Optimal Unipolar PAM Solutions for 100G SMF link from Channel Capacity Perspective

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Outline

- Objective
- PAM-N Generic Simulation Model
- Native PAM-N
  - Minimum Baud-Rate requirement
- AWGN Channel capacity
- Maximum rates
- Enhanced PAM-N
  - Multi-Level Coding
  - Achievable rates
  - Test cases
  - PAM16 system design target
- Summary

Objective

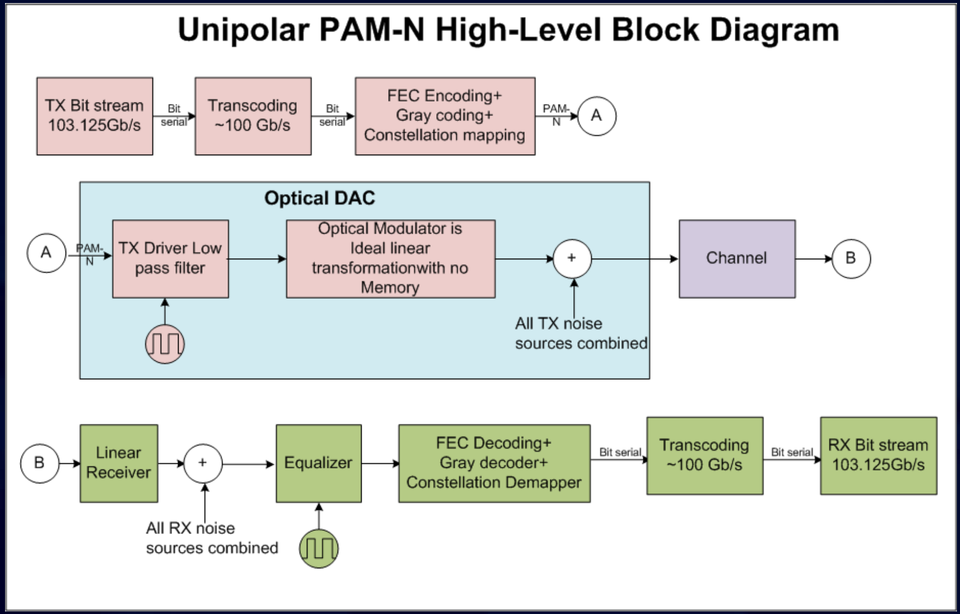
- **In the following presentation we analyze PAM2/4/8/16 and 32 from channel capacity perspective**
- **We derive benchmarks based on native PAM solutions**
- **We propose enhanced PAM systems that achieve the benchmarks while relaxing the SNR/BandWidth requirements of the overall system**
- **Simulation results are presented for PAM8 and PAM16 test cases**

Terms and Definitions

For the purpose of this presentation:

- Native PAM-N: PAM-N with Gray labeling and Hard-Decision-Decoding FEC as specified in 100G Base KR4 standard. To be contrasted with PAM that implements MLC.
- MLC: Multi-Level Coding, a technique of assigning different coding overheads to selected subsets of information bits. Not to be confused with multi-level signaling that PAM signal is often called.
- SNR: Signal to Noise Ratio, defined as average signal power to average noise power, in electrical domain.
- “PAM” means “Unipolar PAM” in this presentation.

PAM simulation environment

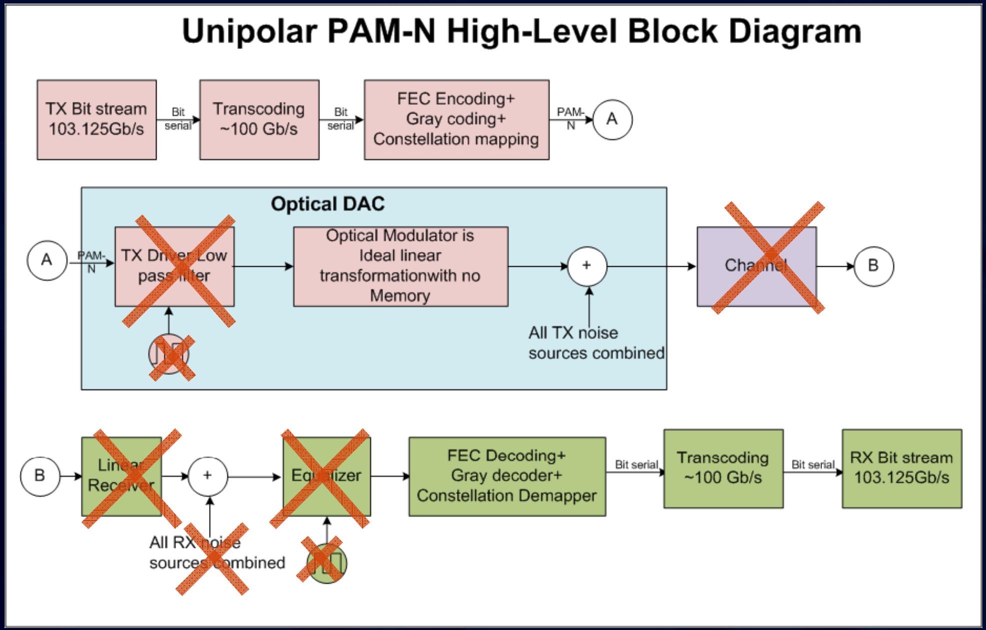


- The 64b/66b transcoding is stripped out and replaced with a more efficient 256b/257b coding to reduce the input bit-rate to around 100Gb/s. Bit transparent support of OTN rate is considered later in the presentation.
- The TX optical DAC is decomposed to a low-pass low-impedance driver controlling a memory-less Optical Modulator with ideal linearity. TX noise is modeled by adding a lumped noise to the output of the TX optical DAC
- Channel is modeled as insertion loss only with some MPI penalty. Chromatic Dispersion is ignored.
- Linear receiver is modeled as a low pass function followed by all RX noise sources added at the output the filter.
- ISI cancellation, Mapping and coding are used to improve the output bit-error-rate of the overall system

Simplified PAM simulation environment

For Channel capacity analysis lets start from a very simple model.

We will switch back to the more complex model later in the presentation



- The TX optical DAC is simplified to an ideal PAM-N transmitter.
- All TX and RX optical and electrical noise sources are simplified to a single lumped AWGN noise source added to the output of TX.
- The channel is assumed to be 1 and there is no jitter on the RX or TX side. No ISI canceller is required
- Mapping and coding are heavily used to improve the output bit-error-rate of the overall system

Minimum Baud Rate requirement

- With the simplified model, table below shows minimum Baud rate requirement for different PAM options without FEC

	Ethernet rate	OTN rate
PAM-2	100.39 Gs/s	111.81 Gs/s
PAM-4	50.20 Gs/s	55.90 Gs/s
PAM-8	33.46 Gs/s	37.27 Gs/s
PAM-16	25.10 Gs/s	27.95 Gs/s
PAM-32	20.08 Gs/s	22.36 Gs/s

- The bit-error-rate requirement for Ethernet is assumed to be 1E-15.
- For OTN the bit error rate target is 1E-17
- In OTN mode, at minimum GFEC code can be assumed (RS(255,239,m=8,T=8)). This requires 4.93E-5 bit error rate into the OTN GFEC Decoder.

Simple PAM2, PAM4 and PAM8 systems

- We consider any Baud-Rate bigger than 30Gs/s as less desirable.
- **Native system**: In Ethernet mode, use 802.3bj 100G Base KR4 FEC in conjunction with Gray labeled PAM-N to design a 100G system. In OTN mode, rely on existing OTUk GFEC

* 100G Base KR4 FEC is RS(528,514,T=7,m=10) and GFEC is RS(255,239,T=8,m=8)

With OTN GFEC: BERo=1e-17 then BERi=4.93E-5

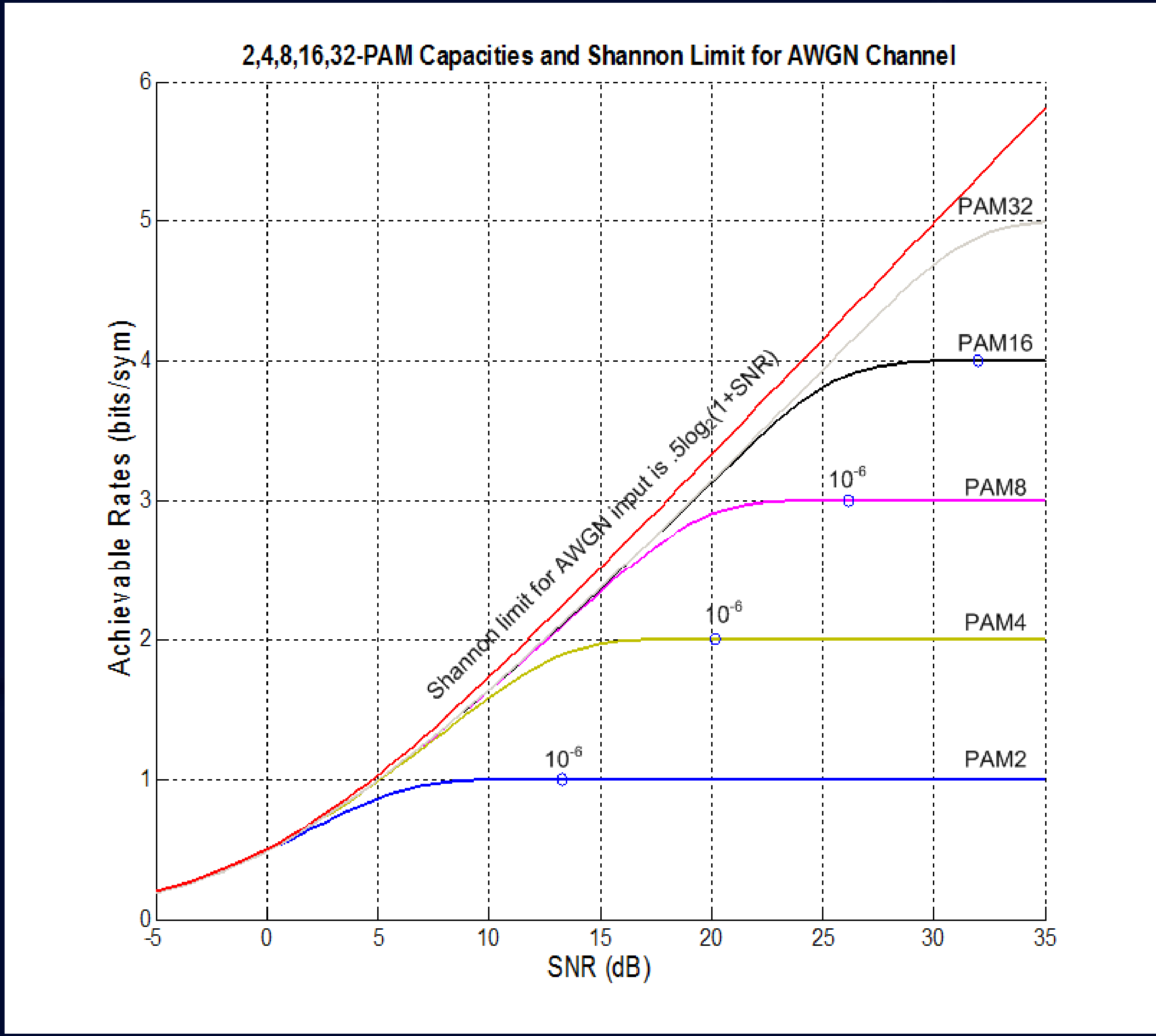
With 100G Base KR4 FEC: BERo=1e-15 then BERi=2.2e-5

- We assume 2.2e-5 for SNR calculations. This results in the below required SNR for different PAM options

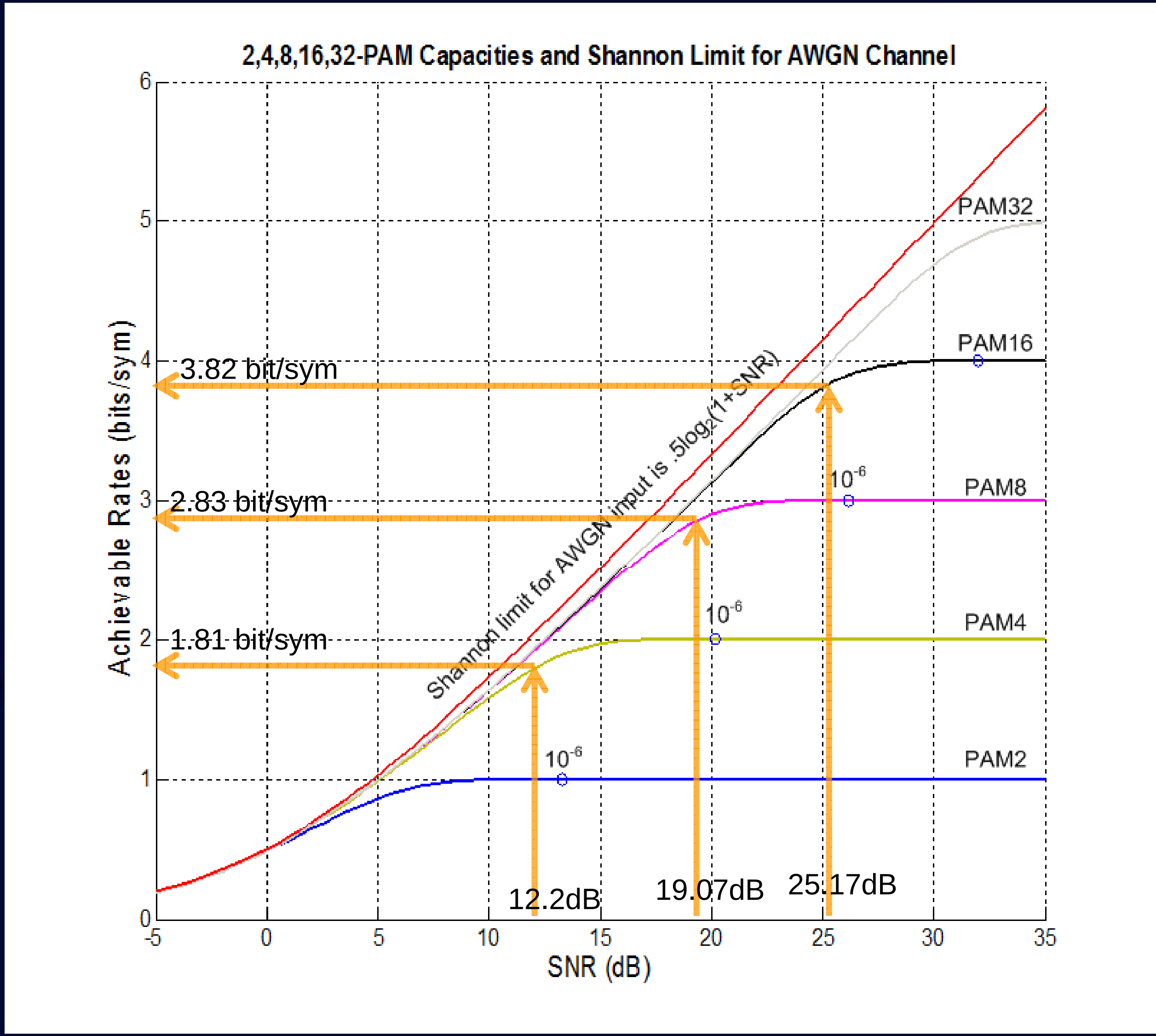
	Ethernet rate	OTN rate	Minimum SNR
PAM-2 native	103.25 Gs/s	111.81 Gs/s	12.22dB
PAM-4 native	51.63 Gs/s	55.90 Gs/s	19.07dB
PAM-8 native	33.46 Gs/s	37.27 Gs/s	25.17dB
PAM-16 native	25.8 Gs/s	29.95 Gs/s	31.13dB

* Native PAM16 SNR is not achievable

AWGN Capacity Curves



AWGN Capacity Curves



Maximum bit rates

- Now we can investigate, given the channel SNR, how many bits can be transmitted for specific modulation scheme

	Ethernet rate	OTN rate	Minimum SNR
PAM-2 native	103.25 Gs/s	111.81 Gs/s	12.22dB
PAM-4 native	51.63 Gs/s	55.90 Gs/s	19.07dB
PAM-8 native	33.46 Gs/s	37.27 Gs/s	25.17dB

SNR	PAM2 achieves	PAM4 achieves	PAM8 achieves	PAM16 achieves	PAM32 achieves	Limit achieves
12.22dB	1.00 bit/Sym	1.81 bit/sym	1.94 bit/sym	1.95 bit/sym	1.96 bit/sym	2.07 bit/sym
19.07dB	1.00 bit/Sym	2.00 bit/Sym	2.83 bit/sym	2.98 bit/sym	2.99 bit/sym	3.18 bit/sym
25.17dB	1.00 bit/Sym	2.00 bit/Sym	3.00 bit/Sym	3.82 bit/sym	3.96 bit/sym	4.18 bit/sym

- The green numbers are the sweet spot given the range of SNR of interest. They provide a substantial bit rate increase for the system complexity increase.
- Given the above table and for the range of the SNR of interest, we are going to ignore PAM32 moving forward in this presentation

Multi-Level Coding

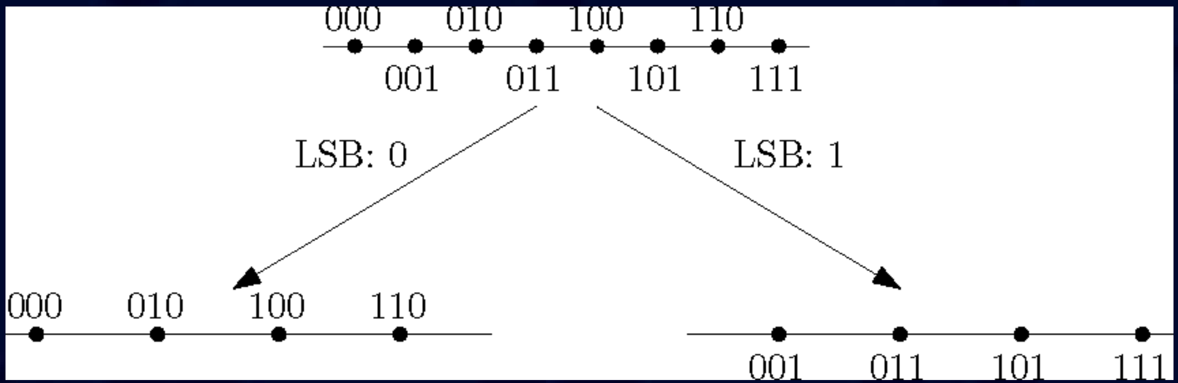
How can we achieve or get close to the bit rates specified in the previous page?

- There are technically infinite number of ways that you can design a system to achieve, approach or get close to the limit by some margin.
- One approach is Multi-Level coding (MLC). In this approach higher order PAM (like PAM-8) are protected with FEC in such a way that after decoding a lower order PAM (like PAM-4) is induced.
- In the following slides we investigate the impact of MLC on 100G Fiber systems.

Multi-Level coding

Lets try to make PAM8 look like PAM4

- Binary FEC is applied to label bits
  - Set partitioning induces better channel for MSBs

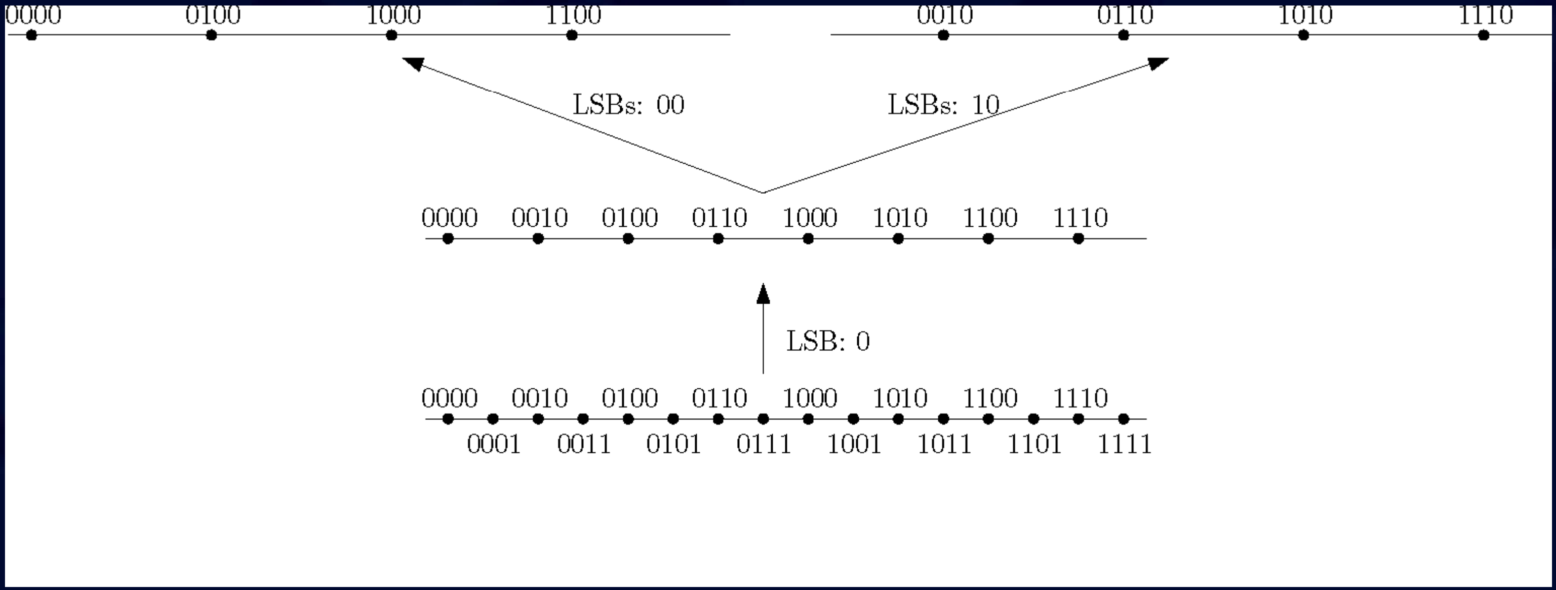


  - For 8-PAM, only code the LSB since the two MSBs do not require any coding
    - Induced partitions “see” channel with +6dB SNR

Multi-Level coding

Now lets make PAM16 look like PAM4

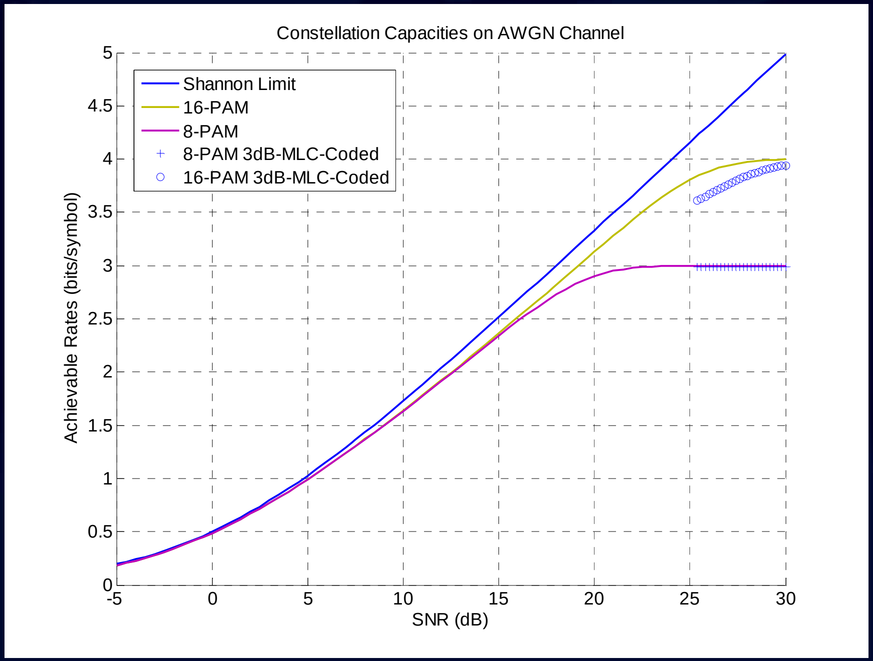
- For 16-PAM, code the two LSBs
  - Induces 4-PAM constellations on MSBs
  - Hierarchical partition of constellation shown below for LSB=0; analogous partition for LSB=1



Multi-Level coding

Achieving capacity on the binary induced channels is very hard

- For 100G Fiber we have both latency and power constraints. These constraints do not allow us to hit the capacity on the binary induced channels
- To tuen this into an easier problem, we back off 3dB on the binary induced channel. This obviously results in a sub optimal achievable rate.



Achievable rates with sub-optimal codes

3dB back-off from capacity on the sub channels

SNR	PAM2 achieves	PAM4 achieves	PAM8 achieves	PAM16 achieves	Limit achieves
12.22dB	1.00 bit/Sym	1.56 bit/sym	N/A	N/A	2.07 bit/sym
19.07dB	1.00 bit/Sym	2.00 bit/Sym	2.59 bit/sym	N/A	3.18 bit/sym
25.17dB	1.00 bit/Sym	2.00 bit/Sym	3.00 bit/Sym	3.58 bit/sym	4.18 bit/sym

- This means the target baud rate of the PAM-16 solution needs to be increased by a factor of 4/3.58

	Ethernet rate	OTN rate	Minimum SNR
PAM-2 native	103.25 Gs/s	111.81 Gs/s	12.22dB
PAM-4 native	51.63 Gs/s	55.90 Gs/s	19.07dB
PAM-8 native	33.46 Gs/s	37.27 Gs/s	25.17dB
PAM-16 native	25.8 Gs/s	29.95 Gs/s	31.13dB
PAM-16 + MLC	28.04 Gs/s	31.23 Gs/s	25.17dB

In the OTN PAM16 mode, the GFEC input bit error rate would be 1E-15. This is different than all the other modes which produce a bit error rate of around 2.2E-5

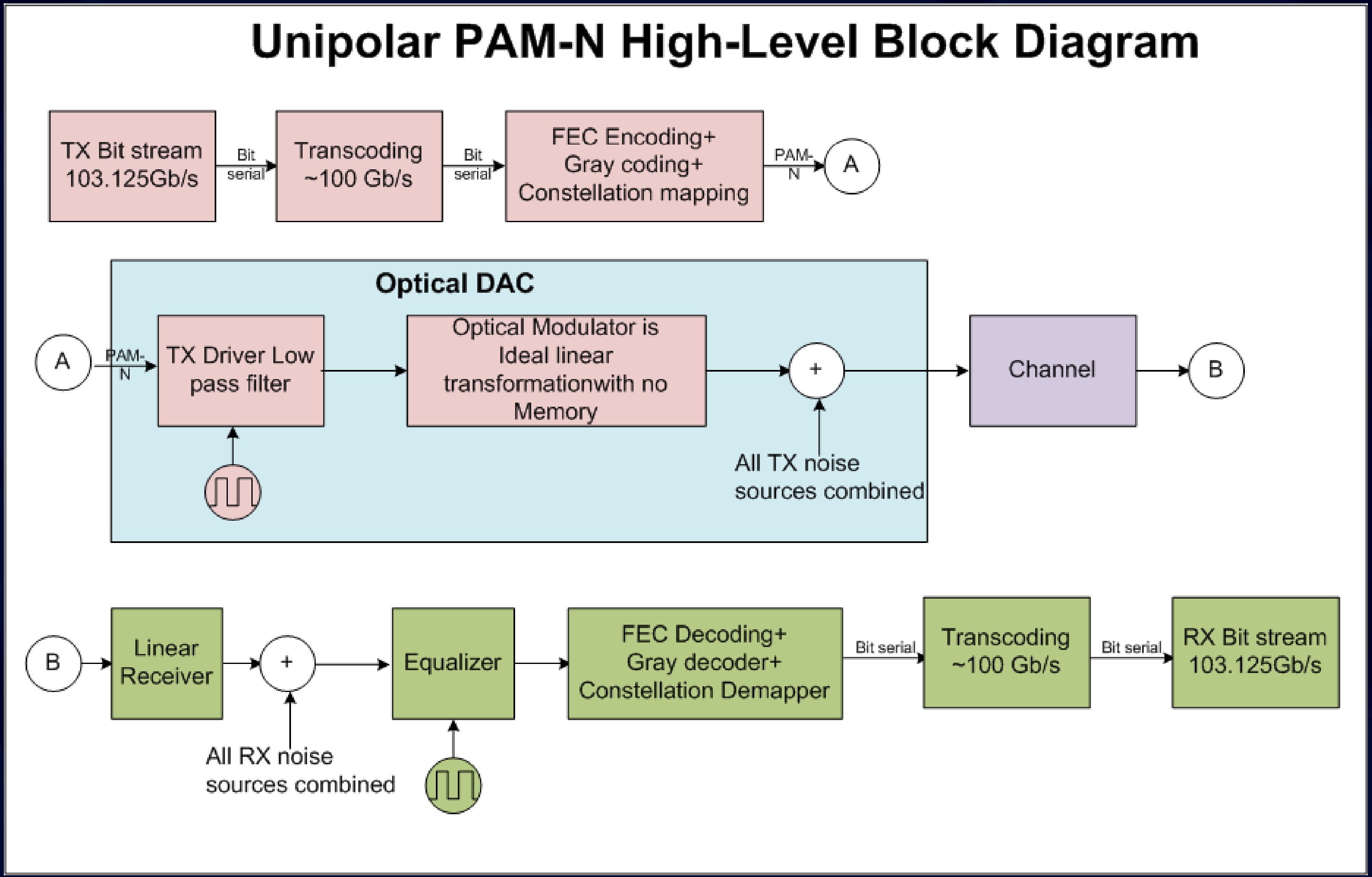
Slicer SNR

We are going to further assume that the Slicer SNR needs at least 1.2dB of margin.

	Ethernet rate	OTN rate	DP SNR
PAM-2 native	103.25 Gs/s	111.81 Gs/s	16.0dB
PAM-4 native	51.63 Gs/s	55.90 Gs/s	20.5dB
PAM-8 native	33.46 Gs/s	37.27 Gs/s	26.5dB
PAM-16 native	25.8 Gs/s	29.95 Gs/s	32.5dB
PAM-16 + MLC	28.04 Gs/s	31.23 Gs/s	26.5dB

- For the rest of the presentation we focus on PAM8 and PAM16 only
- Lets investigate what kind of system parameters can produce 26.5dB SNR for PAM8/16 modes

PAM simulation environment



Test case

Example settings to make the PAM16-MLC work

Ethernet mode:

OMA Power=1dBm, ER=8dB, Channel Loss=4dB (for 2km fiber)

TX_BW=18GHz,TX LPF Model=BT4,TX SNR=31.5dB, TX RJ=400fs RMS , RIN=-145dB/Hz

NEP=13pA/sqrt(Hz), Shot noise is included, Responsivity=.85 A/W

RX_BW=21.5GHz, RX LPF Model=BT4, RX RJ=300fs RMS

RX SNR=34dB, RX ISI canceller is on

Effective AWGN-Like SNR: **PAM8-Native : 25.64dB @ 33.46Gs/s(-.86dB from Target)**

PAM16-MLC : 26.5dB @ 28.05Gs/s(on the target)

OTN mode:

OMA Power=1dBm, ER=8dB, Channel Loss=4dB (for 2km fiber)

TX_BW=18GHz,TX LPF Model=BT4,TX SNR=33.2dB, TX RJ=400fs RMS , RIN=-145dB/Hz

NEP=13pA/sqrt(Hz), Shot noise is included, Responsivity=.85 A/W

RX_BW=21.5GHz, RX LPF Model=BT4, RX RJ=300fs RMS

RX SNR=34dB, RX ISI canceller is on

Effective AWGN-Like SNR: **PAM8-Native : 25.25 @ 37.27Gs/s(1.25dB from Target)**

PAM16-MLC : 26.5 @ 31.23Gs/s(on the target)

Test case

Example settings to make the PAM16-MLC work

Ethernet mode:

OMA Power=1dBm, ER=8dB, Channel Loss=4dB (for 2km fiber)

TX_BW=20GHz,TX LPF Model=BT4,TX SNR=30.9dB, TX RJ=300fs RMS , RIN=-148dB/Hz

NEP=13pA/sqrt(Hz), Shot noise is included, Responsivity=.85 A/W

RX_BW=21.5GHz, RX LPF Model=BT4, RX RJ=300fs RMS

RX SNR=34dB, RX ISI canceller is on

Effective AWGN-Like SNR: **PAM8-Native : 26.54dB @ 33.46Gs/s(on the target)**

PAM16-MLC : 27.35dB @ 28.05Gs/s(+0.85 above the target)

OTN mode:

OMA Power=1dBm, ER=8dB, Channel Loss=4dB (for 2km fiber)

TX_BW=20GHz,TX LPF Model=BT4,TX SNR=32.6dB, TX RJ=300fs RMS , RIN=-148dB/Hz

NEP=13pA/sqrt(Hz), Shot noise is included, Responsivity=.85 A/W

RX_BW=21.5GHz, RX LPF Model=BT4, RX RJ=300fs RMS

RX SNR=34dB, RX ISI canceller is on

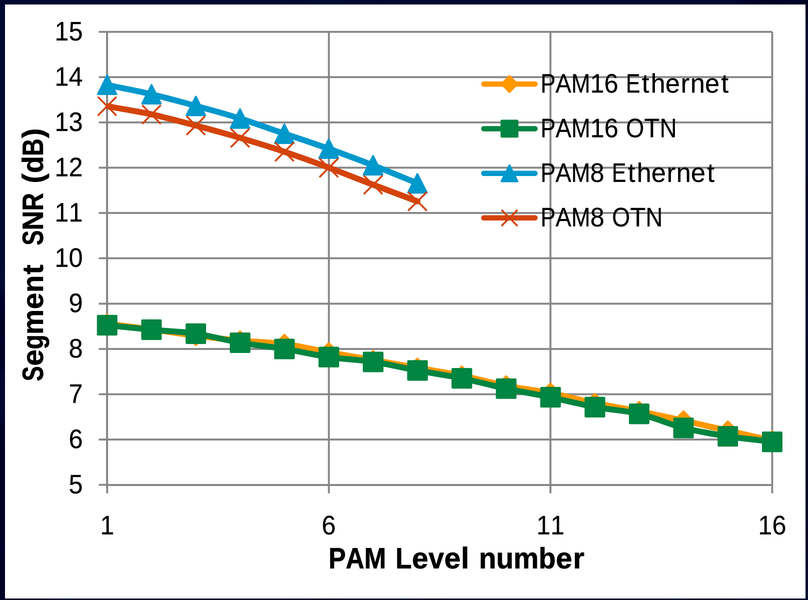
Effective AWGN-Like SNR: **PAM8-Native : 25.25 @ 37.27Gs/s(on the target)**

PAM16-MLC : 27.07 @ 31.23Gs/s(+0.57 above the target)

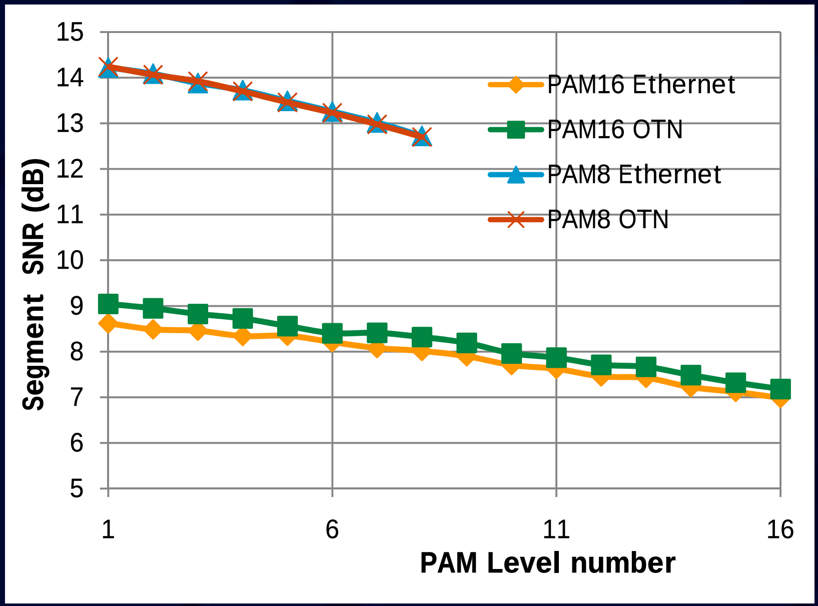
Test Case

Simulation results showing Per segment SNR

PAM16 condition



PAM8 condition



- The segment SNR curves are not flat because RIN and Shot noise are amplitude modulated.

Test Case

Break down of major noise components of PAM16 Ethernet corner

OMA Power=1dBm, ER=8dB, Channel Loss=4dB (for 2km fiber)

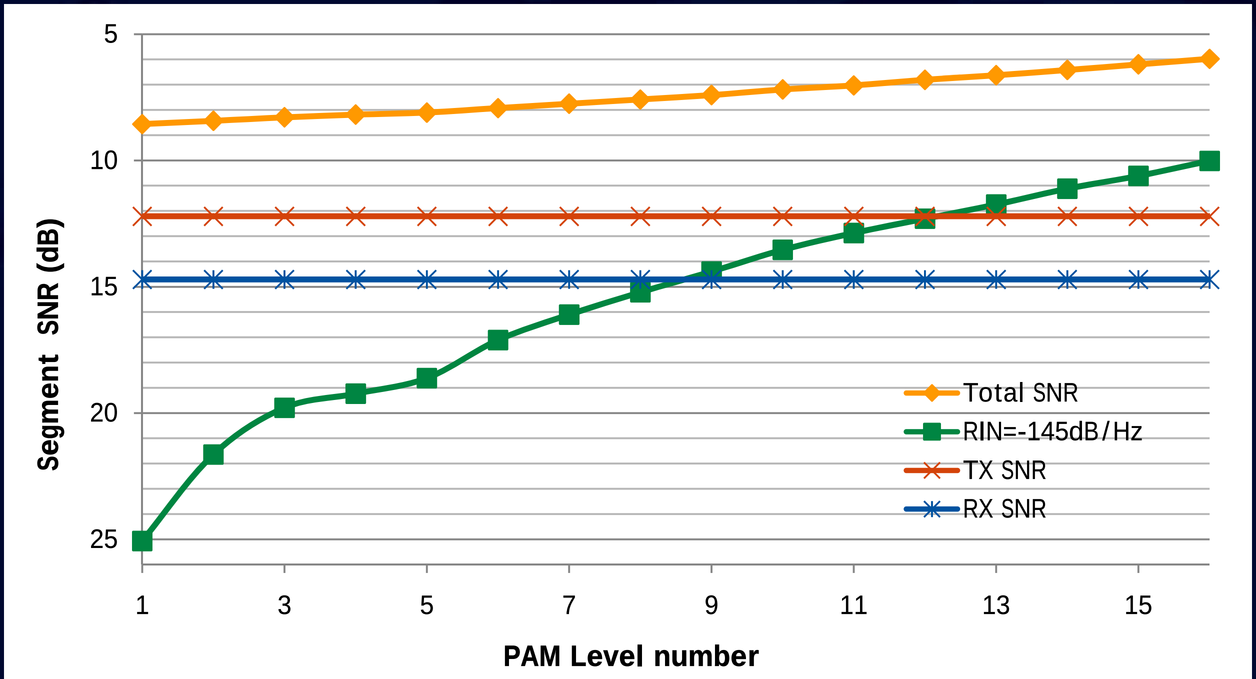
TX_BW=18GHz,TX LPF Model=BT4,TX SNR=31.5dB, TX RJ=400fs RMS , RIN=-145dB/Hz

NEP=13pA/sqrt(Hz), Shot noise is included, Responsivity=.85 A/W

RX_BW=21.5GHz, RX LPF Model=BT4, RX RJ=300fs RMS

RX SNR=34dB, RX ISI canceller is on

Effective AWGN-Like SNR: 26.5dB @ 28.05Gs/s



PAM16 system design target

- Other coding/mapping techniques (than MLC) are available that maybe more favorable to hardware latency/complexity/power.
- Our objective is that the proposed PAM16 system should meet the following targets

	Min	Max	Compare to PAM8 native
SNR	26.5dB	27dB	26.5dB
Slicer SNR margin	1dB	1.3dB	1.2dB
Link budget	4dB	4dB	4dB
Baud rate	31.2GHz	32GHz	37GHz
Latency	250ns	500ns	100ns

Summary

- We analyzed multiple PAM options from channel capacity perspective for both Ethernet mode and OTN mode
- Native PAM system (ie PAM+100G Base KR4 FEC) were compared with enhanced PAM16 systems that use advanced coding/mapping
- We have a high degree of confidence that robust PAM8/16 operation is achievable using advanced modulation and coding/mapping techniques