# Performance Analysis of Various Modulation Techniques Over 448G Channels

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# Introduction

- Higher bandwidth interconnects are needed to continue scaling AI clusters and support next-generation AI models.
- The increase in bandwidth can be achieved by either increasing the number of lanes within a given form factor or increasing the speed of each lane.
- This presentation aims to determine performance requirements for 448G channels and interconnect solutions using known channel configurations.
- The study will assess the performance of these channels at 448G using various modulation techniques.
- The results will be compared to highlight potential advantages and limitations of each modulation scheme within the 448G framework.
- The goal is to forecast the channel requirements that the industry will need to meet to achieve 448G performance.



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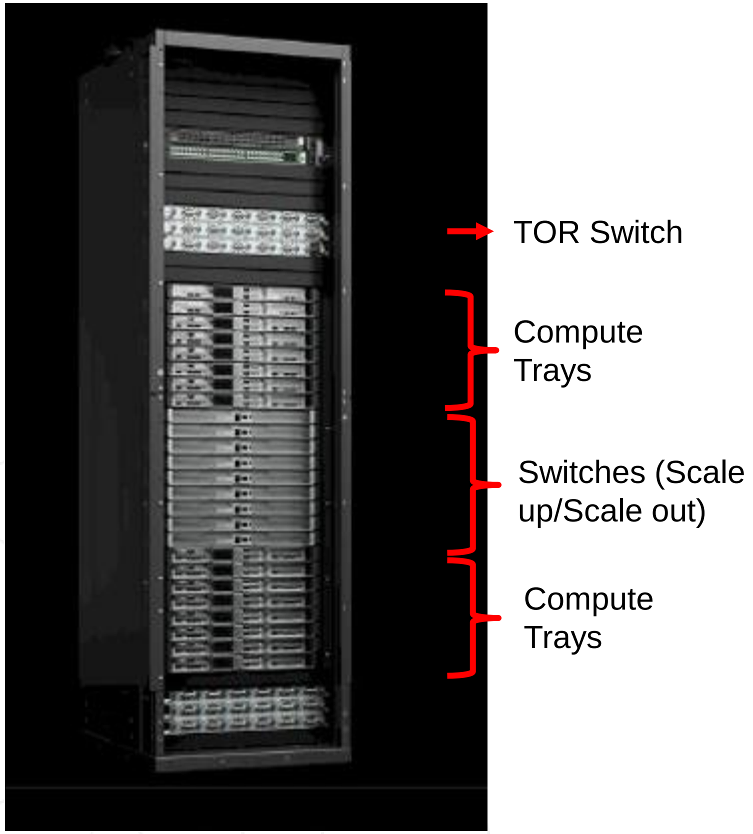
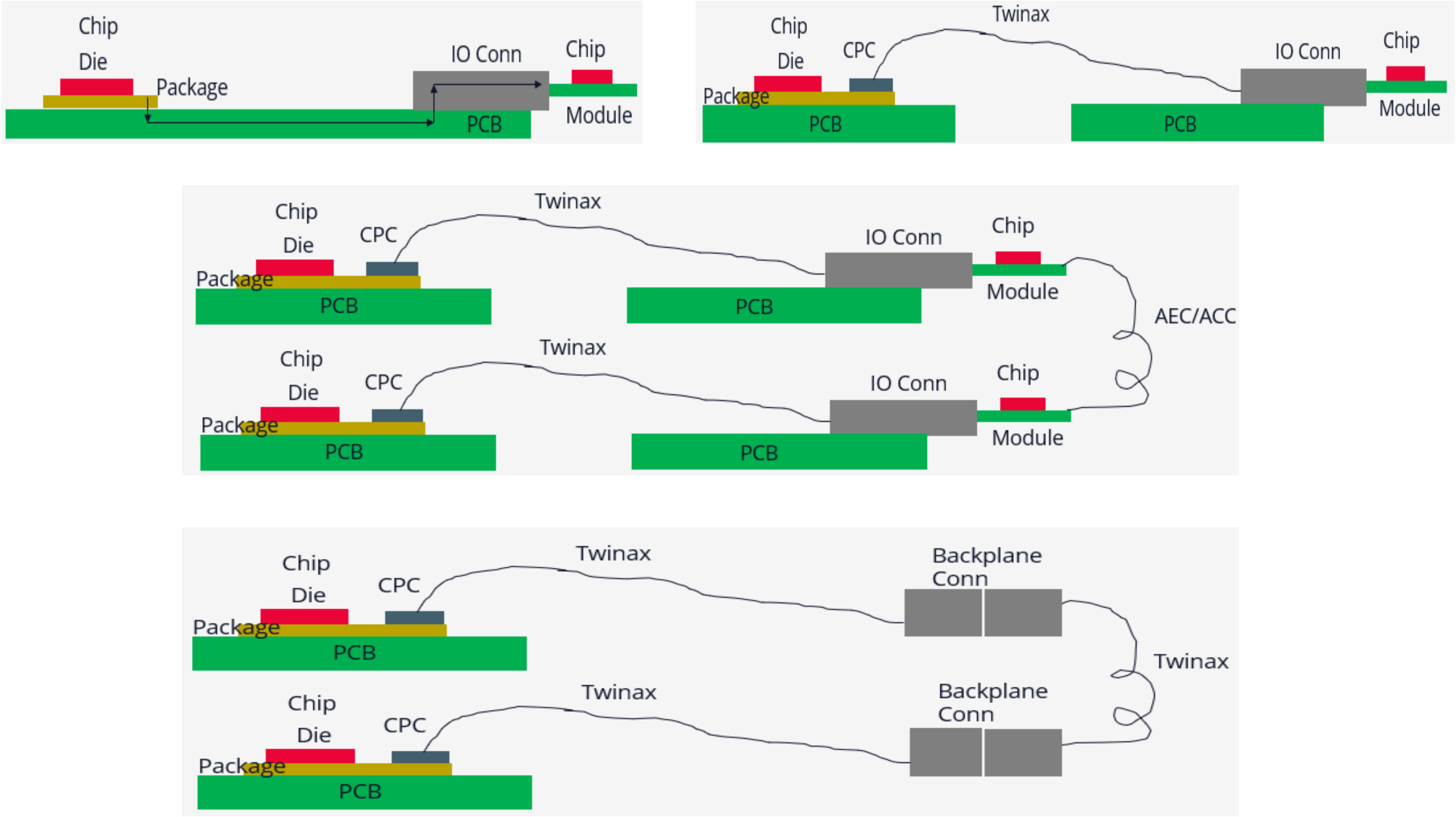
# Typical AI Rack

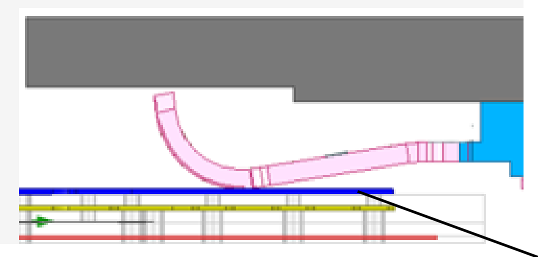


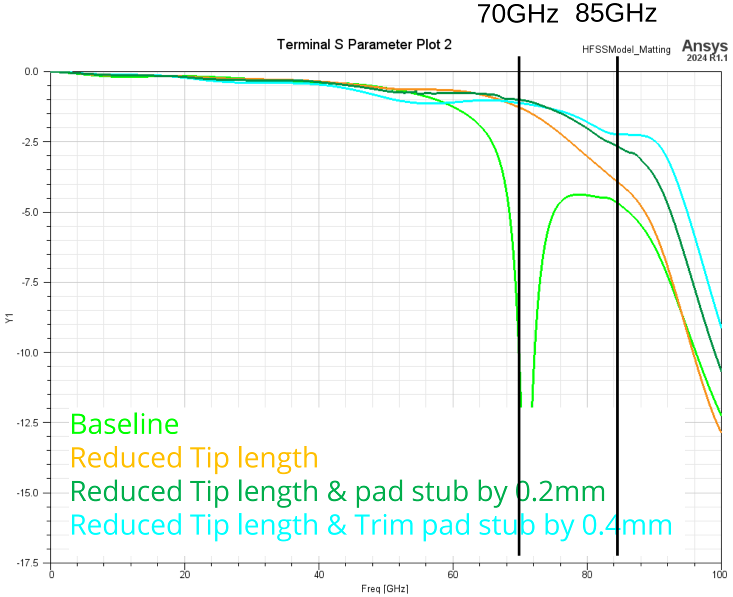

## Typical Scale Out/Scale Up Topologies



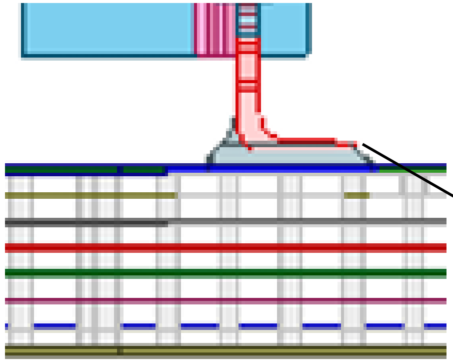
# Interconnect Impairments for 448G data rates

- Separable Mating Interface
  - Cantilever beam lead-in tip stub
  - Gold finger pad stub
  - Lack of full shielding

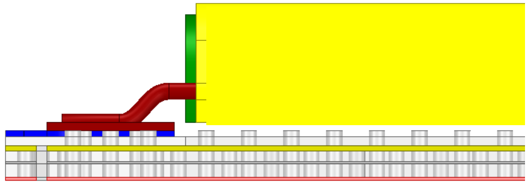





- PCB Attachment
  - SMT “J” Lead
  - Solder inconsistency
  - SMT pad stub
  - Via transition




- Twinax Termination
  - Transition from twinax to PCB pad



Note: Only few impairments are highlighted here



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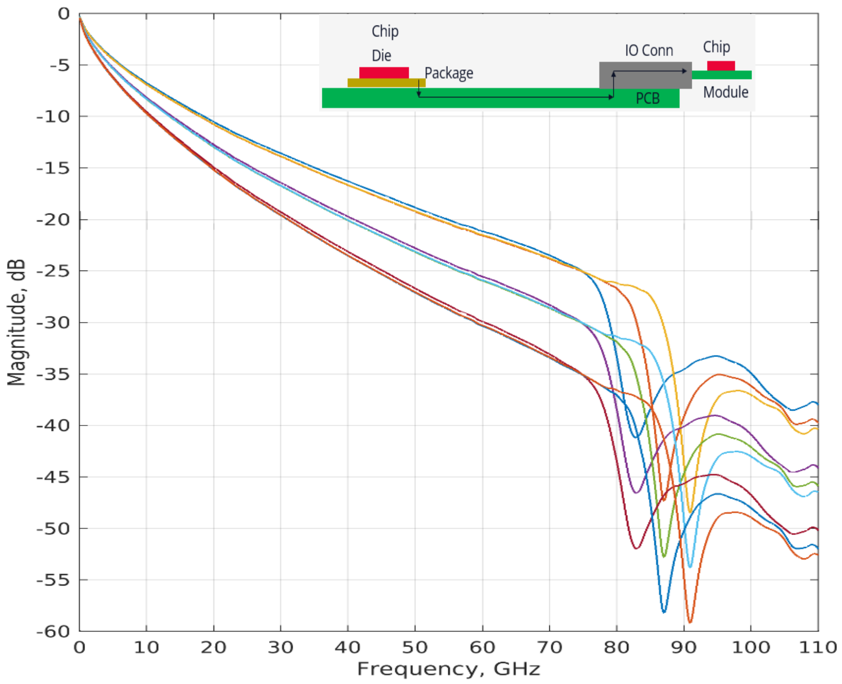
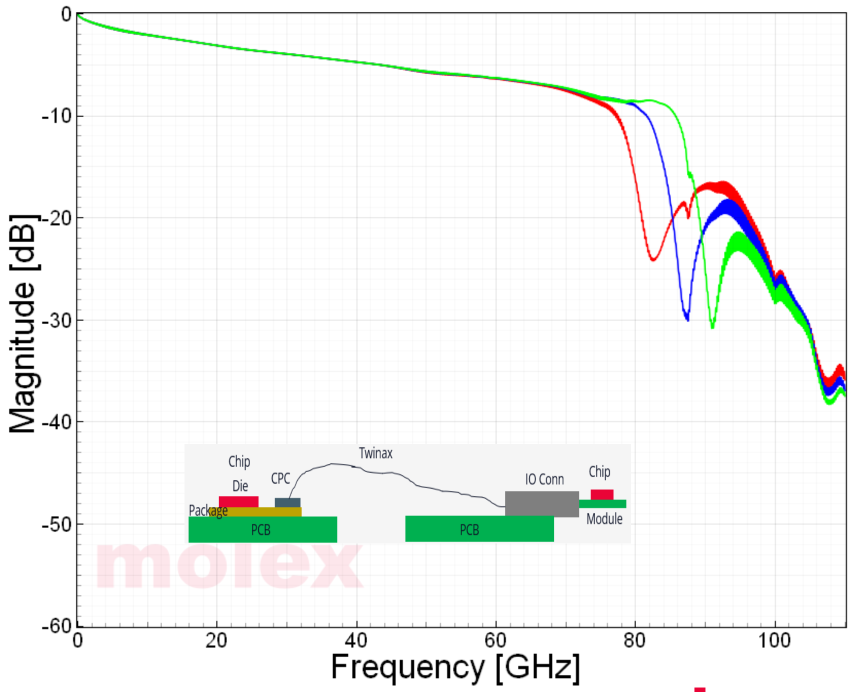
# Analysis Methodology: Idealized Scale-Out Channels

- Two channel topologies, as shown below, are simulated to understand the requirements for 448G data operation
- Channel impairments like Chip BGA attach, Via transition, Connector SMT attachment, twinax termination etc idealized to achieve a smooth Insertion Loss across entire bandwidth
- Bandwidth (i.e. IL resonance frequency) is varied by modifying stub length of mating interface
- Insertion Loss at Nyquist frequencies is varied by adding trace loss.



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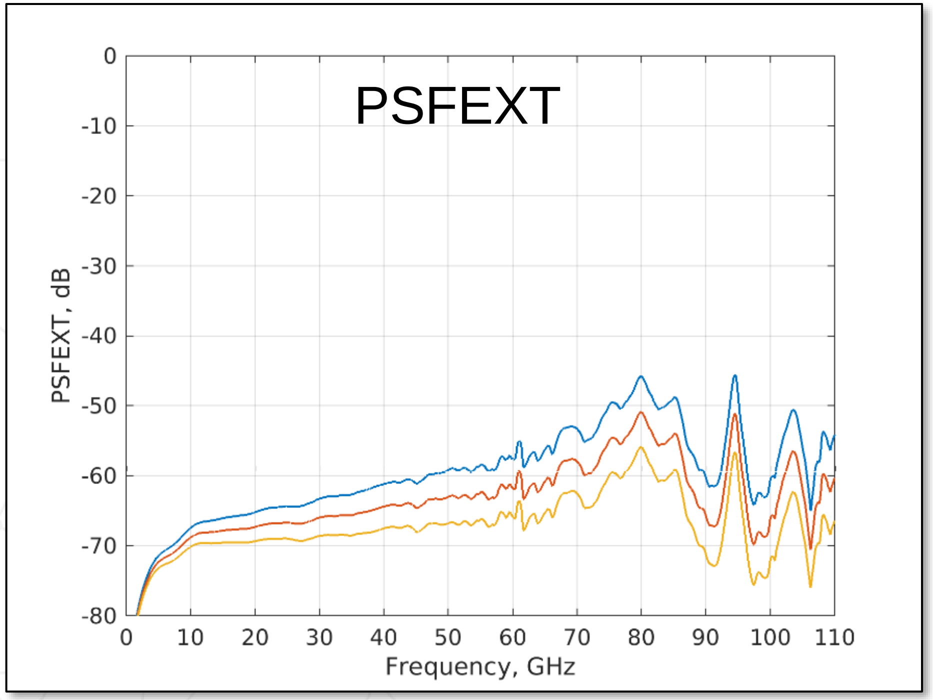
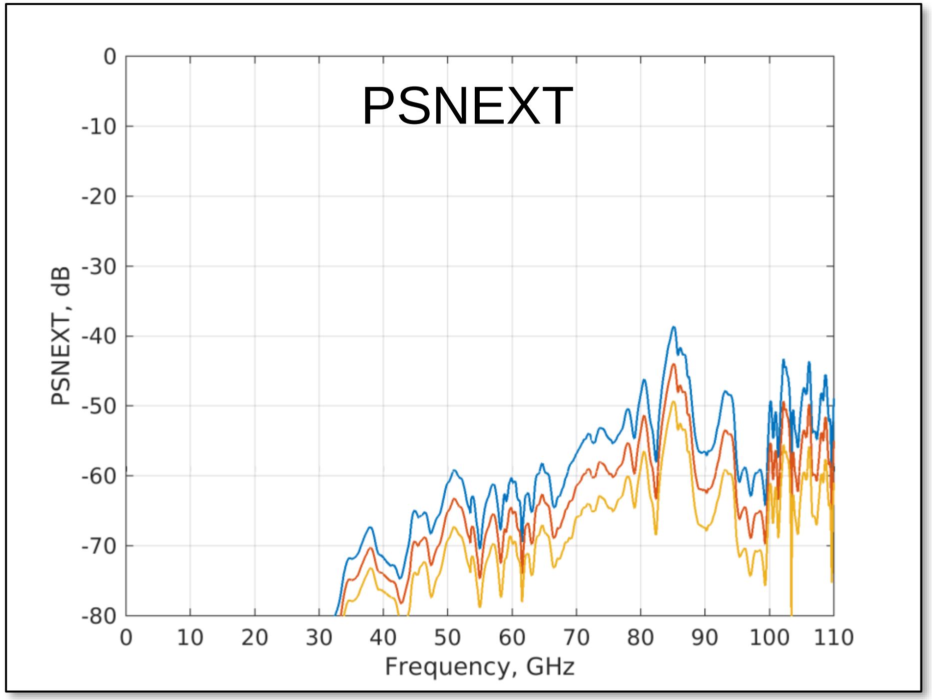
# Analysis Methodology: Idealized Scale-Out Channels

- Co-packaged Copper (CPC) channels allows for longer reach compared to PCB channels for same insertion loss
- Alternatively, CPC channels have lower Insertion Loss for same reach of PCB channels
- Power sum crosstalk (FEXT and NEXT) for both channel topologies is scaled to generate various signal to noise ratios in the analysis



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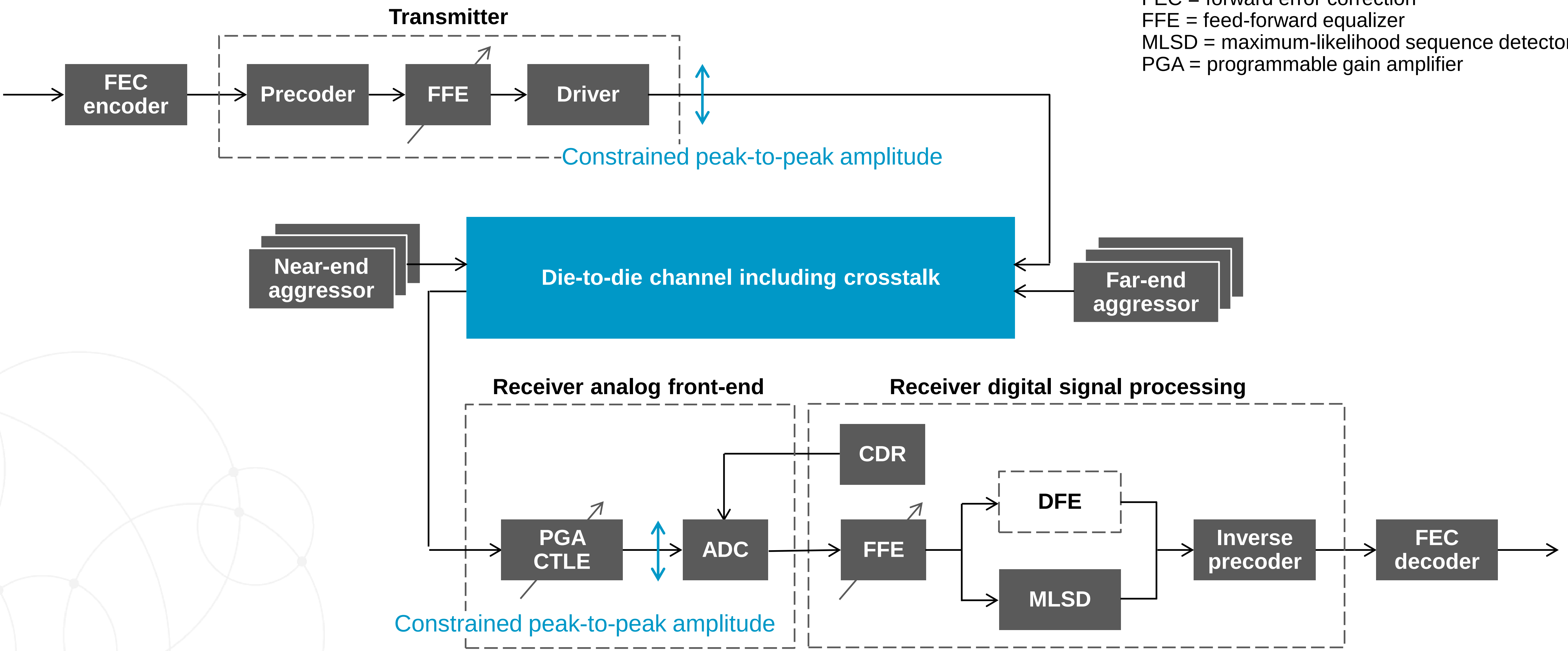
# Link block diagram

ADC = analog-to-digital converter
CDR = clock and data recovery
CTLE = continuous-time linear equalizer
DFE = decision feedback equalizer
FEC = forward error correction
FFE = feed-forward equalizer
MLSD = maximum-likelihood sequence detector
PGA = programmable gain amplifier



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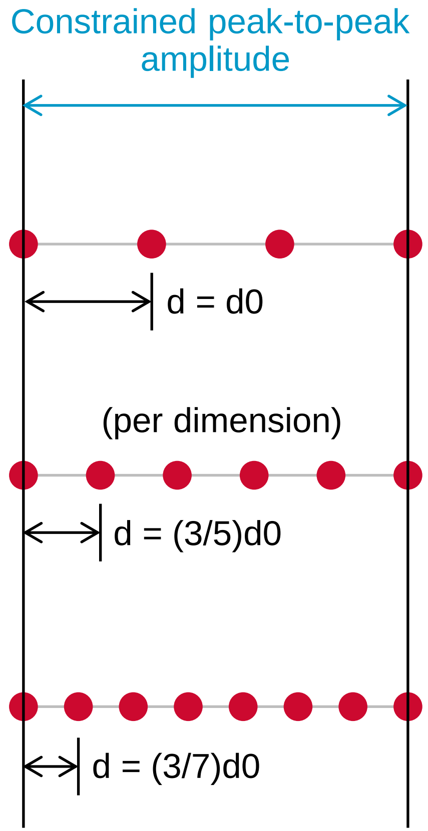
# Baseband pulse amplitude modulation (PAM) basics

**Selection of modulation options for 450 Gb/s** (425 Gb/s)

| Modulation | Dimensions | Bits per dimension | Signaling rate, GBd | Bandwidth, GHz | Distance reduction, dB |
|---|---|---|---|---|---|
| PAM-4 | 1 | 2 | 225 (212.5) | 112.5 (106.25) | — |
| PAM-6 | 2 | 2.5 | 180 (170) | 90 (85) | −4.44 |
| PAM-8 | 1 | 3 | 150 (142.5) | 75 (71.25) | −7.36 |

Reduce bandwidth requirements

Increase difficulty to detect signals



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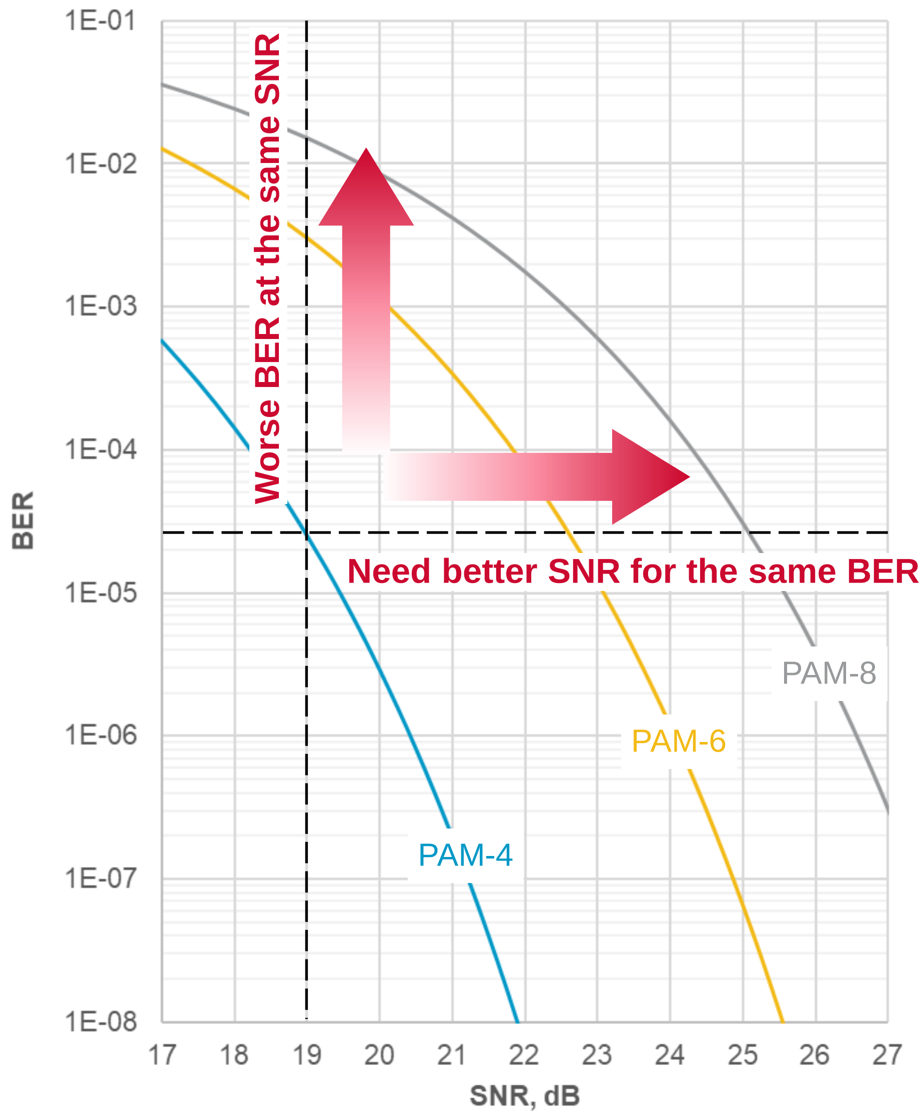
# Performance versus signal-to-noise ratio (SNR)




- Denser constellations require better SNR for the same BER performance

| 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 |

- Insertion loss, return loss (reflections), crosstalk, etc. all influence SNR
- This suggests that lower bandwidth channels also need lower reflections and crosstalk
- Improved detection e.g., maximum likelihood sequence detection, and additional error correction can be used to relax SNR requirements



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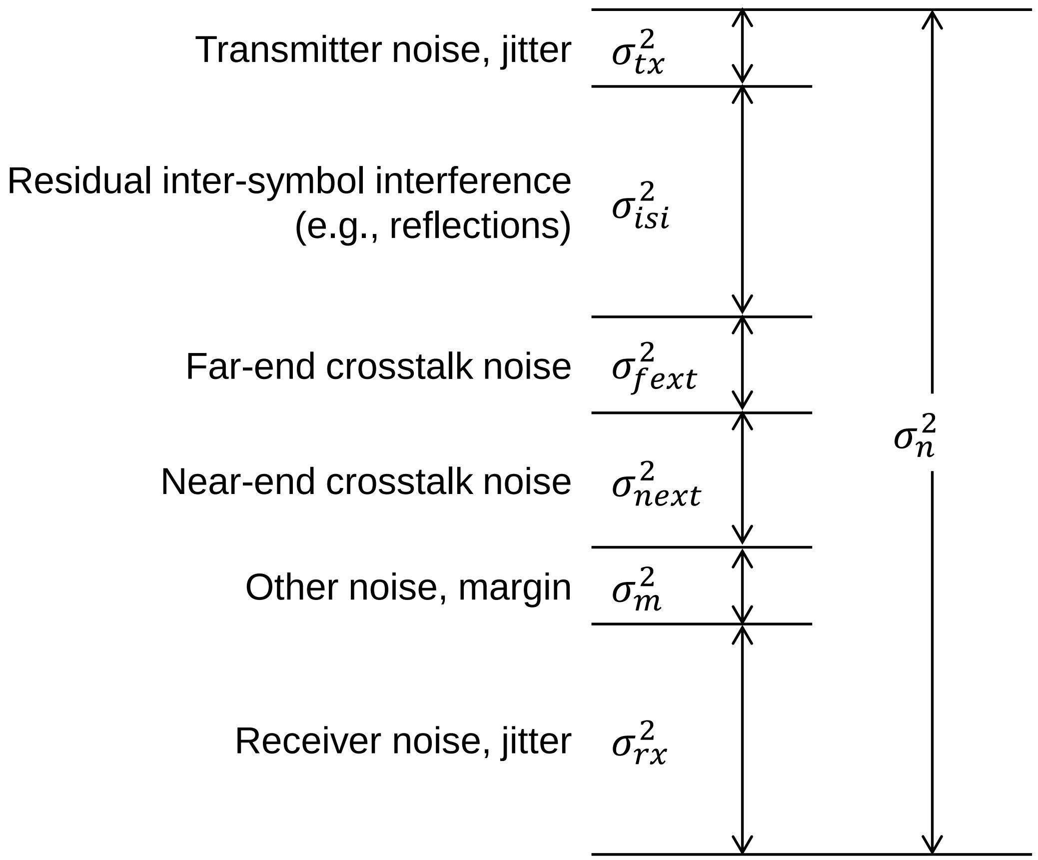
# Translating channel characteristics to link performance

- BER is a function of SNR
- BER target can be translated into a noise power budget
- Map channel characteristics to noise budget terms

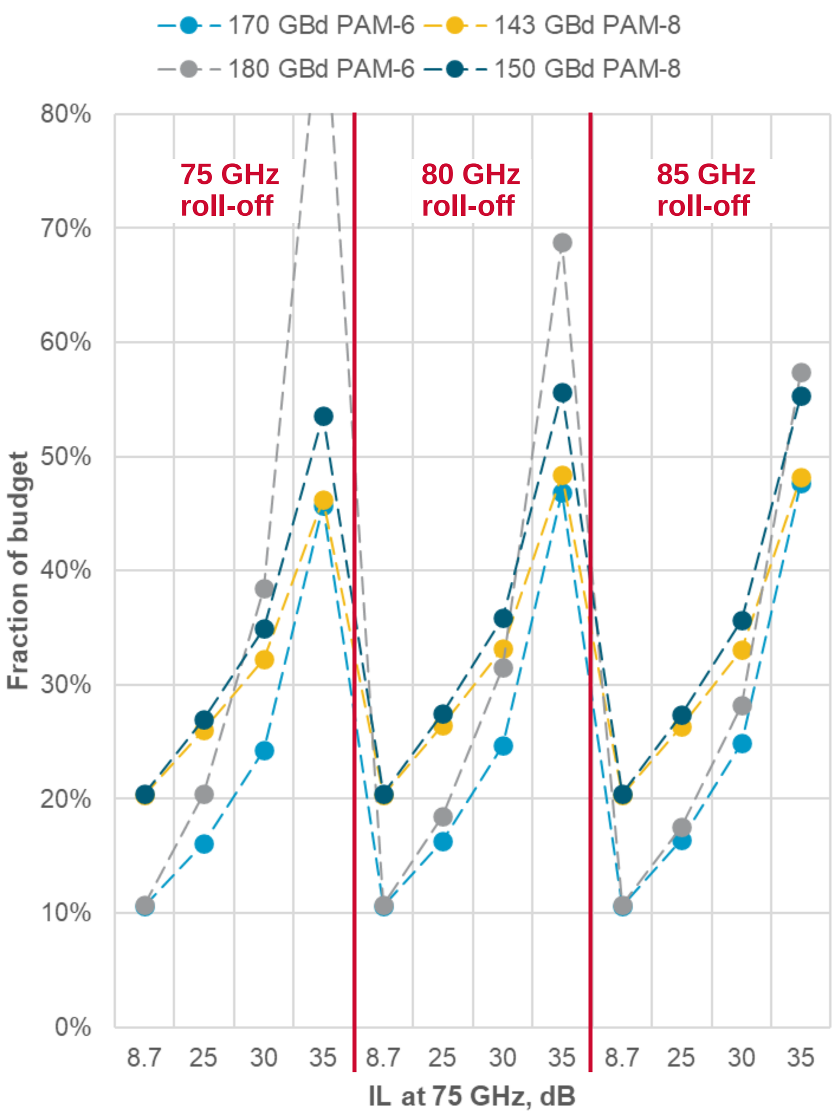
$$SNR = 10\log_{10}\left(\frac{\sigma_s^2}{\sigma_n^2}\right)$$

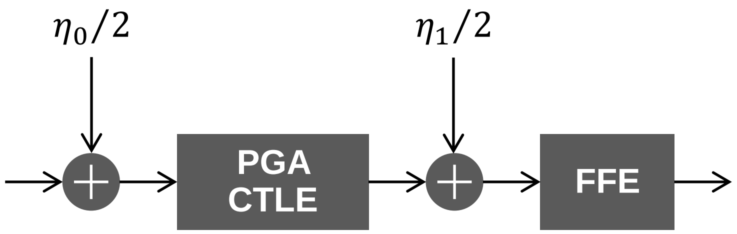
| Characteristic | Noise power budget term(s) affected |
|---|---|
| Insertion loss (IL) | $\sigma_{isi}^2$<br>$\sigma_{next}^2$, $\sigma_{fext}^2$, $\sigma_{rx}^2$ (noise enhancement) |
| Insertion loss deviation (ILD) | $\sigma_{isi}^2$ (reflections)<br>$\sigma_{next}^2$, $\sigma_{fext}^2$, $\sigma_{rx}^2$ (roll-off, noise enhancement) |
| Return loss (RL) | $\sigma_{isi}^2$ (reflections) |
| Power-sum near-end crosstalk (PSNEXT) | $\sigma_{next}^2$ |
| Power-sum far-end crosstalk (PSFEXT) | $\sigma_{fext}^2$ |

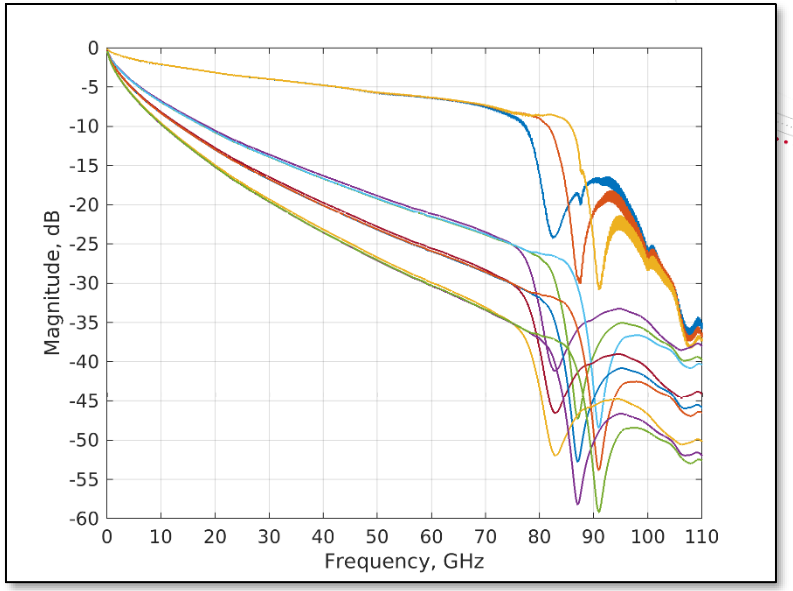
= Addressed in this presentation



# Noise power due to insertion loss and roll-off

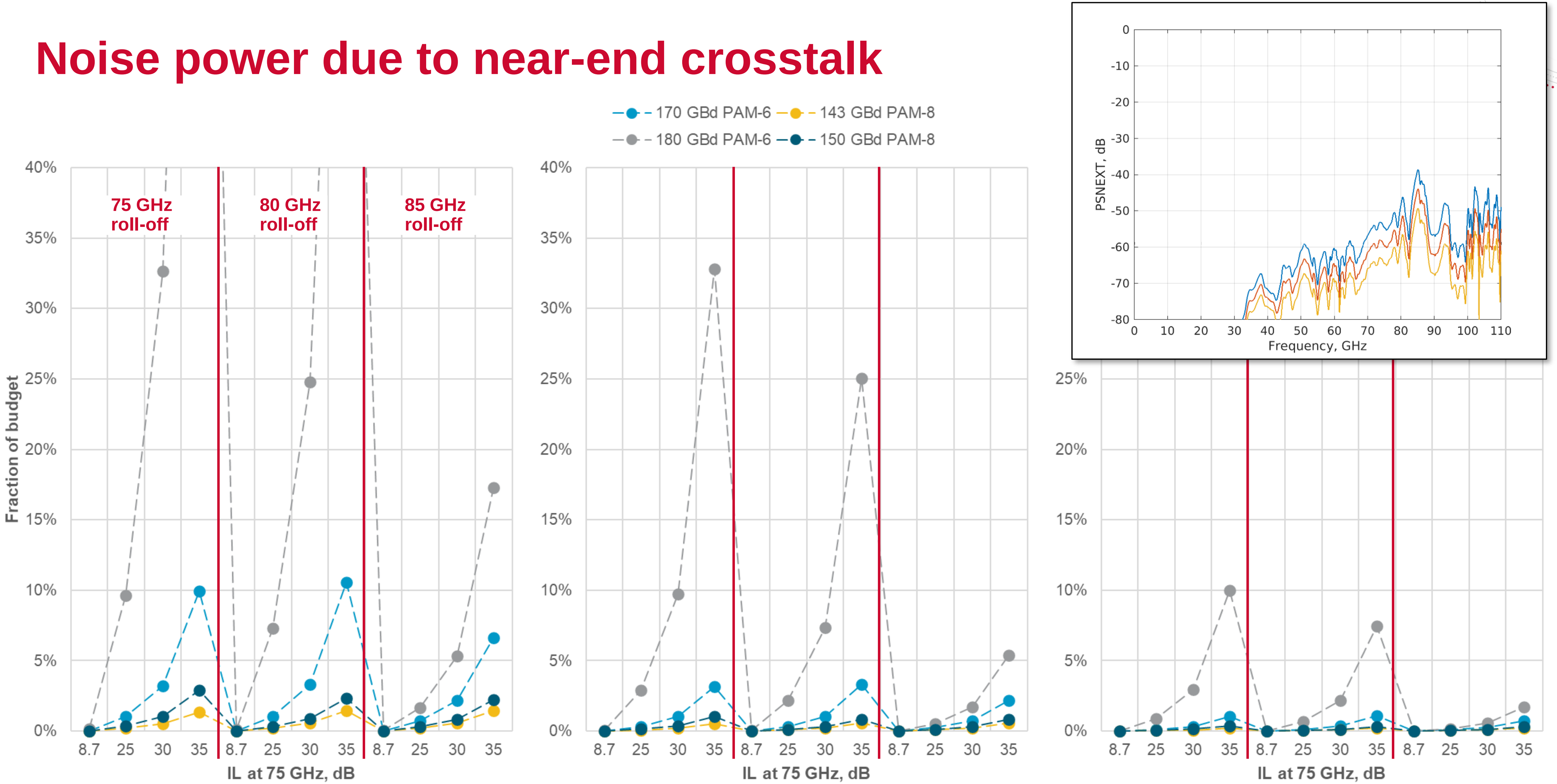



- Insertion loss and roll-off contribute to the noise budget through the receiver equalizer
- Equalizer applies gain to counteract the loss of the channel but this same gain boosts internal sources of noise
- Noise may be introduced at multiple points in the signal processing chain
- The same principles apply to the enhancement of crosstalk noise
- For a given channel, PAM-8 requires less equalization but is more sensitive to noise

# Noise power due to near-end crosstalk




PSNEXT = −55 dB at 75 GHz

PSNEXT = −60 dB at 75 GHz

PSNEXT = −65 dB at 75 GHz

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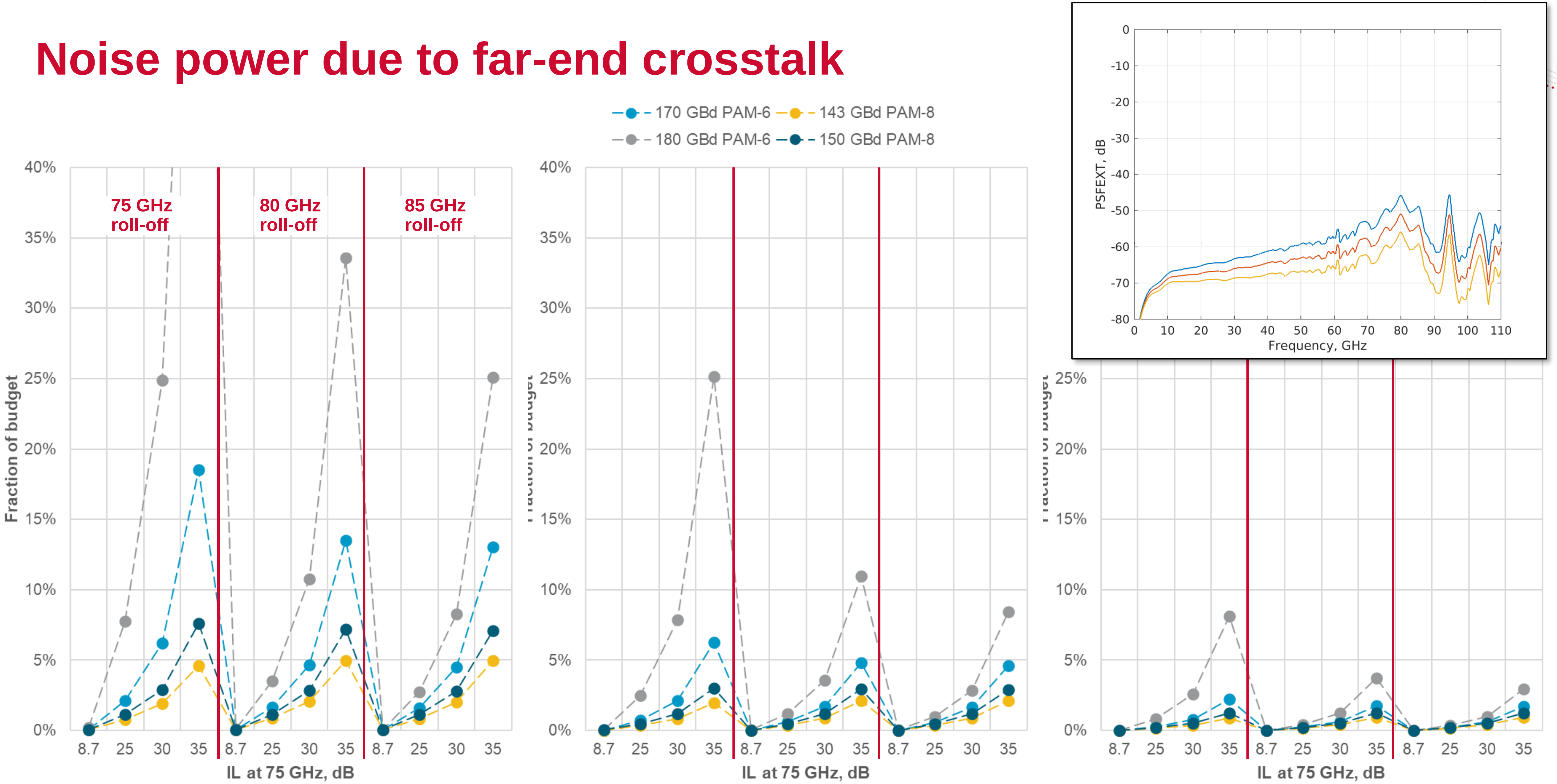
# Noise power due to far-end crosstalk




PSFEXT = −50 dB at 75 GHz

PSFEXT = −55 dB at 75 GHz

PSFEXT = −60 dB at 75 GHz

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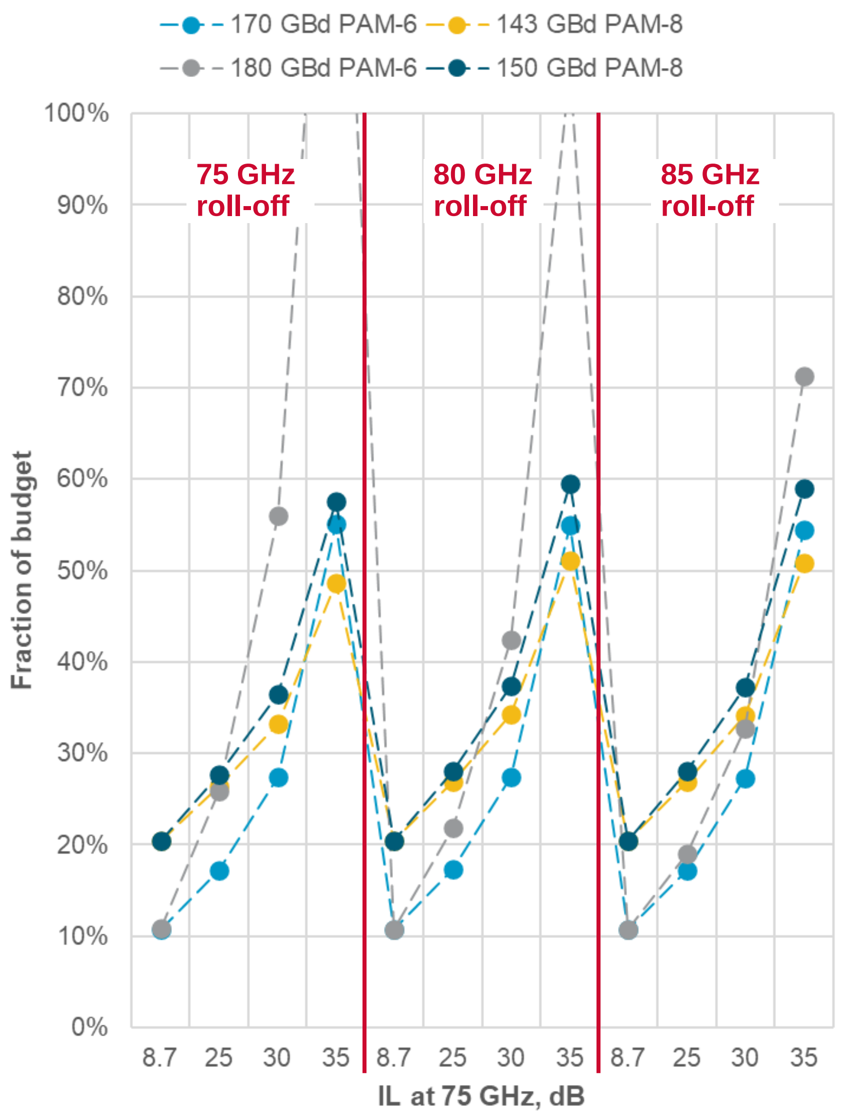
# Putting it all together




**PSNEXT = −60 dB at 75 GHz, PSFEXT = −55 dB at 75 GHz**

- Add noise terms for comparison to the total budget
- Modulation advantage for one noise term can be offset by a disadvantage for another noise term (or terms)
- Portion of the noise budget must be reserved for terms not included in this analysis e.g., reflections, jitter
- Higher unallocated budget means higher confidence that a working link is achievable

- Roll-off relative to signaling rate has significant influence on the fraction of the noise budget consumed however roll-off frequency just past Nyquist frequency might be sufficient

# Summary and conclusions

- Encouraging signs that next-generation channels will be able to support 400G/lane using baseband pulse amplitude modulation
- Channel bandwidth observations
  - PAM-8: Better suited for longer-reach channels with the lowest bandwidth
  - PAM-6: Best reach achieved at highest roll-off frequency (85 GHz)
  - PAM-4: Not considered, roll-offs much lower than the Nyquist frequency (106-112 GHz)
- PAM-8 has the most challenging noise budget
- Generally, smaller constellations are preferred if the channel bandwidth supports it
- Crosstalk must be managed for best performance and resonances at higher frequencies should be avoided
- Interconnect feasibility
  - PAM-8: Potential to support longer reaches (than alternatives) over existing form factors
  - PAM-6: Benefits from improvement to existing form factors (that may break backwards-compatibility)
  - PAM-4: Requires completely new form factor and technology to meet performance requirements

# Thank You

Q&A