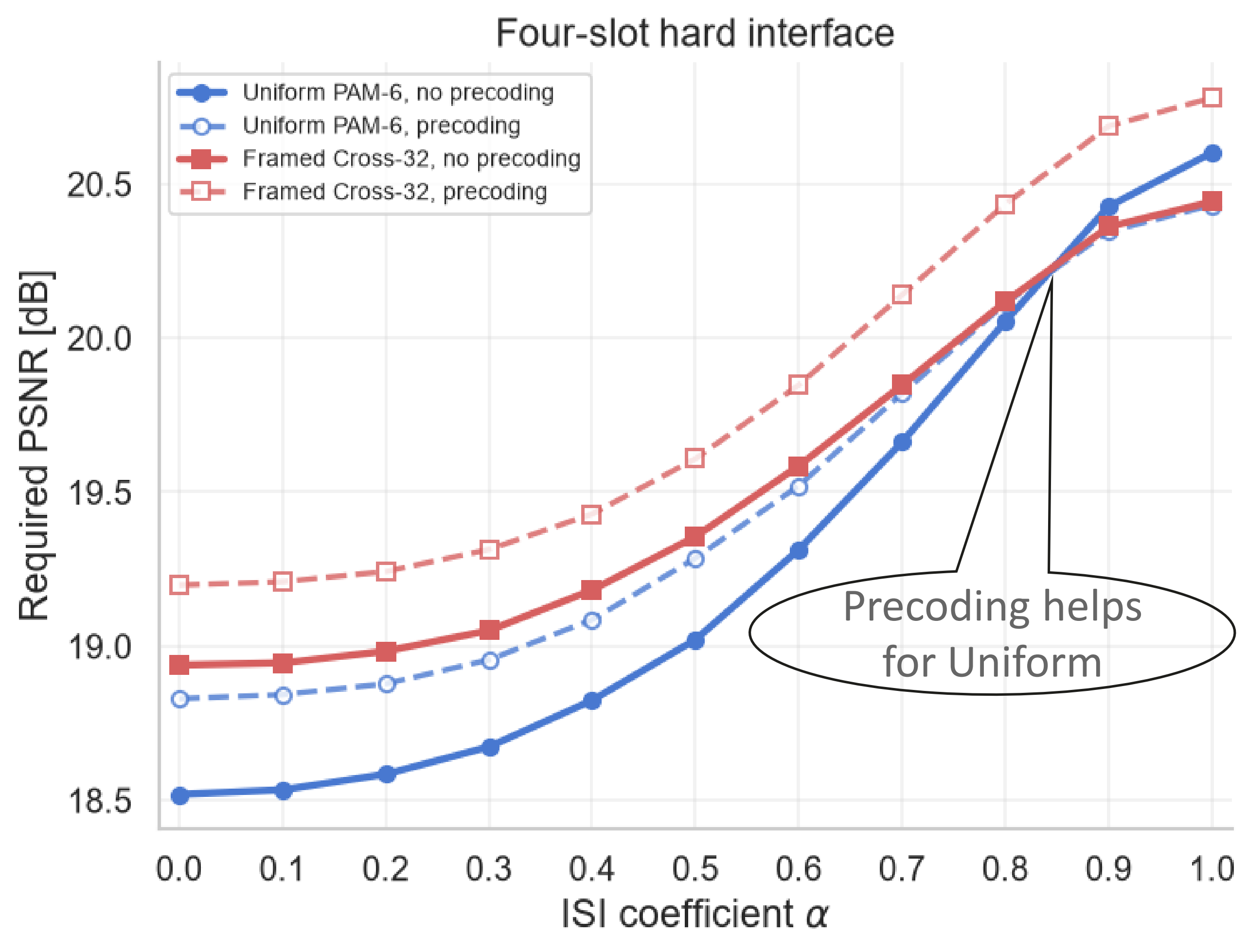
Modulo-6 precoding

$$b_i = (a_i - b_{i-1})\text{mod}6$$

with input a_i, output b_i

Key results for four-slot hard interface

- Framed Cross-32 prefers no precoding over the complete memory range
- Uniform PAM-6 benefits beyond $\alpha \approx 0.84$
- The maximum precoding gain in our setup is around 0.2 dB
- Recall: we assume asymptotically long codes



Uniform Is Best or Equivalent Across the Memory Range

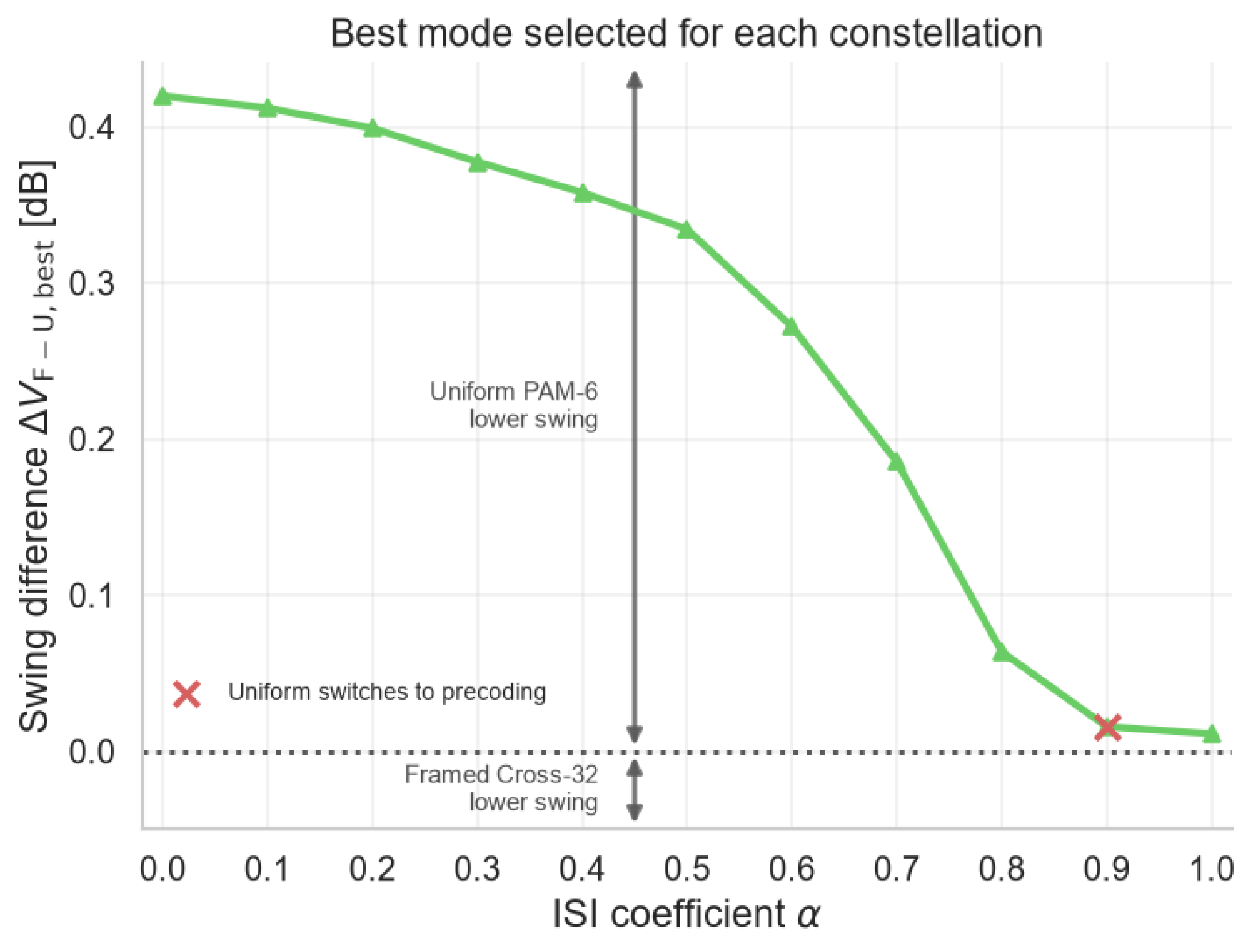
Best-mode comparison

At each α, independently select precoding or no precoding for each constellation:

$$\Delta V_{\mathrm{F-U}} = 20 \cdot \log_{10} \frac{V_{\mathrm{F,best}}}{V_{\mathrm{U,best}}}$$

Key results

- Uniform saves approximately 0.4 dB at $\alpha = 0$
- Its advantage decreases as channel memory increases
- The formats become essentially equivalent at very high memory



Key Findings

Using the unit-tap-energy effective 1+αD model, we compared the relative transmitter swing required by Uniform PAM-6 and Framed Cross-32 at the same net data rate

Which option requires less swing?

- Ideal AWGN benchmark: Uniform PAM-6 requires approximately 0.7 dB less swing
- Four-slot hard-decision interface: Uniform requires approximately 0.4 dB less swing at $\alpha = 0$

How does channel memory or precoding change the answer?

For the four-slot hard-decision interface:

- Increasing memory **reduces Uniform's swing advantage**
- **Without precoding:** Framed Cross-32 slightly wins only at very high memory
- **With best-mode selection:** Uniform is **never worse**; both become essentially equivalent at very high memory

Next step

Practical Uniform PAM-6 setup with concrete bit mapping, interleaving, finite-length FEC

Thank you