Use of Higher Order Modulation to Achieve Single Wavelength 100Gbit/s Links For Data Center Applications

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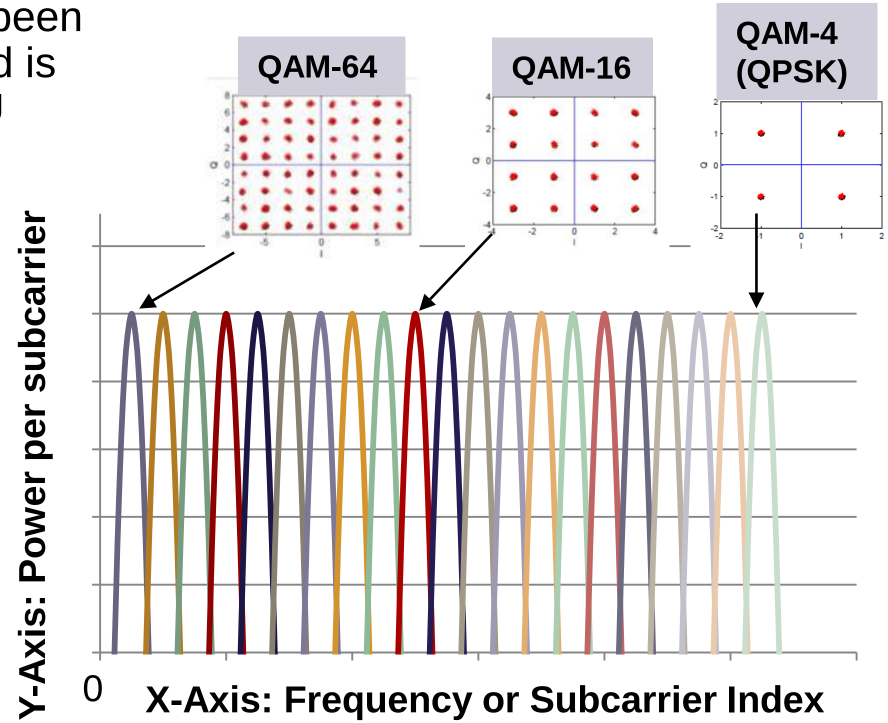
Agenda

- We will present experimental data on the application of Discrete Multi-Tone higher order modulation to achieve data rates of 100Gb/s on a single wavelength for data center applications.
- Results will be presented for both 1310nm and 1550nm transmission to support both intra and inter data center links.
- The impact of OSNR, dispersion and bandwidth on the resulting transmission performance will be discussed

Discrete Multi-Tone (DMT): Introduction

- DMT transports data using a set of orthogonal intensity-modulated subcarriers, each subcarrier is encoded with data using QAM modulation
- Transmitted data is broken up into discrete symbols separated by a cyclic prefix
- Size of the QAM constellation and the number of bits per symbol carried by each subcarrier can be adjusted based on the subcarrier's SNR
- By allowing a flexible modulation complexity on each of the uniformly spaced subcarriers within the available spectrum, DMT can compensate for many link impairments and achieve the best overall use of the available signal channel bandwidth and SNR
- DMT is a mature technology that has been used in DSL for over two decades, and is standardized for this application in ITU G.992.1



DMT Protocol Implementation

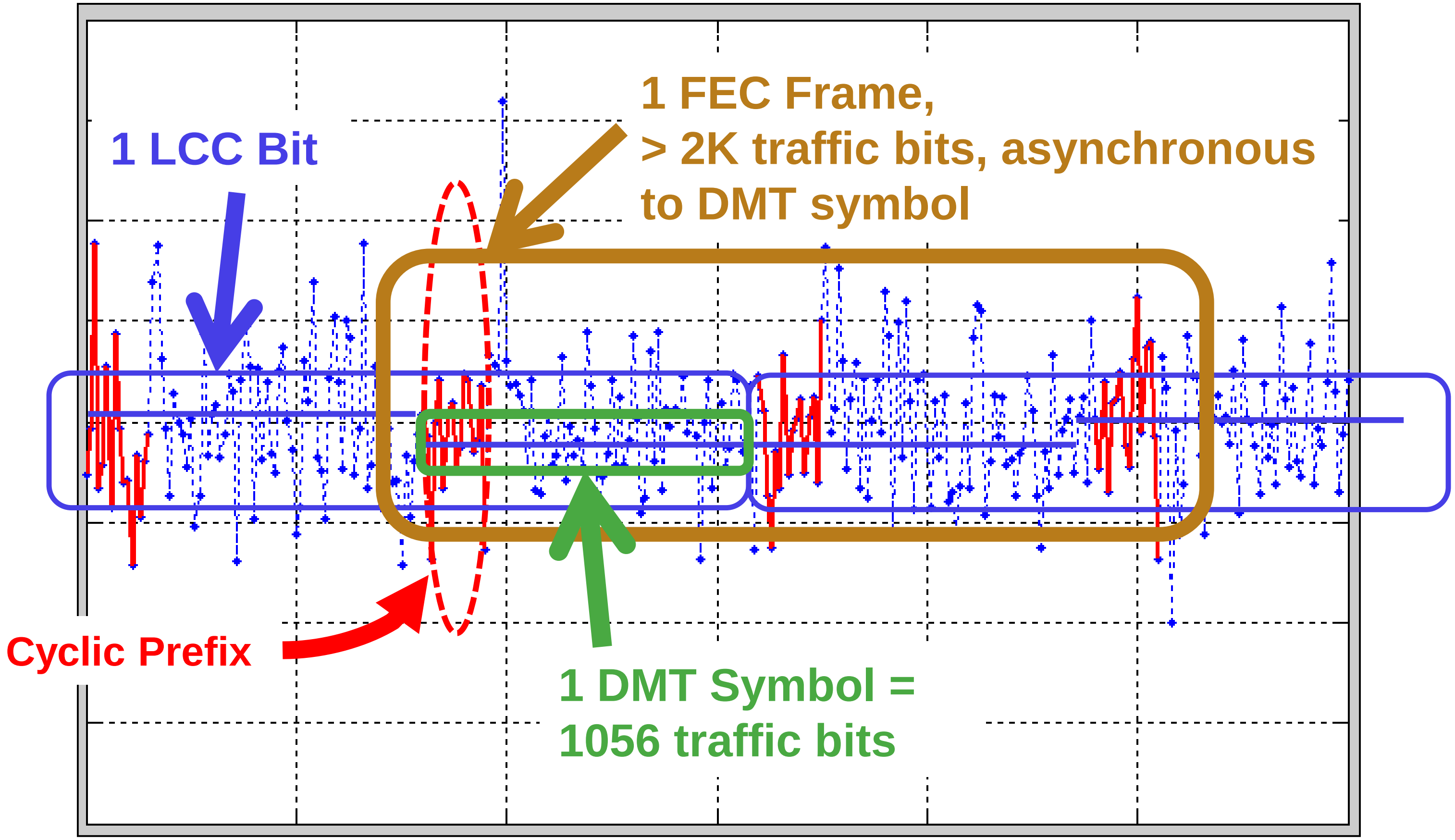
- DMT is very flexible which presents a wide number of options for implementing the protocol to achieve 100Gb/s transmission on a single wavelength
  - Options include number of subcarriers, signal BW, FEC overhead and cyclic prefix length
  - Choice of 256 subcarriers enables use of 512 point iFFT/FFT balances power and latency with flexibility
  - 2 adjacent subcarrier tones are dedicated for DMT-Symbol frame-synchronization
  - Two FEC Options
    - FEC 1: BCH (2288, 2048) + 16 Frame marker – 12.5% OH
    - FEC 2: BCH (9193, 8192) + 16 Frame marker + 7 bit pad – 12.5% OH
  - Short Cyclic-Prefix is appended to each symbol (16 samples) to prevent ISI penalties
  - A baseband LCC is provided for link parameter negotiation

DMT Protocol Table for single λ 100GE

100G Lane Bit-Rate	B_R	103.1250 + 12.5% = 116.0156 Gbit/s
Sample Rate	$F_S = B_R / 2$	58.0078 GS/s
Number of Subcarriers	$N_{FFT}/2$	256
Subcarrier spacing	ΔF	113.2965 MHz
Highest subcarrier	$F_S / 2$	29.0039 GHz
Cyclic Prefix Length	CP	16
#samps / DMT-symbol	$N_{FFT} + CP$	528
Symbol (Frame) Rate	$F_F = F_S / (N_{FFT} + CP)$	109.8633 MHz
# Bits/DMT-Symbol	$b_F = B_R / F_F$	1056

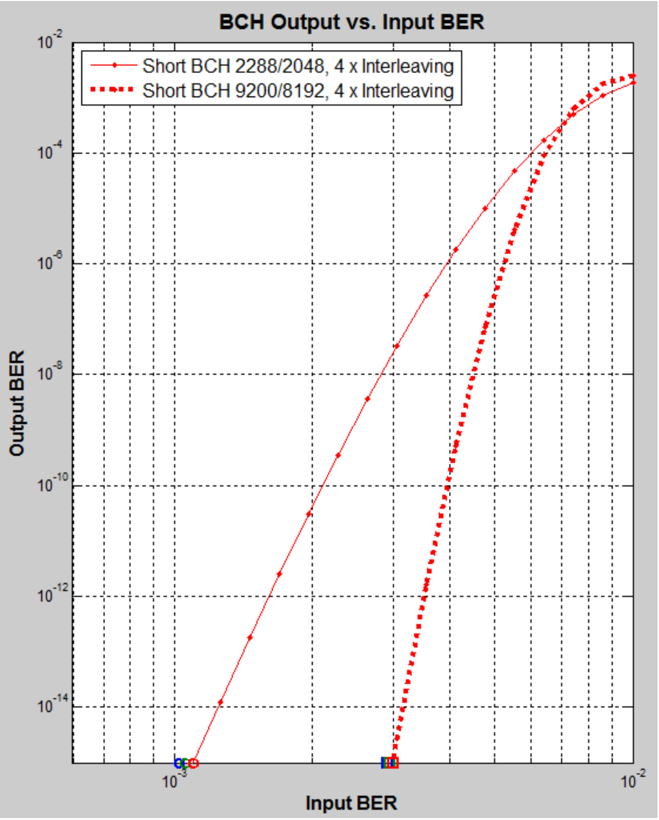
DMT Transmission Frames

- By design, FEC and DMT frames are completely asynchronous to client protocol frames.
  - Ensures transparency to protocols.
- The chart below illustrates the DMT frame and its proposed components.
  - Scale is exaggerated (Cyclic Prefix, LCC amplitude) for better viewing.



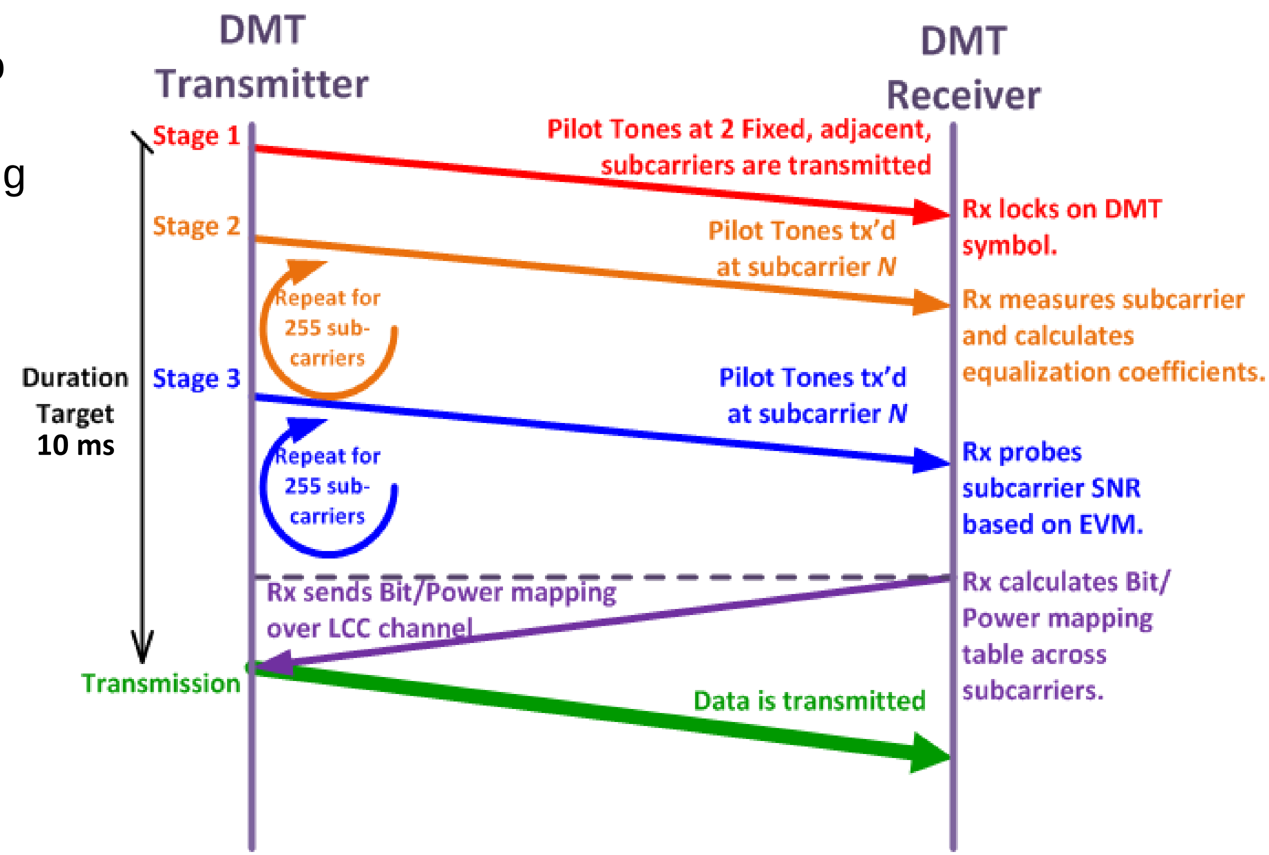
DMT Implementation FEC

- 100G DMT solution includes a low latency FEC to achieve target BER <= 1E-15
- To facilitate standardization and achieve low latency a short word length BCH based FEC approach is recommended
- Two options being considered
  - BCH (2288,2048) Pre-FEC BER = 1.2E-3, Net coding gain = 7.8 dB
  - BCH (9193, 8192) Pre-FEC BER = 3.3E-3, Net coding gain = 8.7 dB
  - Overhead rate is 12.5% including frame-marker:
  - Interleaving over multiple DMT frames employed to improve tolerance to burst-errors associated with signal clipping and other impairments
  - FEC frame is on same order as DMT-symbol, in terms of bit-length, so correction is achieved after small finite number of DMT-symbols. Note that FEC frame is asynchronous with DMT symbol
- Solution is protocol agnostic and can support 100GE, OTU4 or proprietary data
- FEC can be bypassed for applications where the host data already has strong FEC



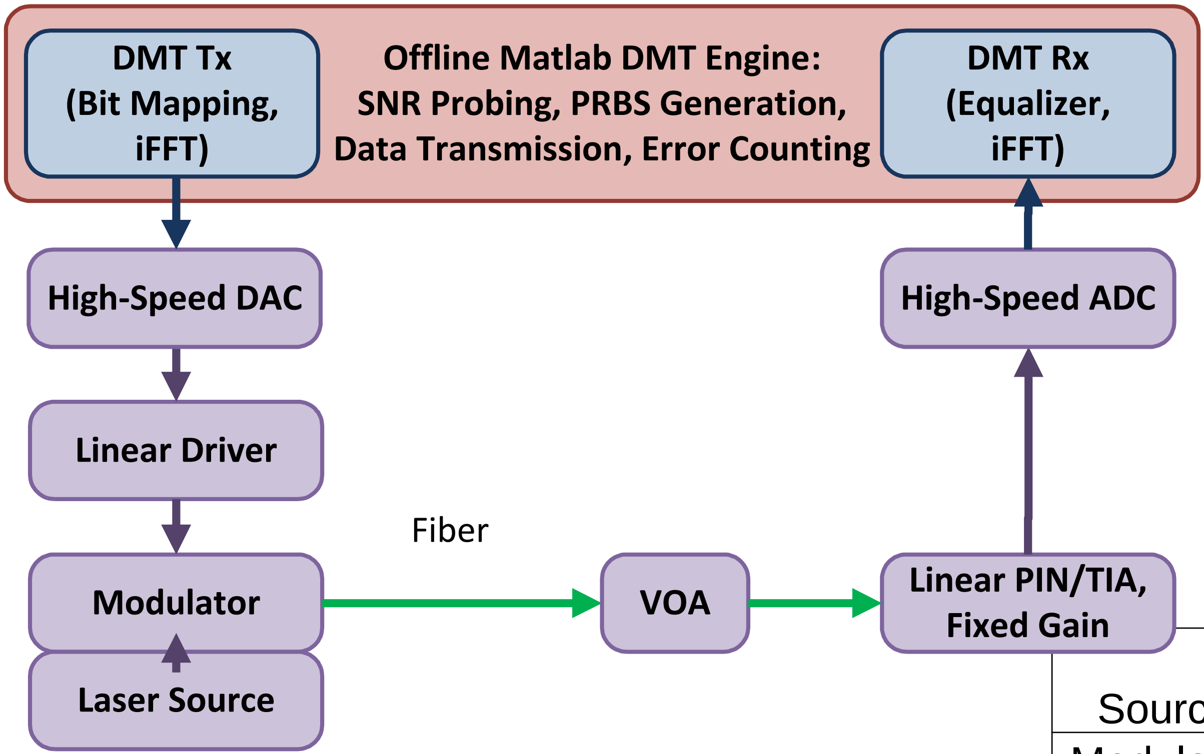
DMT Link Communication Channel and Negotiation

- DMT requires bi-directional overhead communication to enable negotiation and adaptive features: Link Communication Channel (LCC)
- Out-of-band LCC proposal is robust.
- Link negotiation: 3-step process.
- Relies on LCC for final bit/power mapping.
- Non-disruptive after link negotiation is complete (no need to repeat).
- Continuous EVM monitoring and LCC protocol allow for non traffic-affecting bit-swapping between sub-carriers, to optimize performance.



Transmission Experiments for Intra Data Center Links <2Km

Experimental Test Bed



Source	1310nm EML or 1550nm ITLA
Modulator	MZM, 30 GHz BW
Driver	27 GHz BW
PIN/TIA	30 GHz BW, 500 Ohm, 18 pA/rt-Hz
DAC	8-bits, 16 GHz BW, 56 - 64 GHz
ADC	8-bits, 19 GHz BW, 56 - 64 GHz

- *In order to reflect real-world implementation, following test-results all include:*
  - *Dedicated adjacent tones at sub-carriers 64 & 65 for symbol-synchronization purposes.*
  - *Manchester-encoded link-communication channel carrying PRBS traffic.*
  - *No signal grooming (non-linear compensation) is performed.*
- *Data rate is 126 Gbit/s unless otherwise stated.*

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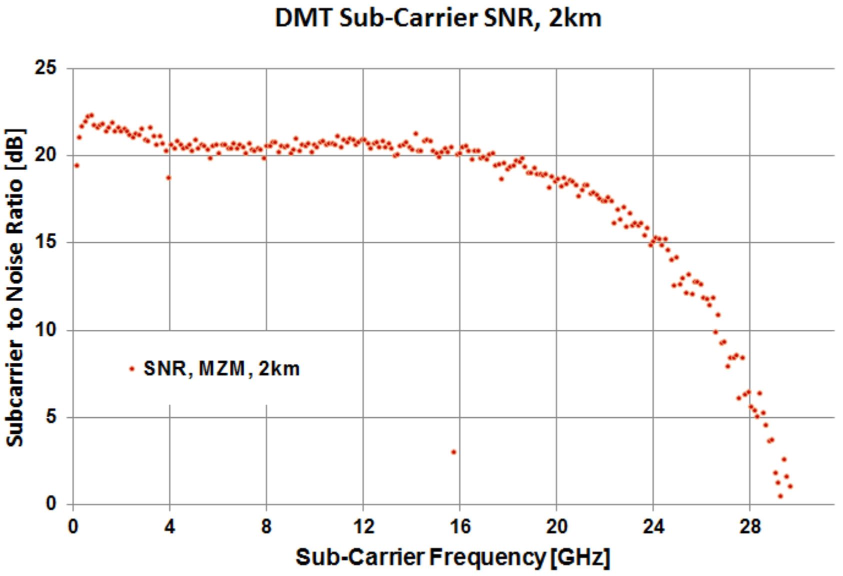
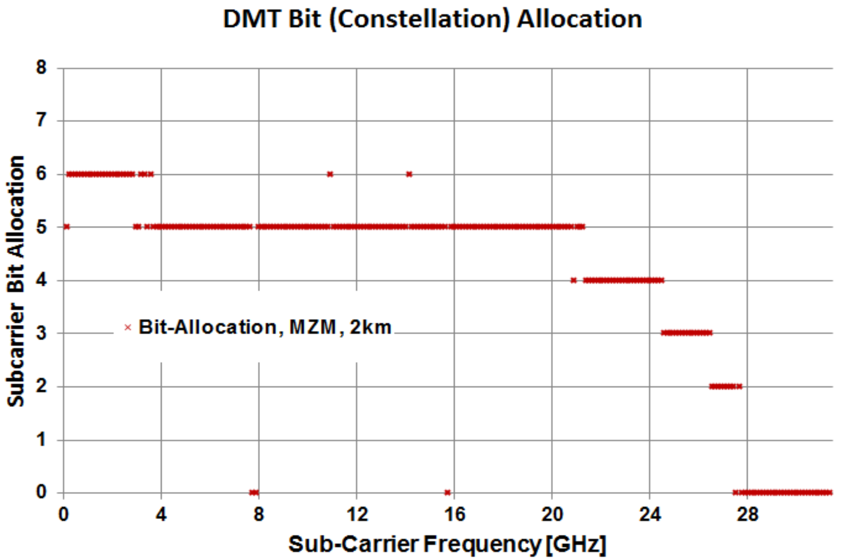
DMT Bit to Sub-Carrier Mapping

- During link initialization, DMT Tx probes path with pre-determined tones on each sub-carrier.
- DMT Rx measures sub-carrier constellation and compares it with expected response: SNR is calculated by DSP per sub-carrier from Error Vector Magnitude (EVM).
- Algorithm allocates bits per sub-carrier based on SNR distribution.

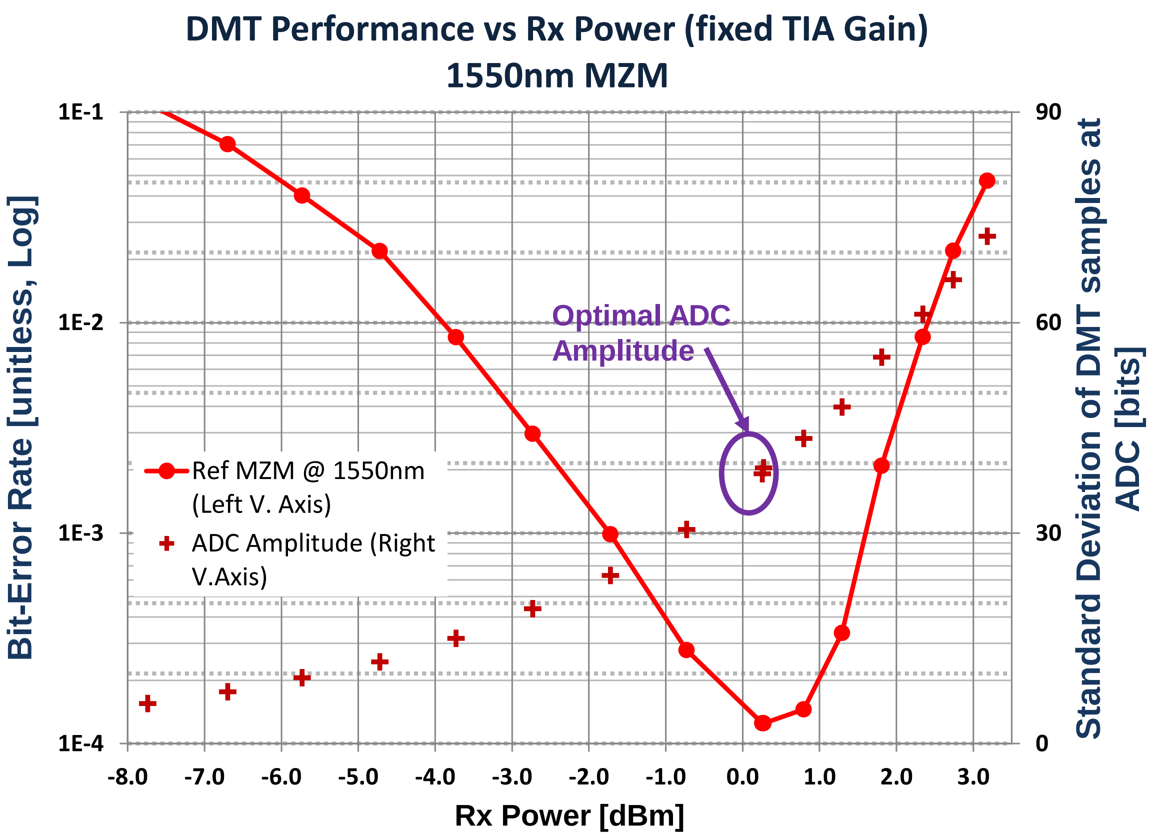
- SNR and bit-allocations to right illustrate spectra for MZM @ 1550 nm over 2km of fiber.
  - Data-Rate = 126 Gbit/s
  - Sampling-Rate = 63 GS/s





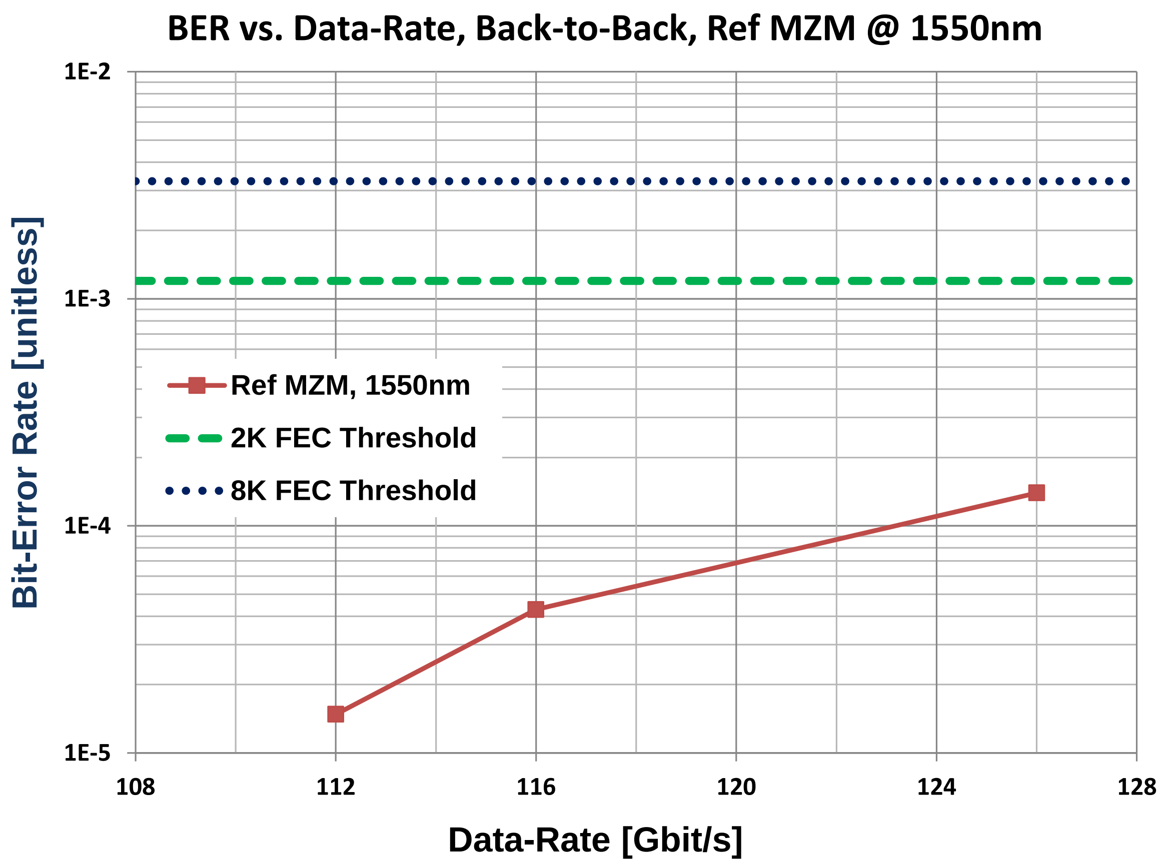
Experimental Results ADC Amplitude

- Receiver input power was swept for results shown here, in a B2B configuration.
- Since testbed PIN/TIA has fixed gain, results reflect BER vs. ADC-amplitude rather than sensitivity performance:
  - The DAC clips in order to reduce the peak-to-average power ratio
  - Rx should control ADC input amplitude to optimize dynamic range but not introduce further clipping
- Left part of curve dominated by thermal noise and underfilling the ADC
- Right part dominated by saturation and additional clipping at ADC
- Dynamic range at BER threshold is ~ 4 dB
- A linear TIA with variable gain will significantly broaden the dynamic range



Experimental Results Performance vs Bit-Rate

- For each wavelength, expected line-rates are 112, 116 &126 Gb/s.
- DMT performance tested in B2B conditions over this range using Reference 1550 MZM.
- Expected FEC thresholds shown for comparison,
  - Sampling rate = 63 GS/s, no signal grooming
    - Linearity compensation or equalization



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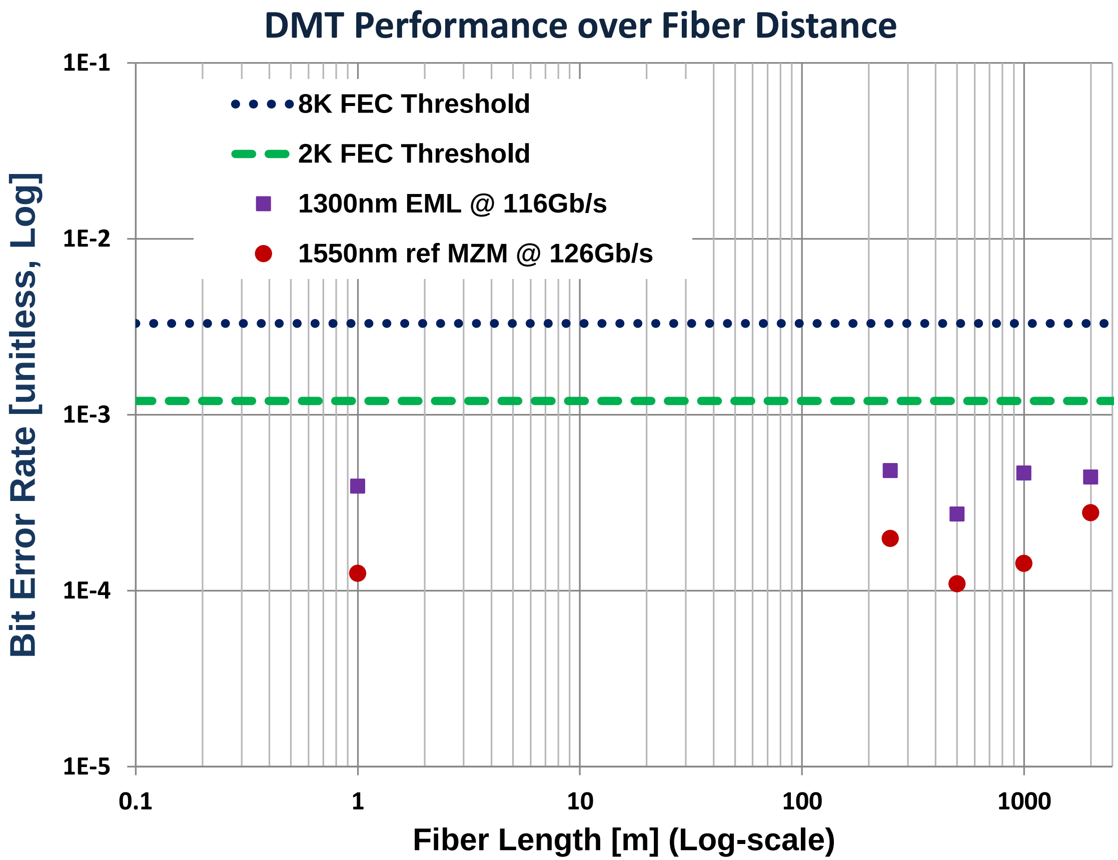
Experimental Results Performance over Fiber

- Fiber distance explored:
  - At 116 Gbit/s with existing 100G LR4 EML, and
  - At 126 Gbit/s with Reference 1550 MZM transmitter.
  - No signal grooming or dispersion compensation in these results.
- Low-RIN EML development expected to equal reference MZM in DMT performance.
  - Less significant dispersion penalty trades-off less linearity.



Summary of Intra Data Center Test Results

- Initial results show promising performance for 2km transmission with DMT using conventional 25G BW 1310nm EML technology and PIN PD receiver
- No significant transmission penalties observed over the 2km span for 1310nm or 1550nm tests
- Performance is sensitive to data rate and laser RIN performance
  - May make a lower overhead FEC option more attractive, key tradeoff is latency
- Linear variable gain TIA will be required for increased dynamic range in the receiver
- Low RIN < -145dB/Hz transmit laser preferred for best performance

DWDM Transmission Experiments for Inter Data Center Links <80km

Inter Data Center Links

- DMT has the capability to support low cost Non-Coherent 100G DWDM links for Data Center Interconnect
- Goal 10 TB/s per fiber, cost << coherent solutions
- Power and size compatible with existing client side pluggable form factors
- Assumptions
  - Link will have chromatic dispersion compensation
  - Link will have optical amplification
- Implementation test
  - Single channel DMT solution running at 100Gb/s per channel
  - Channel spacing 50GHz
  - Maximum link capacity 96 channels at 103.125 Gb/s = 9.9 Tb/s
  - Tests use fixed grid 100G AWG + 50G Interleaver mux/demux solutions
  - Requires high gain FEC solution to meet OSNR budget

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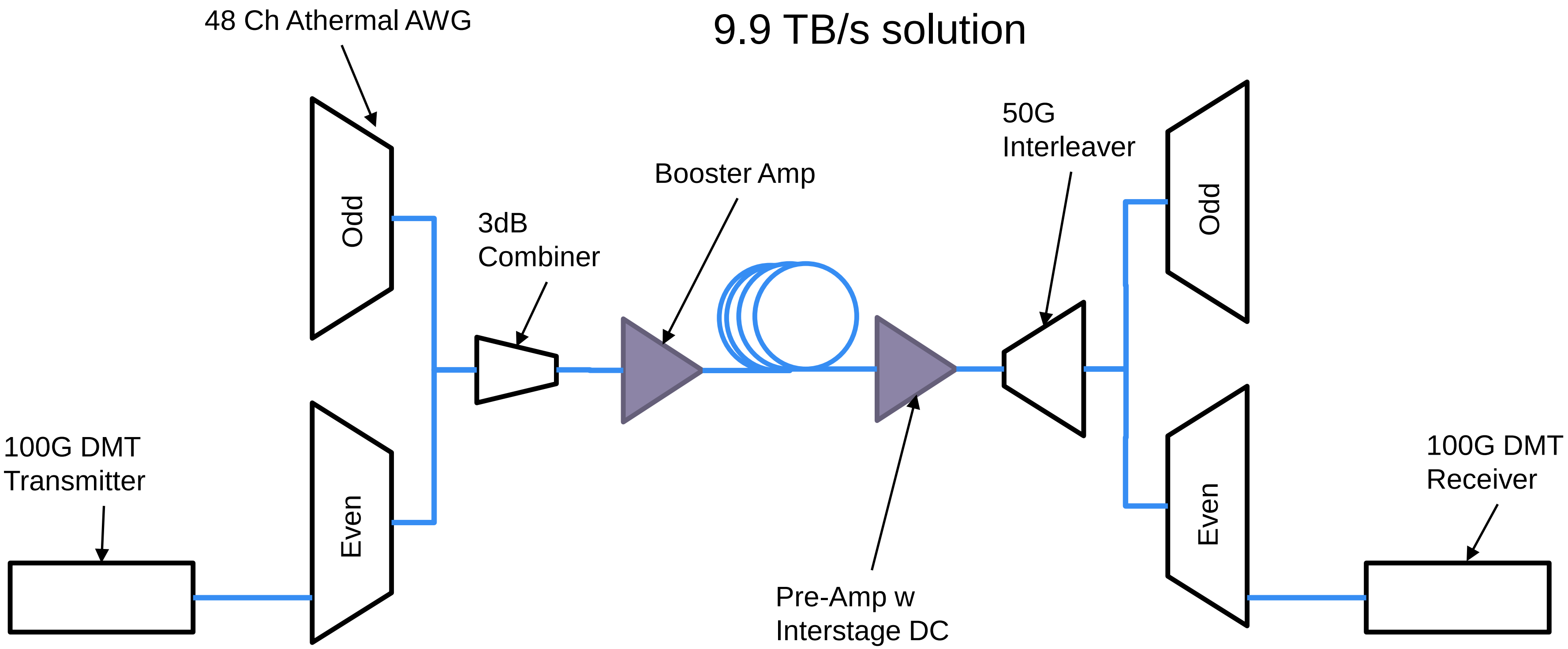
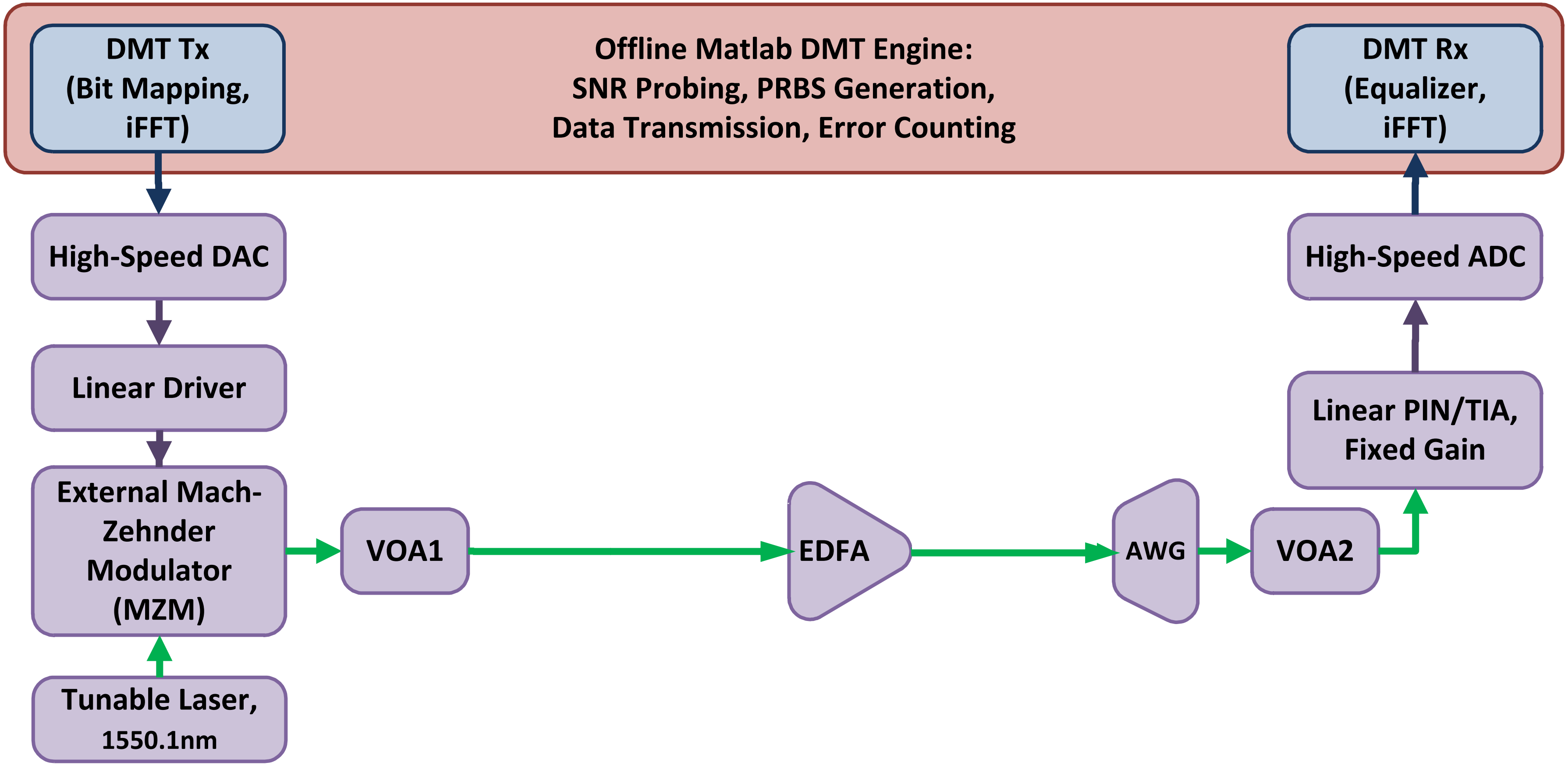
Link Configuration DMT 96 Channels 100G / ch 50G Grid



- Proposed link setup for 100G single lambda
- Uses athermal 48 channel even and odd AWG
- 50G interleaver and or 3dB combiner on transmit side

DCI OSNR Investigation: Configurations

- DMT transmission performance was investigated using the test bed setup shown here.
  - Experiments were done with 0, 1 and 2 interleavers



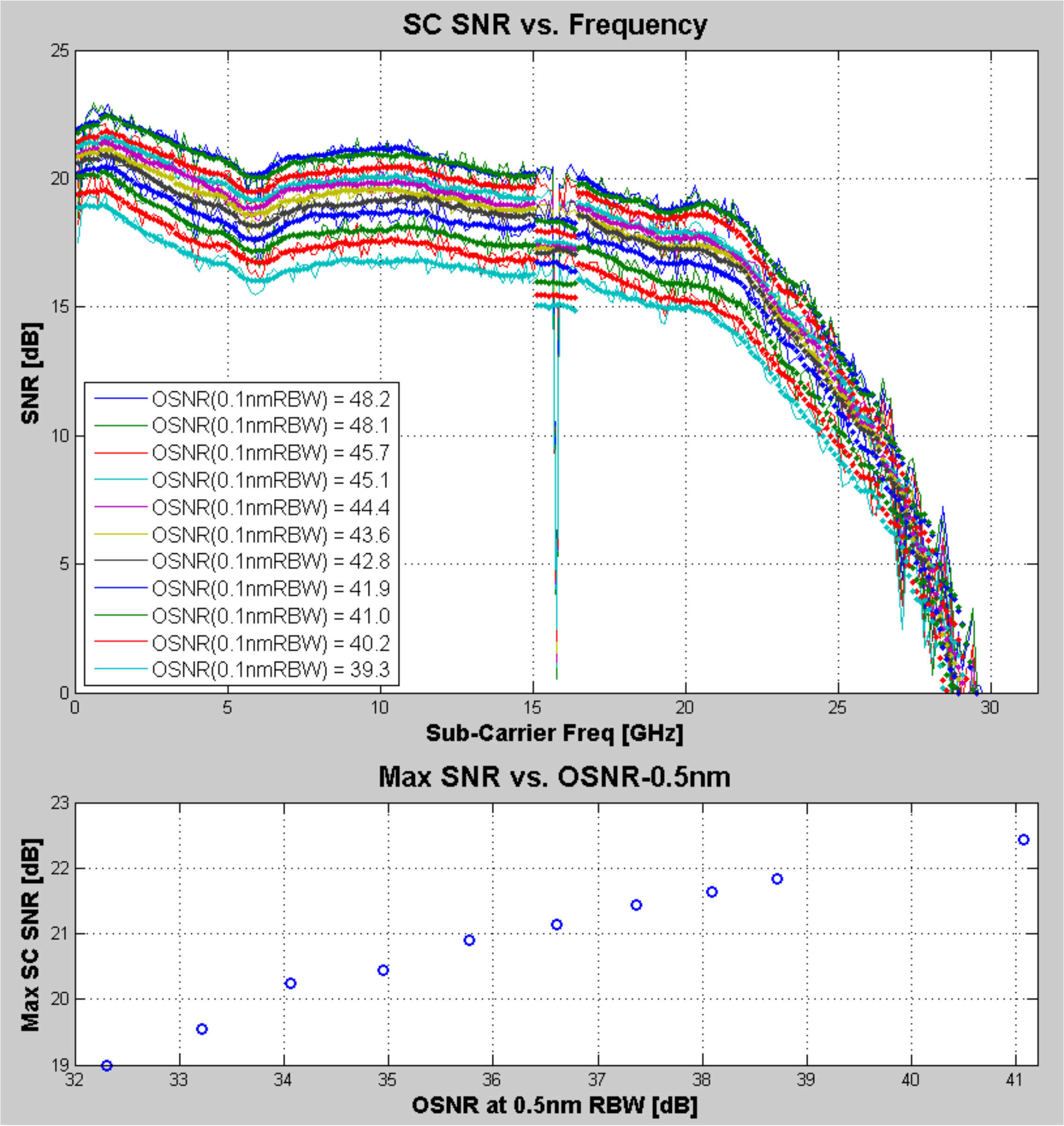
DCI OSNR Investigation: Test parameters

Parameter	Setting
Sample-Rate	63 GHz (Fixed)
Bit-Rate	116 Gb/s (100GE + 12.5% Overhead)
Cyclic-Prefix	16
Wavelength	1550.15 nm (on Odd 50GHz Grid)
RIN	Better than -150 dB/Hz
Rx Optical Power	0.8 dBm (maintained by VOA2)
OSNR	0.1nm RBW, meas at +/- 50GHz*
DeMux	Athermal AWG, off-grid (odd channels), 5.8dB max loss
Interleavers	Athermal, 12.5dB max loss

- Drive-amplitude was optimized for best BER performance
- Sample-rate of 63GHz is 8.6% higher than target for final ASIC
- 2 Sub-carriers dedicated to DMT frame-synchronization, as per real implementation
- OSNR varied by changing attenuation on VOA 1.
- * Note that double-sided bandwidth of 63 GHz corresponds to ~0.5nm: OSNR RBW of 0.5nm would be more appropriate.

DCI OSNR Investigation: SNR

- OSNR degradation has visible effect on sub-carrier SNR.



- Note that DMT signal with 63GHz sampling-rate occupies ~0.5nm at 1550nm

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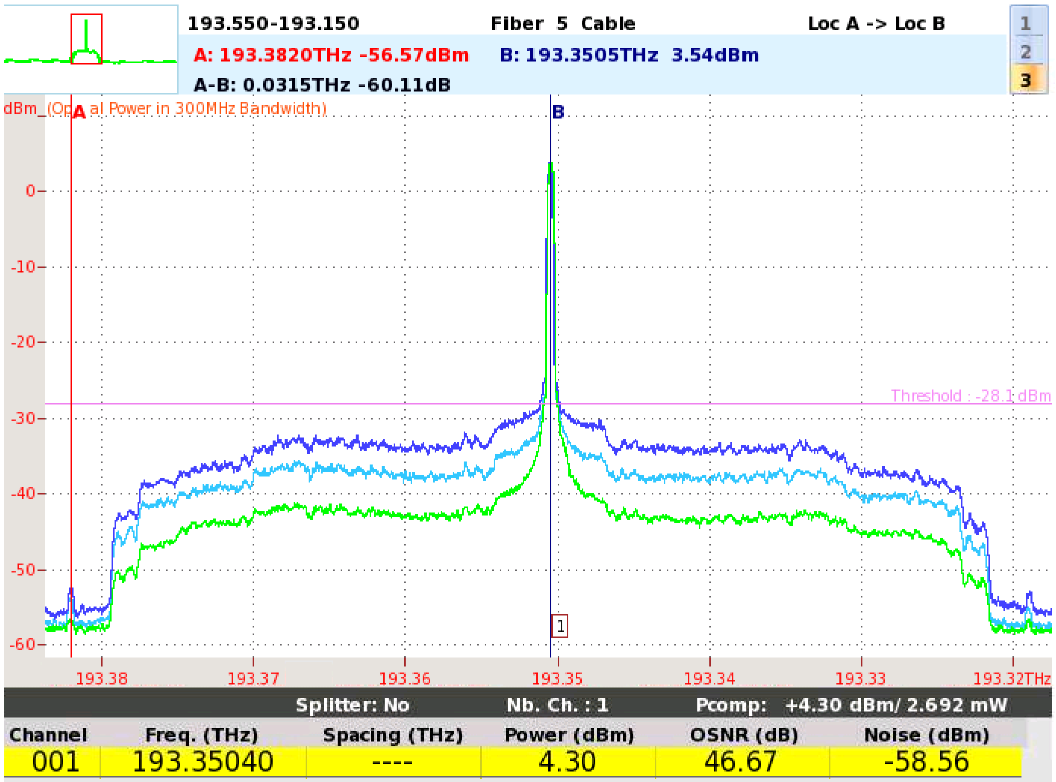
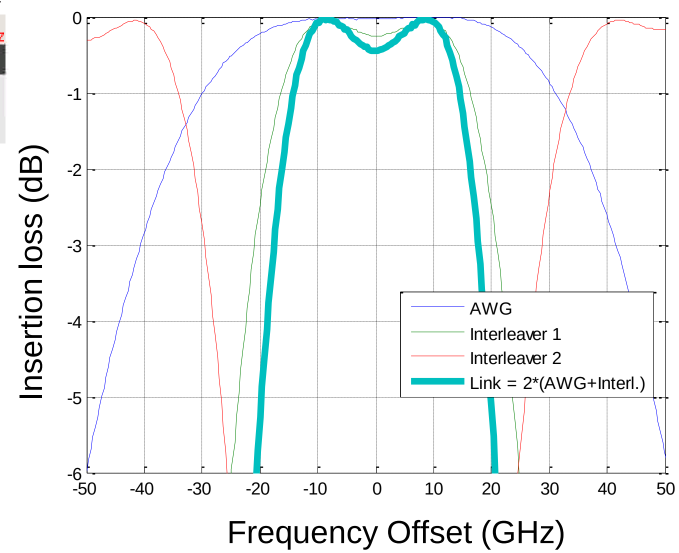
DCI Cascaded Filter BW Penalties

- Optical filtering has impact on available DMT bandwidth
- AWG bandwidth impact is negligible but interleaver BW has significant impact
- Two cascaded interleavers narrows optical bandwidth to ~36 GHz
- Configuration with single interleaver increases optical bandwidth to ~42GHz



DMT Signal Spectrum

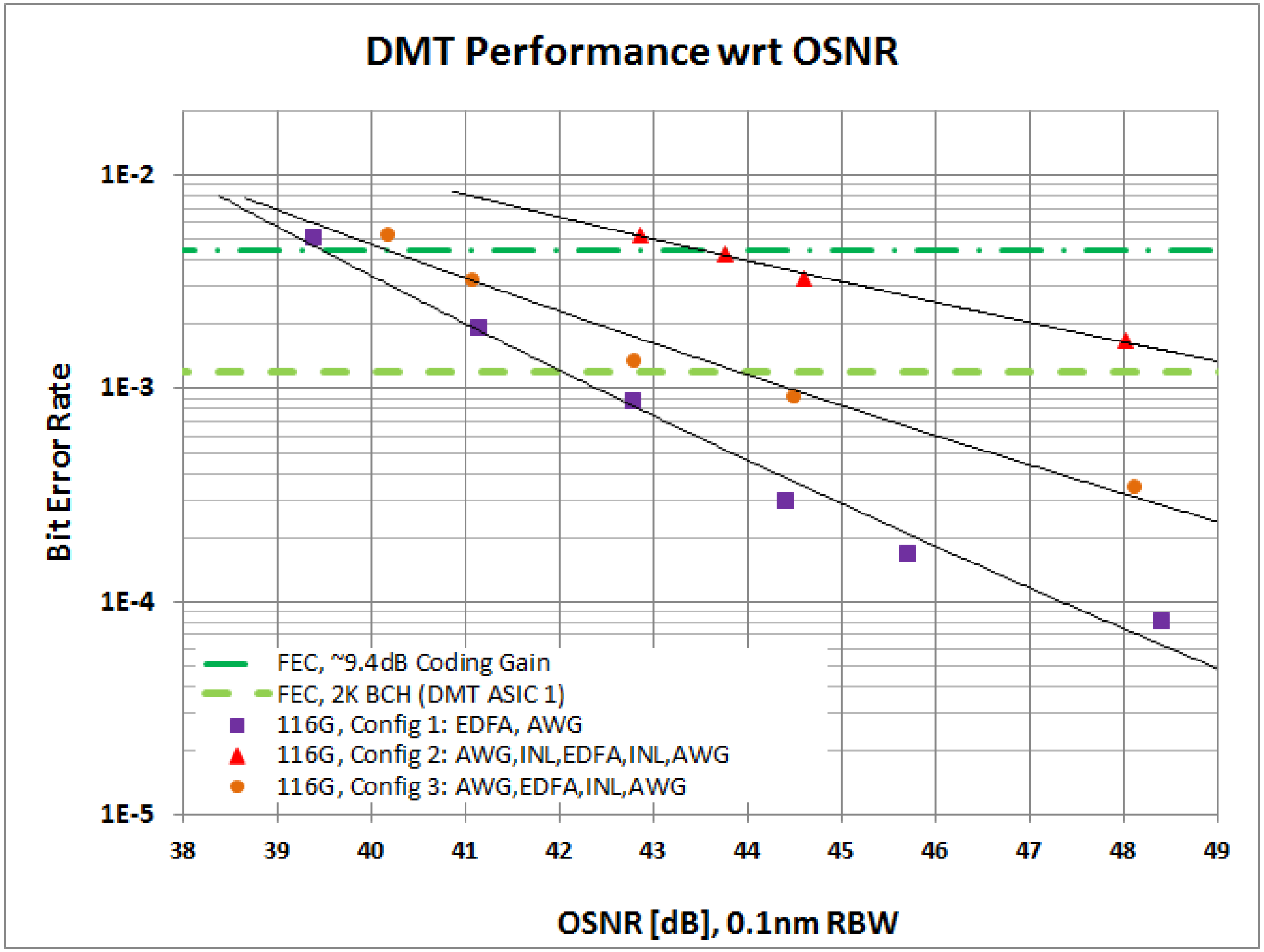
Cascaded Filter Spectrum ⇨



DCI OSNR Investigation: Results

- Measured DMT BER plotted below against OSNR (0.1nm RBW)
- Results measured on system test bed using offline processing and 28nm DAC/ADC test chips

- Baseline OSNR Performance
  - Need **39.5dB** OSNR for high-coding gain FEC.
- With original system
  Mux = AWG+Interleaver,
  Dmx = Interleaver + AWG
  - Need OSNR = ***43.5*** dB for high-coding gain FEC.
- With modified system
  Mux = AWG+3dB coupler
  Dmx = Interleaver + AWG
  - Need OSNR = **40.5 dB** for high-coding gain FEC.



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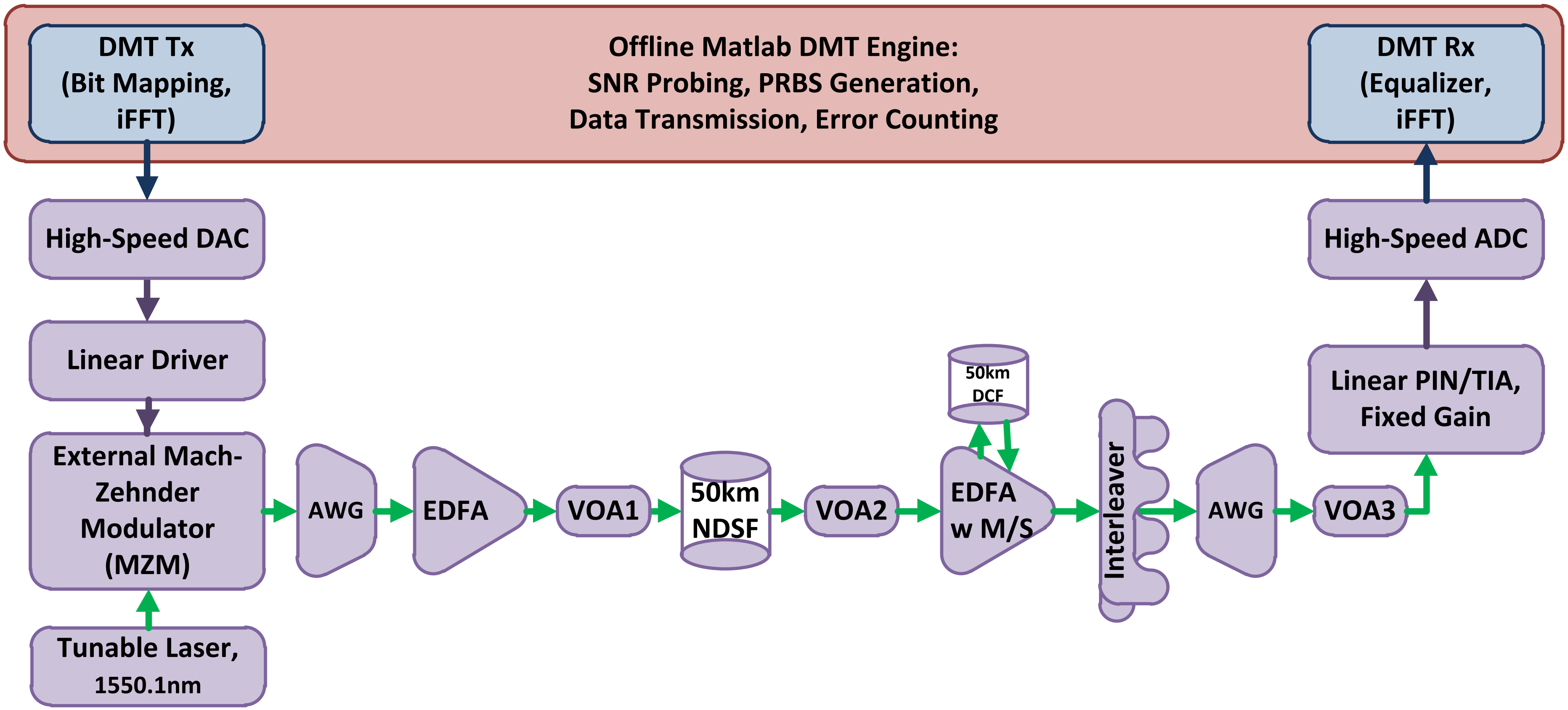
OSNR Investigation: Launch-Power

- Setup shown below used to control launch power into 50km G.652 fiber (NDSF) (@ VOA1)
- Fiber dispersion compensated at a Pre-Amp EDFA with mid-stage access.
  - DCF slope-matched to G.652, 95% compensation (~47 ps/nm or ~ 2.75km residual)
- VOA2 used to control OSNR. VOA3 used to maintain optimal ROP.



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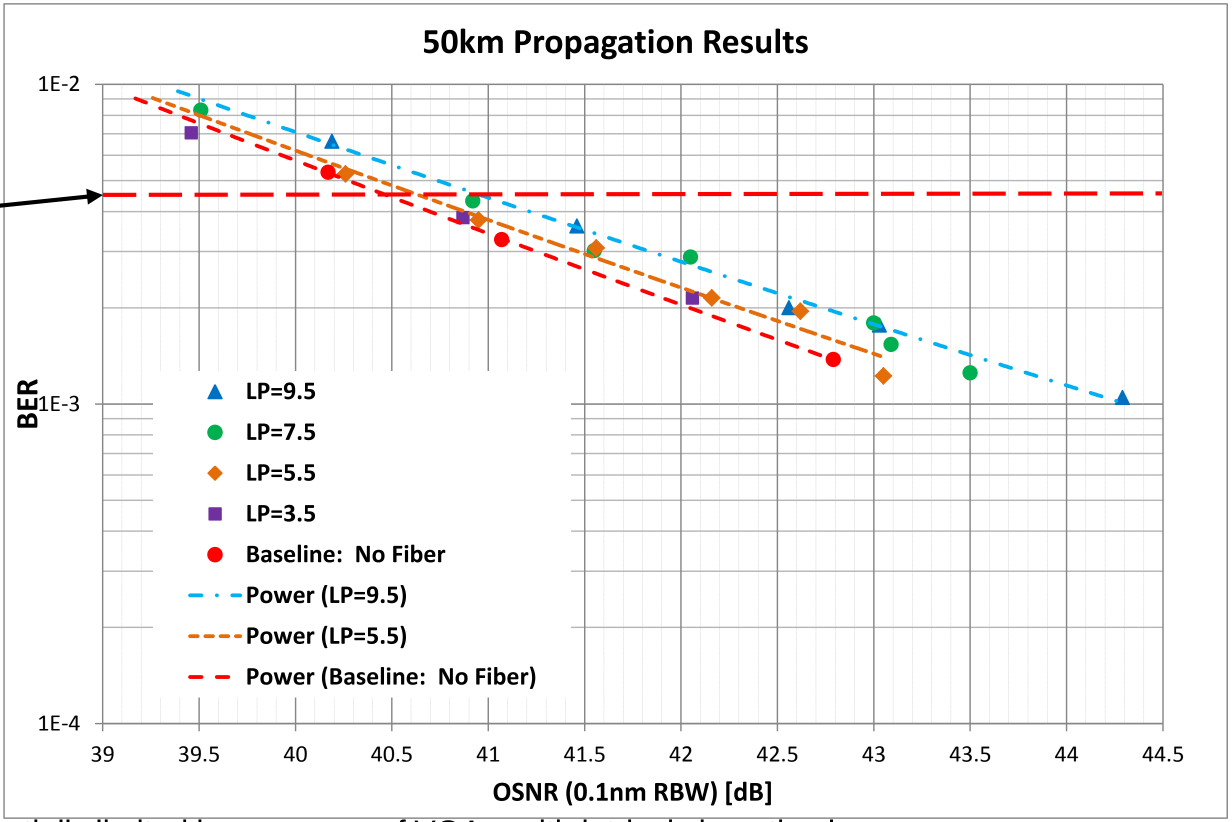
OSNR Investigation: Launch-Power

- Signs of non-linear effects were manifested.
  - SBS caused time-varying power fluctuations at Pre-Amp and downstream.
    - Mitigated by enabling linewidth-enhancing feature at tunable source.
    - Feature enabled for launch-powers > +9 dBm
  - Slight performance-degradation trend with launch-power was observed over measured range.

FEC Threshold



Note: experimental OSNRs in this setup partially limited by presence of VOAs, with intrinsic insertion loss.

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DCI OSNR Investigation: Summary

- Capability for longer reach DWDM transmission at 100G per wavelength demonstrated with DMT modulation – 50km reach demonstrated
- Tests based on use of a high gain FEC threshold ~4.5e-3 (~9.4 dB coding gain):
  - Need 40.5 dB OSNR (+ margin) with a *modified* system (only one interleaver (Rx), none at Tx)
- BW penalty from cascaded interleavers can be significant single demux interleaver proposed
  - Need to control signal spectrum at transmitter to minimize cross talk
- Amplified system considered below:
  - DMT performance investigated for higher launch power
  - SPM penalties are <0.5dB up to +9.5dBm launch powers for 50km link
  - Effects of XPM and adjacent channel cross talk need to be investigated
- For higher span loss systems co and counter propagating Raman will be needed to ensure margin to OSNR budget
- Baseline design indicates 16 to 18dB link budget can be supported Not including mux / demux losses
- Next steps are to look at dispersion tolerance, XPM and adjacent channel cross talk

Thank You