112Gbps Serial Transmission over Copper – PAM4 vs PAM8 Signaling

Speaker:

Min Wu, Xilinx Inc.
minw@xilinx.com

Paper Authors:

Min Wu, Xilinx
Kelvin Qiu, Cisco
Geoff Zhang, Xilinx

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SPEAKERS

Min Wu

SerDes System Architect

minw@xilinx.com

Min Wu is currently a SerDes System Architect at Xilinx. He has over 20 years of industrial experience in the development and implementation of single-carrier modulation and multi-carrier modulation modems/demodulators/PHYs, which include but not limited to V.34/V.90/ADSL/VDSL modems, DVB-T/ATSC demodulator, and 10G Base-T/40G/56G transceivers. Prior to joining Xilinx, he was a Principal Systems Engineer at Applied Micro. Before Applied Micro, he held various engineering positions with Cresta Technology, Genesis, STMicroelectronics, Creative Labs, etc. He holds Master degree from Tennessee Tech and Bachelor degree from Fudan University, both in Electrical Engineering.

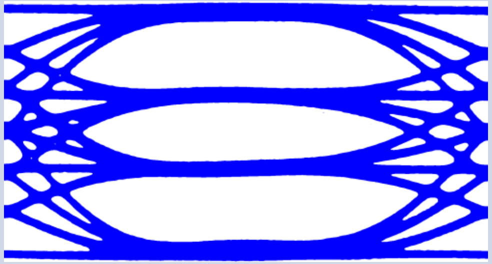
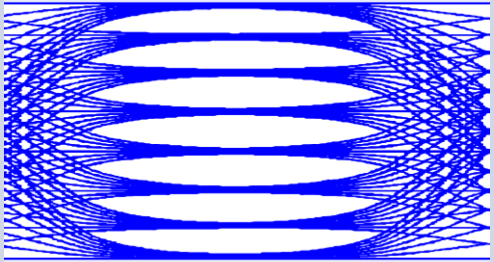
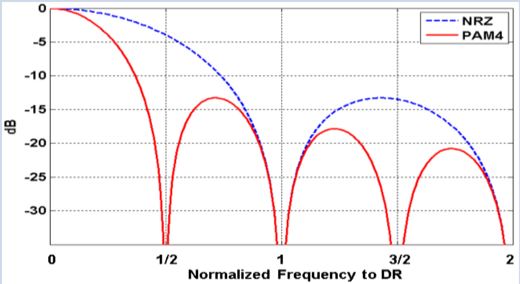
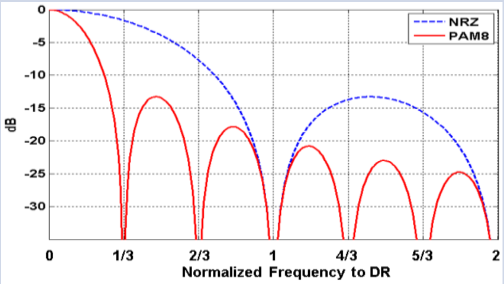
Outline

- Review of PAM4 and PAM8 basics
- Three backplane channel systems for analysis
- System SER vs. SNR for PAM4 and PAM8
- Salz SNR margin analysis for the selected channels
- Channel SNR margin with more practical equalizations
  - Without crosstalk: results, observations, and discussions
  - With crosstalk: results, observations, and discussions
- PAR impact on system SNR
- Summary of the work

PAM4 and PAM8 Basics Review – 1

Modulation	PAM4		PAM8	
Number of bits per symbol $log_2(M)$	$log_2(4) = 2$		$log_2(8) = 3$	
distinct symbols, *M*	1 0 1 1 0 1 0 0	$M = 4$	1 0 0 1 0 1 1 1 1 1 1 0 0 1 0 0 1 1 0 0 1 0 0 0	$M = 8$
Distinct eyes, *M-1* Each symbol is mapped to of the *M* levels – an example of Gray coding		$M\text{-}1 = 3$		$M\text{-}1 = 7$
Symbol unit interval (UI) $log_2(M)/DataRate$	For 112 Gbps UI = 17.8571 ps		For 112 Gbps UI = 26.7857 ps	

PAM4 and PAM8 Basics Review – 2

<table>
<tr><th>Modulation</th><th>PAM4</th><th>PAM8</th></tr>
<tr><td>Eye Diagrams</td><td></td><td></td></tr>
<tr><td>Nyquist frequency
DataRate/(2*log$DataRate/(2*log_2(M))$</td><td>For 112Gbps
$f_{Nyquist}$ = 28 GHz</td><td>For 112Gbps
$f_{Nyquist}$ = 18.6667 GHz</td></tr>
<tr><td>Signal PSD
First null of PAM8 is 2/3 of PAM4</td><td>
</td><td>
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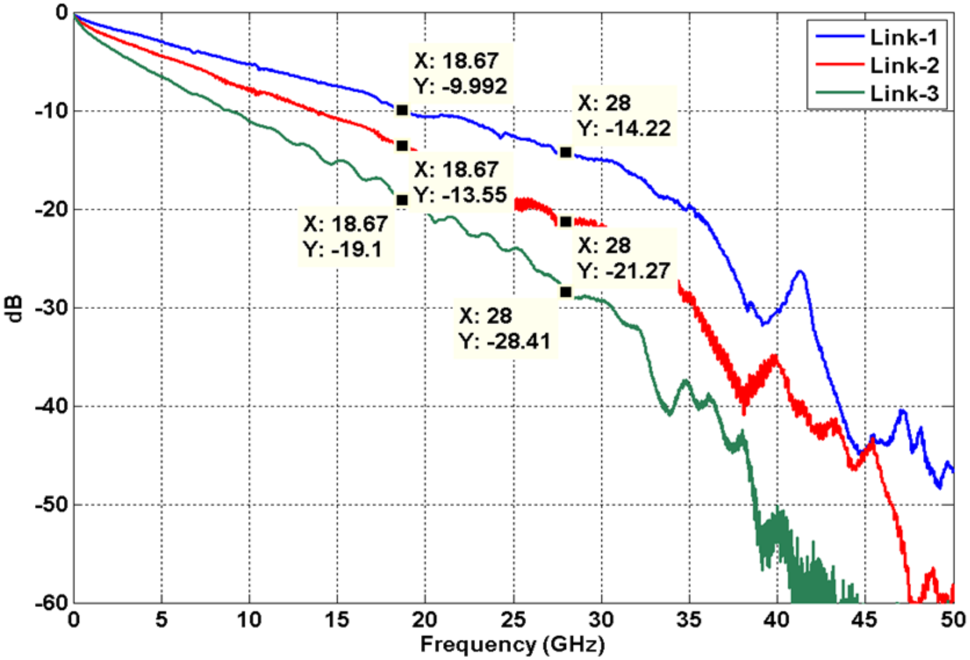
Link Channel Descriptions – Frequency Domain

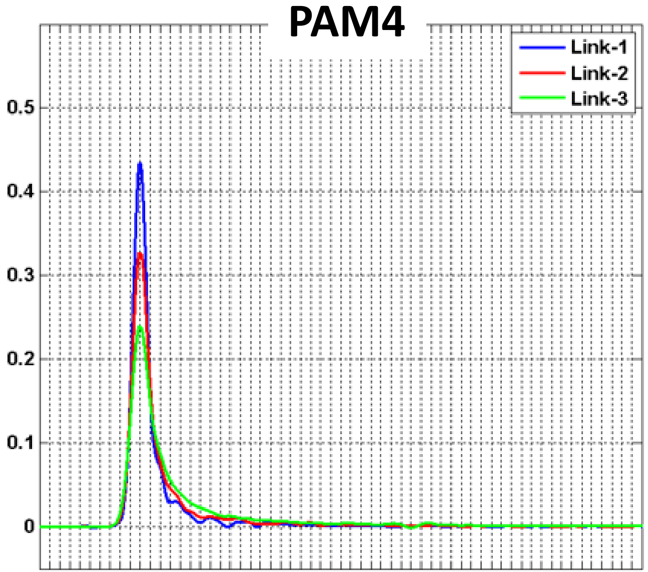
- Three basic link channels are chosen from prototype systems
- The losses for PAM4 and PAM8 are marked for 112Gbps operations

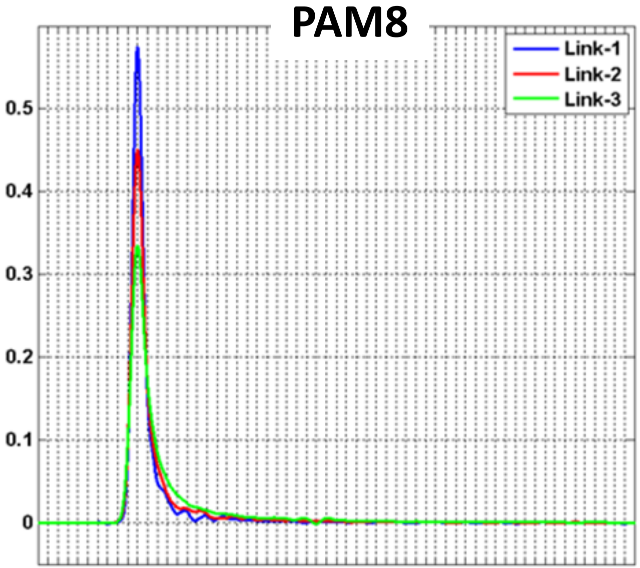
Nyquist Frequency (GHz)	Link-1	Link-2	Link-3
PAM4 at 28.00	14.22 dB	21.27 dB	28.41 dB
PAM8 at 18.67	9.99 dB	13.55 dB	19.10 dB
Loss difference	4.23 dB	7.72 dB	9.31 dB



Link Channel Descriptions – Time Domain

- Channel pulse responses for PAM4 (left) and PAM8 (right)
  - PAM8 has larger amplitude than PAM4 for any given channel
  - The more lossy the channel, the less the response strength



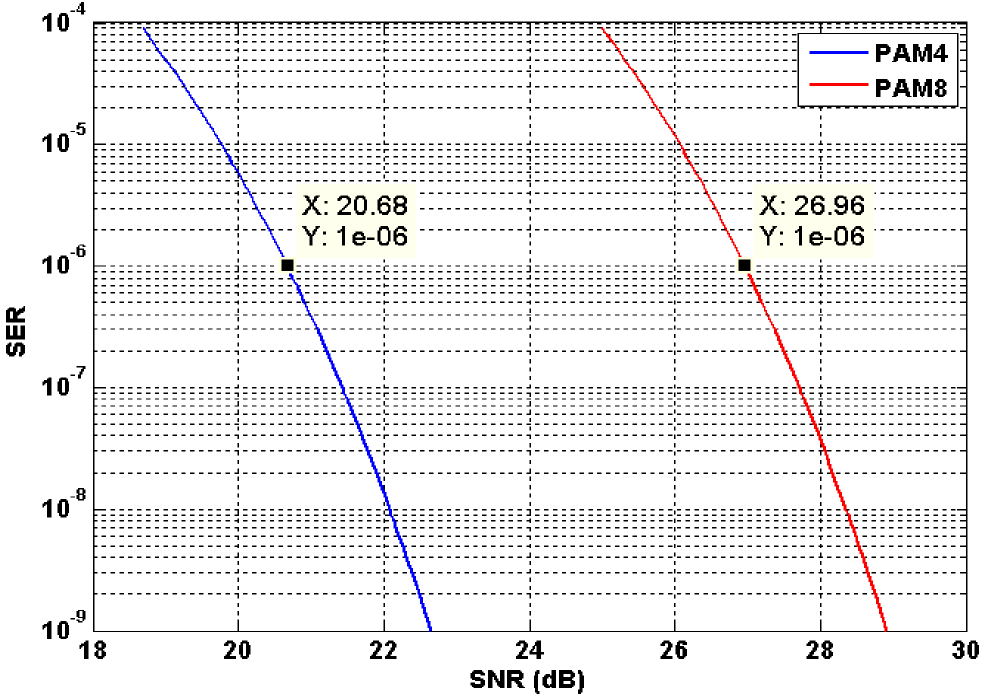


System SNR and SER

- System SER and SNR at the decision point are related as

$$SER = \frac{2M-2}{M} \cdot Q\left(\sqrt{\frac{3 \cdot SNR}{(M^2-1)}}\right)$$

$$= \frac{M-1}{M} \cdot erfc\left(\sqrt{\frac{3 \cdot SNR}{2 \cdot (M^2-1)}}\right)$$



- Example: to achieve SER = 1e-6,
  - PAM4 requires SNR of 20.68dB
  - PAM8 requires SNR of 26.96dB

Salz SNR Analysis and Salz SNR Margin

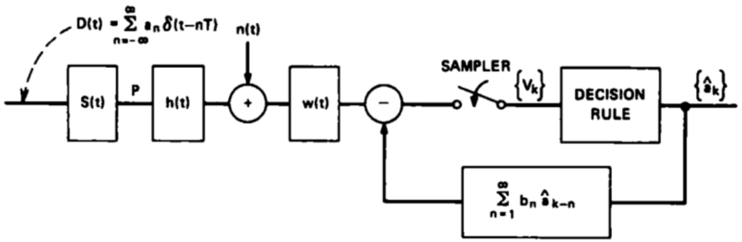
- The Salz SNR is computed for the maximum achievable SNR the decision point

$$SNR_{Salz} = 10 \cdot \log_{10}\left\{exp\left[\frac{1}{F_N}\int_0^{F_N} \ln\left(1 + \frac{S(f)}{N(f)}\right) \cdot df\right]\right\}$$

$$\approx \frac{1}{F_N}\int_0^{F_N} 10 \cdot \log_{10}\left[\frac{S(f)}{N(f)}\right] \cdot df = AVG_{0<f<F_N}[SNR_{dB}(f)]$$

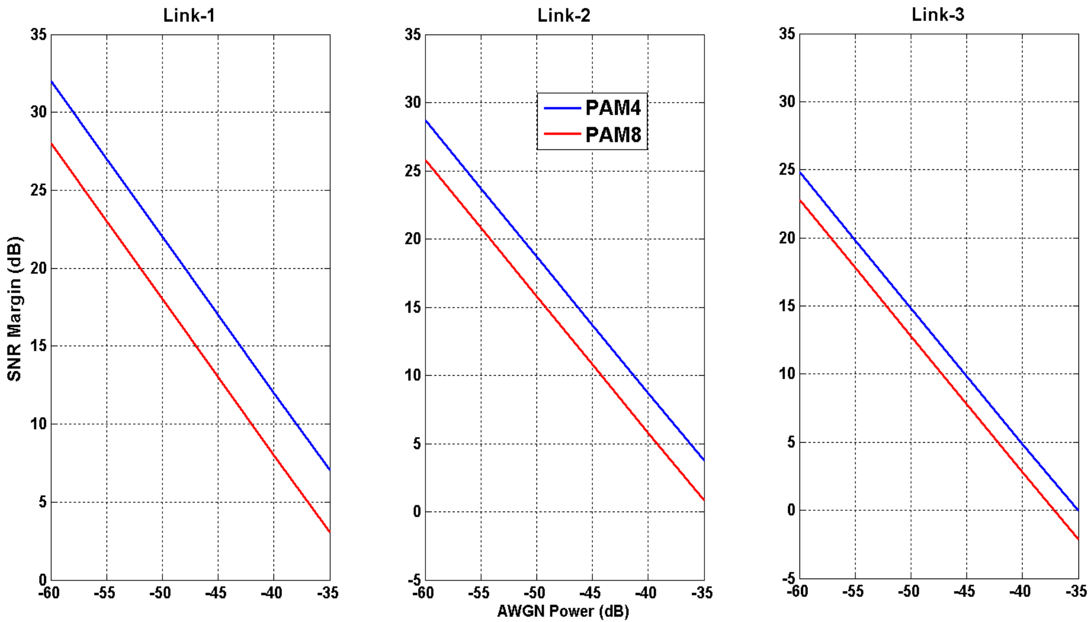
- The Salz SNR margin is used to estimate the system operating margin

$$Salz\ SNR\ Margin = SNR_{Salz} - SNR(SER)$$



Salz SNR Margin for the Three Channels

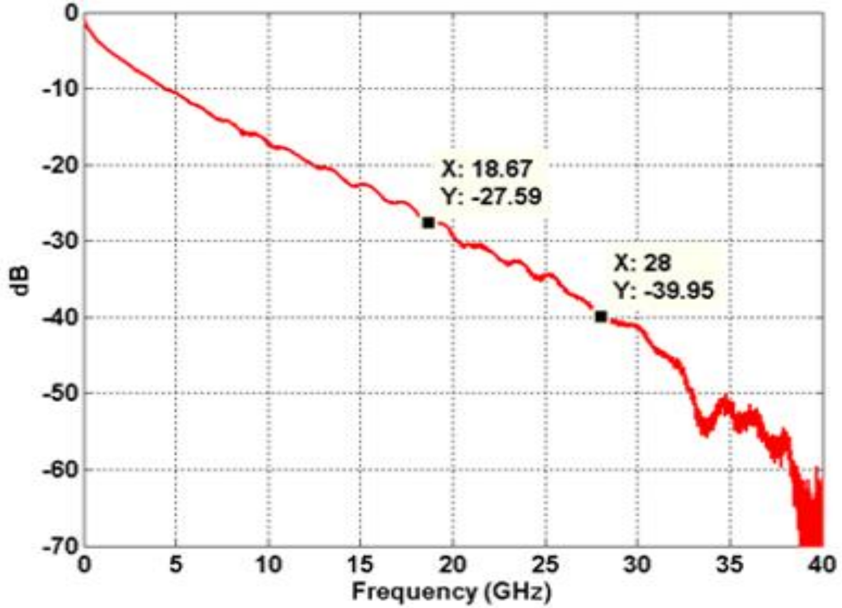
- The Salz SNR for the 3 channels is calculated for different AWGN power levels
- The Salz SNR margin for SER at 1e-6 is then computed; it is seen that

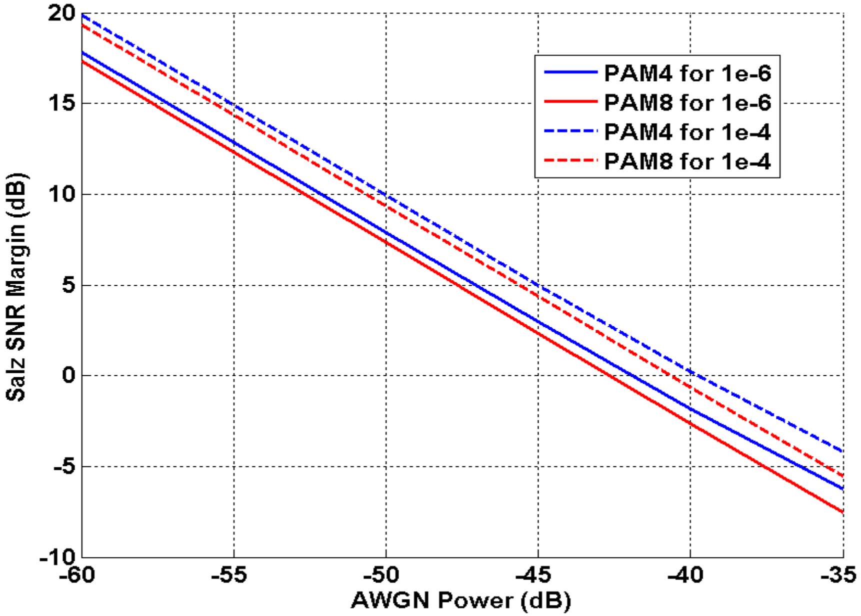


- PAM4 has more SNR margin than PAM8 for all three channels
- For the same noise power Link-1 has more margin than link-2, and Link-2 more margin than Link-3
- The SNR margin difference between PAM4 and PAM8 becomes smaller when channel loss becomes larger
- When loss exceeds a certain level neither PAM4 nor PAM8 can provide the required SNR

Salz SNR for a Lossy Channel

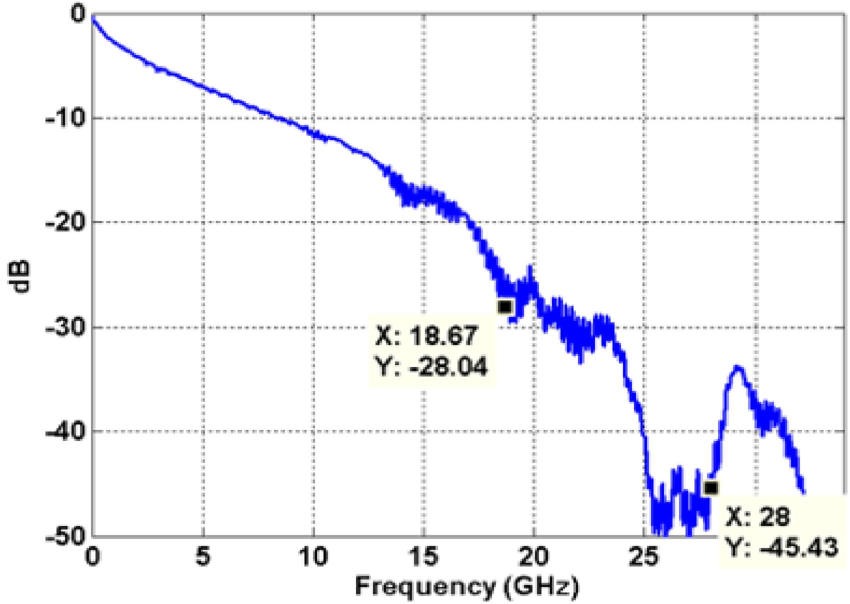
- PAM4 outperforms PAM8 with Salz SNR for this very lossy channel
  - The channel is relatively smooth up to 30GHz

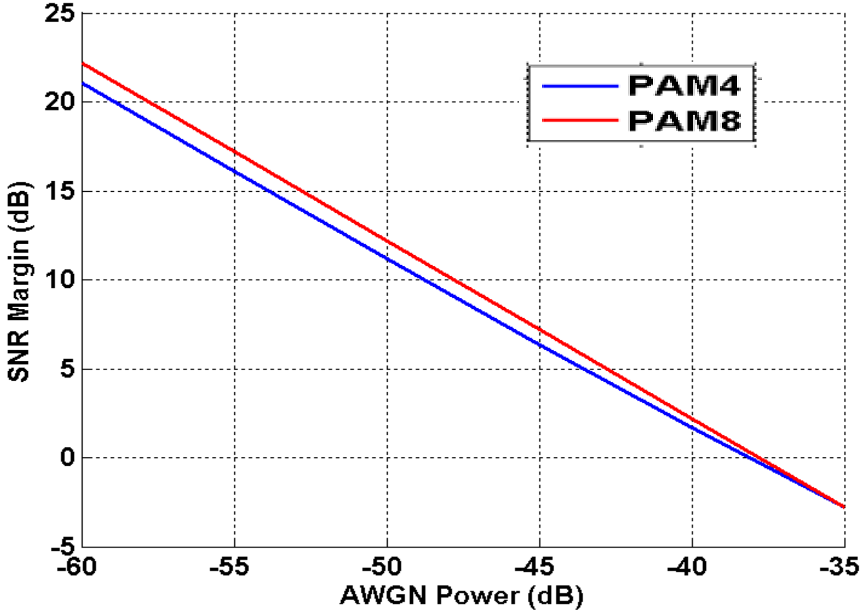




Salz SNR for a Channel with Suck-outs

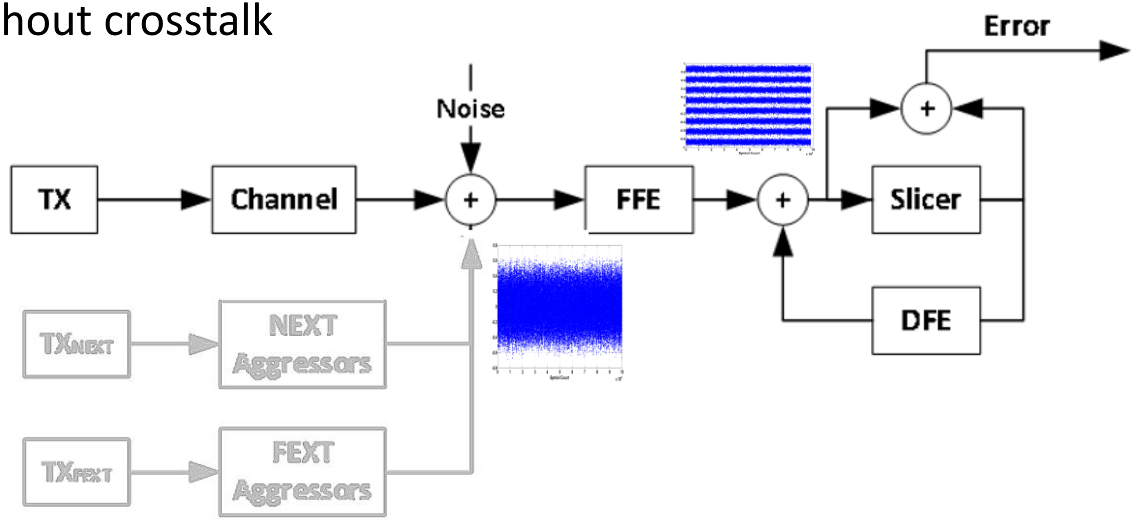
- PAM8 outperforms PAM4 for this channel with suck-outs
  - with high AWGN the two are comparable: the case when crosstalk is considered





Moving from Salz to More Realistic Approaches

- Simulation setup – without crosstalk



- Signal SNR at data slicer

$$SNR = \frac{P_{signal}}{P_{slicer\_error}}$$

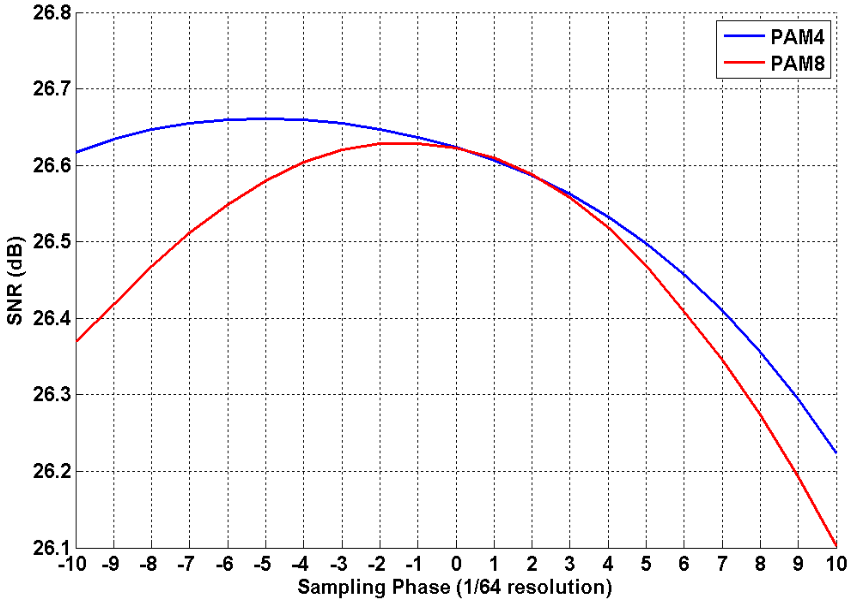
Selected Equalization Configurations

- FFE center tap location is optimally determined for each application

Equalization Configurations	FFE Taps	DFE Taps	Signal Modulation	FFE Pre-Cursor Taps		
				Link-1	Link-2	Link-3
EQ1	128	32	PAM4	19	13	9
			PAM8	5	4	6
EQ2	64	1	PAM4	13	7	9
			PAM8	6	4	6
EQ3	32	1	PAM4	8	7	6
			PAM8	2	4	5
EQ4	24	1	PAM4	6	6	6
			PAM8	2	3	4
EQ5	16	1	PAM4	4	5	5
			PAM8	2	3	3

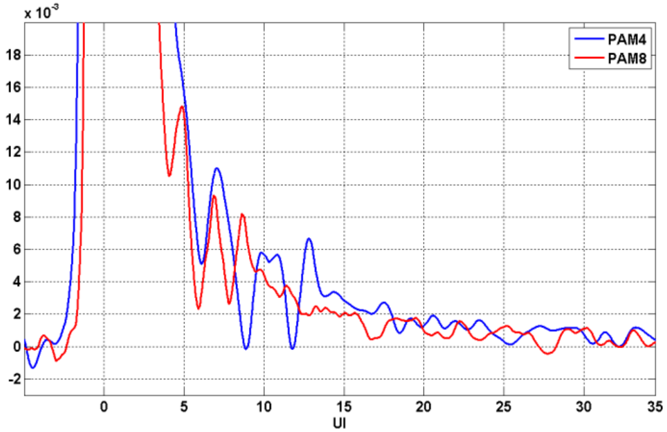
Sampling Phase Discussions

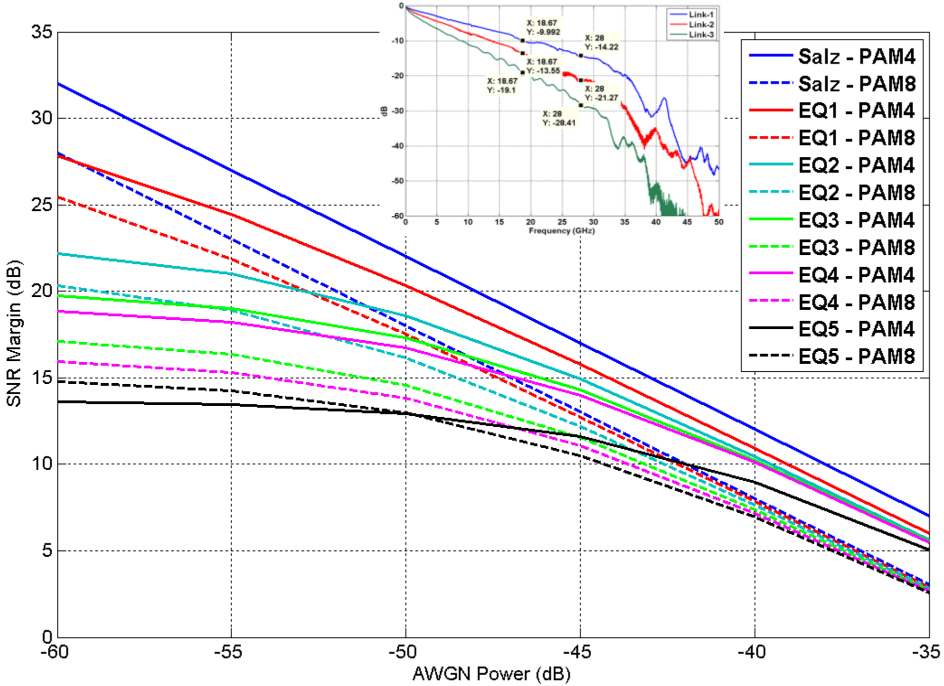
- The sampling phase is chosen at the location where the pulse response peaks
  - The choice does not guarantee the optimal sampling phase in terms of SNR
- The achievable SNR with EQ3 for Link-2
  - For PAM8 the SNR is normalized to that of PAM4 at phase 0, by subtracting 4.754dB for this specific case
  - It is seen that the optimal phase lies within 0.1UI from the peak. The loss in SNR is really small for both
  - However, PAM8 is much more sensitive to phase perturbations than PAM4



SNR Margin – Link-1

- In general, PAM4 outperforms PAM8

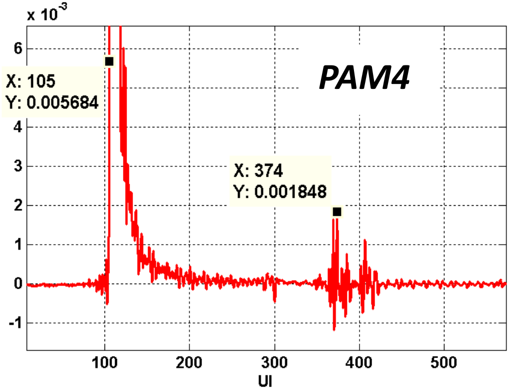


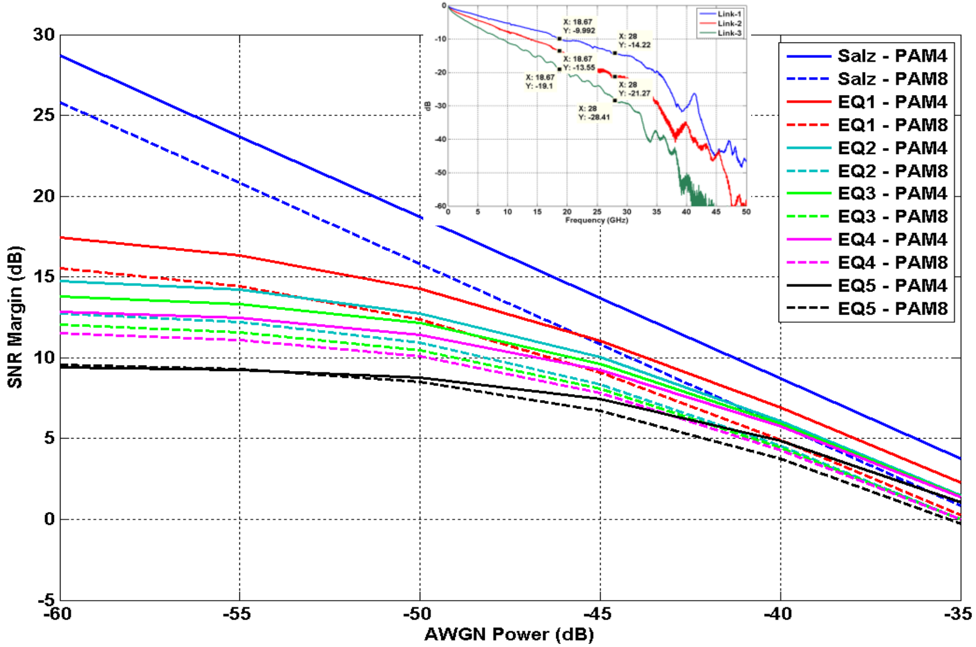


- For EQ5 (16 taps of FFE; 11 post-cursor taps for PAM4 and 13 post-cursor taps for PAM8) there is a crossover of PAM4 and PAM8 at around AWGN equals to -50dB
  - Beyond the 11th post-cursor tap there is still non-negligible energy for PAM4
  - Beyond the 13th tap the energy for PAM8 is relatively small

SNR Margin – Link-2

- There exists large SNR margin gap at low AWGN for Link-2 from the Salz analysis

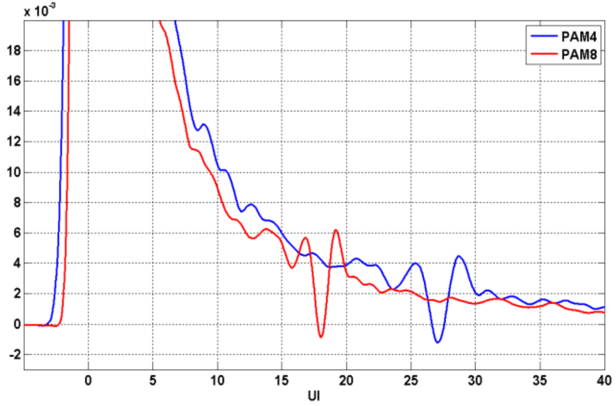


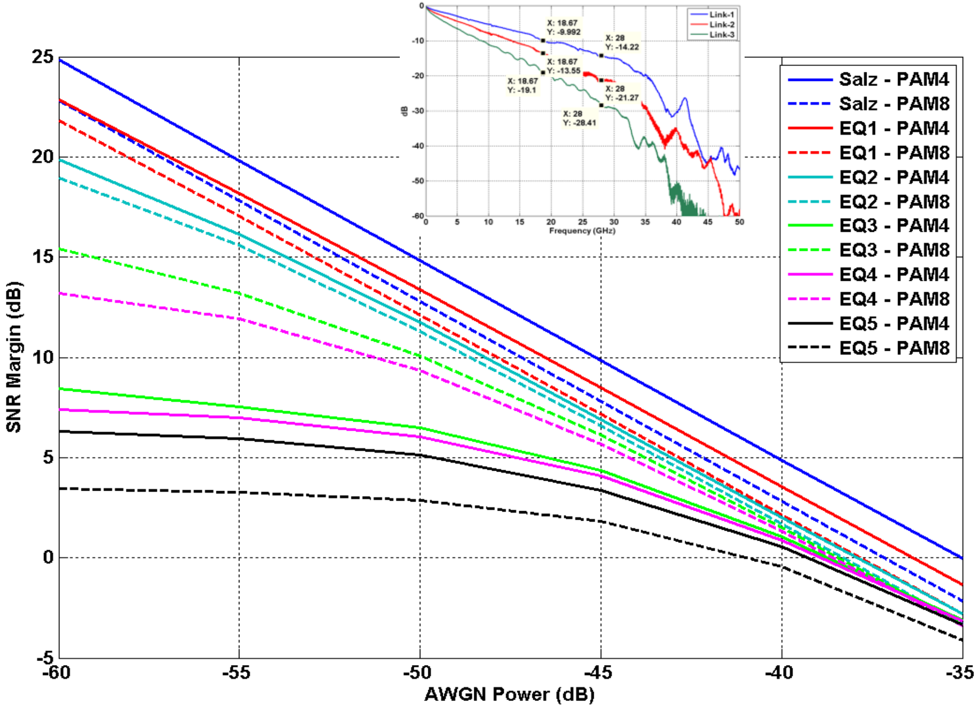


- There exist relatively strong reflections just over 250 UI away in the case of PAM4. None of the equalization schemes studied can remove those reflections, thus causing SNR degradation
- When AWGN becomes larger the reflection impact becomes less dominant. As a result, the overall SNR margin starts to resemble more closely to that of Salz SNR margin

SNR Margin – Link-3

- For high SNR, PAM8 works better than PAM4 with EQ3 and EQ4
- PAM4 works better with the rest of EQ's

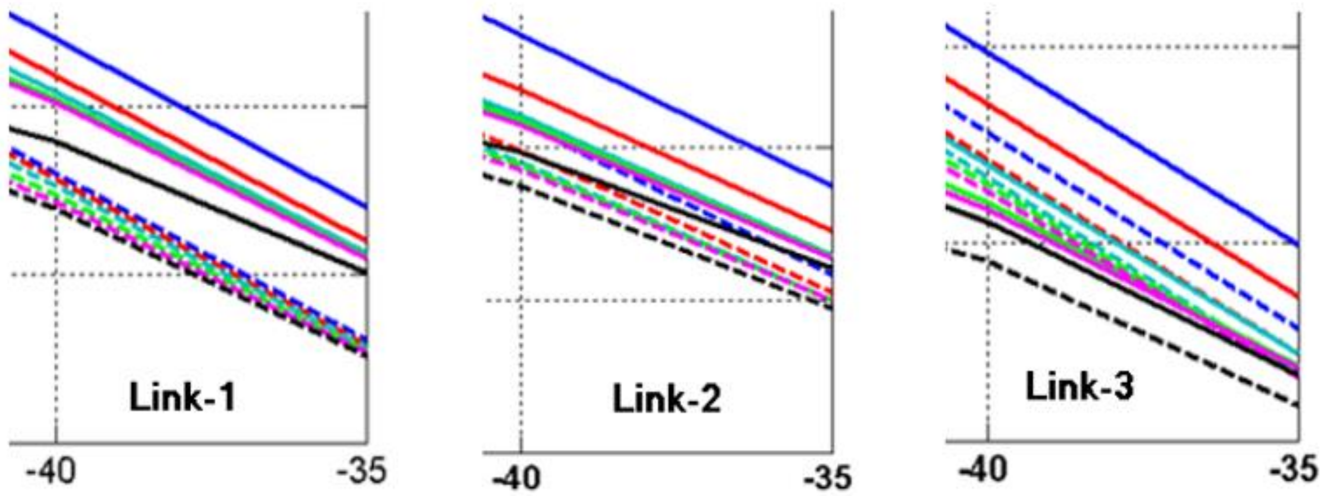




- EQ3 and EQ4 have 25 and 17 post-cursor taps for PAM4, and 26 and 19 post-cursor taps for PAM8
- EQ3 and EQ4 can basically cover the reflections for PAM8: red fluctuations just below 20th tap
- EQ3 and EQ4 cannot cover the reflections for PAM4: blue fluctuations beyond the 25th tap

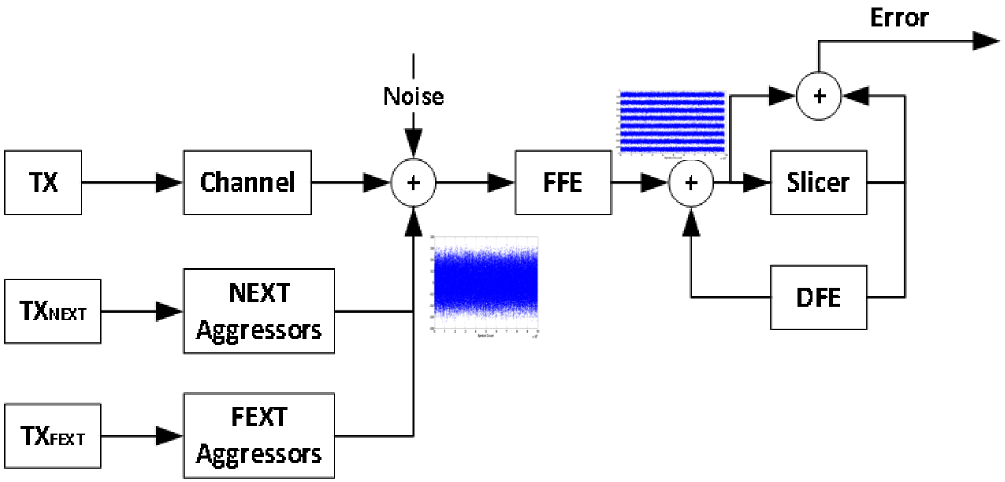
More Observations and Discussions

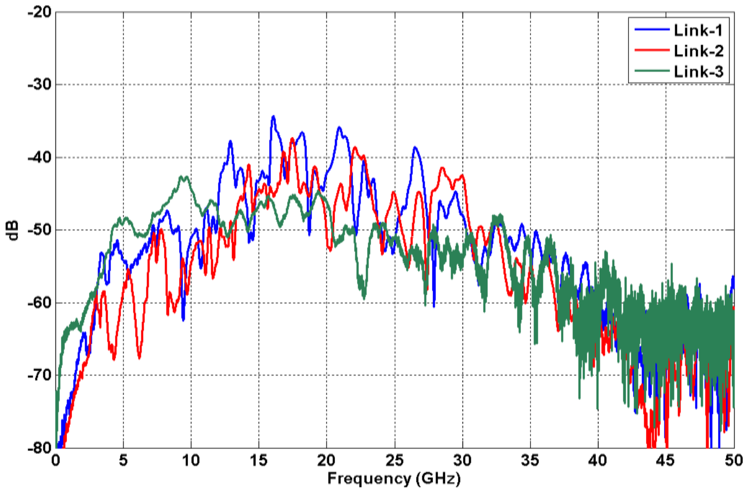
- For the low-loss channel (left most), PAM4 (solid lines) shows advantages over PAM8 (dashed lines) when noise is high; this is because SNR is dominated by noise
- For the high loss channel (right most), PAM4 does not show obvious advantages over PAM8; this is because residual ISI and noise are comparable



Setup with Crosstalk Included

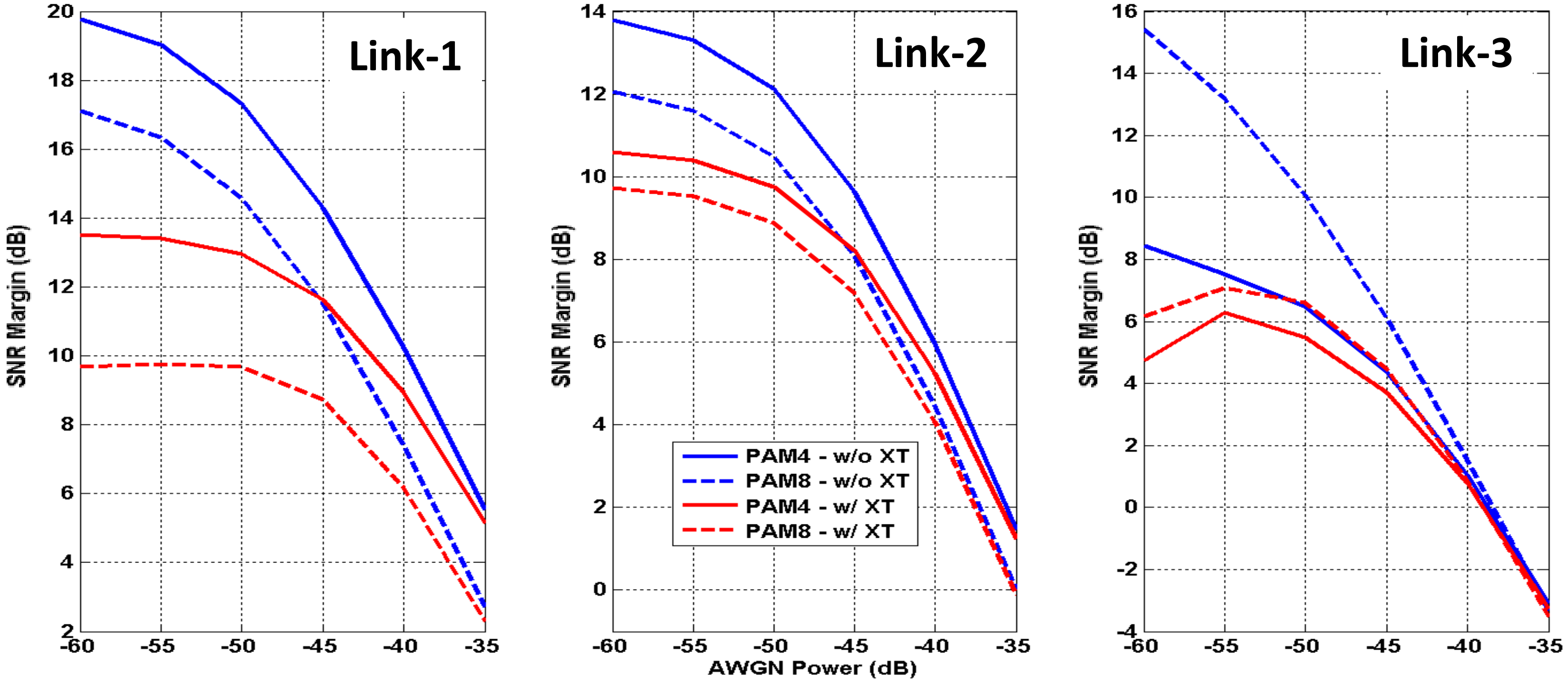
- Using EQ3 as an example, whose architecture = 32-tap FFE + 1-tap DFE
- Crosstalk PSXT profiles for the three systems
  - For each link there are two aggressors, one NEXT and one FEXT
  - Crosstalk impact is individually included in the simulation





SNR Margin with Crosstalk using EQ3

- The simulated SNR margin for SER=1e-6 for the three link channels

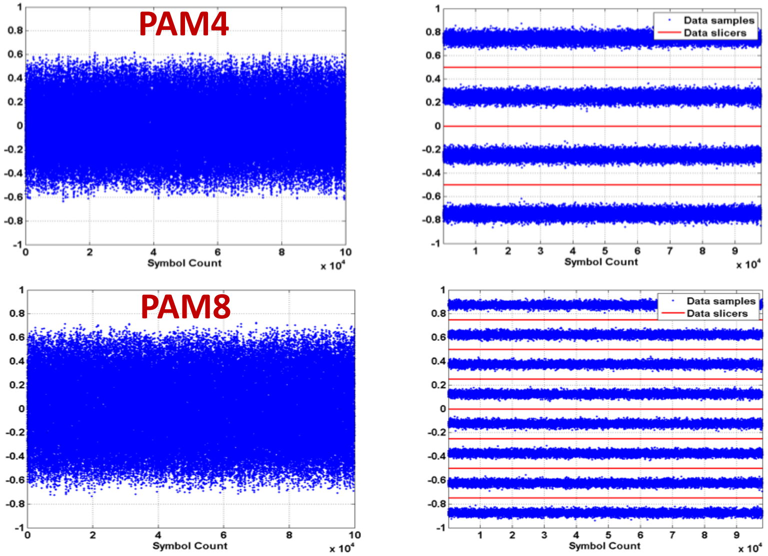


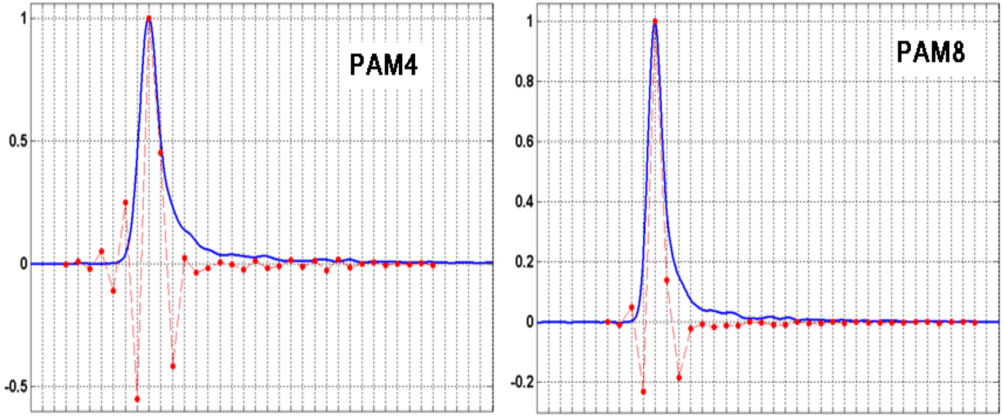
Observations

- As long as the loss is controlled to around 25dB at 28GHz, PAM4 has advantages over PAM8, regardless of high or low AWGN levels
  - For Link-1 there is around 3dB more margin for PAM4
  - For Link-2 there is about 1dB margin for PAM4
  - For Link-3 the margin is comparable
- For a higher loss channel (Link-3) PAM4 still outperforms PAM8 in general
  - PAM8 only showed more margin than PAM4 under specific conditions. For example, using EQ3 the impact from some unaccounted-for reflections in PAM4 made PAM8 slightly superior
    - Increasing the equalizer range should be able to handle the more extended major reflections
  - For relatively low SNR end, the SNR margin is almost the same for PAM4 and PAM8
    - Considering compatibility back to the 50G designs, SerDes complexity, implementation cost, parameter sensitivity, and system robustness, PAM4 should still be prioritized over PAM8
- PAM4 should be recommended over PAM8 for the 100G applications over copper
  - An extra margin, e.g., 3dB, should be allocated to account for unincluded impairments and nonidealities

Example: Link-2 with EQ3 and AWGN = -40dB

- Comparing PAM4 and PAM8
  - FFE optimal coefficients
  - Sampled eyes before and after EQ
  - Estimated SER and BER





	SNR (after 3dB margin)	Estimated SER	Estimated BER
PAM4	22.91 dB	3.04e-10	1.52e-10
PAM8	28.02 dB	3.44e-8	1.15e-8

A Note on PAR Impact

- Signal PAR, peak-to-average ratio, needs to be taken into account

$$PAR = 10log_{10}\frac{Sig_{peak}^2}{Sig_{rms}^2}$$

  - For the TX, the PAR for PAM4 and PAM8 is 2.55dB and 3.68dB. Therefore, PAM4 has about 1dB advantage over PAM8
  - Link channel also affects signal PAR

Channel	Link-1	Link-2	Link-3
PAM4	6.16 dB	7.80 dB	9.33 dB
PAM8	4.41 dB	6.06 dB	7.65 dB
Difference	1.75 dB	1.74 dB	1.68 dB

Combined	Link-1	Link-2	Link-3
PAM4	8.71 dB	10.35 dB	11.88 dB
PAM8	8.09 dB	9.74 dB	11.33 dB
Difference	0.62 dB	0.61 dB	0.55 dB

- When the signal PAR and channel PAR are combined, PAM8 gained roughly 0.6dB in SNR
  - PAM4 BER is modified from 1.52e-10 to 2.10e-9, while PAM8 BER is still about 1.15e-8

Summary of the Work

- PAM4 and PAM8 are compared in terms of system operating margin for the target SER, under the assumption of AWGN and crosstalk noise. Based on the study, PAM4 is recommended for the 100G copper transmission over PAM8.
- It is seen that channels with loss at 25dB at the Nyquist frequency of 28GHz can be handled using PAM4 signaling for 100G copper applications.
- If stronger FEC can be applied such that the raw SER can be relaxed, channel loss from package ball to ball could likely be extended up to 30dB.
- Channel impedance discontinuity control, crosstalk management, system manufacturing variability reduction, and active components PVT performance assurance should be seriously given attention to for a product worthy system at the 100G node.
- With the development of new technologies 100G discussions will continue before standard bodies nail down detailed specifications.
- At the 100G system level specs are more about the combined effect than the individual impact. COM-like tools should be studied and developed for the link system analysis.

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Thank you!

QUESTIONS?