PAM-N Comparison

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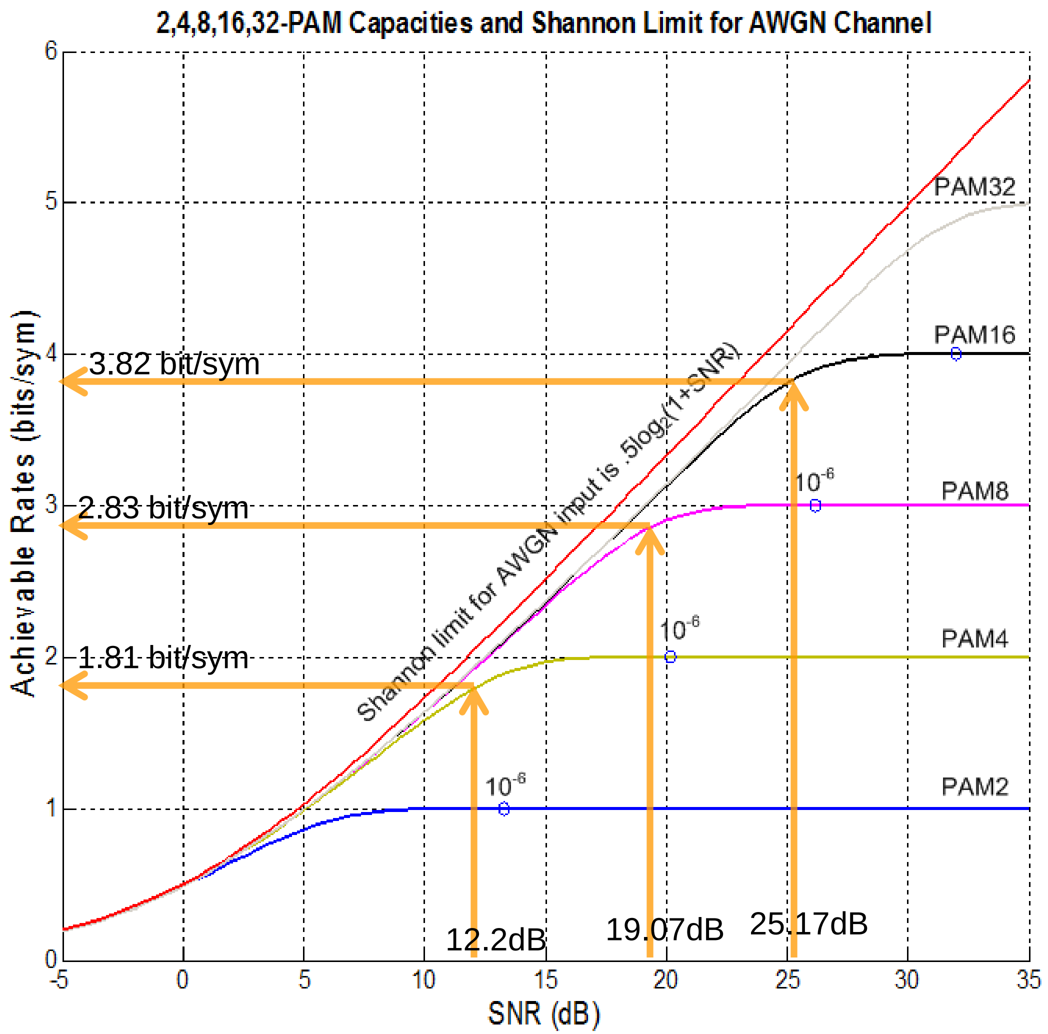
Acknowledgment

- Thanks to David Lewis (JDSU) and Beck Mason (JDSU) for their advice and support.

Outline

- PAM 8/12/16 Bandwidth and SNR tradeoffs
- Enhanced FEC: Benefits of Multilevel coding (MLC)
- 3.5 bits/symbol using 2D PAM constellations
- Optical Simulation model
- Link Simulations
- Summary

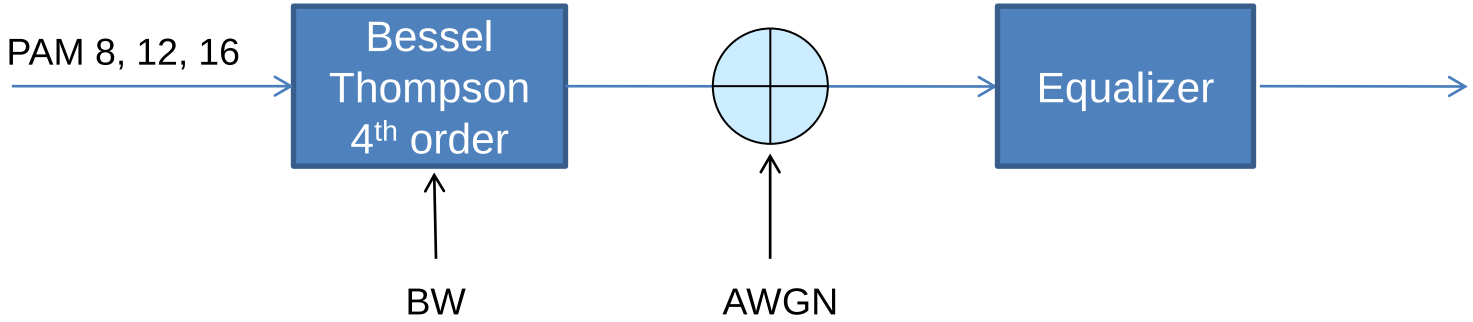
PAM Sweet Spots



The optimal choice of N in PAM-N depends on achievable SNR and bandwidth.

Ref: "Optimal Unipolar PAM Solutions for 100G SMF link from Channel Capacity Perspective" by A. Farhood, Sep 2012, 802.3bm

PAM-N SNR

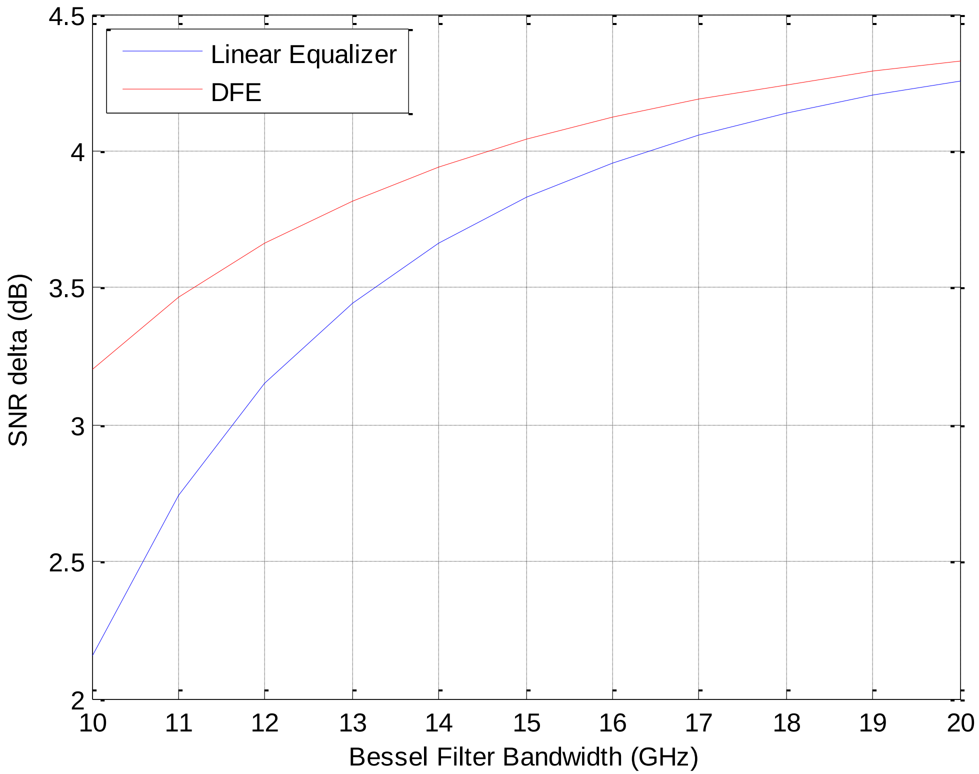


- 802.3bj NRZ RS(528, 514, t = 7) supports input BER = 2.2 E-5 for 1E-15 output BER (5.8dB coding gain)
- 802.3bj PAM4 uses a higher overhead code

	Baud Rate	Bits Per Symbol	Required Slicer SNR for 2.2E-5 (dB)	Noise BW Penalty (dB)	Relative SNR delta with .bj RS (dB)*
PAM8	34.4G	3	25.2 (+0)	1.25	0
PAM12	29.5G	3.5	28.7 (+3.5)	0.58	2.83
PAM16	25.8G	4	31.1 (+5.9)	0	4.65

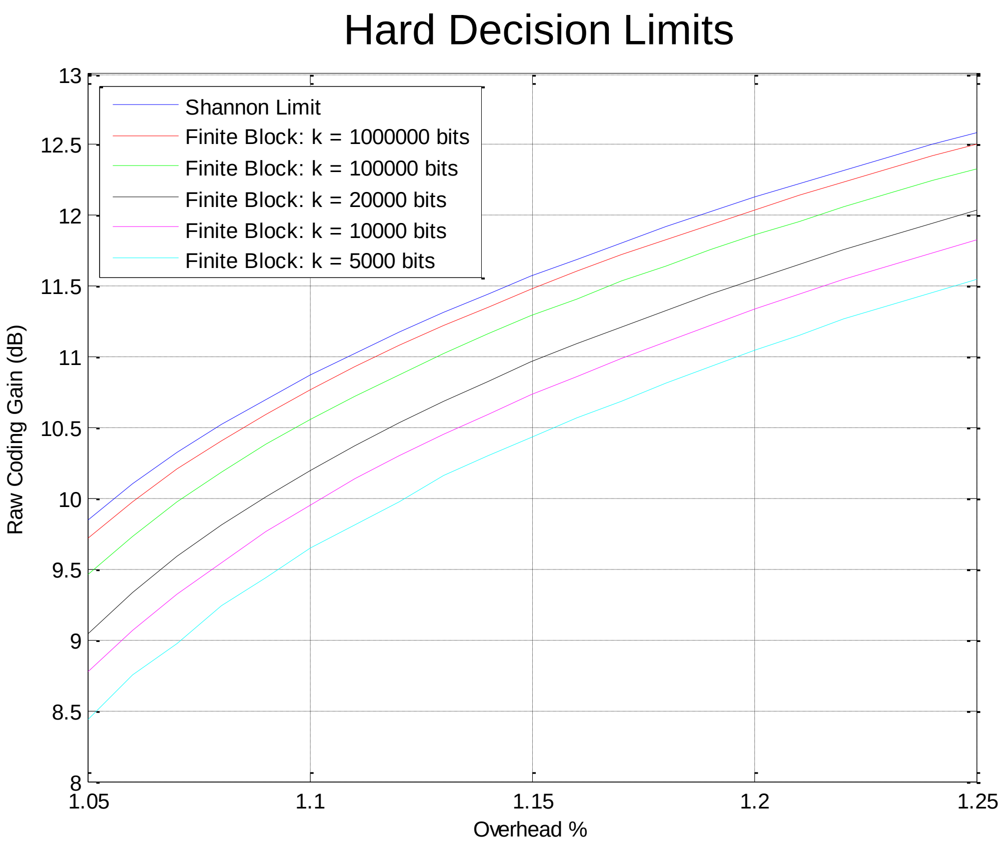
* The actual delta is smaller. These numbers are ignoring the bandwidth effect. See next page.

PAM8 vs. PAM16 Bandwidth effect



- Example: At 20 GHz bandwidth, the PAM8-PAM16 SNR difference shrinks from 4.65 dB to ~4.2 dB.
- SNR delta can be compensated by over clocking PAM16, and use the extra bits for a higher-gain FEC than 802.3bj.

FEC Coding Gain at 1E-15 vs. Overhead



- Hard decision limit is 12dB coding gain for 20% overhead (which is ~6.2dB higher coding gain than 802.3bj RS)

Coding Gain Tradeoff Table

Block Latency (ns)	Block Size (bits)	Required Error Correction (t)	Raw input BER for 1E-18 output BER	Raw coding gain for 1E-18 o/p BER	Raw input BER for 1E-15 output BER	Raw coding gain for 1E-15 o/p BER	Hamming Sphere Packing Rate (Gb/s)	Delta over 100GE-LR4 rate	BCH Rate (Gb/s)	BCH Delta over 100GE-LR4 rate
41.62	4261	3	1.66E-08	4.0	9.26E-08	3.7	25.59	-0.72%	25.63	-0.61%
69.32	7098	5	4.22E-07	5.0	1.34E-06	4.6	25.60	-0.70%	25.63	-0.60%
4.80	526	5	5.70E-06	6.0	1.80E-05	5.7	27.42	6.37%	28.06	8.83%
15.14	1593	6	5.70E-06	6.0	1.53E-05	5.6	26.30	2.01%	26.49	2.74%
35.97	3724	7	5.70E-06	6.0	1.36E-05	5.5	25.88	0.40%	25.98	0.76%
4.82	535	6	1.70E-05	6.5	4.56E-05	6.1	27.72	7.53%	28.60	10.93%
11.71	1249	7	1.70E-05	6.5	4.04E-05	6.1	26.67	3.45%	27.06	4.96%
23.39	2451	8	1.70E-05	6.5	3.68E-05	6.0	26.19	1.59%	26.43	2.50%
40.98	4253	9	1.70E-05	6.5	3.42E-05	6.0	25.95	0.64%	26.11	1.27%
65.34	6742	10	1.70E-05	6.5	3.21E-05	6.0	25.80	0.06%	25.89	0.42%
8.29	906	8	4.60E-05	7.0	9.96E-05	6.6	27.32	5.97%	27.85	8.02%
14.71	1572	9	4.60E-05	7.0	9.24E-05	6.5	26.72	3.63%	27.10	5.10%
49.78	5176	12	4.60E-05	7.0	7.93E-05	6.5	25.99	0.82%	26.18	1.55%
14.29	1543	11	1.10E-04	7.5	1.98E-04	7.0	27.00	4.73%	27.55	6.87%
20.28	2165	12	1.10E-04	7.5	1.90E-04	7.0	26.68	3.50%	27.20	5.50%
36.02	3789	14	1.10E-04	7.5	1.77E-04	6.9	26.30	2.01%	26.57	3.05%
15.63	1701	14	2.45E-04	8.0	3.95E-04	7.5	27.21	5.56%	27.92	8.29%
24.82	2659	16	2.45E-04	8.0	3.75E-04	7.4	26.78	3.88%	27.37	6.15%
36.20	3839	18	2.45E-04	8.0	3.61E-04	7.4	26.51	2.82%	26.90	4.36%
23.61	2564	20	5.00E-04	8.5	7.13E-04	7.9	27.15	5.30%	28.01	8.66%
31.09	3346	22	5.00E-04	8.5	6.94E-04	7.9	26.90	4.35%	27.57	6.92%
44.00	4691	25	5.00E-04	8.5	6.73E-04	7.9	26.65	3.38%	27.28	5.82%
36.50	3965	31	1.00E-03	9.0	1.29E-03	8.4	27.16	5.34%	28.02	8.68%

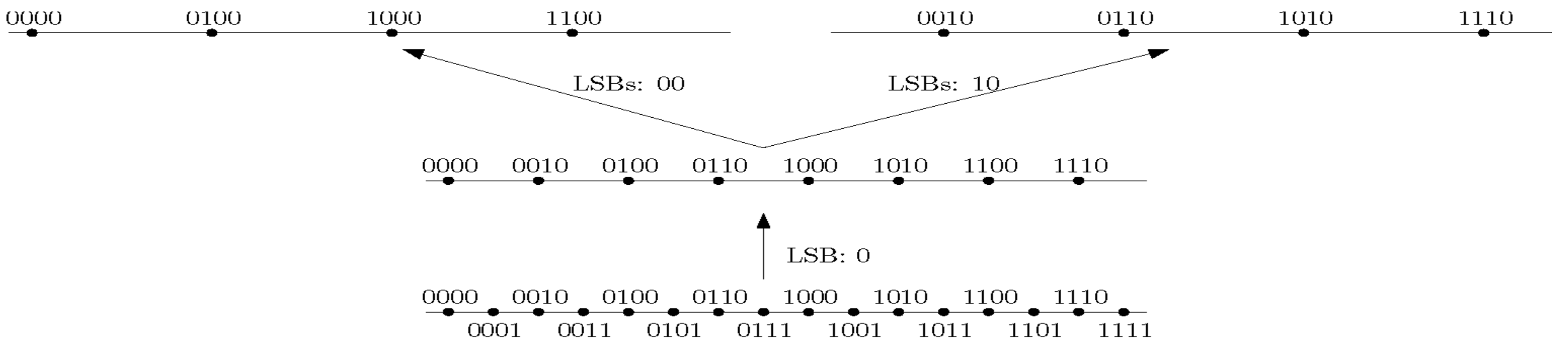
- Rates here are calculated based on 65b/64b transcoding. Rates can further improve by 1.15% if we change the transcoding to 257b/256b.
- S. Bhoja, M. Gustlin, "FEC Triple Tradeoffs & 100GCU SG Objectives", IEEE 802.3 100 Gb/s Backplane and Cable Study Group, March '11

Coded Modulation

- Over clocked PAM12 or PAM16 with stronger FEC compared to 802.3bj RS is under investigation
- Coded Modulation can combine mapping with FEC to close the link budget.

Example 1: Multi-Level Coding (MLC) on PAM-16

- Code the two LSBs and induce 4-PAM from 16-PAM
- Hierarchical partition of constellation shown below for LSB=0; analogous partition for LSB=1



Coded Modulation Example 1: MLC, 16-PAM

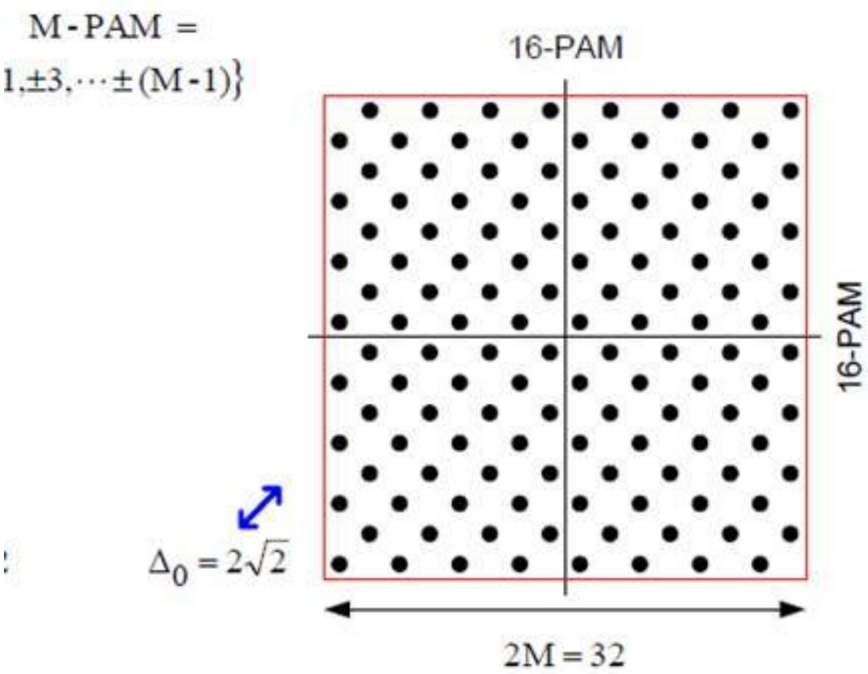
- Consider each bit a sub-channel
- Assuming PAM16 SNR=25.2dB, the capacity for Sub-Channel4 (ie LSB) is 0.8335 bits per symbol and Sub-Channel3 is 0.9997 bits per symbol.
- With our low latency requirement, it is very hard to approach channel capacity. If we back-off 3dB from the limit, then Sub-Channel4 can send 0.6089bit per symbol and Sub-Channel3 can send 0.9868 bits per symbol.
- The overall rate is (1+1+0.9868+0.6089)/4=0.8989. The baud rate needs to be expanded by 1/0.8989. So the 25GHz transcended rate is increased to 28GHz. This is equivalent to 12% OH.
  - Latency (ns) will increase by a factor of 4 due to lower throughput

Coded Modulation Example 2: Mapping/2D constellation

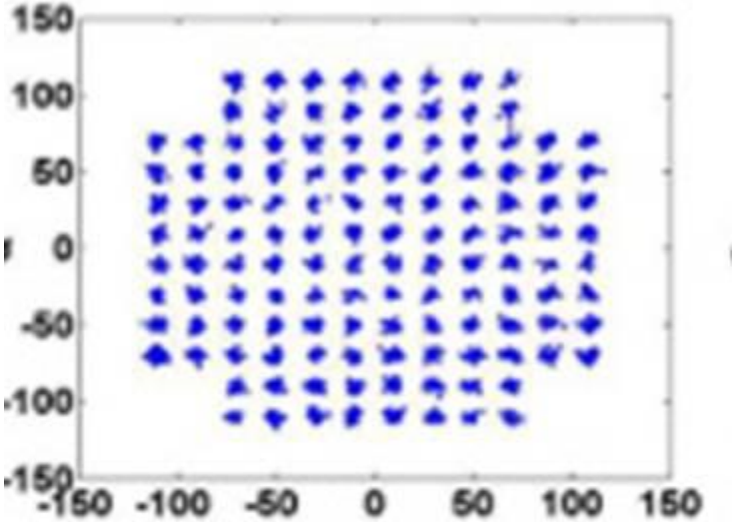
- 128 constellation points over 2 symbol periods allows for integer bit mapping
- Intermediate option to PAM8 and PAM16
- 2D constellation is constructed from 2 successive unipolar PAM symbols in time.
- Many 2D choices possible. Under investigation

Example 2D constellations

128-DSQ (Double SQuare)



128 Cross



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Electrical PAM-N comparison

	PAM8 + 802.3bj FEC	PAM16 + 802.3bj FEC	PAM8 with coded modulation	PAM16 with coded modulation
Baud rate	34.4G	25.8G	40G	28G
FEC Target BERi for 1e-15 BERo	2.2E-5	2.2E-5	1.15E-2	1.15E-2
Latency Target	100ns	100ns	<500ns	<500ns
Coding Overhead	2.72%	2.72%	19.5%	12%
Mapping / Coding gain	5.8dB	5.8dB	10.9dB	10.9dB

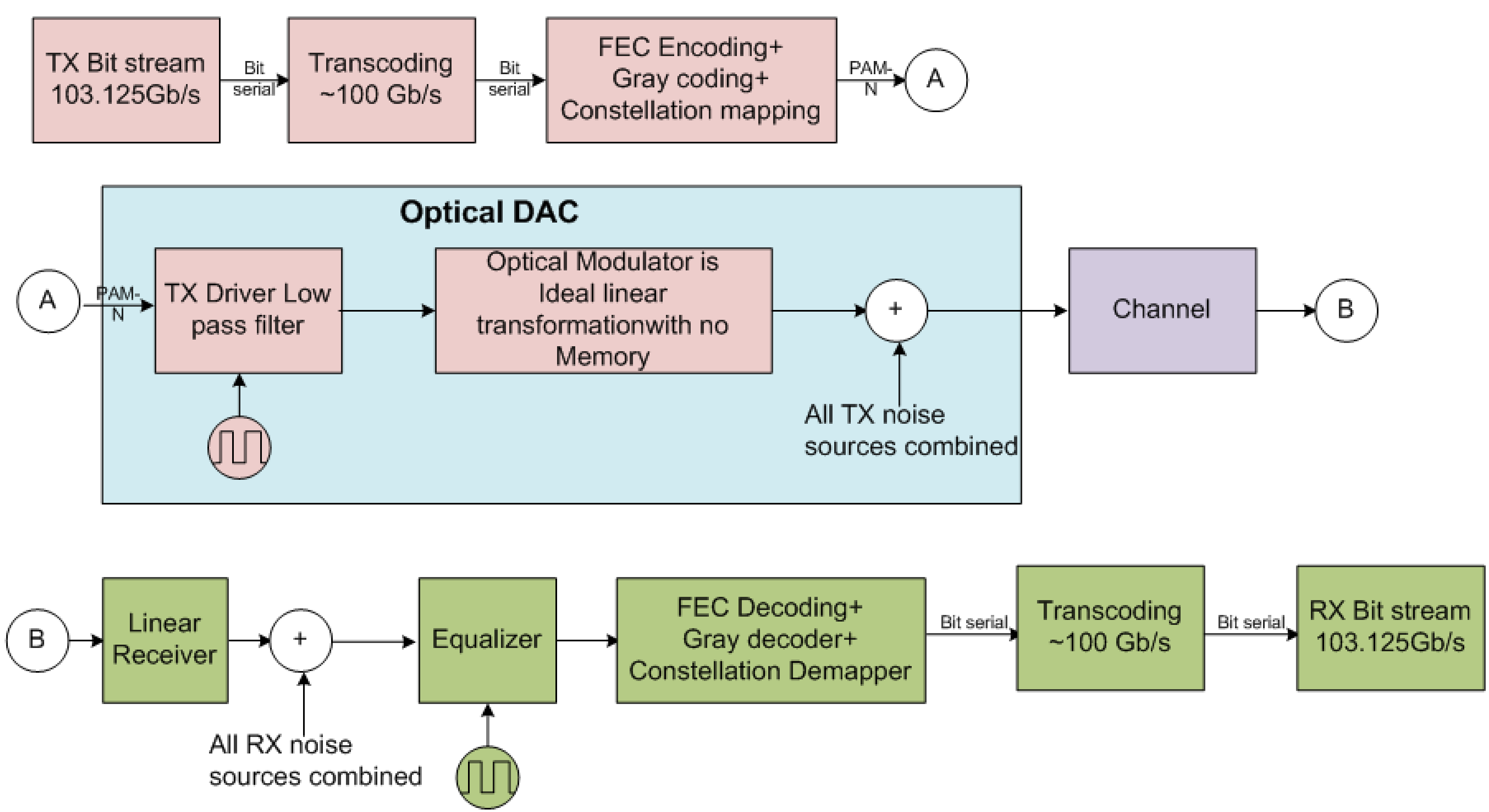
- Coded Modulation with 12% overhead can work with 3 orders of magnitudes higher BER than .bj RS FEC
- Latency increases up to 500ns from 100ns

Electrical PAM-N comparison

	PAM8 with 802.3bj FEC	PAM16 with 802.3bj FEC	PAM8 with Coded Modulation	PAM16 with Coded Modulation
Baud rate	34.4G	25.8G	40G	28G
FEC Target BER	2.2E-5	2.2E-5	1.15E-2	1.15E-2
Required SNR (dB)	25.2	31.1	19.5	25.2
Relative Noise BW Penalty (dB)	1.25	0	1.9	0.36
Relative ISI Penalty, 20G BW (dB)	0.5	0	0.9	0.12
Net (Noise + BW) Penalty (dB)	1.75	0	2.8	0.48
Relative SNR Margin (dB)	0	-4.15	+4.65	+1.27

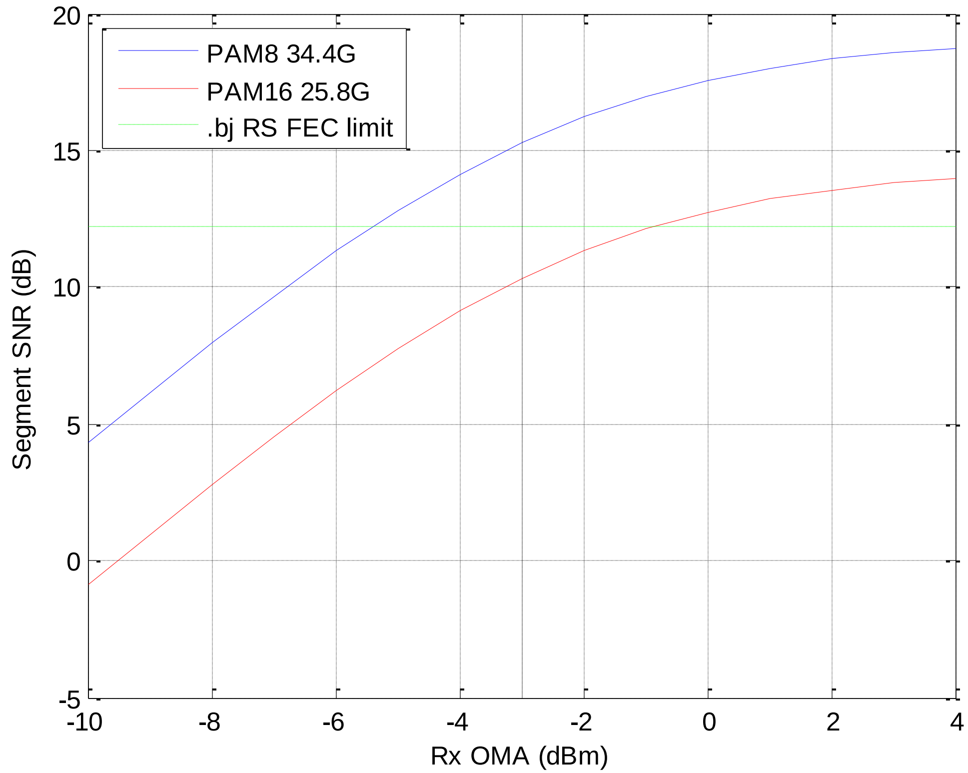
- Coded Modulation for 28G PAM16 can reduce the baud rate and provide 1.27dB margin vs. PAM8 with .bj FEC
- Over-clocked PAM8 with Coded Modulation (40G) improves SNR by 4.65dB.

Unipolar PAM-N High-Level Block Diagram



Aug, 2012

Optical link comparison with 802.3bj FEC



20GHz Tx BW

21.5 Rx BW

34dB Tx SNR

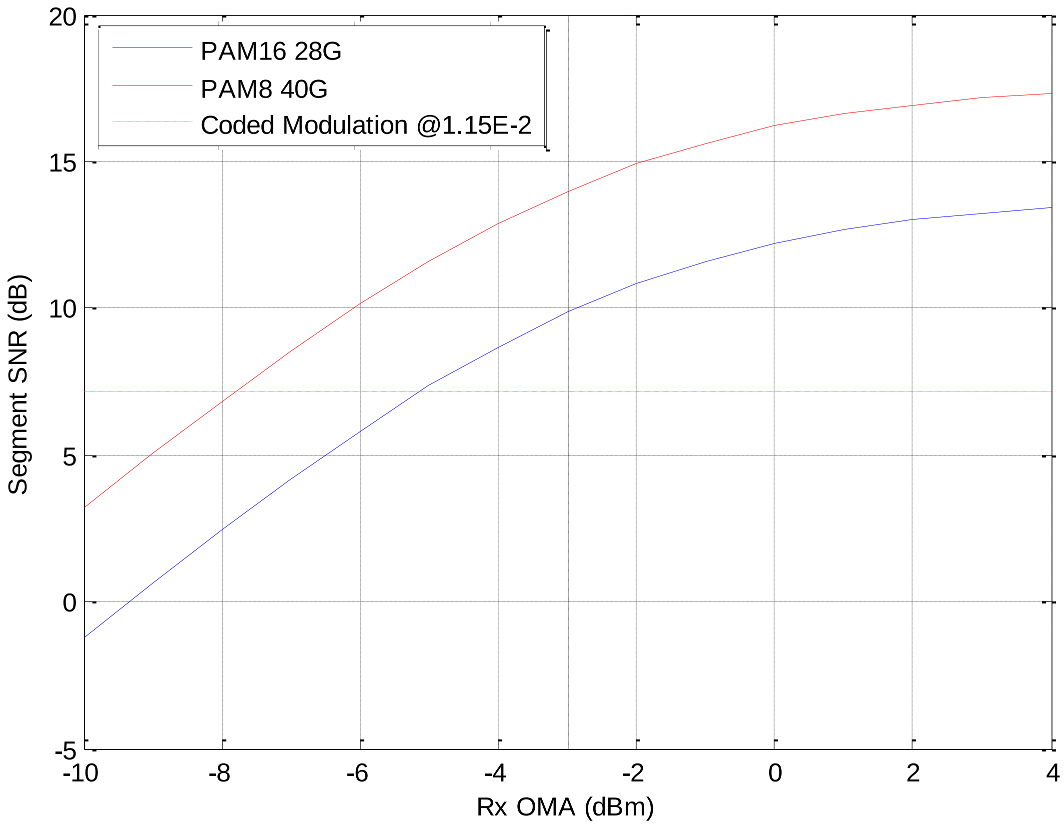
RIN -148dB/Hz

ER 8dB

TIA 13pA/sqrt(Hz)

- PAM8 supports 4dB link budget with Tx OMA of +1dBm
  - 2.5dB margin
- PAM16 with 802.3bj RS FEC will require higher OMA

Optical link with coded modulation



20GHz Tx BW

21.5 Rx BW

34dB Tx SNR

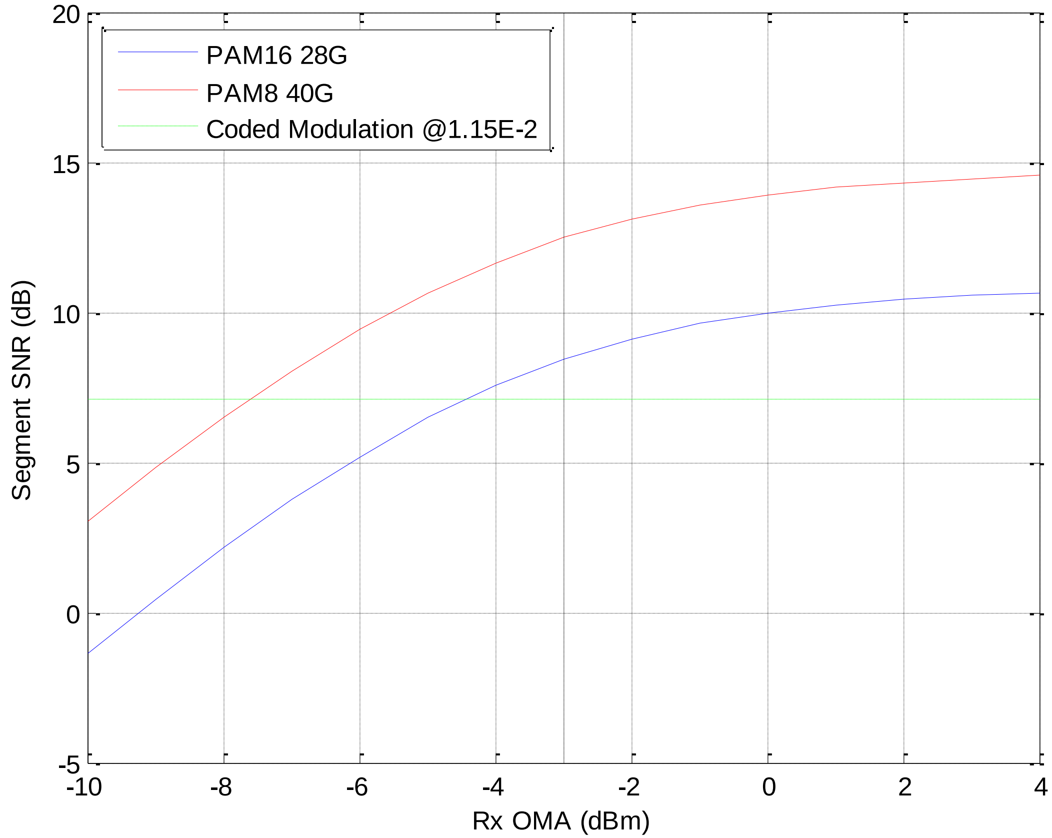
RIN -148dB/Hz

ER 8dB

TIA 13pA/sqrt(Hz)

- Coded Modulation enables PAM16 at 28G and PAM8 at 40G.
- For a 4 dB channel budget, PAM16 supports 2.2 dB slicer margin, and PAM8 supports 4.85dB slicer margin

Optical link with coded modulation



20GHz Tx BW

21.5 Rx BW

34dB Tx SNR

RIN -145dB/Hz

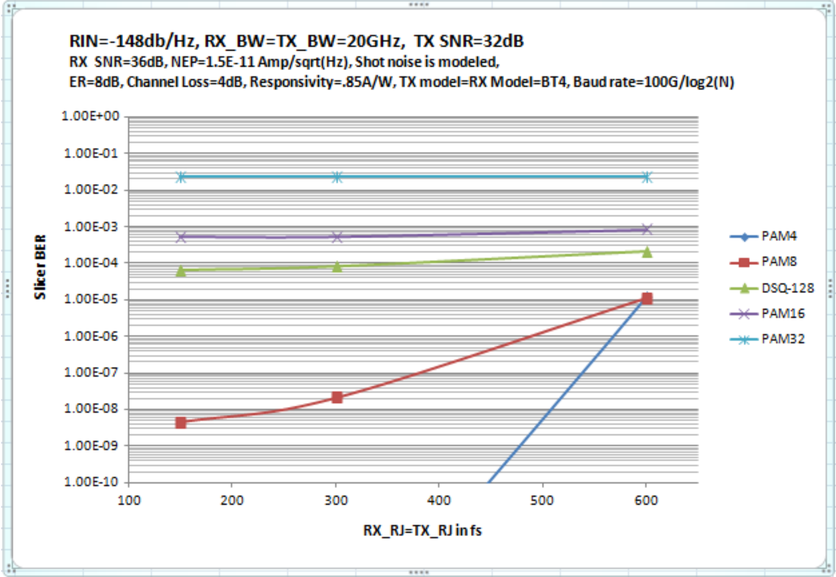
ER 8dB

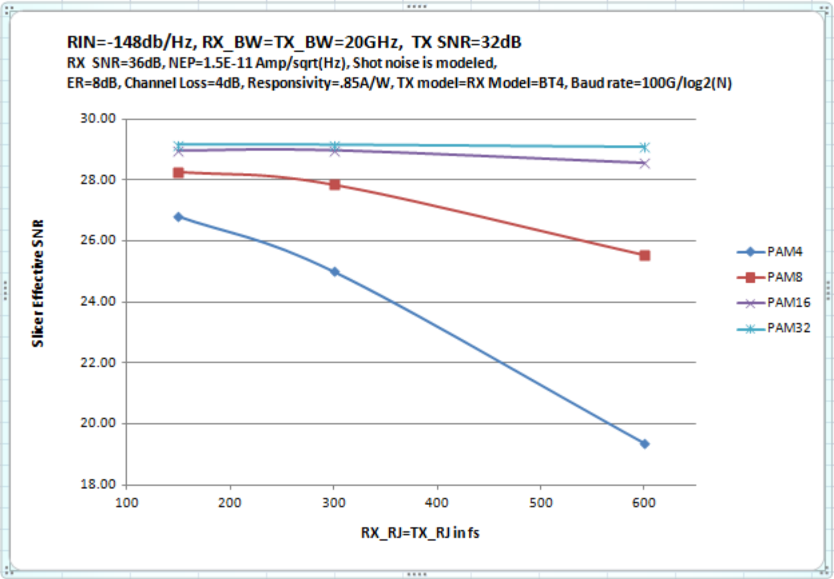
TIA 13pA/sqrt(Hz)

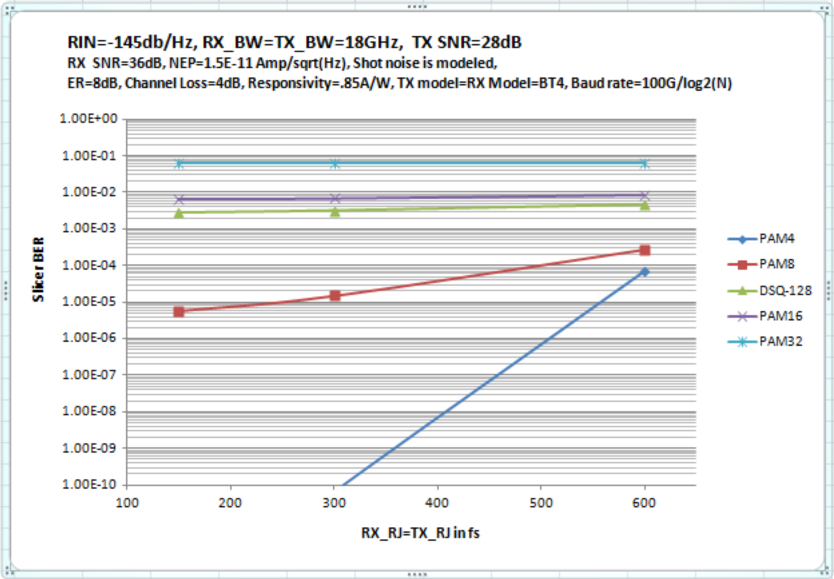
- Coded Modulation enables PAM16 at 28G and PAM8 at 40G.
- For a 4 dB channel budget, PAM16 supports 1.2 dB slicer margin, and PAM8 supports 4.6 dB slicer margin

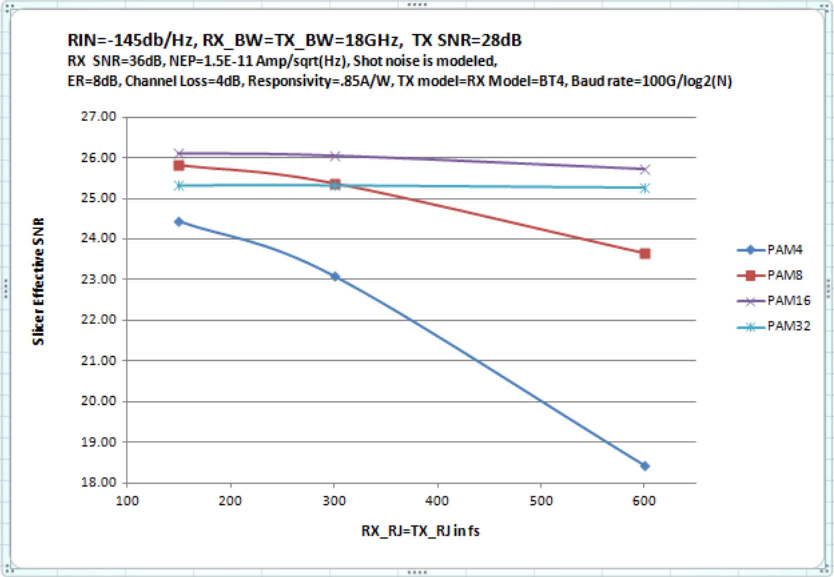
Monte-Carlo Simulations

BER/SNR curves as a function of Jitter



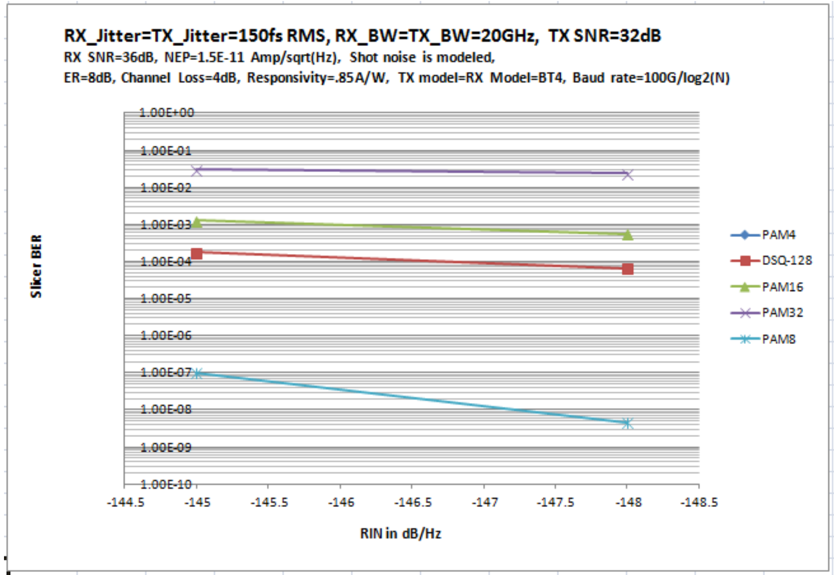


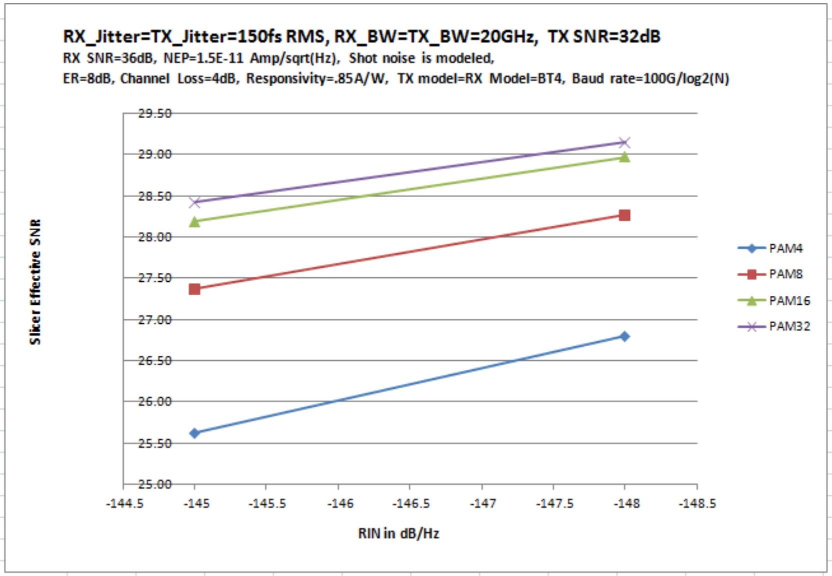


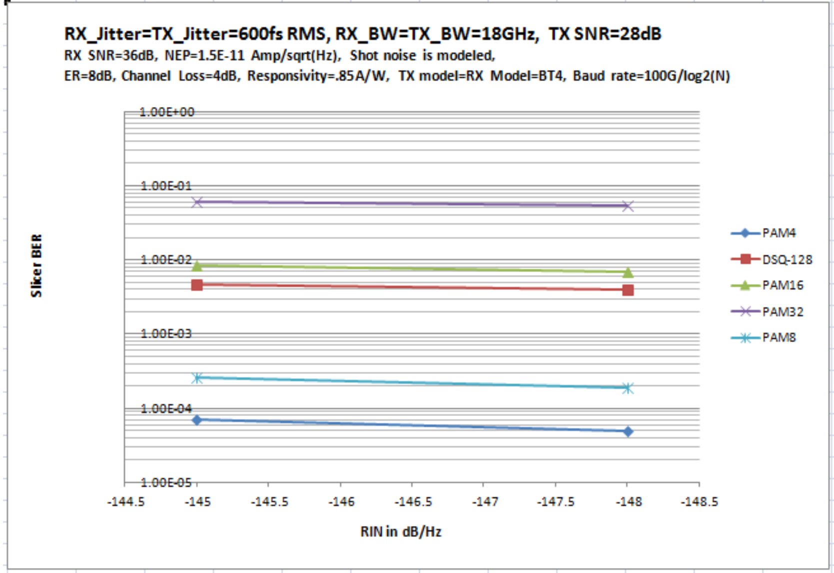


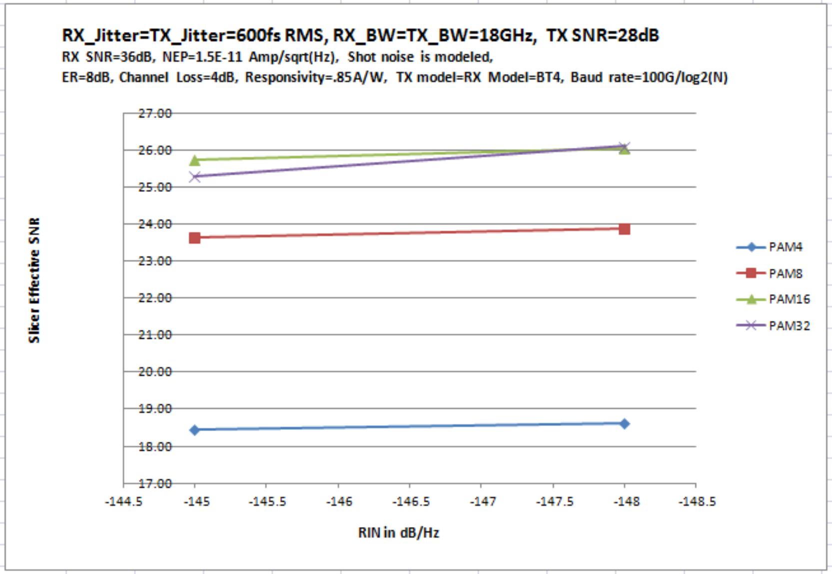
Monte-Carlo Simulations

BER/SNR curves as a function of RIN



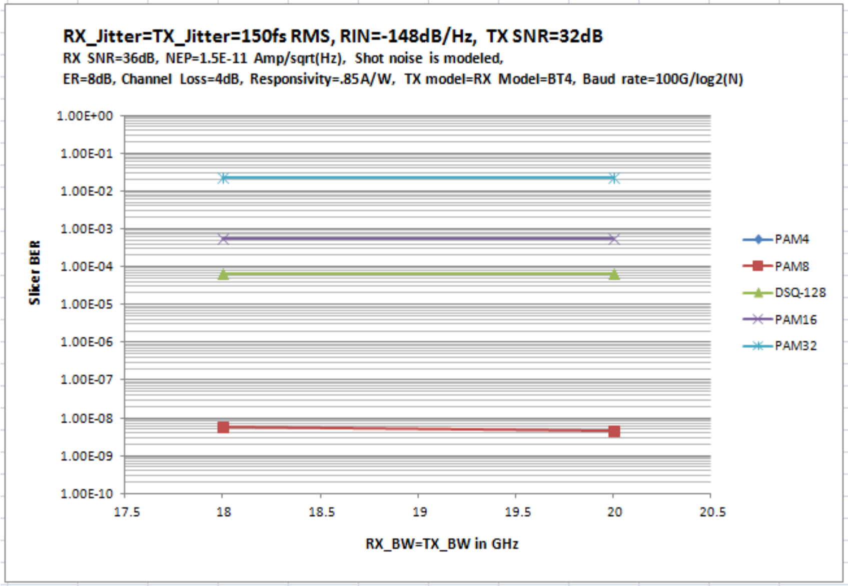


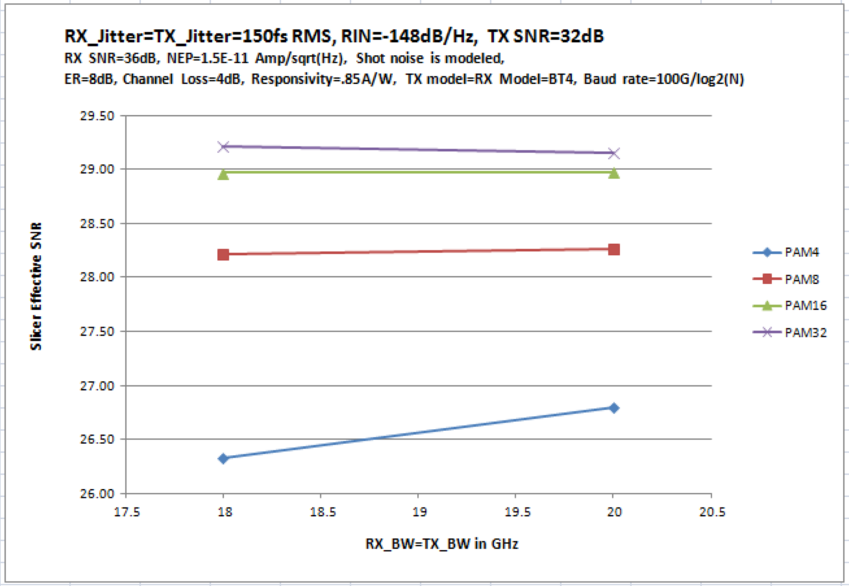


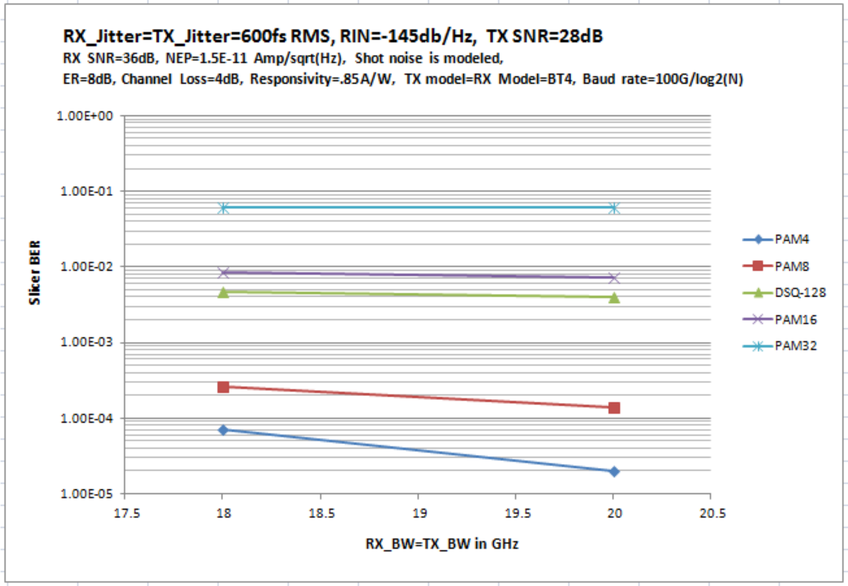


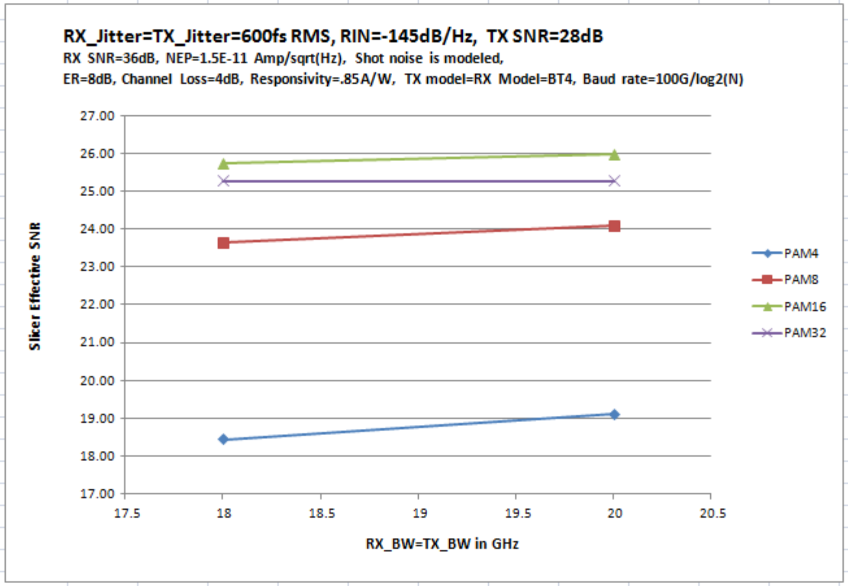
Monte-Carlo Simulations

BER/SNR curves as a function of Bandwidth



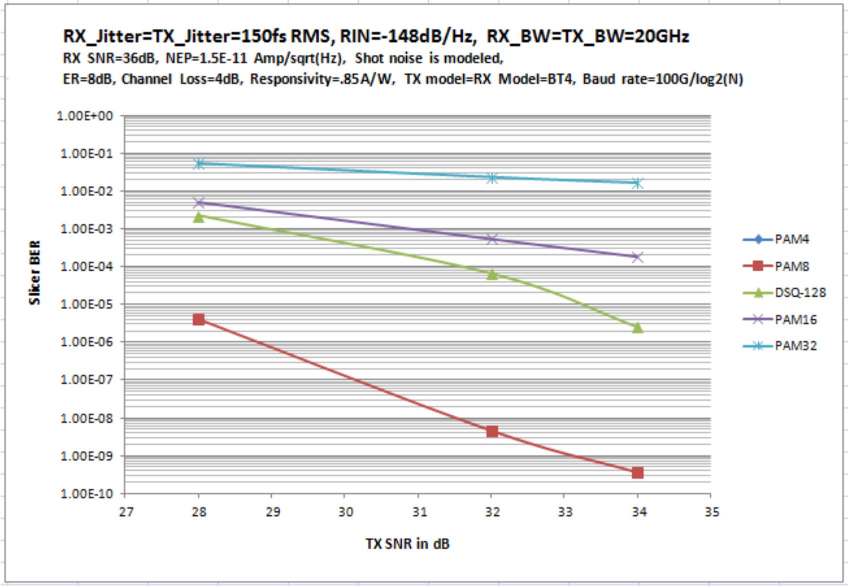


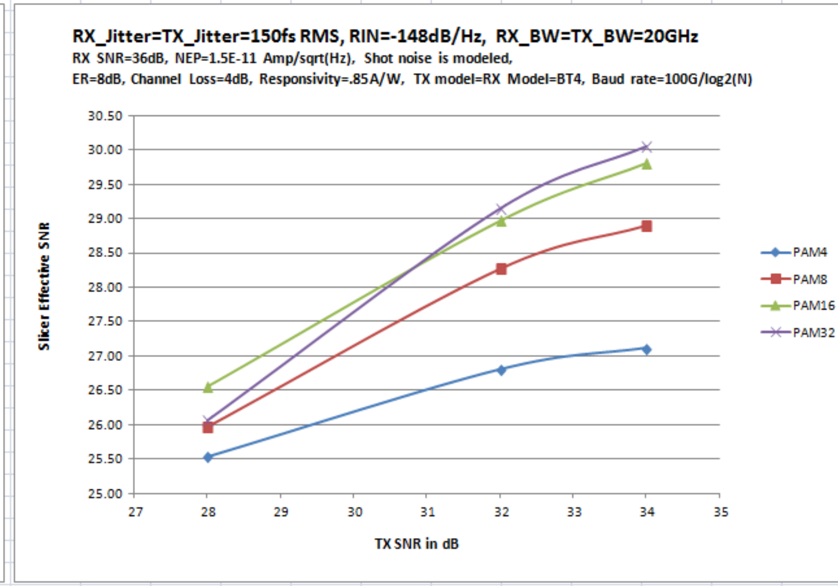


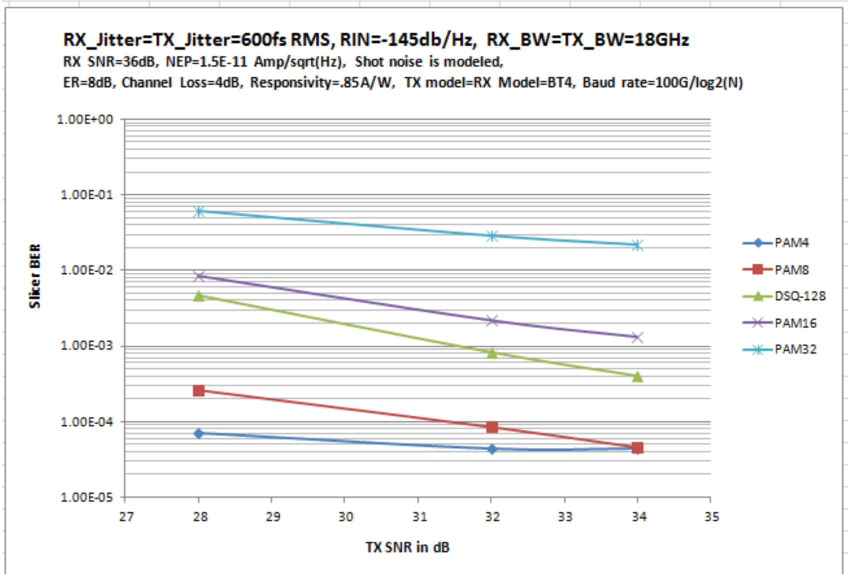


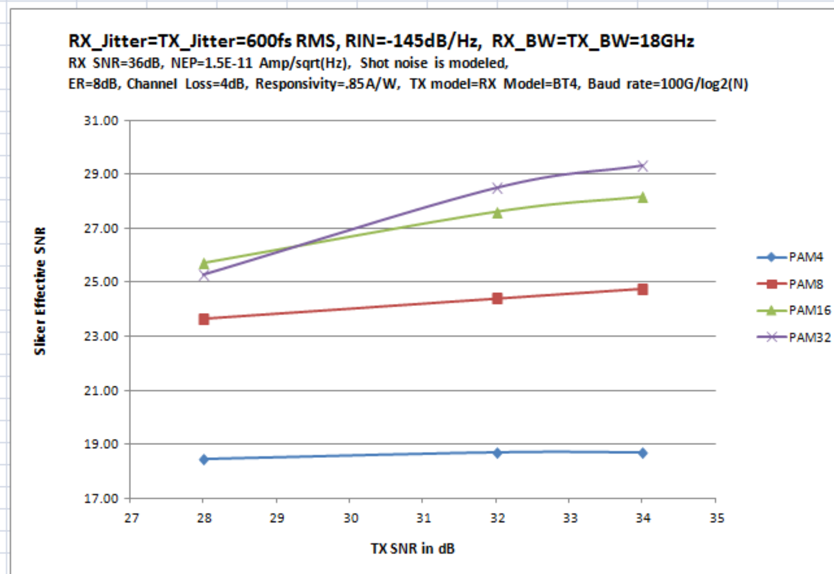
Monte-Carlo Simulations

BER/SNR curves as a function of TX SNR









Summary

- We have proposed new coding and mapping alternatives for PAM.
- We have a high degree of confidence in technical feasibility.
- Coded modulation trades up to 500 ns of latency to provide a robust optical link.
- SNR Requirements and bandwidth impacts of PAM8 and PAM16 were investigated.
- Coded Modulation enables 28G over-clocked PAM16, and 40G over-clocked PAM8, with margin.