400G DMT PMD for 2km SMF

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Agenda

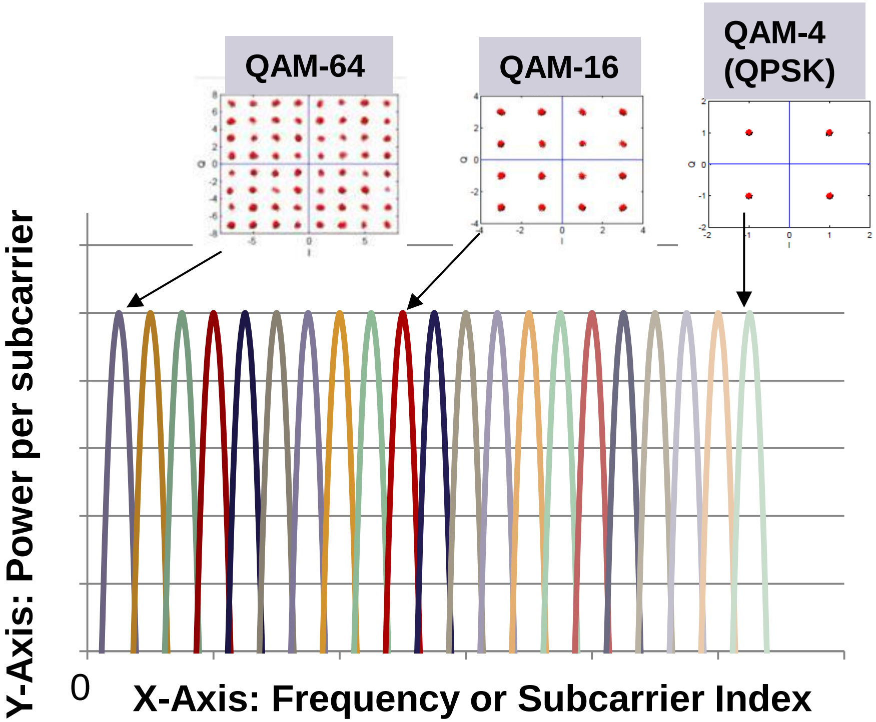
- Discrete Multitone Protocol Proposal for 2km Link Solution
- DMT Technology
- Proposed Link Budget
- Experimental Demonstration of DMT Transmission

Link Proposals For 2 and 10km

- For the 400G 2km and 10km link PMD’s we propose a solution based on four wavelengths with 100G capacity per wavelength transmitted using a Discrete Multi-Tone (DMT protocol)
- The proposal includes FEC as part of the pluggable module solution and not as part of the PCS
- The wavelength channels would be aligned to the LAN-WDM grid used in the 100GBASE-LR4 standard
  - Enables compatibility between 2 and 10km PMD standards
  - Reduces variation in dispersion over wavelength which can be up to 92ps/nm for a CWDM grid over 10km
  - Reduces variation in loss over wavelength which can be up to 0.4dB for a CWDM grid over 10km
- In this presentation we will focus on the 2km PMD solution and present experimental verification the approach
- The 10km PMD is proposed in isono_3bs_01_0514.pdf

Discrete Multi-Tone (DMT): Introduction

- DMT transports data using a set of orthogonal intensity-modulated subcarriers, each subcarrier is encoded with data using quadrature amplitude modulation (QAM)
- The transmitted data is broken up into discrete symbols separated by a cyclic prefix
- The size of the QAM constellation and thus the number of bits per symbol carried by each subcarrier is 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
- Transmit data mapped into the subcarriers in the frequency domain and combined into a time domain signal using iFFT and high speed DAC
- Receiver employs direct-detection followed by fast ADC to sample the transmitted symbols
- FFT converts the received symbol back into frequency domain where subcarrier amplitude and phase are mapped into received data
- 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 Details

- Design approach takes into consideration capabilities of A/D, D/A and FFT / iFFT technology
  - D/A and A/D sampling rates tied to bit-rate: simplifies DSP clocking architecture
  - Short Cyclic-Prefix is appended to each symbol (16 samples) prevents ISI penalties
  - 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

DMT Detail Table for each λ of 400GE

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

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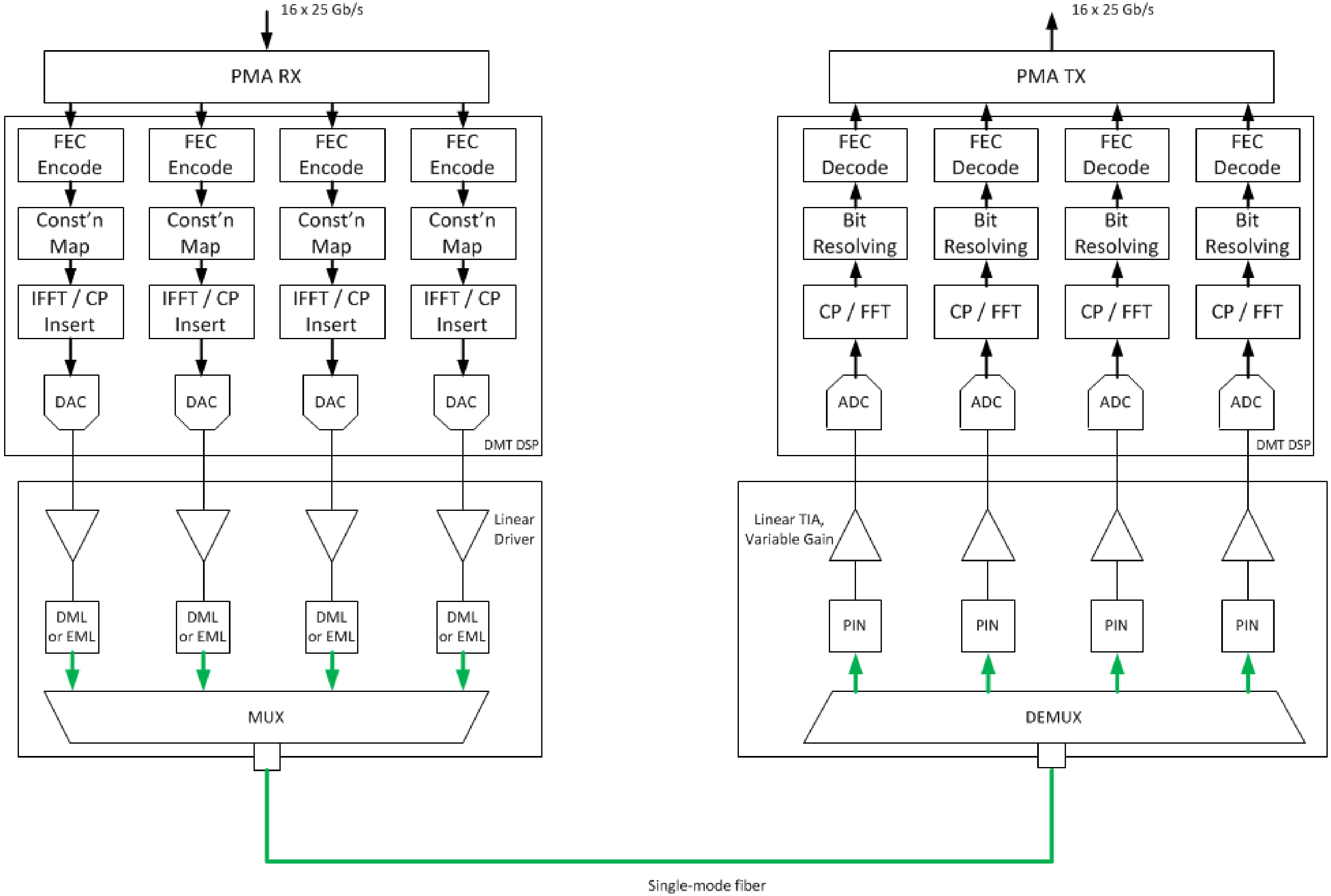
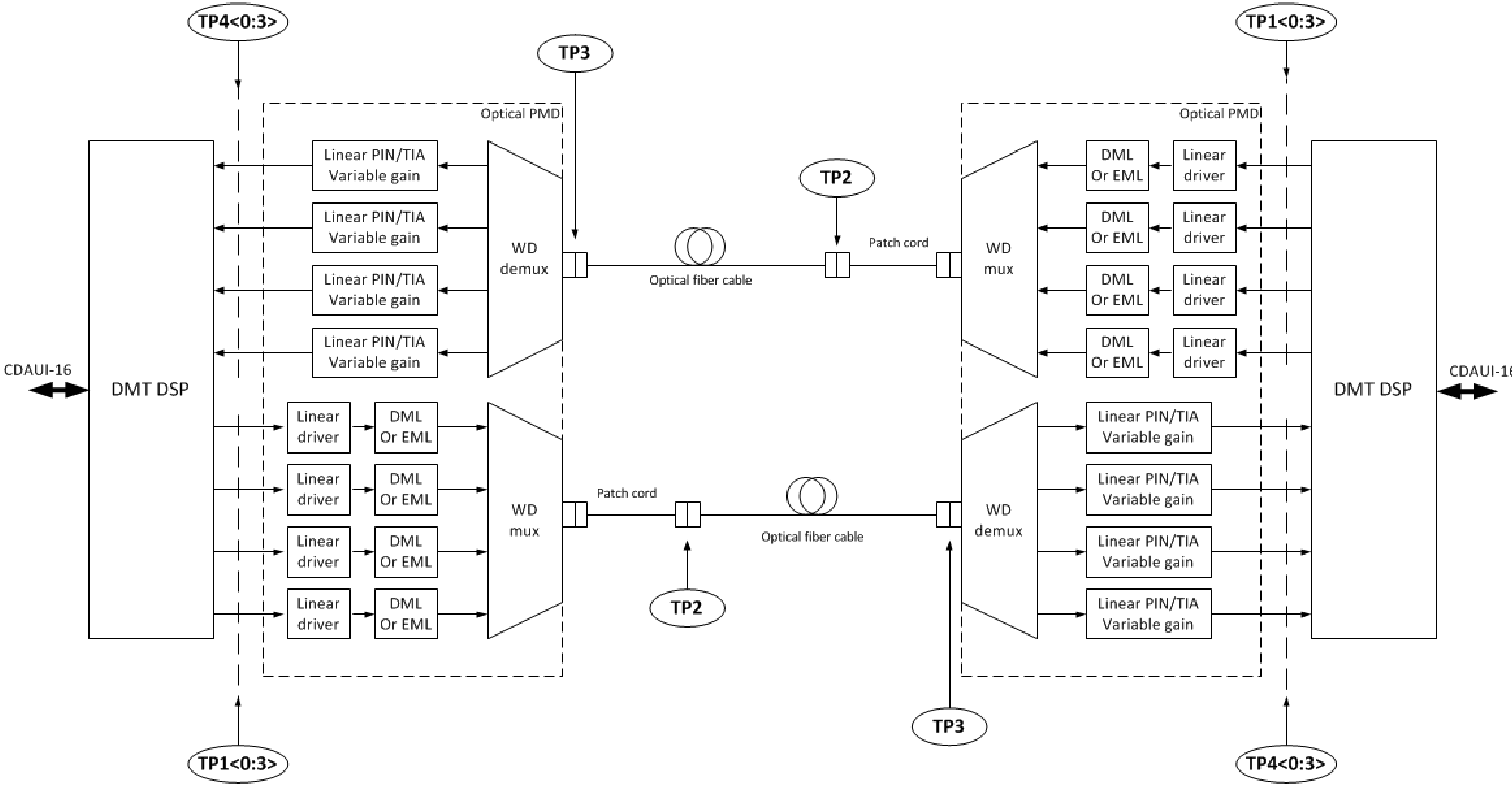
400G DMT Block Diagram

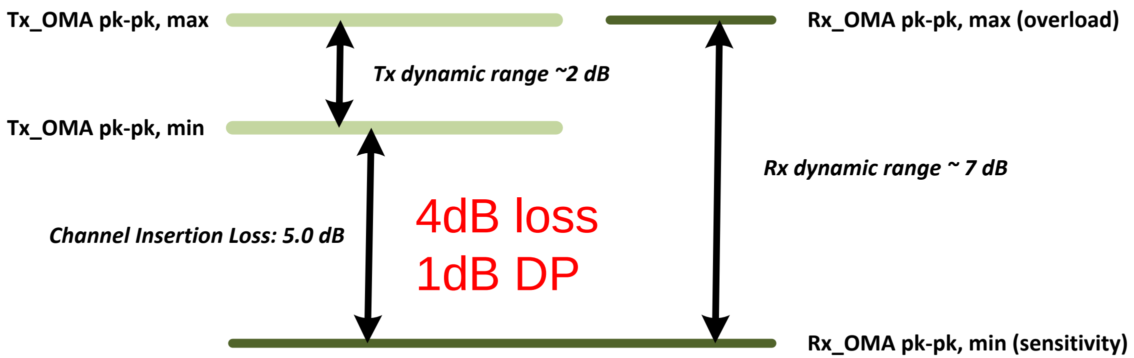


400G DMT Interoperability Test Points



Link Budget and Range

- TP2 to TP3 link length is 0 to 2 km over SMF
  - Fiber transmission penalty budget is 1.0 dB
- Channel insertion loss is 4 dB
- Dispersion is minimal for 2km link at 1310nm
  - Max negative dispersion = 5.47 ps/nm at 2 km
  - Max positive dispersion = 1.68 ps/nm at 2 km
- At TP3: DMT signal amplitude (OMA), pk-pk is determined by Rx clipping ratio (propose ~ 3.15 sigma) and the need to use the ADC dynamic range.
- At TP2: Average power is determined by minimum extinction of the optical source and by the Tx clipping ratio (propose ~ 3.15 sigma).



Note: OMA is the pk-pk amplitude of the DMT signal – limited by clipping ratio
Average power is determined by the Tx extinction ratio (DMT signal max positive / max negative)

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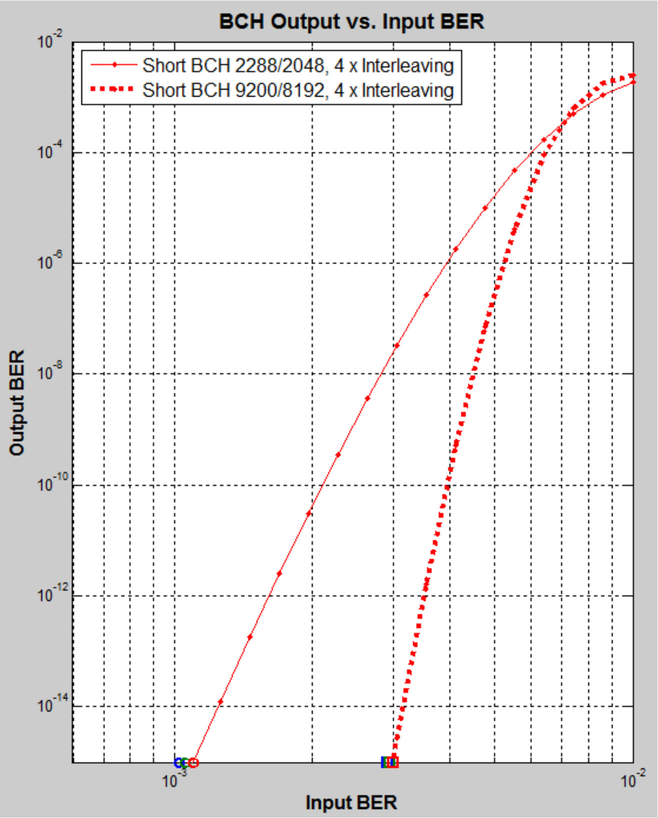
DMT Standardization

- Protocols and parameters to be addressed in the standard:
  - How to map sequence of bit constellations (Binary Coded Gray)
  - Method to synchronize bit mapping between Rx and Tx
  - DMT symbol synchronization
  - Link communication protocol and commands
  - Link negotiation details
  - Low-latency, high-coding gain, Forward-Error Correction details

- Optical parameters to be in the standard:
  - TP2: min/max values for OMA pk-pk, Pavg, Extinction Ratio, Clipping ratio, wavelengths
  - TP3: min/max for OMA pk-pk, Pavg, Clipping ratio, wavelengths

System Overview: FEC

- 400G 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 not synchronous with DMT frame (symbol).
- Solution is protocol agnostic and can support 400GE, 4x100GE, 4xOTU4 or future OTU5 standard
- FEC can be bypassed for client data with strong FEC, 4xOTU4 rates supported with FEC at 4x125.8 or without FEC at 4x111.8Gb/s



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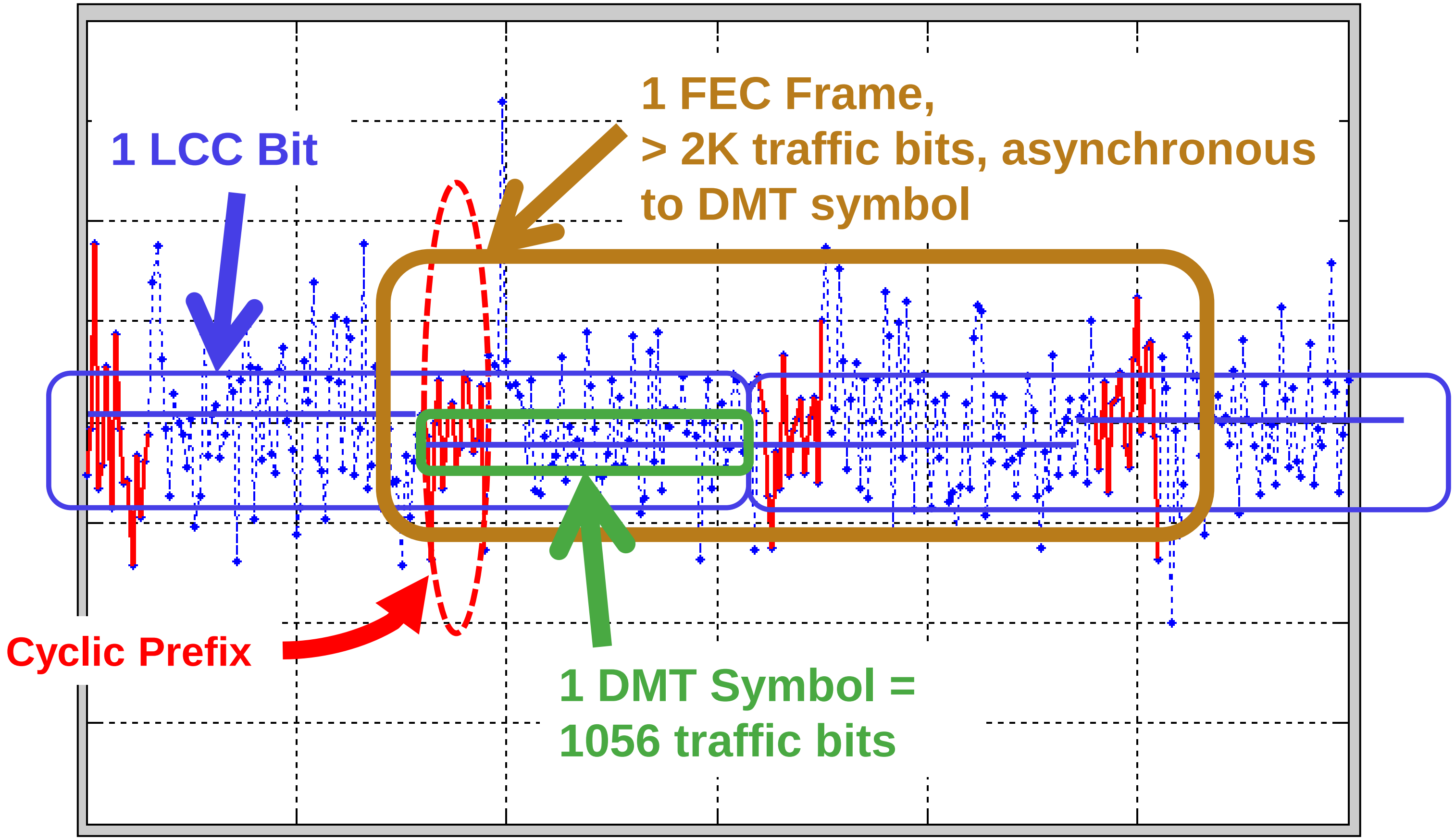
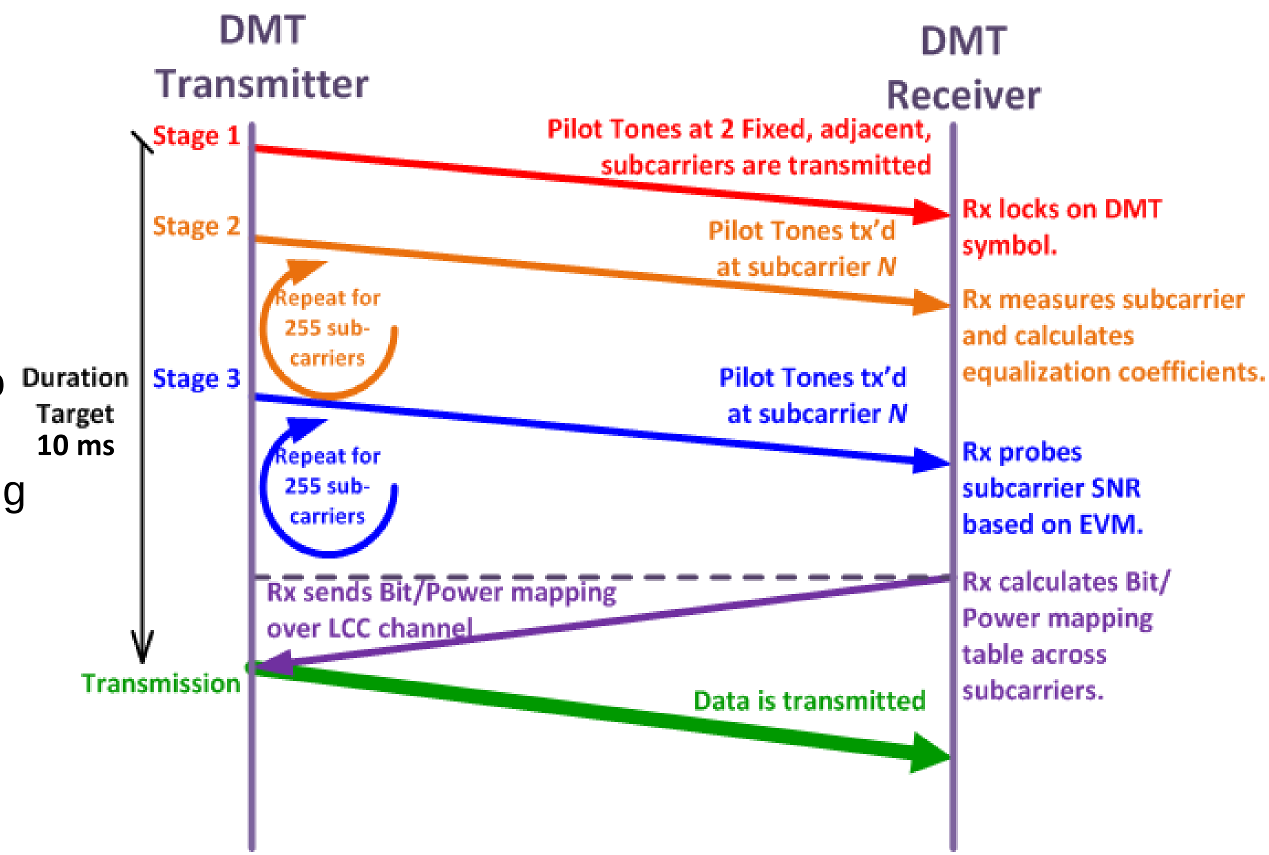
System Overview: Frame Synchronization

- 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.



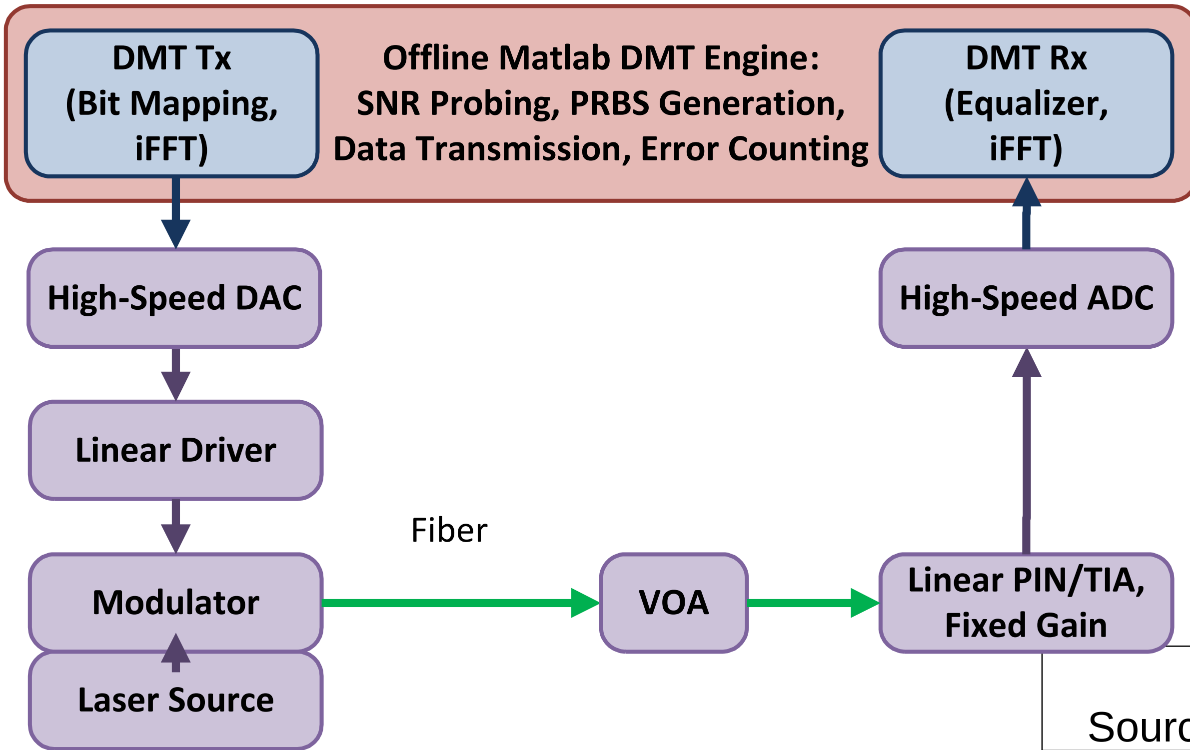
DMT Link Communication Channel and Negotiation

- 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.
- Some definition required for command suite such as:
  - Tone Bit-power assignment
  - Bit-swap execution
  - Diagnostic request (eg, BER), etc...
- 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.



Test Bed Results

Experimental Test Bed

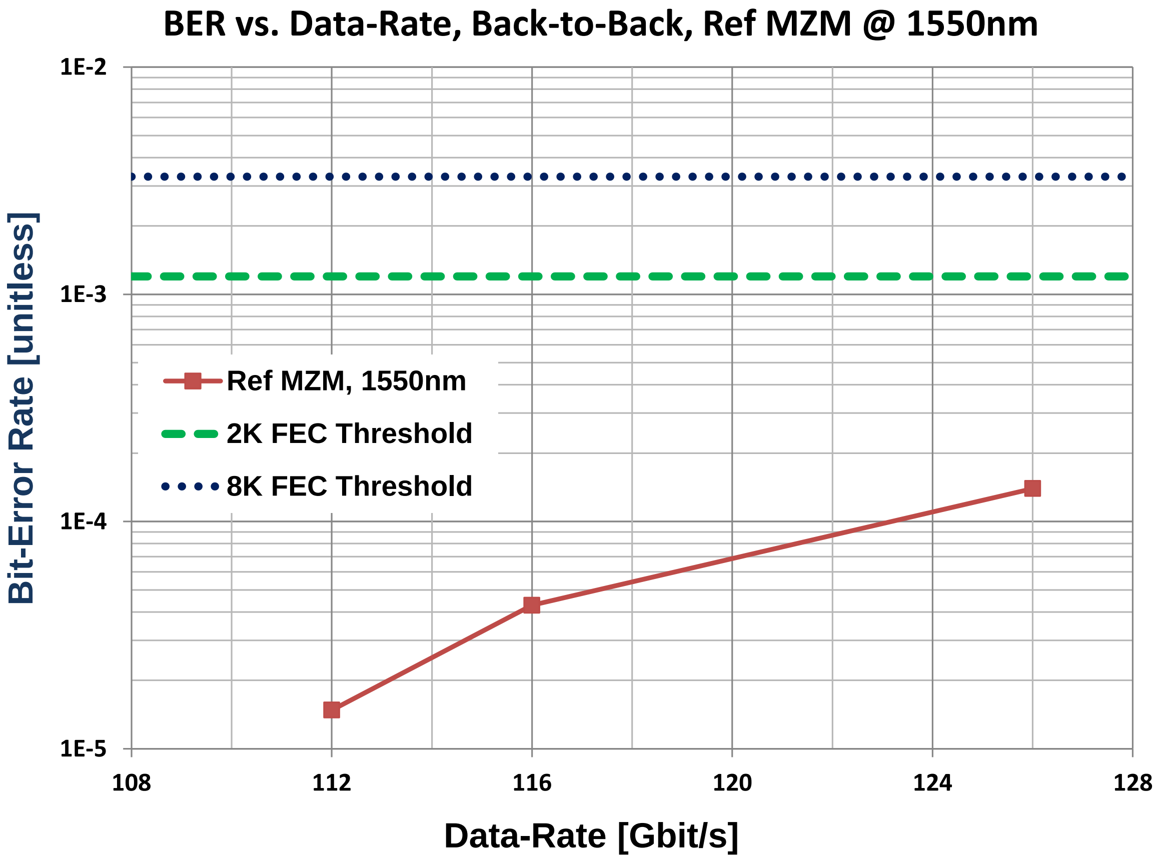


Source	1550nm XFP-Grade Tunable Laser,
Modulator	MZM, 30 GHz BW
Driver	27 GHz BW
PIN/TIA	30 GHz BW, 500 Ohm, 18 pA/rt-Hz
DAC	8-bits, 16 GHz BW, 56 - 64 GHz
ADC	8-bits, 19 GHz BW, 56 - 64 GHz

- *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.*
  - *126 Gbit/s unless otherwise stated.*
- *Furthermore, no signal grooming (non-linear compensation) is performed.*

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.
  - Test-results on following slides reported at worst-case data-rate of 126 Gb/s.



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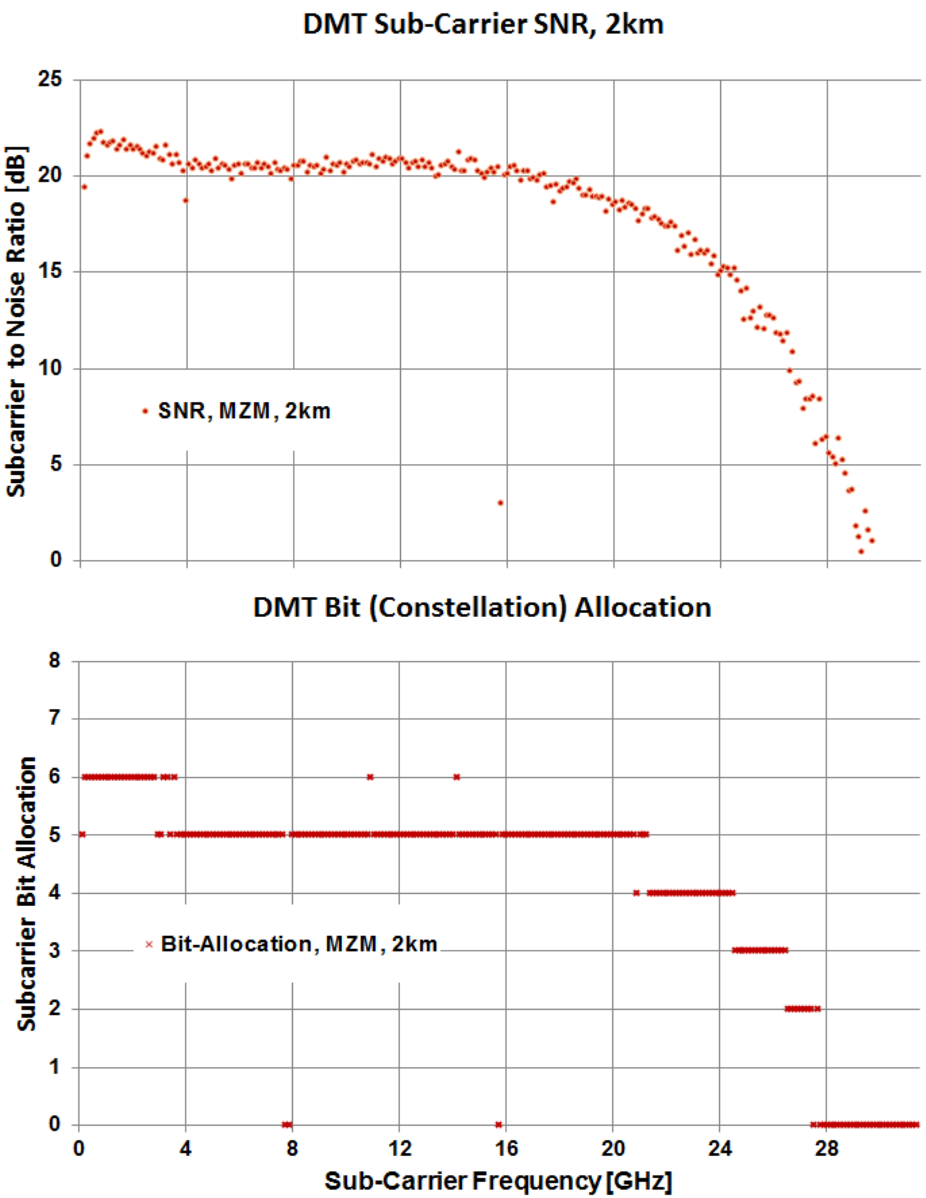
DMT Bit to Sub-Carrier Mapping

- 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.

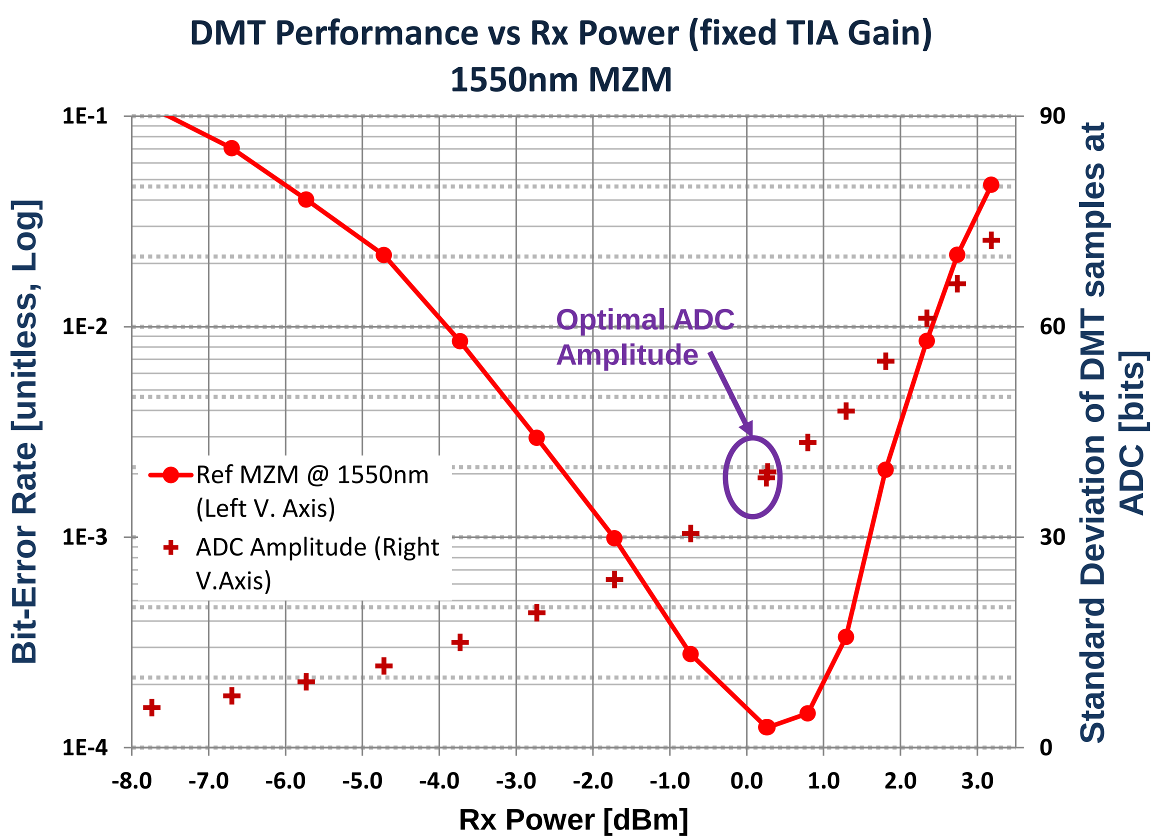
- SNR and bit-allocations to right illustrate spectra for MZM @ 1550 nm over 2km of fiber.
  - Data-Rate = 126 Gbit/s
  - Sampling-Rate = 63 GS/s



Experimental Results
ADC Amplitude

- Receiver input power was swept for results shown here, in a B2B configuration.
- Since lab 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
- Expecting better results with variable gain, lower noise TIA



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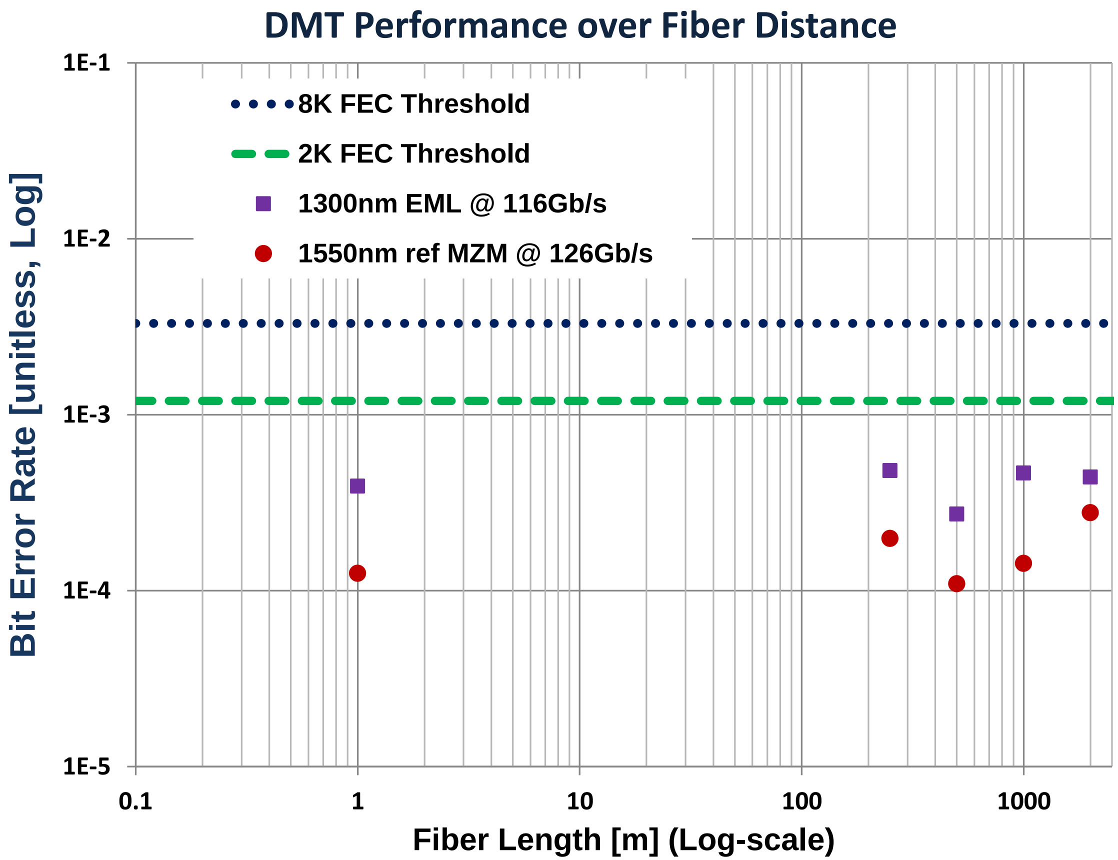
Experimental Results
Performance over Fiber

- 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.



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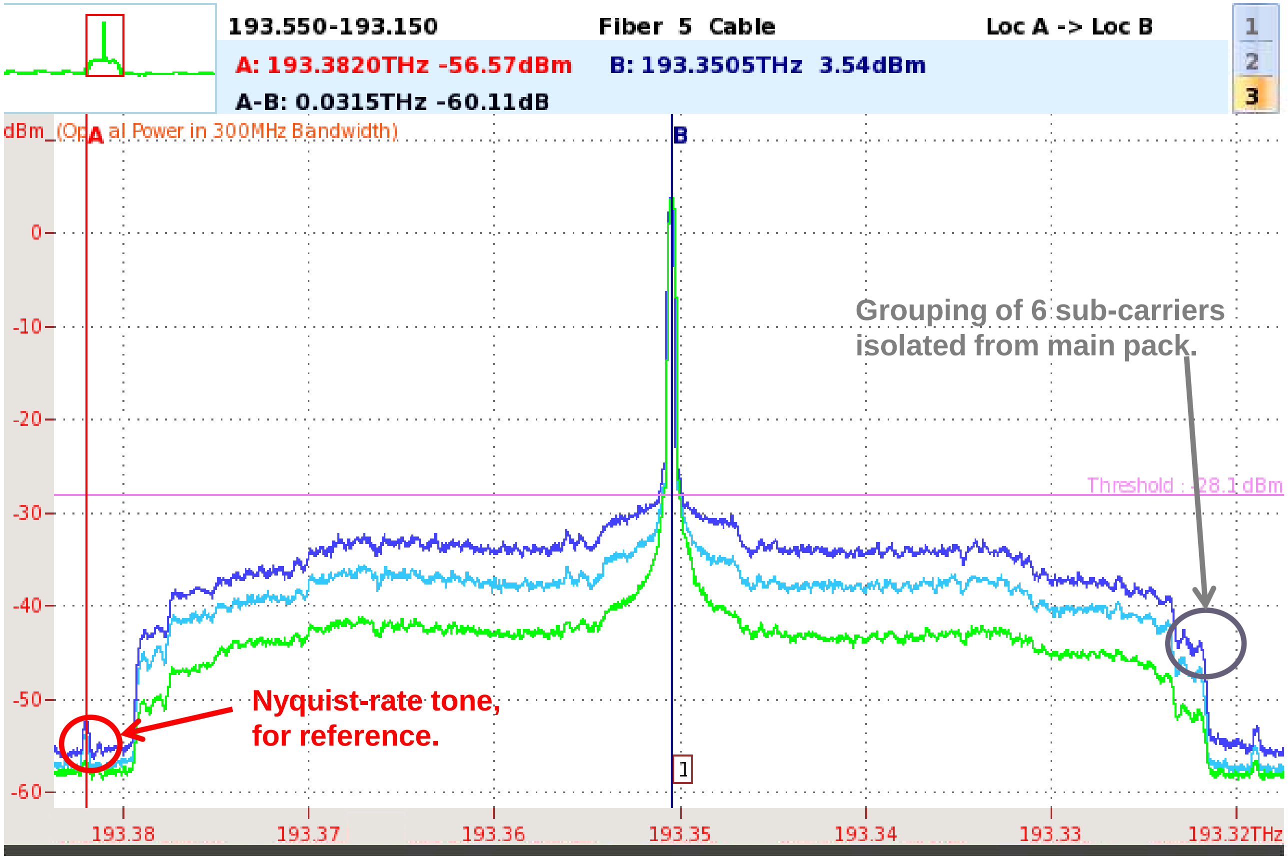
Spectral Profiles

- The optical DMT spectrum from the reference 1550 MZM is presented below.
  - 63 GHz sampling rate, 126 Gb/s.
- Optical spectrum from high-resolution scan (coherent OSA)/
  - Nyquist rate tone added for reference (31.5GHz)
  - 3 traces show 3 different modulation amplitudes.



Optical Spectrum Analyzer, output of Reference MZM

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Component Requirements

- DMT component requirements are:
  - DMT DSP IC
    - 256 Sub-Carriers, 512-pt FFT
    - SerDes, FEC, Cyclic Prefix
    - DAC and ADC ENOB = 6
  - Cascaded Tx (DAC/Driver/EML or DML) bandwidth >= 15 GHz
  - Cascaded Rx (PIN-TIA / ADC) bandwidth >= 15 GHz
  - Optical Transmitter
    - Laser RIN < -145 dB/Hz
    - Linear driver with THD < 2%
    - LanWDM optical mux
  - Optical Receiver
    - LanWDM optical demux
    - PD with 0.5 A/W, 30GHz BW
    - Variable Gain Linear TIA

      Gain = [80, 5000] Ω

      THD < 2%

      Input referred noise < 15 pA/√Hz
- All above components are expected to be available between 2014 and 2016

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Summary

- Proposed 400GE PMD for 2km SMF
  - 4 wavelengths at 116 Gbps per wavelength on LanWDM grid
  - 1056 bits per DMT symbol on up to 256 subcarriers
  - PMD module includes DMT DSP and FEC
  - Required protocols to be standardized
- Link Power Budget
  - 4dB loss + 1dB for penalties
  - 2dB Tx dynamic range
- Presented experimental data
  - 126 Gb/s with 1550nm tunable source and fixed gain optical Rx
  - 116 Gb/s with 1310nm EML -- 2km transmission at < FEC threshold BER

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Thank You