400G DMT PMD for 2km SMF

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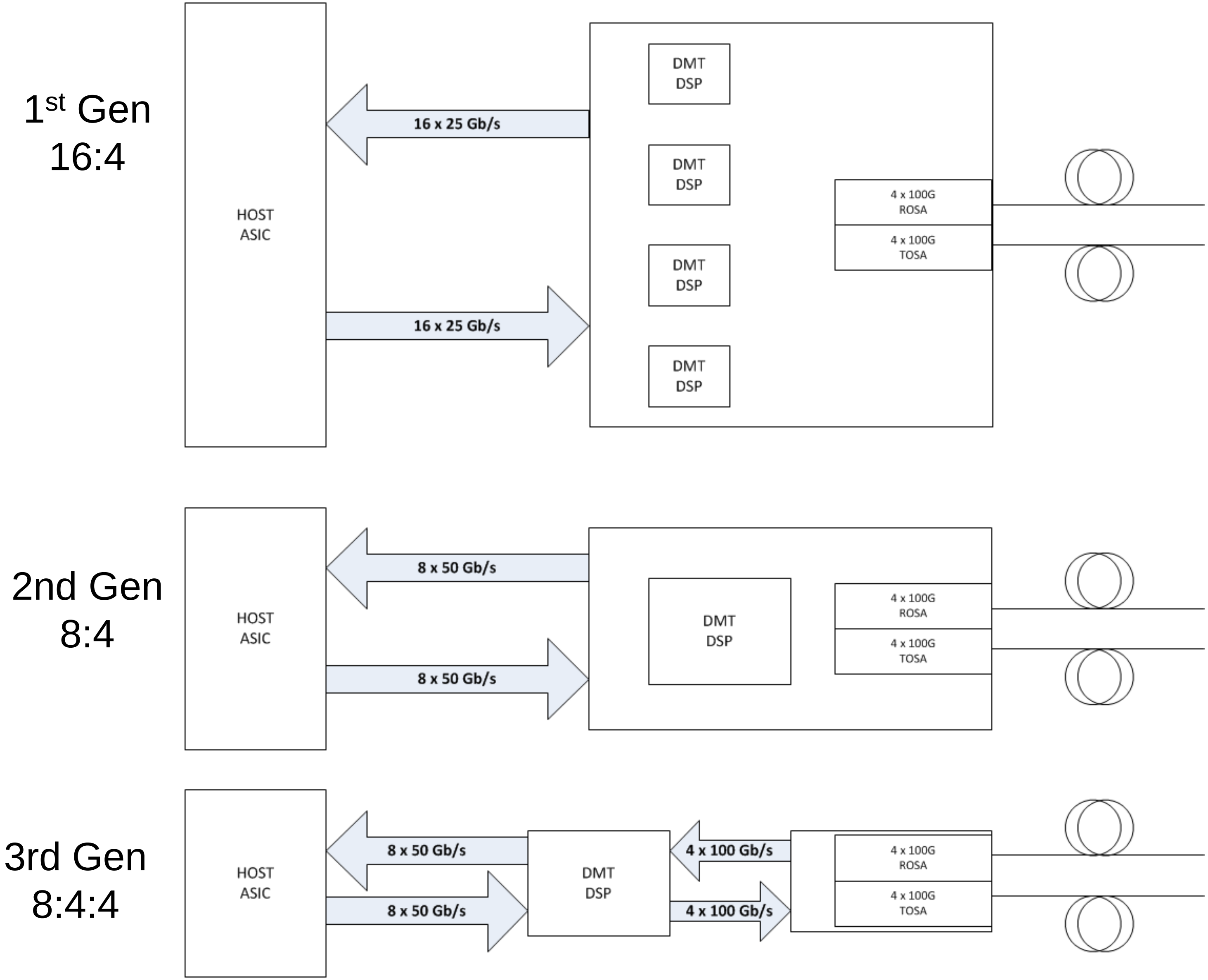
Outline

- Progression to high-density with 100G/λ
- 2km SMF PMD Proposal Recap
- DMT Link Communication Channel (LCC) update
  - Time-of-flight: what it means wrt DMT control
  - What types of dynamic changes DMT can be expected to handle
  - More details on command requirements.
- DMT Testability
- DMT Diagnostics
  - Built-in measurements available from DSP
- Component requirements update
  - Minimum requirements and target values

Progression to high density 400GE duplex SMF



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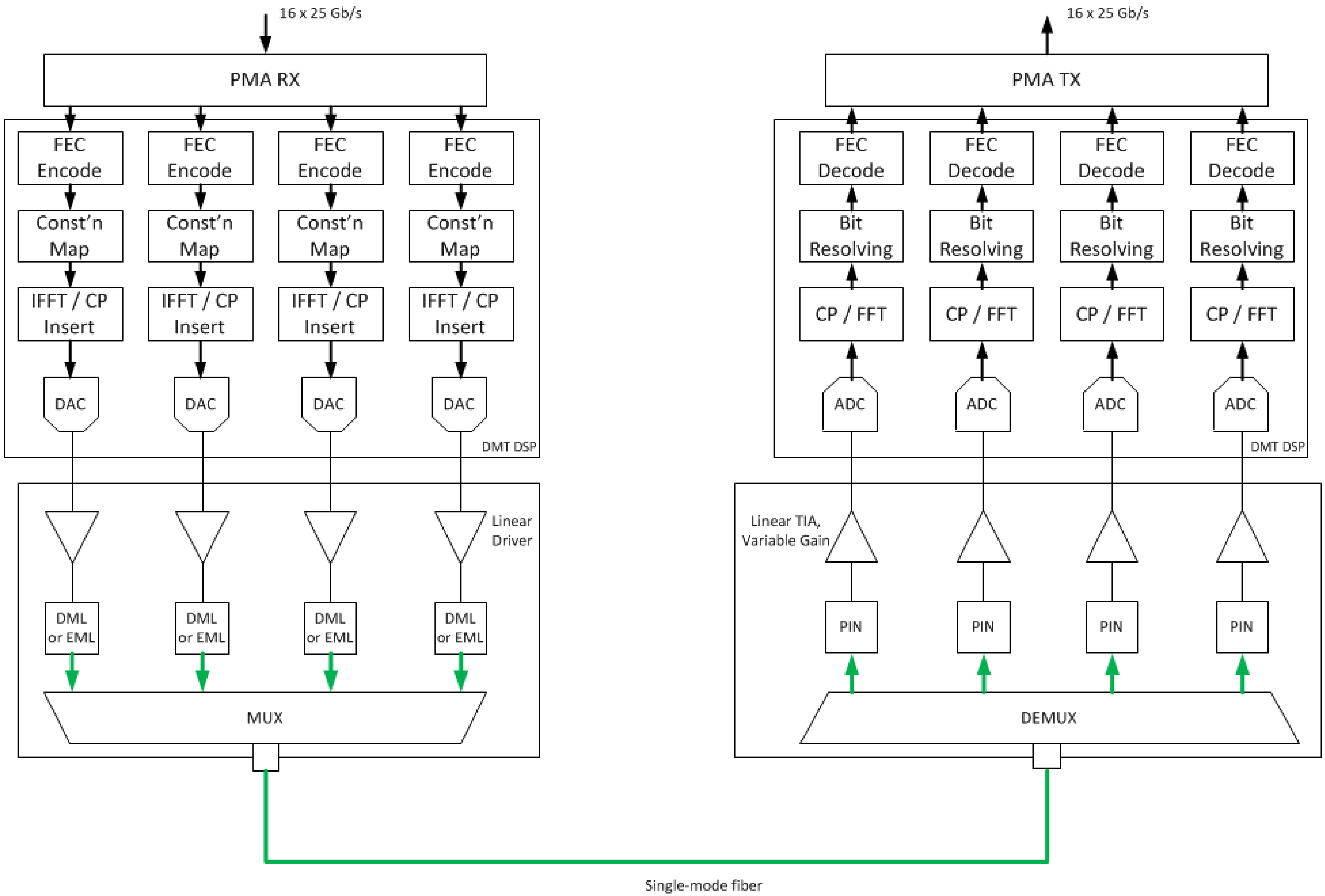
2km SMF PMD Proposal Summary

- For the 400GE 2km and 10km SMF PMD's we propose four optical lanes at 100G on the LanWDM grid using a Discrete Multi-Tone (DMT protocol)
- FEC is part of the pluggable module and increases the bit rate per lane from 103.125 to 116.02 Gb/s (+12.5%)
- The DMT symbols carry 1056 bits per symbol at 109.86 MBd
- A full duplex link communication channel (LCC) on subcarrier 0 (baseband) enables link initialization, link performance monitoring and enhances testability
- Two adjacent subcarriers carry tones for frame synchronization
- LAN-WDM advantages over CWDM:
  - Compatibility between 2 and 10km PMDs
  - Cooled D/EML will have better RIN than un-cooled D/EML
  - Reduced loss variation between optical lanes compared to CWDM
    - Less than 0.1 dB over 10km for LanWDM
    - Up to 0.6 dB over 10km for CWDM

400G DMT Block Diagram



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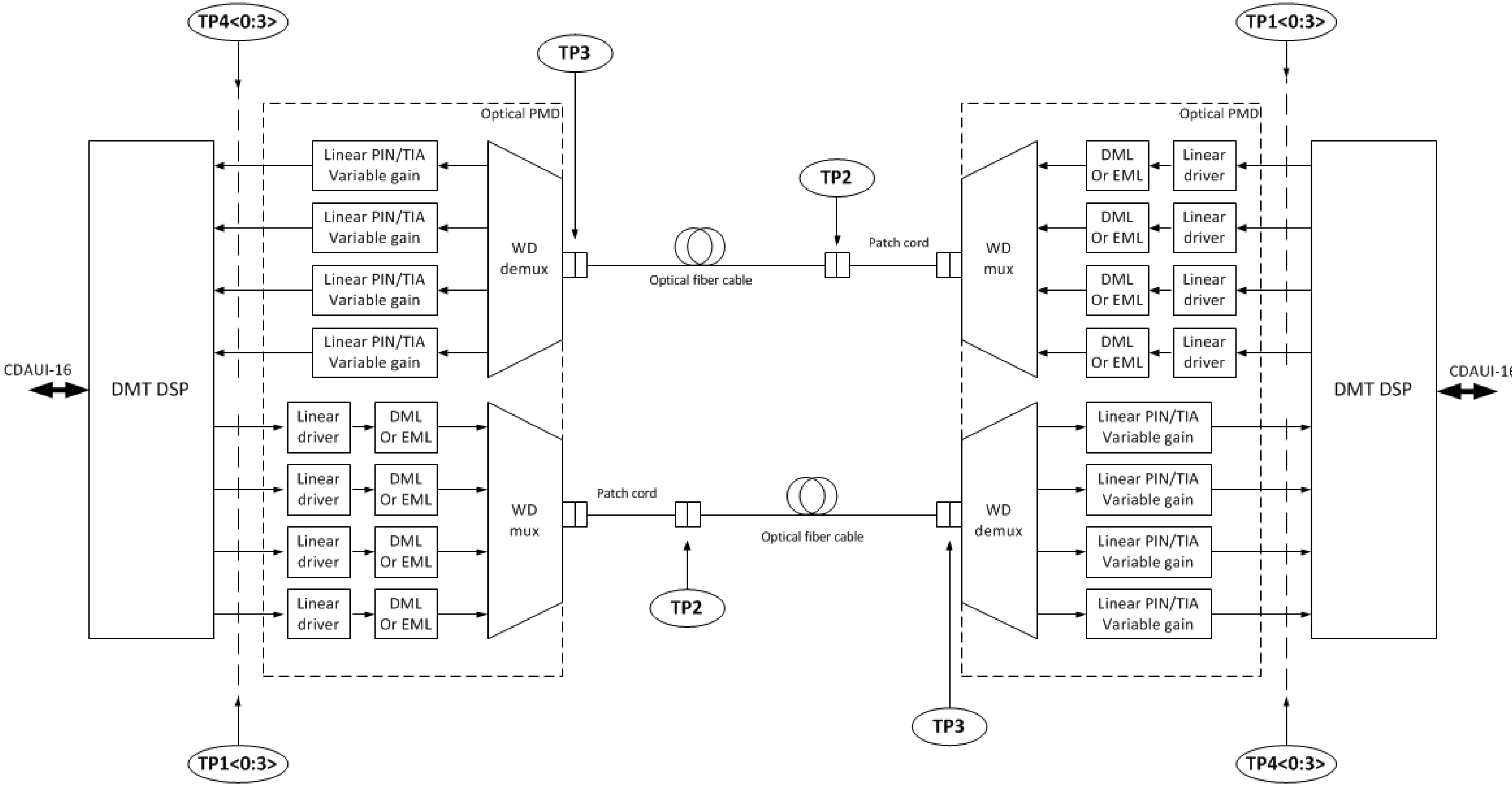
400G DMT Interoperability Test Points



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) to prevent 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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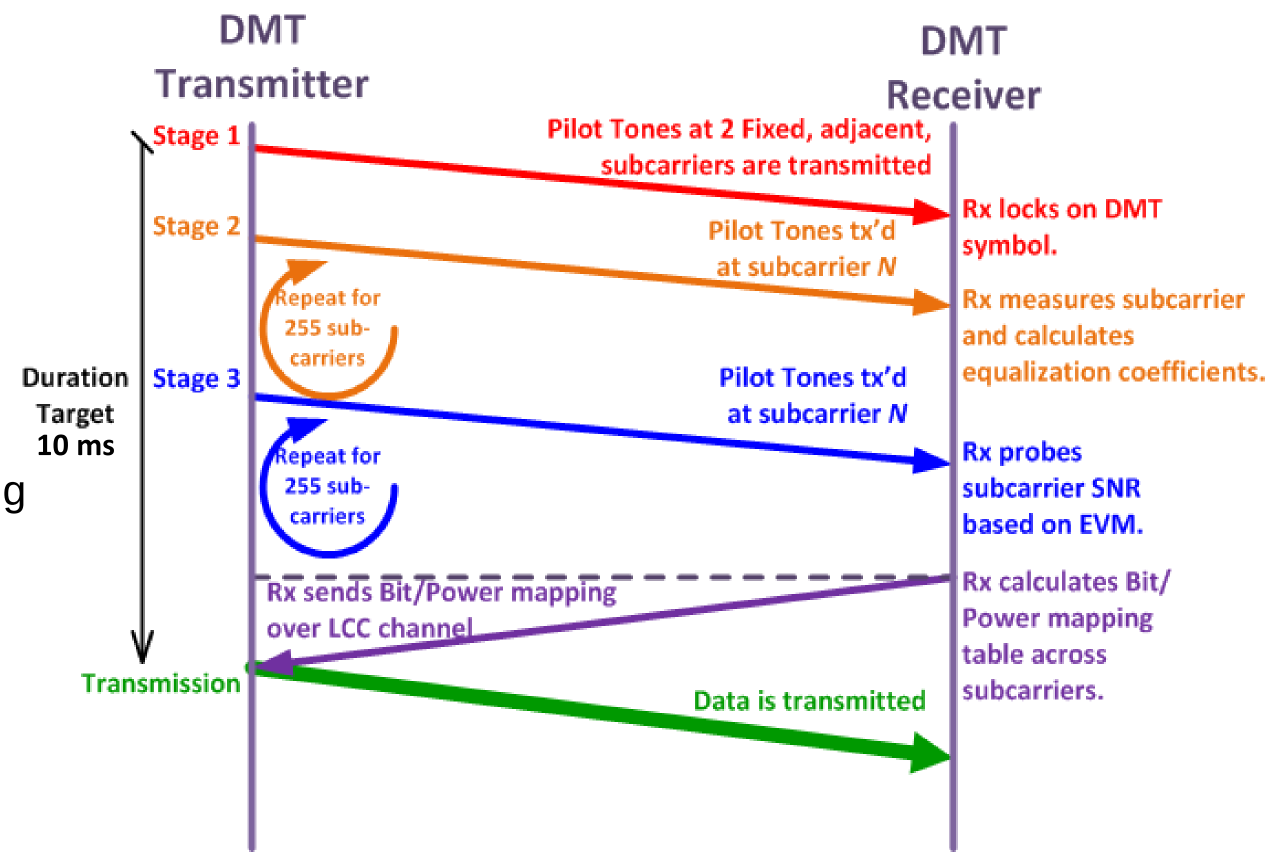
DMT Link Communication Channel (LCC) update

- 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 subcarriers, to optimize performance.



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Clock Synchronization Details

- Precise clock synchronization is critical for DMT, as for any other high data-rate modulation format
  - Received clock jitter translates to a phase-error in each subcarrier's symbol detection
  - However, DMT well poised to provide end-to-end clock alignment, by dedicating 2 subcarriers.
    - Synchronization tones continuously available on both dedicated subcarriers
    - Phase difference between both tones provides precise frame-sampling alignment
  - Availability of high-speed tone(s) for synchronization is at least on-par with clock-recovery from intensity modulated data.
- Jitter-cleaner required to reduce symbol phase-detection error.

Dynamic Control – impact of "time-of-flight"

- Time-of-flight is not relevant for DMT operations.
  - Time of flight does impact the acknowledgement process, and will also affect the duration of the link-negotation.
  - But link-negotiation can be optimized to reduce its impact, by reducing acknowledgements required during the process.

- Round-trip delay must be taken into consideration for any control loops requiring far-end feedback.
  - Speed-of-light over fiber ~2.0e8 m/s

	1 m	2 km	10 km
Time-of-flight	4.9E-9	9.8E-6	49.0E-6
Round-trip-delay	9.8E-9	19.6E-6	98.1E-6

- But dynamic control is not a necessity for 100Gb/s/λ DMT.
  - Dynamic control could be used to compensate "slow" drifting effects, such as temperature variation of component performance, where the drift time-constant exceeds the round-trip-delay.

$$\tau_{effect\text{-}to\text{-}compensate} >> {}_{max}\,\tau_{round\text{-}trip}\ (\sim 100\ \mu s)$$

  - Dynamic control would essentially shift bit allocations from subcarriers whose SNR has degraded, to subcarriers with good SNR. It preferably requires a link with some margin.

  - *Note that in ADSL, dynamic control is primarily used to compensate for radio interference. This is not an issue for this application.*

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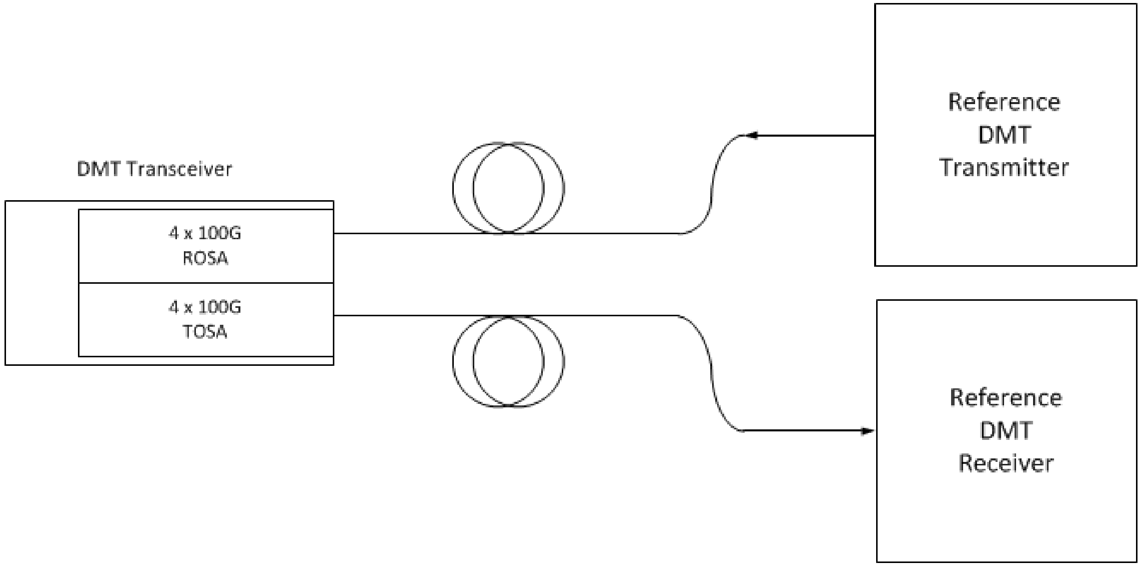
DMT Testability



Settings:
- Power by subcarrier (SC)
- Bit allocation by SC
- Added stress / jitter
- Special test patterns

Measurements:
- Power by subcarrier (SC)
- Constellation / EVM by SC
- SNR by SC

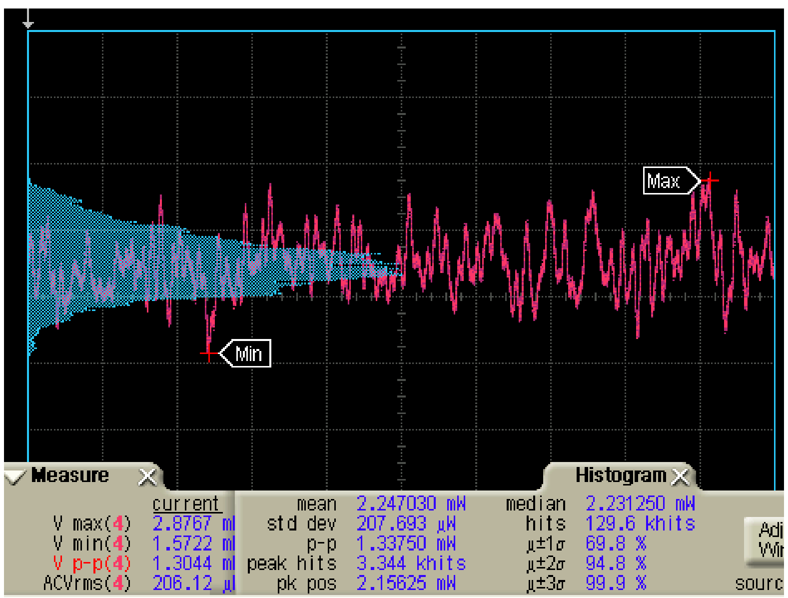
- A high-end reference receiver (similar to high bandwidth oscilloscopes, CSA/DCA), and a high-end reference transmitter (secondary to reference receiver), are required for comprehensive testing.
- Advanced-modulation diagnostic software already exists as a built-in feature of some real-time sampling oscilloscopes (Agilent)
  ⇨ equivalent to DMT Reference Rx
- Ideal equivalent to DMT Reference Tx ⇨ would be a next-generation waveform generator synthesizer
  - Stressed signals can be generated at Tx to test Rx for compliance.
- Can use the DSP chip within the DMT transceiver to acquire DMT diagnostics.
- Existing DSP chip implementations can be used in production testers.
  - On-chip processor can use alternate firmware to better focus on diagnostics rather than data transmission.

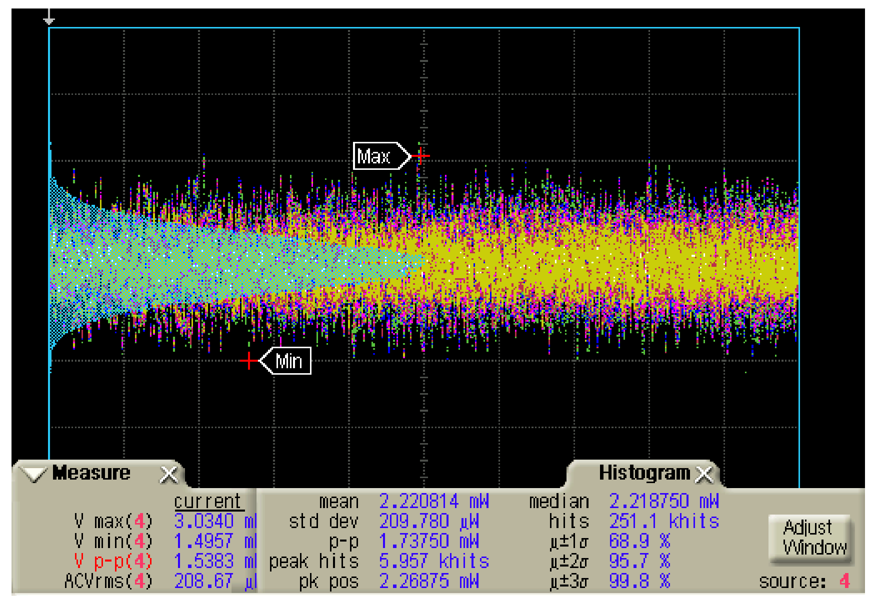
DMT Testability (cont'd)

- An Optical Spectrum Analyzer (OSA) can be used at TP2
- High-resolution OSAs (coherent) are particularly useful
  - Measure spacing and relative power between LAN-WDM channels.
  - Estimate active subcarriers
    - Frequency measurements are more informative than for NRZ signals.

DMT Transmitter RMS OMA Measurement

- As with NRZ, optical modulation amplitude (OMA) plays an important role
- Extinction-Ratio (ER) and OMA provide the same information, but OMA may be easier to measure
- In NRZ systems, ER is well defined with respect to the eye for a given pattern
- Translated to DMT, ER would be defined as ratio of max to min optical power
  - Difficult to identify which measurement samples represent peaks, and what effect noise has on these measurements
- Propose to use a statistical measurement from a histogram - the RMS OMA
  - Tx RMS noise is included in the composite signal RMS OMA





<u>Limited (Left)</u> and **<u>Extended (Right)</u>**Time-Sampling of DMT Signal

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DMT Diagnostics

- DMT engine can provide following diagnostics based on *link-negotiation phase*:
  - SNR on a per-subcarrier basis
  - Bit-Allocation on a per-subcarrier basis
  - Power-allocation per-subcarrier (each subcarrier's constellation magnitude can afford some equalization pre-emphasis)
- DMT engine has ability to measure Error-Vector-Magnitude (EVM) in *real-time*.
  - EVM is translated to continuously-monitored SNR, on a per-subcarrier basis.
- Link pre-FEC Bit-Error-Rate from built-in FEC also available in *real-time*

Component Requirements Update

- From an equipment manufacturing perspective, high-performing components are desired to improve margin, flexibility, link-reach, and scale to a wide variety of data-rates.
- From a system perspective, a 2 - 10 km reach can be achieved with existing components, meeting a different set of criteria.

	High-Confidence Specification	**Minimum Requirement**
DAC and ADC ENOB	6	6 for [0 - 5] GHz
Cascaded Tx (DAC + Driver + EML)	>= 15 GHz	
Cascaded Rx (PIN-TIA + ADC)	>= 15 GHz	
Cascaded System (DAC + Driver + EML + PIN-TIA + ADC)		>= 10.5 GHz
Laser RIN	Peak < -145 dB/Hz	Integrated: < -145 dB/Hz (Peak can be -140 dB/Hz) over [0 - 29] GHz
THD for Driver and TIA	< 2%	< 2% for [0 - 10]GHz,
PIN Responsivity* *taking into account LAN WDM Dmx Loss	0.5 mA/mW	0.45 mA/mW
Variable Gain Linear TIA: Gain	[80 - 10000] Ohms	[80 - 5000] Ohms
Variable Gain Linear TIA: IRN	< 15 pA/√Hz	< 25 pA/√Hz

Summary

- 100G per lambda DMT enables a path to high-density QSFP28/CFP4 modules for duplex SMF 400GE links
- Provided DMT Link Communication Channel (LCC) details
- Explained clock synchronization need
- Dynamic control – not critical for SMF applications
- Testing and diagnostics capabilities
- Updated component requirements matrix