Multi-Level Analog Signaling Techniques for 10 Gigabit Ethernet

MAS Tutorial Presenters

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MAS Tutorial Agenda

- Introduction
- Alternatives: T-Wave, PAM, QAM
- Architecture
- PMA
- PMD - focus on Laser Linearity
- PCS
- Acknowledgements

Introduction: What is MAS?

- MAS is a generic term used to describe various methods of Multilevel Intensity Modulation
- Multilevel modulation is applicable to most media including Copper, Wireless, Fiber, etc.
- Methods include T-Waves, PAM, QAM, etc.
- Multilevel signaling lowers the line rate for a given payload rate - reducing system cost and increasing distance

Impetus for MAS

- MAS previously deemed unnecessary for Optics
  - Binary signaling was sufficient for the LAN & WAN
  - Fiber was assumed to have infinite BW - It does NOT!
- Even for 1.25 Gbps, limitations were noticed in attempting to go faster and farther than 1 Gbps
  - Distances reduced from original GbE objectives
  - New phenomena found (e.g. DMD, MMF launch)
- MAS is dominant in modems, DSL, Cu Ethernet...
  - Invaluable to re-use existing cable plants at higher rates
- 10 GbE places 10× demands on media BW

Technology Basis

- Trade off silicon capability against laser/optics and high-frequency electronics complexity and cost.
- Bet that silicon costs less and that cost will continue to improve faster than the laser/optics high-frequency electronics.
- “Lasers don't follow Moore's Law.” - Piers Dawe, HP
- Compared to copper, fiber has higher bandwidth.
    - No hard requirement to use multiple channels like UTP
    - No hard requirement to use high-speed compensation

Features

- MAS enables a single integrated PHY solution
    - Applicable to MMF, SMF, Short-haul Copper
    - Applicable to SX, LX, EX, CX variants
- GbE Auto-Negotiation capable
- Open Architecture, no IP, proven technology base
- Compatible with single or multi-channel optics
    - MAS w/Multi-channel optics enable higher speeds
    - Parallel fiber or WDM multi-channel
    - 40 Gbps or more possible

Economics

- Driving towards low-cost CMOS to:
  - + Reduce optics cost
  - + Increase optical link budget
  - + Increase PHY reliability, especially Laser
  - + Decrease system BER
- Lower Baud to simplify critical electronics design: CDR, Optoelectronics, signal integrity and EMC
- Enables the use of One low-cost laser
- Enables integrated PHY Transceiver product

MAS Alternatives

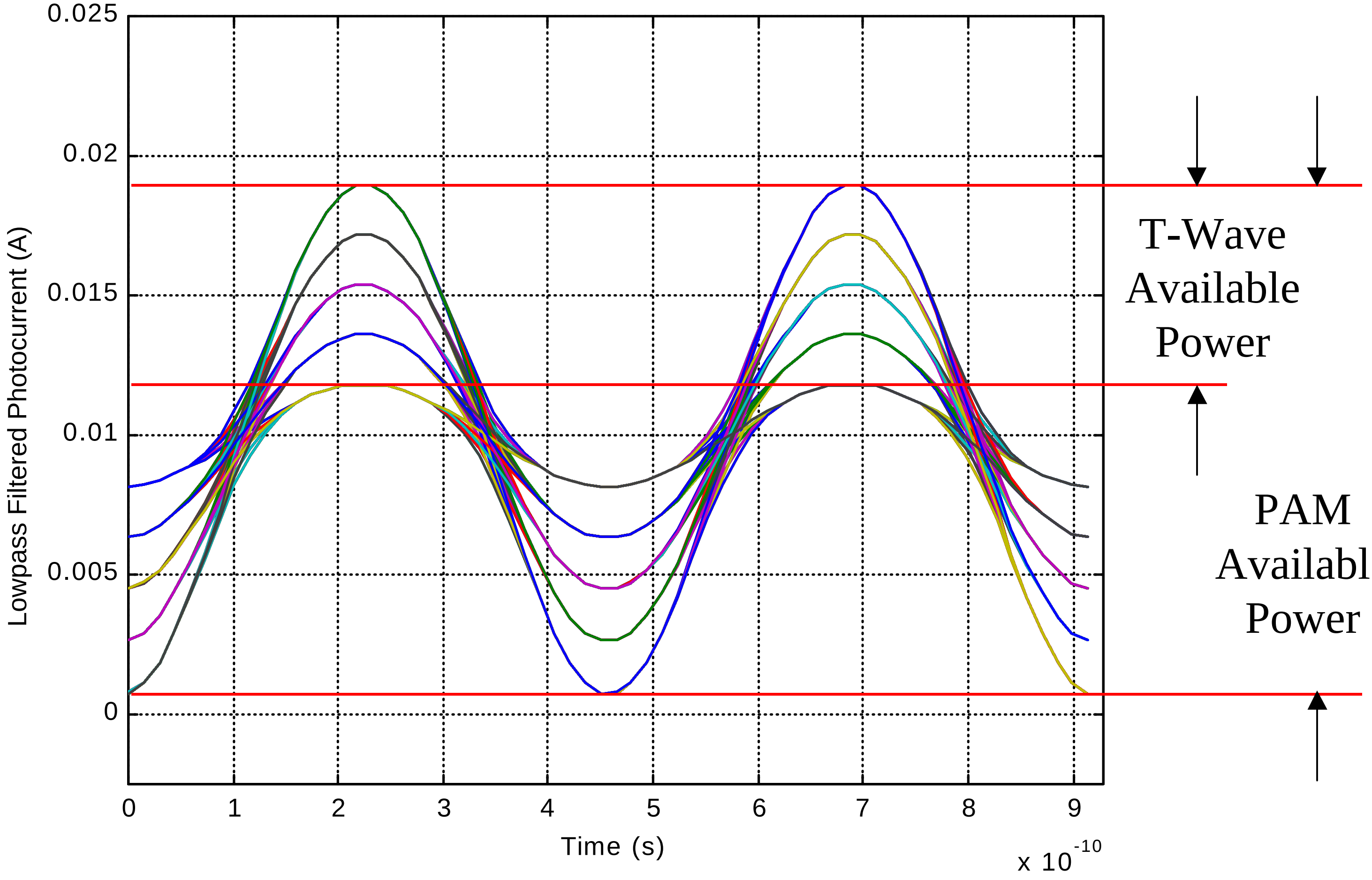
- T-Waves
- PAM
- QAM

T-Waves

- Synthesized, Multilevel, Intensity Modulation
  - Waveform synthesis/Waveform capture
- Narrowband Frequency Spectrum
  - Approximately $f/2$ to $1.5f$
  - Reduced spectrum compared to OOK and PAM
- High Resistance to Dispersion and Nonlinearity
  - System is loss-limited, not dispersion-limited
  - Simple sine-wave modulation enables mechanisms to characterize and compensate for dispersion and media impulse response

T-Wave Signaling

T-Wave5 Example



T-Wave Available Power

PAM Available Power

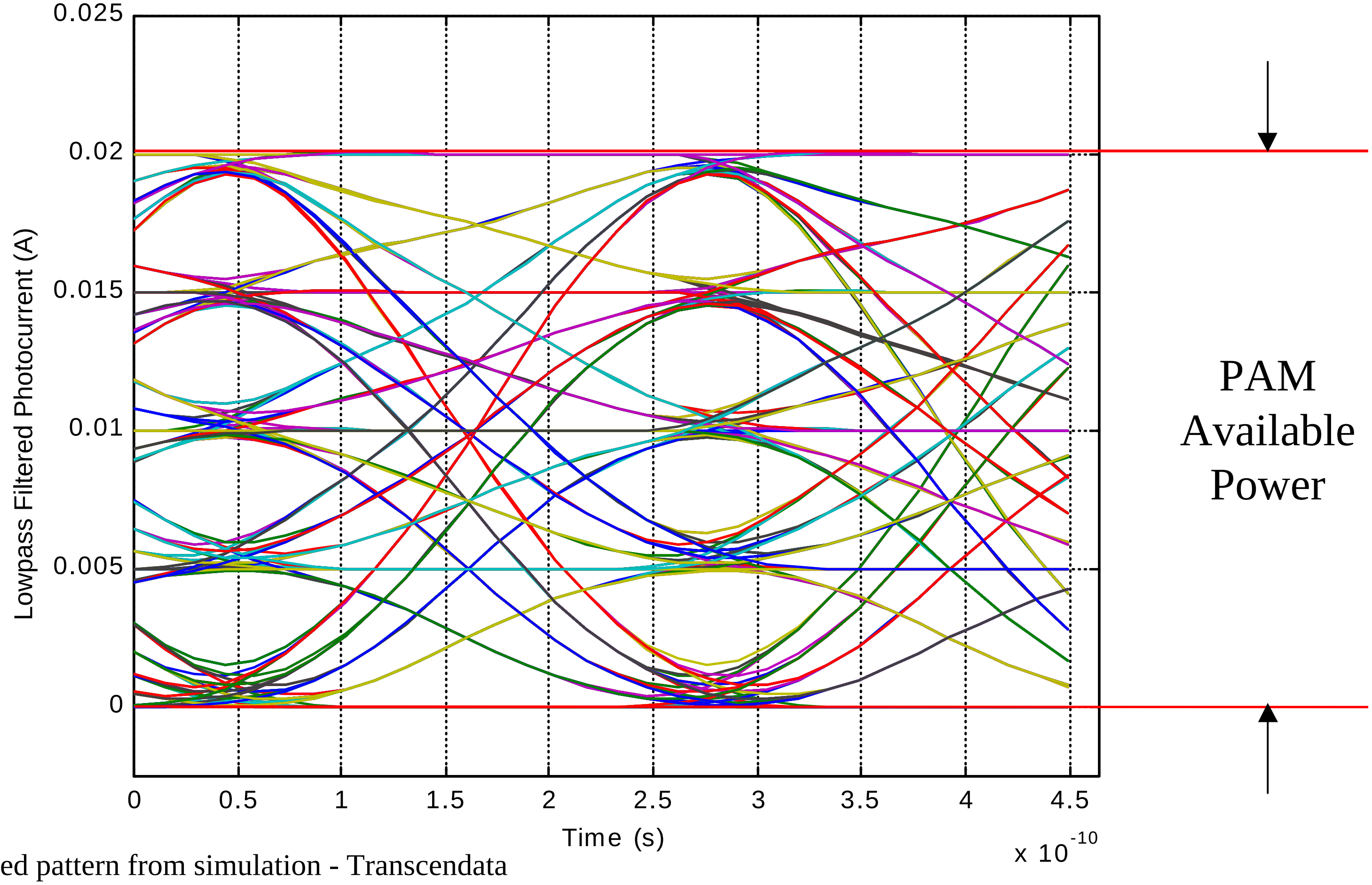
Received pattern from simulation - Transcendata

Pulse Amplitude Modulation Basics

- Most existing optical links employ binary signaling a.k.a. On-Off-Keying (OOK), PAM2, Serial TDM
  - Each transmitted symbol represents just one bit (0 or 1)
- PAMn, where n>2, transports >1 bit/Baud
  - PAM3 and above lowers line rate but decreases SNR
  - PAM3 (e.g. MLT-3), decreases SNR by 3 dB
- PAM5 provides better utilization of limited BW
- PAM5 is 250% as efficient as OOK & 8B/10B
  - 10 GbE: PAM5 @ 5 GBaud = OOK & 8B/10B @ 12.5 GBaud
  - 10 GbE: PAM5, decreases SNR by 6 dB

PAM Signaling

PAM5 Example



PAM
Available
Power

Received pattern from simulation - Transcendata

T-Wave vs. PAM

– Significant Link Penalty compared to PAM
  - ◆ 4.5 dB penalty for the same number of levels since only half of available levels, less average power, are used.

– Signal Compensation at multi-gigabit rates is complex and expensive in terms of logic
  - ◆ Probably not a good tradeoff for 10 GbE environments

– T-Wave Waveform Synthesis logic 3 × PAM

– PAM is more efficient, simpler in ‘easy’ environments (e.g. most 10 GbE applications)

+ T-Waves may be more efficient in ‘difficult’ environments (e.g. very long links, high dispersion)

Optical QAM

- Many Quadrature Amplitude Modulation techniques are possible.
- QPSK is the simplest form of QAM (QAM4)
  - Multicarrier Modulation (MCM)
    - Multiple digital streams are modulated onto carriers at different frequencies, permits transmission with minimal ISI.
  - Intensity modulation most applicable to optical systems
- Overkill in complexity for 10 GbE
  - Work in Progress: Roy You and Joseph M. Kahn, “Average-Power Reduction Techniques for Multiple-Subcarrier Optical Intensity Modulation”, IEE Colloquium on Optical Wireless Communication, London, England, June 22, 1999.

MAS Alternatives - Direction

- T-Waves
  - Large Optical Penalty, Too Complex for 10 GbE

√ PAM

  √ Best Tradeoff between Cost and Complexity

- QAM
  - Too Complex for 10 GbE, need RF carrier(s)

MAS Basics - Line Rate Reduction

- Reduce line rate to support 10 GbE to 5 GBaud
  - + Use multi-level signaling, PAM5 to increase #bits/Baud
  - + 5 GBaud = 2.5 GHz enables the use of low cost CMOS
  - + Enables the use of low cost Lasers (e.g. OC-48)
  - – PAM5 signaling costs 6 dB in SNR
  - + Get back >6 dB with Forward Error Correction (FEC)
  - ± FEC adds latency/costs gates. Impact negligible
  - – PAM5 needs nominally linear lasers & signal symmetry
  - + Linearity requirements offset by Link Calibration

MAS Basics - One vs. Multi-Channel

- Reduce cost/complexity by using one channel
  - + Fiber has sufficient bandwidth, unlike UTP
  - + One channel is cheaper/simpler than 2/4/8/12, etc.
  - + One channel is more reliable than multiple channels
  - + No multiplexing of data streams required
  - + No skew management and associated delay
  - + MAS channels can directly feed a “dark wavelength” to enable higher data/rates

Signal Design Challenges

- 10 GbE serial data stream transmission presents several design challenges.
  - High speed logic requirements, 10 × GbE, CDR, Optics
  - Attenuation
  - Dispersion/Group Delay
  - Noise from increased Bandwidth
  - Crosstalk
  - Signal Integrity and Transmission Line Effects
  - Parasitic effects in Components and Packaging
  - Electromagnetic Emissions and Susceptibility

MAS Circuit Design Challenges

- Waveform Synthesis and Capture
  - 5 GigaSymbols per second (Gsps)
- Clock and Data Recovery
  - Low Jitter PLL for PAM5 clock & data recovery
- Forward Error Correction (FEC)
  - TBD, focusing on Reed-Solomon codes
  - High efficiency, high coding gain, negligible latency
  - E.g. RS(255,239) code in 10^{-4} BER, out 10^{-14} BER

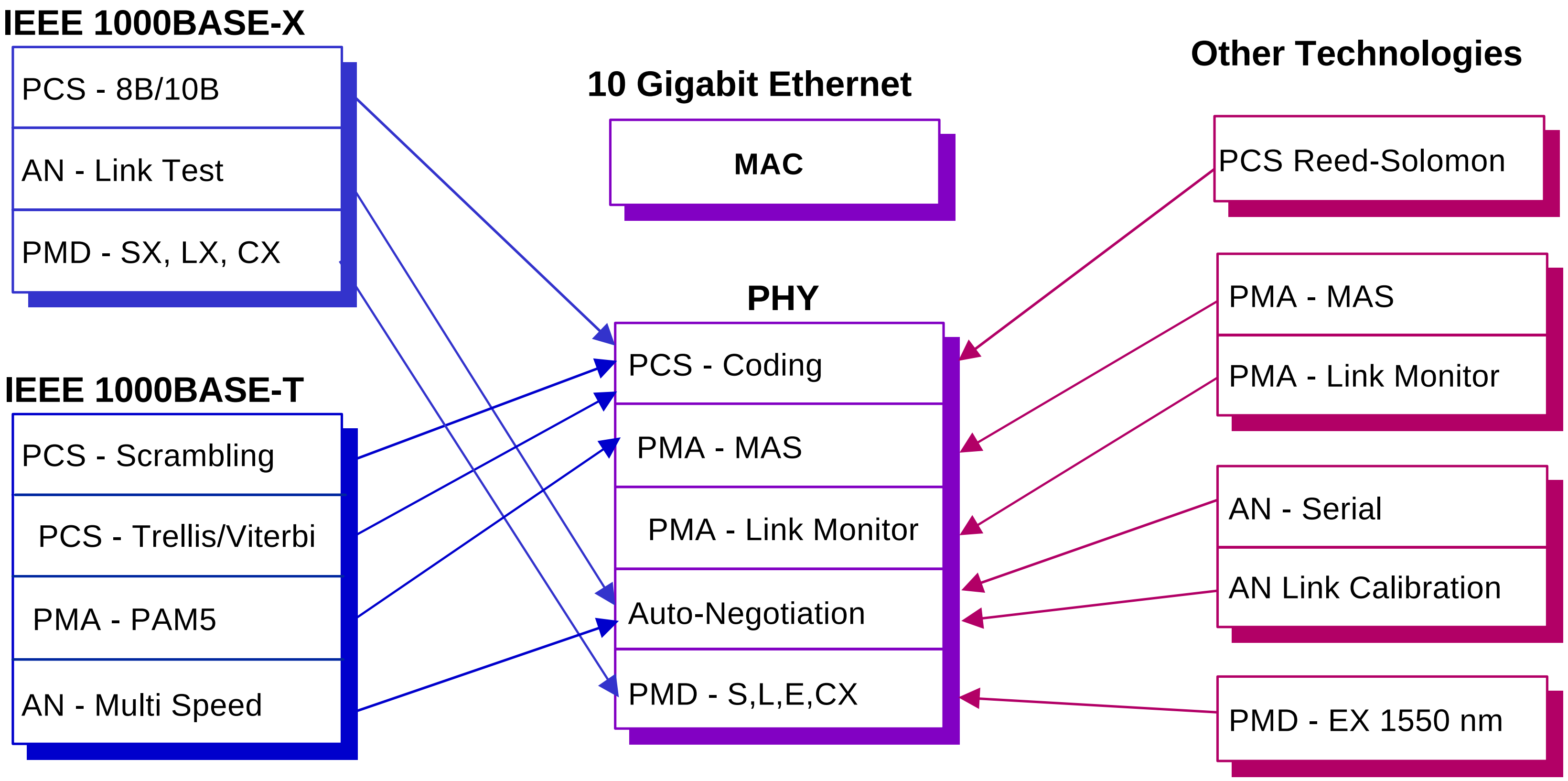
CMOS Capabilities

- Submicron CMOS can achieve 10 Gbps
- Reference designs:
  - Farjad-Rad, Ramin, et al, “0.4um CMOS 10-Gbps 4-PAM Pre-Emphasis Serial Link Transmitter”, IEEE JSSC Vol. 34 No 5, May 1999
  - Ellersick, W., et al, “A 12-GS/s CMOS 4-bit A/D Converter for an Equalized Multi-Level Link”, IEEE 1999 VLSI Circuits Symposium, Kyoto, Japan
- Example gate delay per inverter in ring oscillator

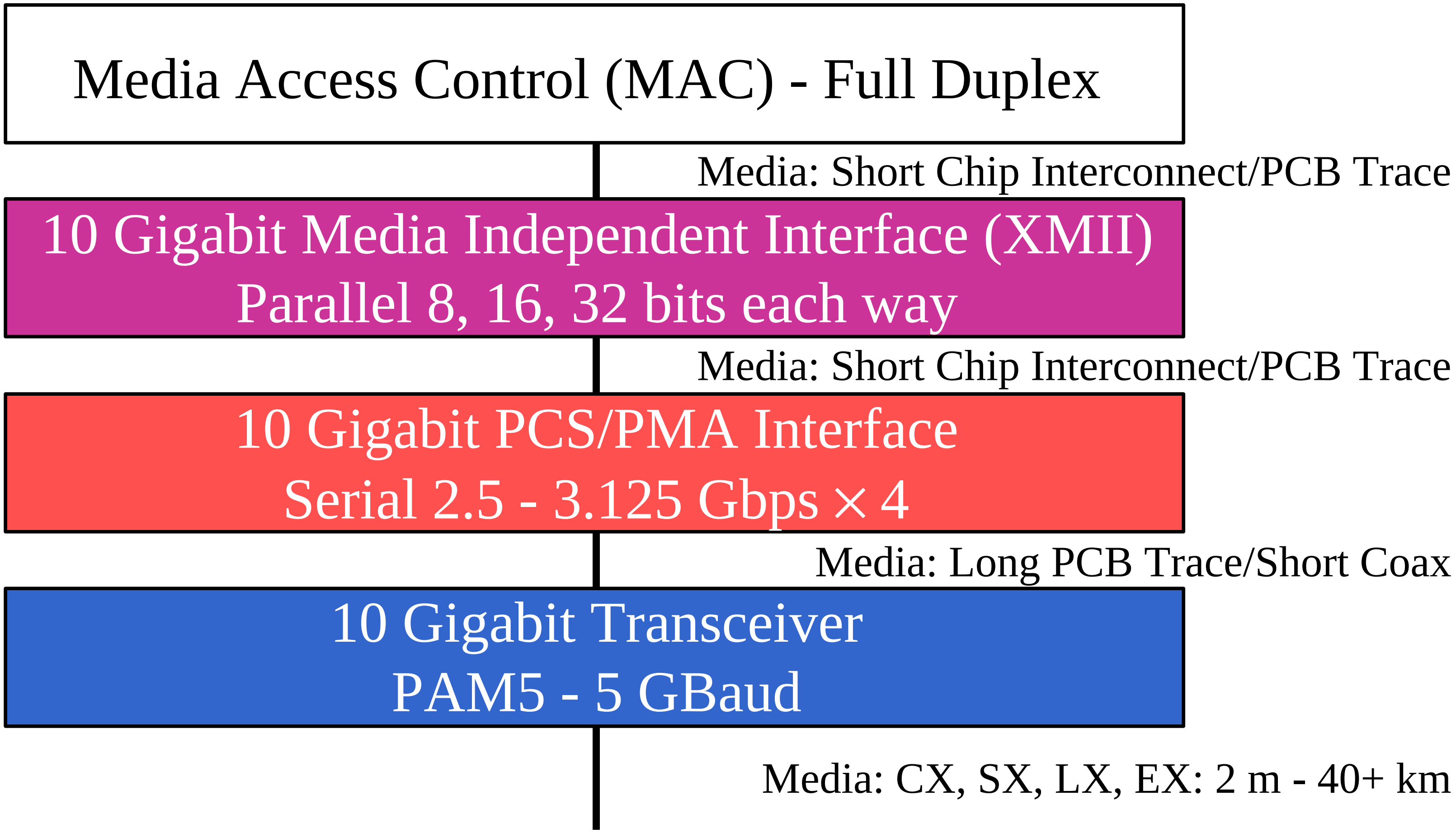
0.35 um	55 ps
0.25 um	40 ps
0.18 um	30 ps ➡ 33 GHz

+ Low cost, High Density and readily available

MAS 10 GbE Technology Basis



MAS Architecture



Media Access Control (MAC) - Full Duplex

Media: Short Chip Interconnect/PCB Trace

10 Gigabit Media Independent Interface (XMII)
Parallel 8, 16, 32 bits each way

Media: Short Chip Interconnect/PCB Trace

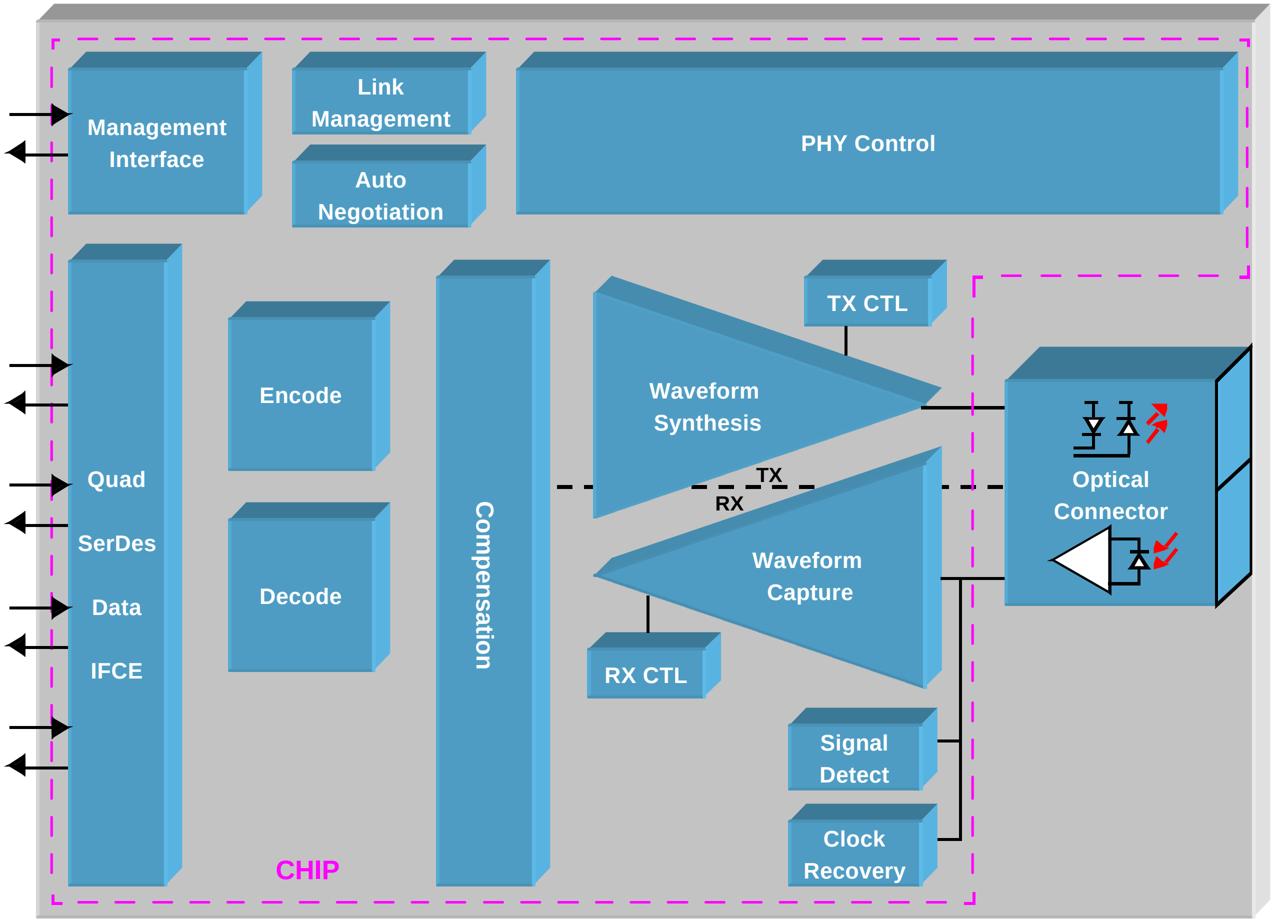
10 Gigabit PCS/PMA Interface
Serial 2.5 - 3.125 Gbps × 4

Media: Long PCB Trace/Short Coax

10 Gigabit Transceiver
PAM5 - 5 GBaud

Media: CX, SX, LX, EX: 2 m - 40+ km

MAS Block Diagram - Transceiver

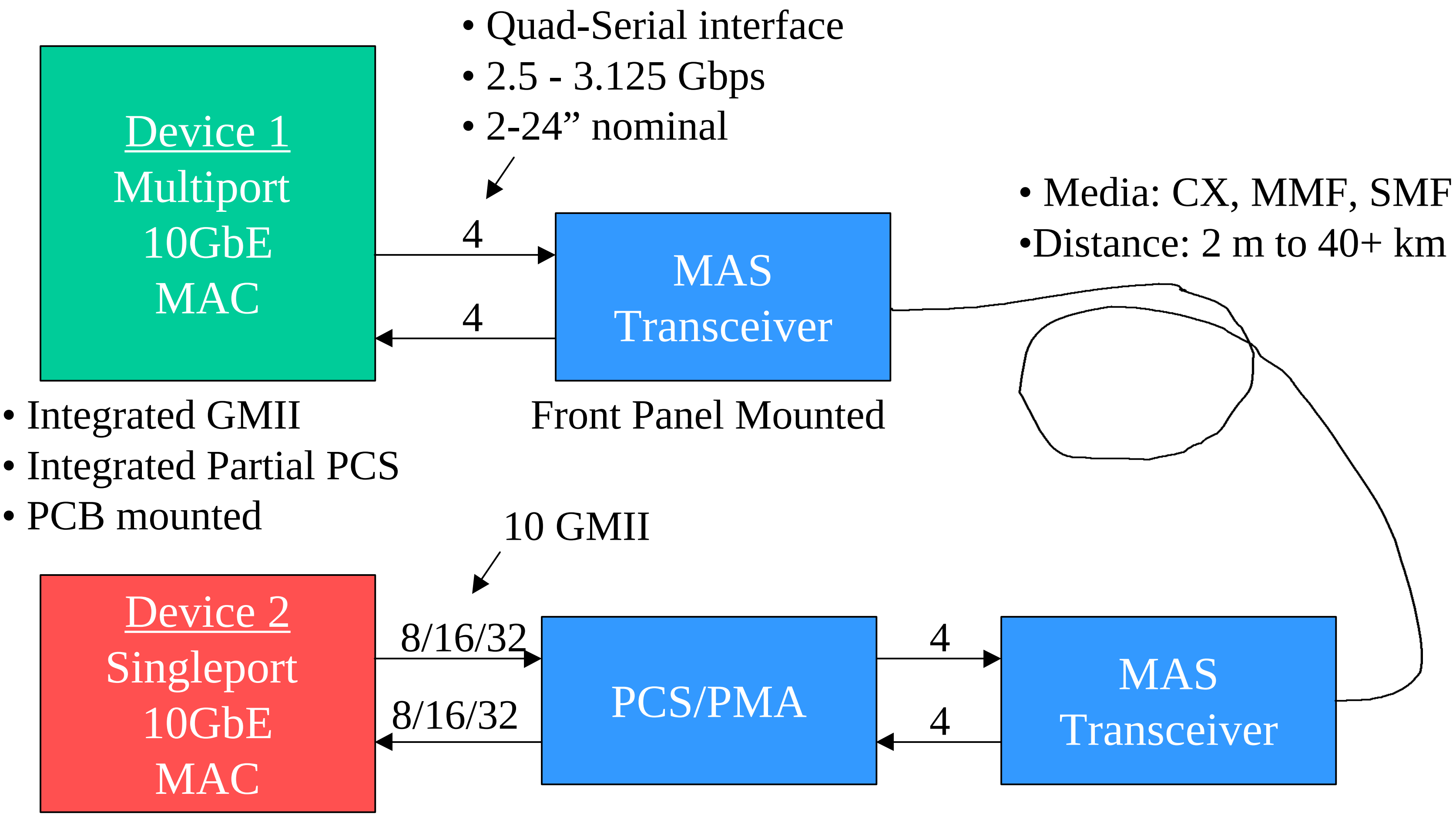


Optics Version shown, Alternatives: CX Version

MAS Link Elements

- Contain high-speed logic to Transceiver
- Support flexible interfaces to MAC
    - Quad Serial 2.5 - 3.125 Gbps to Transceiver
    - Provides flexible MAC/PHY to Transceiver interconnect
    - Per Cisco July; HP, Sun, TI June proposals
    - Applicable to MAS, Serial TDM, WDM, Parallel Optics
- PAM5 Transmission link operates independently of Quad Serial links to MAC/PHY at each link end

MAS System Structure Example



- Quad-Serial interface
- 2.5 - 3.125 Gbps
- 2-24” nominal

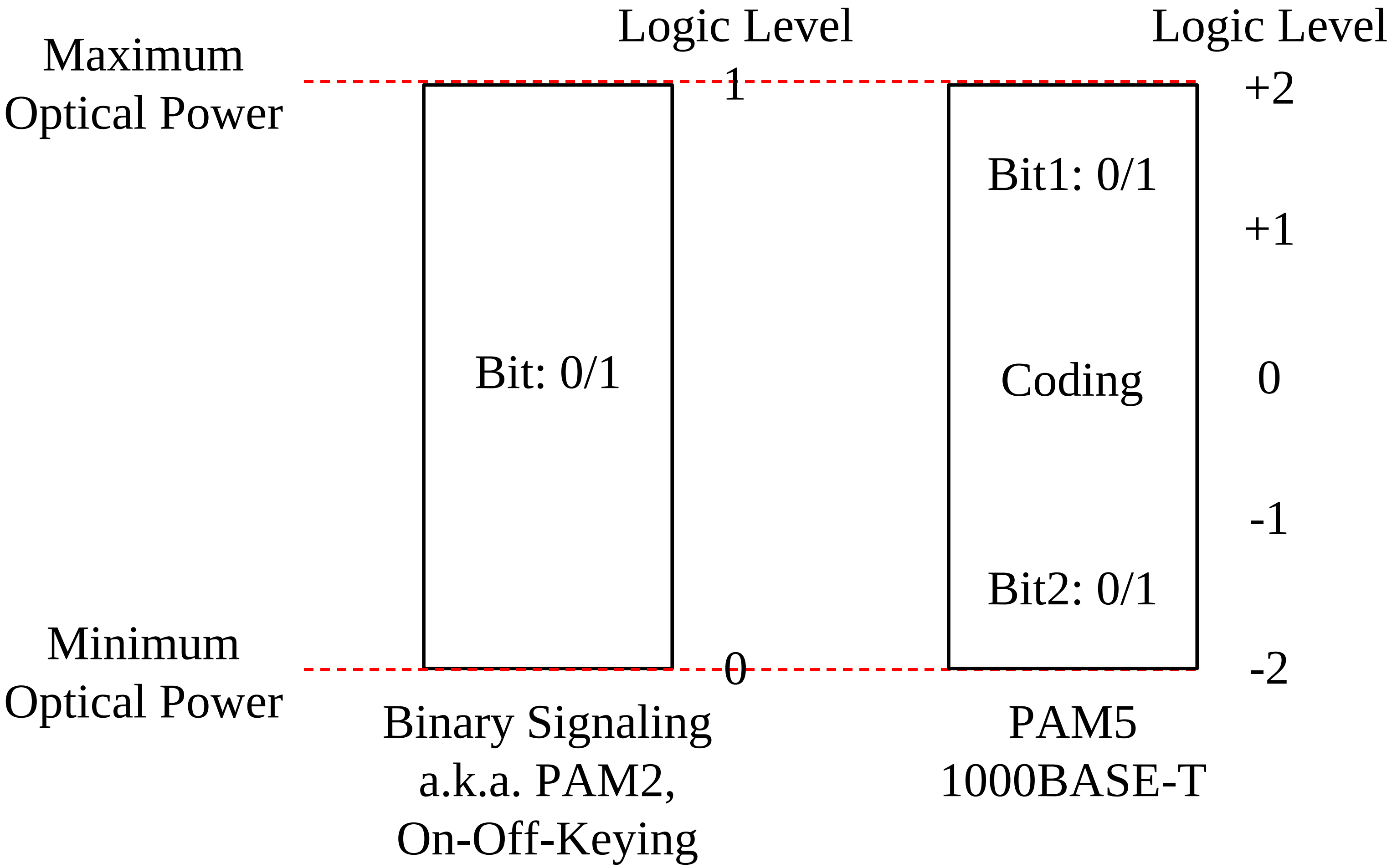
- Media: CX, MMF, SMF
- Distance: 2 m to 40+ km

- Integrated GMII
- Integrated Partial PCS
- PCB mounted

Front Panel Mounted

10 GMII

PMA - Binary vs. PAM5 Signaling



Logic Level

Logic Level

Maximum
Optical Power

1

+2

Bit1: 0/1

+1

Bit: 0/1

Coding

0

-1

Bit2: 0/1

Minimum
Optical Power

0

-2

Binary Signaling
a.k.a. PAM2,
On-Off-Keying

PAM5
1000BASE-T

PAM’s History in Ethernet

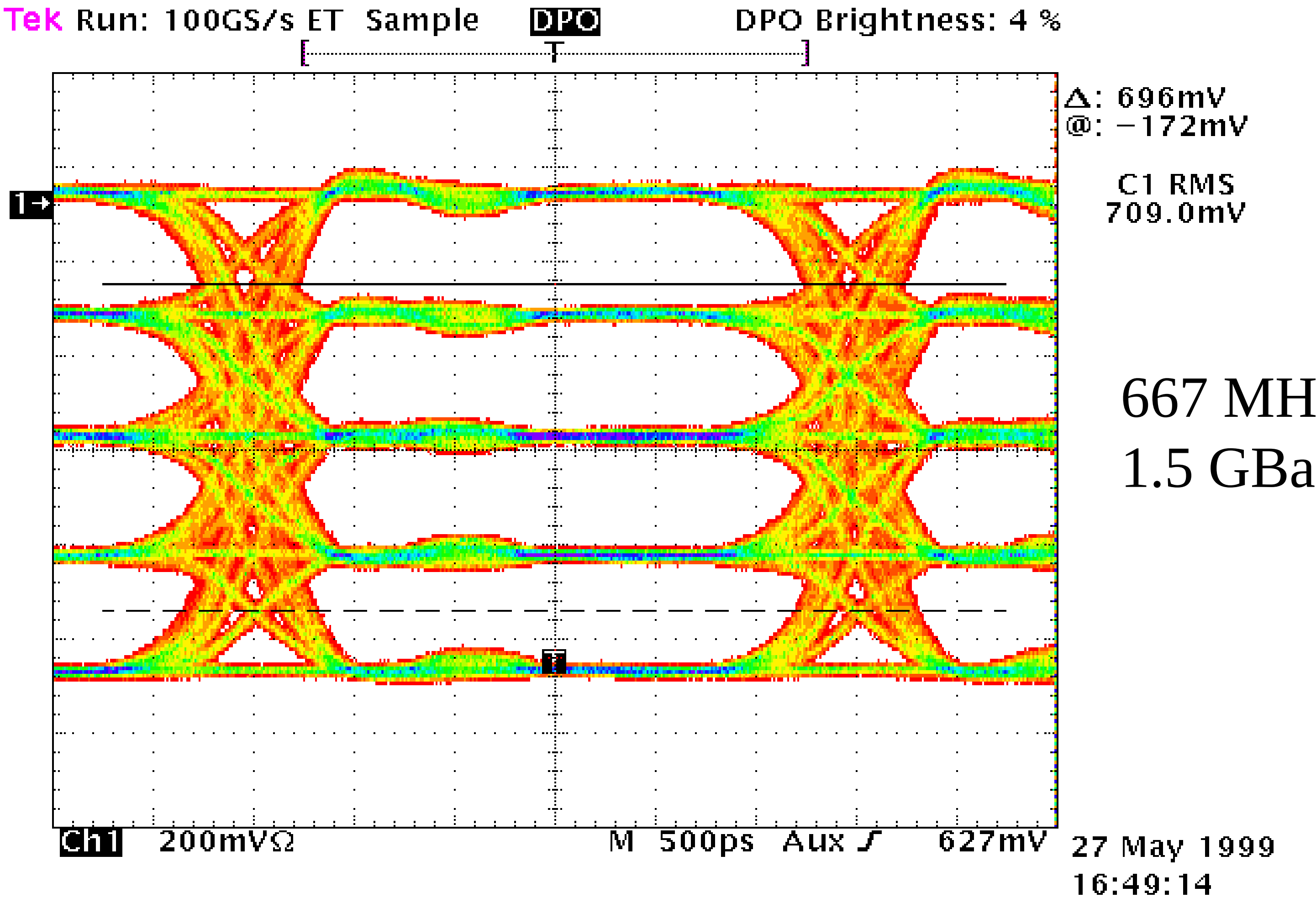
- 100BASE-TX uses multi-level coded symbols
- 100BASE-T4 uses multi-level coded symbols
- 100BASE-T2 uses PAM5
- 1000BASE-T uses PAM5

- MAS, PAM5, is NOT new to Ethernet

PAM5 in 1000BASE-T

- 1000BASE-T employs PAM5 on 4 channels
  - Symbols represents one of five levels (-2, -1, 0, + 1, +2)
  - Each symbol represents two bits plus one extra level
  - PAM5 SNR penalty is 6 dB
  - Extra level provides FEC, special codes, transition density
  - FEC buys back most of the SNR lost by PAM5
  - Equalization buys back the rest
  - 1000BASE-T utilizes PAM5 + FEC + Equalization to get 250 Mbps on each wire pair at only 62.5 MHz, allowing cat 5 UTP usage to 100 m.

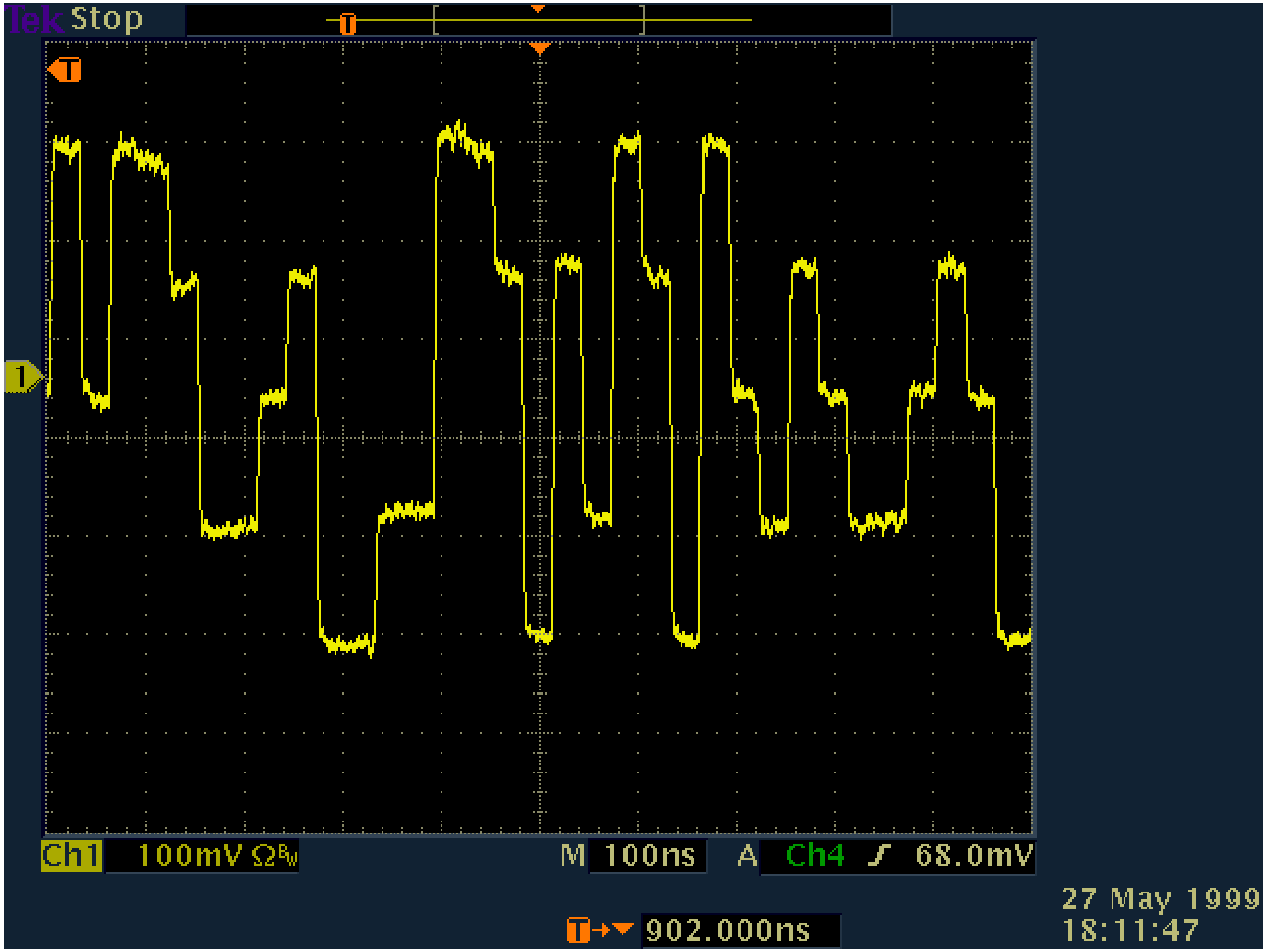
PAM5 Eye Diagram on MMF



667 MHz

1.5 GBaud

PAM5 Signal Appearance Example



30 MHz
60 MBaud

PMD - MAS Optics

- Single Channel Basis
- Laser Diode
- Optical Receiver
- Packaging
- Optical Non-Issues
- Power Penalties

Optical Issues: One vs. Multi-Channel

- Electrical Crosstalk N(N-1) terms (N=#channels)
  - Coupling via parasitics, substrate, supply, etc.
- Optical Crosstalk (2N-2) terms
  - Non-ideal demultiplexer filters or Rx isolation
  - Out-of-band LD emission or Tx isolation
- Optical Attenuation terms
  - Tolerancing in parallel mux/demux in WWDM
  - Additional loss penalty for WDM due to SM optical combiner and WDM demux splitter
- Optical Power Control Link Budget Penalties
  - Multi-channel power skew

OptoEconomics - MAS Transceivers

- Very mature technology
  - Dozens of optical module/transceiver vendors have experience with single-channel optics
- Low entry cost for prospective module vendors
- Complex optical schemes can lock out or substantially delay competitive entry
- Competition = Lower prices for end users
- Simplicity: Reduced parts count, Tolerancing
  - Single LD, PD, associated optics, coupling
- Single critical high-frequency electrical path

OptoEconomics - MAS LD Support

- LD cost dominates the cost of most optical PHYs
- Multiple Laser vendors interested in supplying optoelectronics suitable for MAS
- Indications that MAS Laser costs will compare to standard, low-cost OC-48 Lasers
- As usual, volume needed to drive costs down

Laser Diode Attributes

- Wavelength
- Optical Power
- Bandwidth
- Linearity
- Noise

Laser Wavelength - LW 1310 nm

- MAS independent of Laser Wavelength
  - ◆ Essentially a laser cost vs. distance tradeoff
- Longwave (1310 nm)
  - \+ Higher Class I Laser Safety limit (~ 6 mW)
  - \+ Low attenuation (< 0.5 dB/km)
  - \+ Bandwidth•distance product of legacy fiber is > SW
  - \+ Supports SMF and MMF
  - – Mode conditioning required with MMF
  - \+ Higher reliability
  - \+ Lower LD bandgap and forward voltage
  - – Cost penalty above shortwave lasers

Laser Wavelength - LW 1550 nm

- Longwave (1550 nm) all of 1310 plus:
  - \+ Higher Class I limit (~10 mW)
  - \+ Lower fiber attenuation (< 0.4 dB/km)
  - – Cost penalty above LW 1310 nm lasers
  - \+ Cost penalty may be due to volume difference
  - \+ Can use temperature control to assign to a specific ITU-grid wavelength for DWDM
  - \+ Compatible with EDFAs
  - – Higher dispersion unless Dispersion Shifted Fiber (DSF) is used

Laser Wavelength - SW 850 nm

- Shortwave (850 nm)
  - + Low cost VCSELs
  - – Low Class I limit (~ 0.35 mW)
  - – High fiber attenuation (< 3.5 dB/km)
  - + High bandwidth (to ~2.2 GHz•km) on enhanced MMF

Laser Optical Power

- Maximum power set by laser safety limits, nonlinear threshold, drive, reliability, or receiver saturation, whichever is the lowest.
- Minimum power set by worst-case media loss, penalties, and receiver sensitivity.
- Laser power range may be tightened, depending on the laser power control circuit error, drift, aging, laser safety margin and calibration uncertainty.

Laser Bandwidth

- OC-48 Lasers performance is often encumbered by packaging parasitics.
- BW requirement diminished by half for PAM5 (encoded) relative to 10 GBaud (unencoded)
- BW Laser ~ 1.1 Baud in GHz = 5.5 GHz
- Higher production yield for lower BW lasers
- Lower packaging & integration costs for lower BW lasers

Laser Nonlinearity

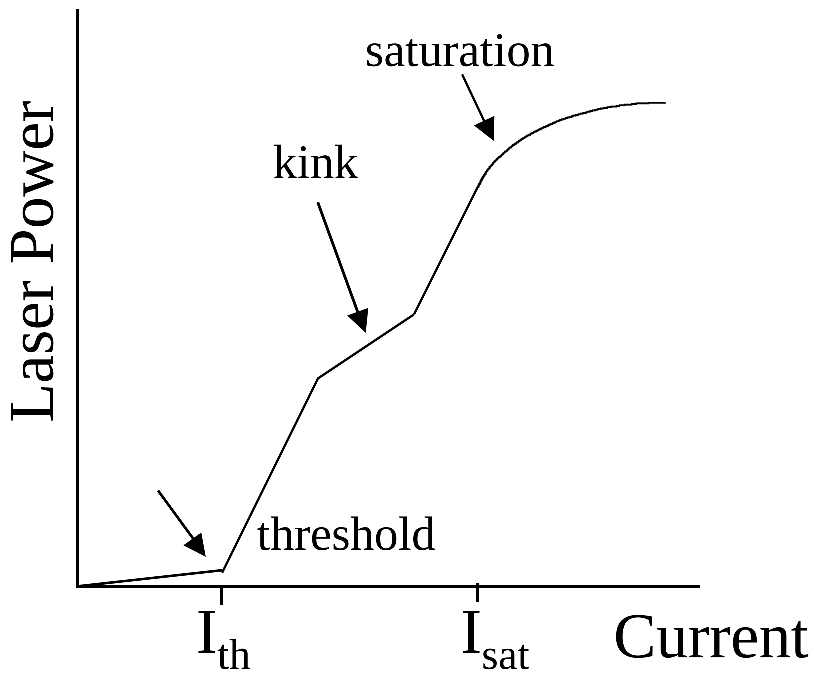
- Causes of Nonlinearity in Laser Diodes
    - Threshold (easily avoided)
    - High-power limiting (VCSELS and detectors)
    - Dynamic self-heating effects (low-frequency)
        - Coding related: DC Balance, Scrambling, etc.
    - Overdrive or operation near resonance such as relaxation oscillation frequency
- Nonlinearity & distortion in drive electronics
- Kinks in the I-L curve

Nonlinearity Effects on the Link

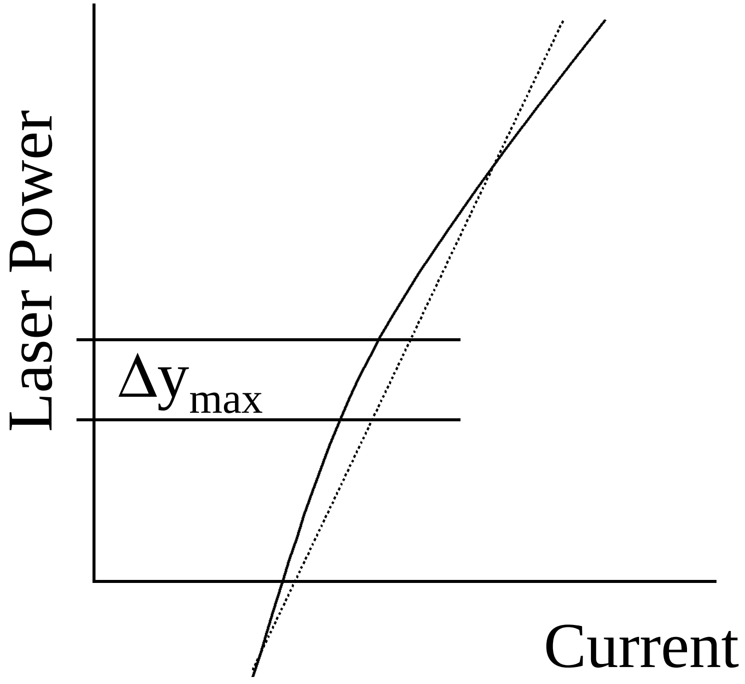
- Large-signal effects such as threshold (I_{th}) and Rx saturation induce a duty cycle distortion.
    - Avoid (I_{th}) and don’t saturate the receiver
- Power penalty due to eye closure
- 2nd, 3rd harmonic, sum & difference frequencies
- Easy for kink-free digital lasers to pass
    - Requirement for kink-free performance over temperature and operating range

Large and Small-Signal Nonlinearity

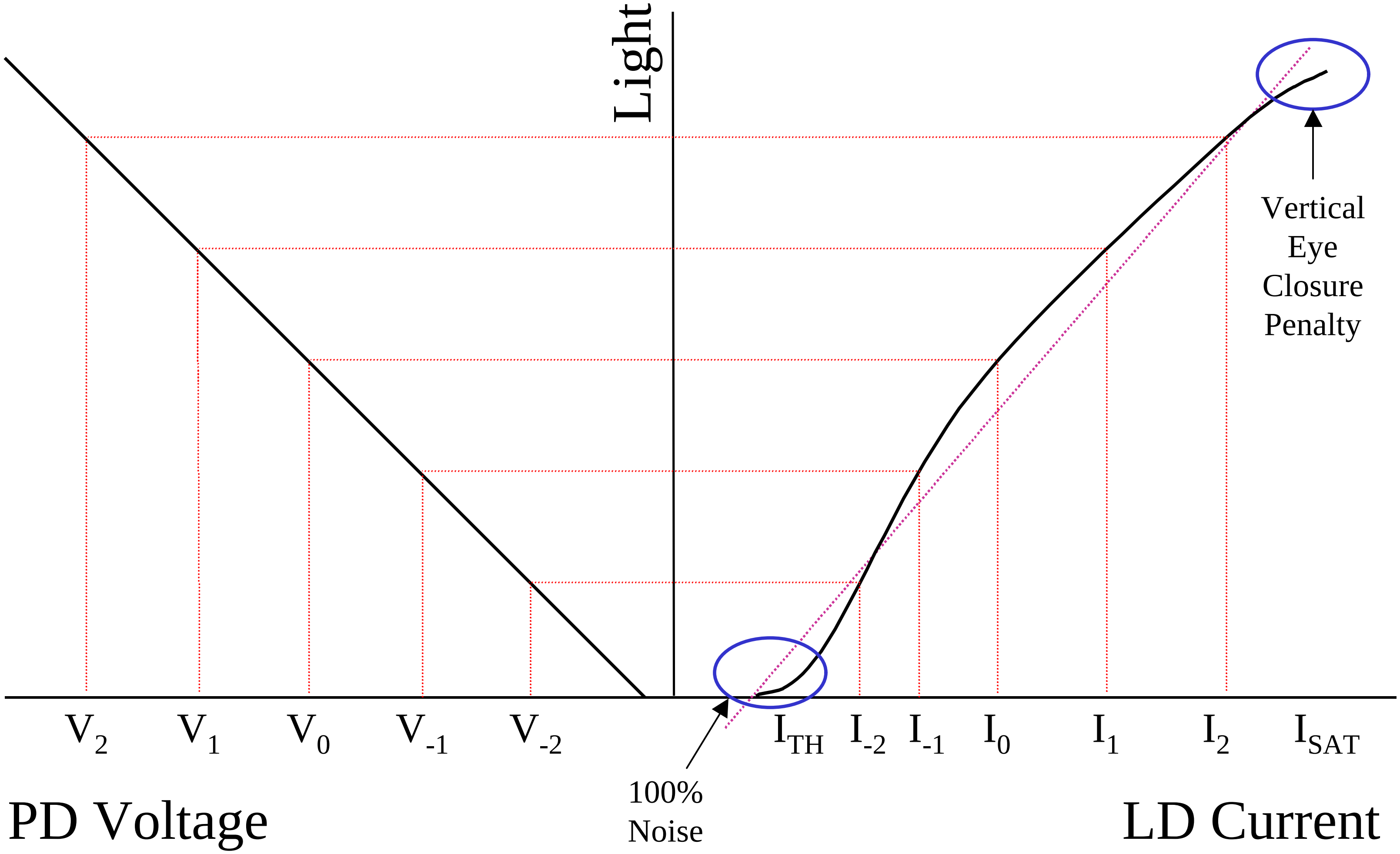
LD Gross Nonlinearity



LD Small-Signal Nonlinearity



Linearity Compensation

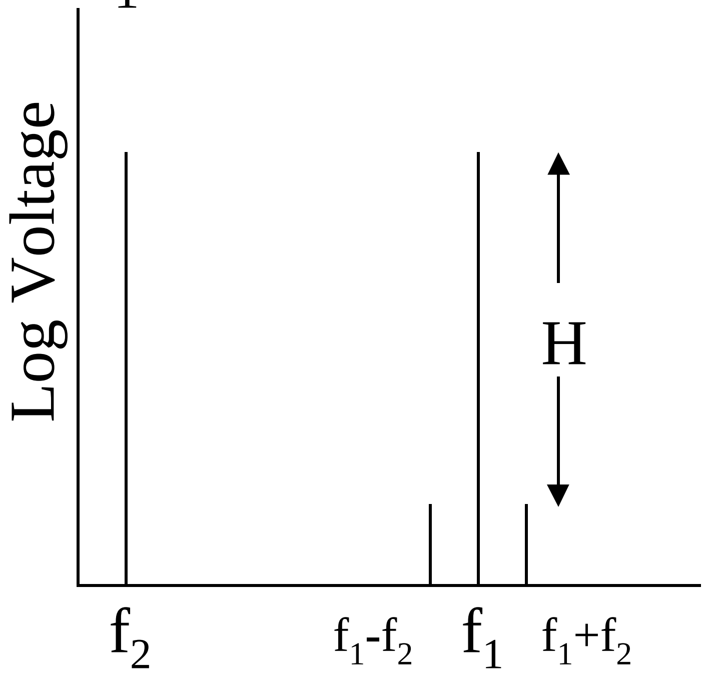


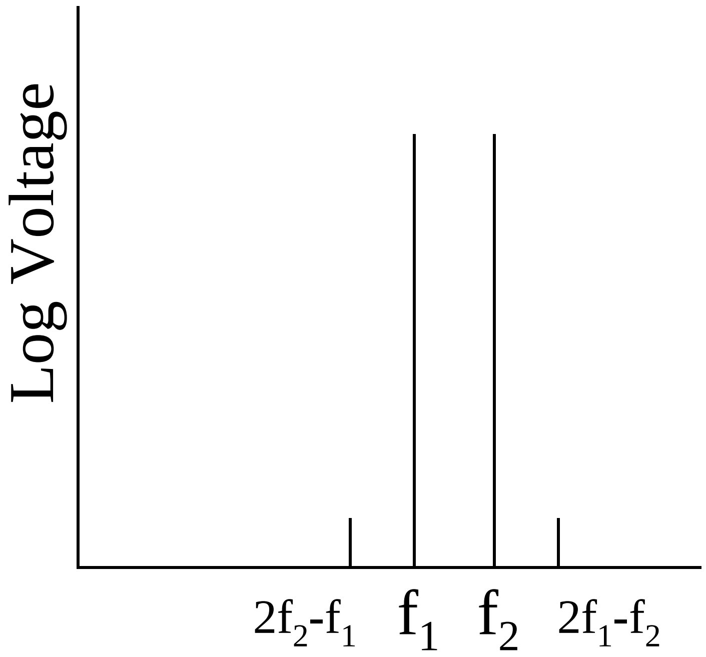
Linearity Experiment

- 2-tone testing
- System baseline > 90 dB not including PD
- PD & amplifier linearity > 70 dB below saturation
- 2 Vendor’s digital 1300 nm DFB lasers
- Measured 3rd harmonic
  - over frequency (250 MHz - 4 GHz)
  - over power (0.25 mW - 2 mW)
  - over modulation index (0.05 - 0.5)
- Both devices were linear (> 40 dB)

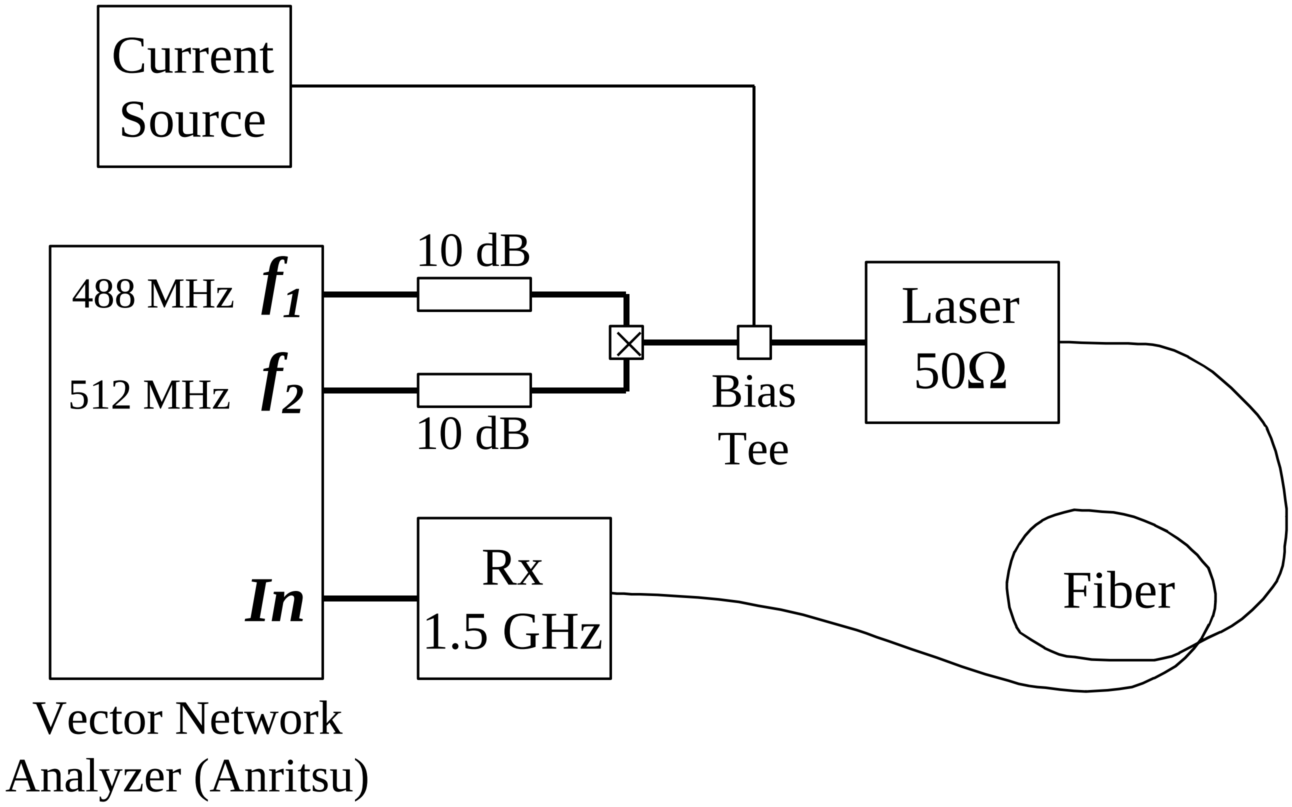
2-Tone Testing

- 2nd-order: Measure ratio H of fundamental tone at f_1 to the intermodulation signal at $(f_2 - f_1)$
- 3rd-order: Measure ratio H of fundamental tone at f_1 to the intermodulation signal at $(2f_2 - f_1)$





2-Tone Nonlinearity Test Setup


Current Source

10 dB

488 MHz f_1

512 MHz f_2

10 dB

Bias Tee

Laser 50Ω

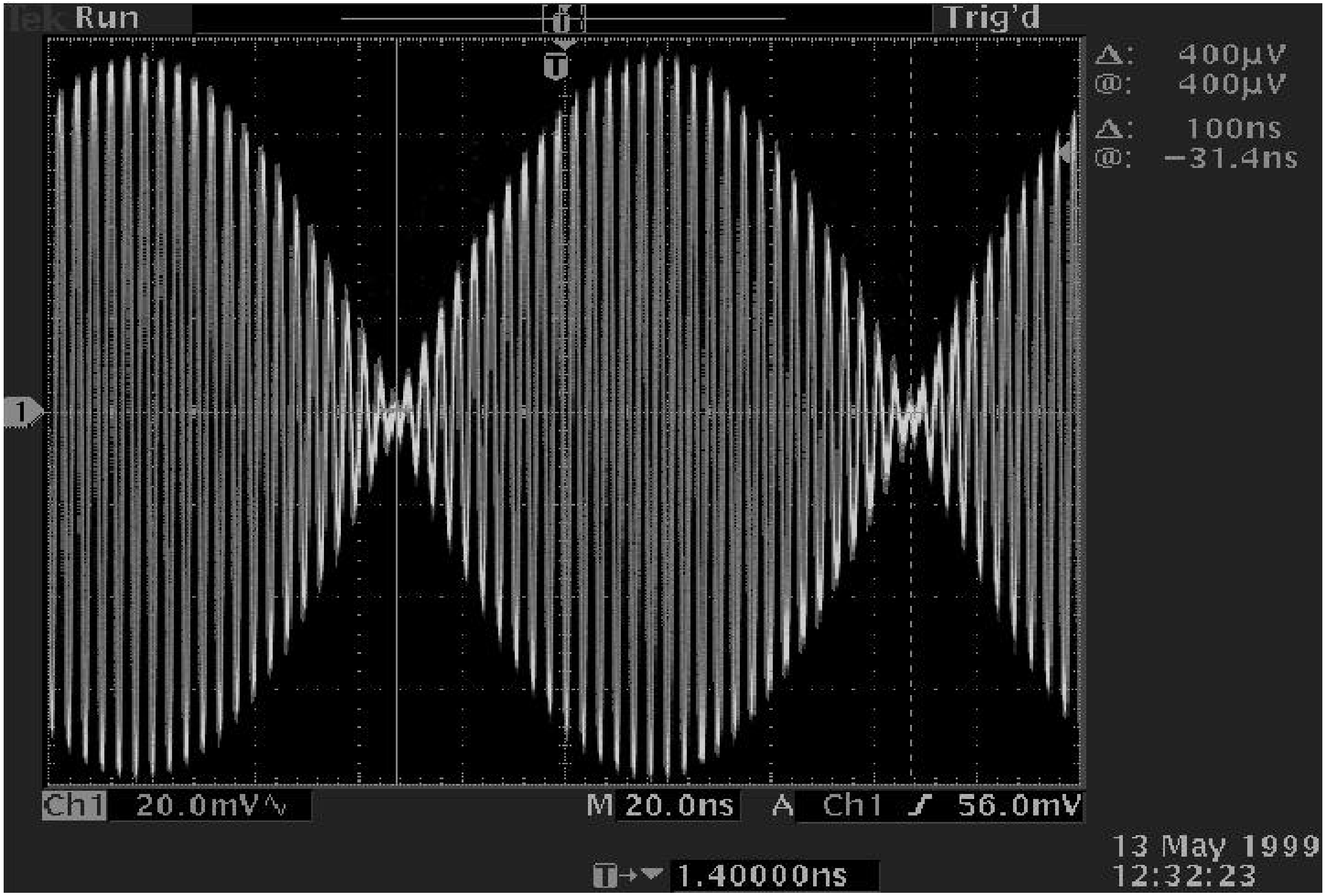
In

Rx 1.5 GHz

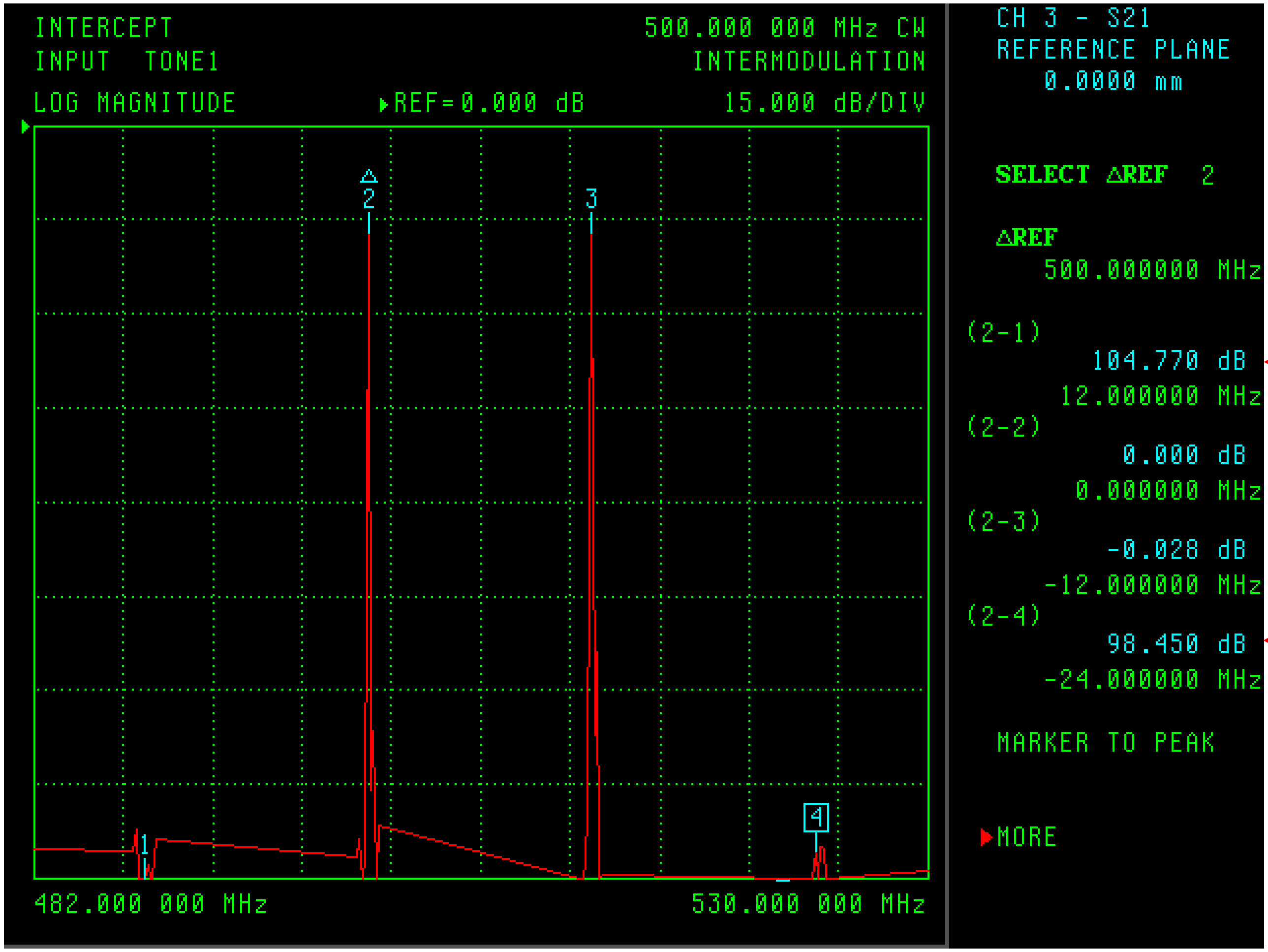
Fiber

Vector Network Analyzer (Anritsu)

Time Domain Baseline



Frequency Domain Baseline



INTERCEPT
INPUT TONE1
LOG MAGNITUDE ▸REF=0.000 dB

500.000 000 MHz CW
INTERMODULATION
15.000 dB/DIV

CH 3 - S21
REFERENCE PLANE
0.0000 mm

SELECT ΔREF 2

ΔREF
500.000000 MHz

(2-1)
104.770 dB
12.000000 MHz

(2-2)
0.000 dB
0.000000 MHz

(2-3)
-0.028 dB
-12.000000 MHz

(2-4)
98.450 dB
-24.000000 MHz

MARKER TO PEAK

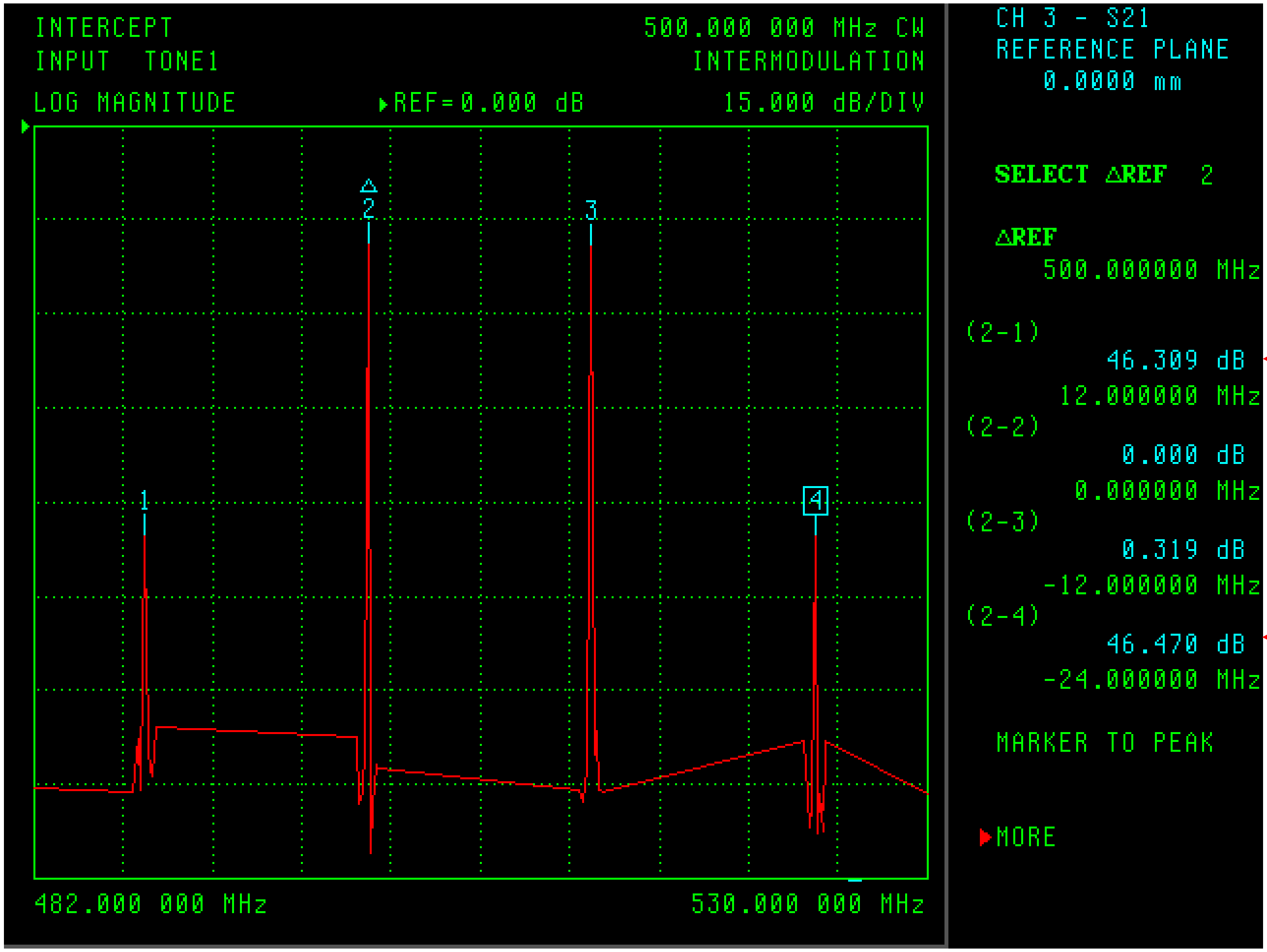
▸MORE

Test System
Nonlinearity
w/o LD/PD

H = ~104 dB

H = ~98 dB

Vendor 1 Laser @ 1 mW



```
INTERCEPT                               500.000 000 MHz CW
INPUT   TONE1                             INTERMODULATION
LOG MAGNITUDE          ▸REF=0.000 dB        15.000 dB/DIV

482.000 000 MHz                           530.000 000 MHz
```

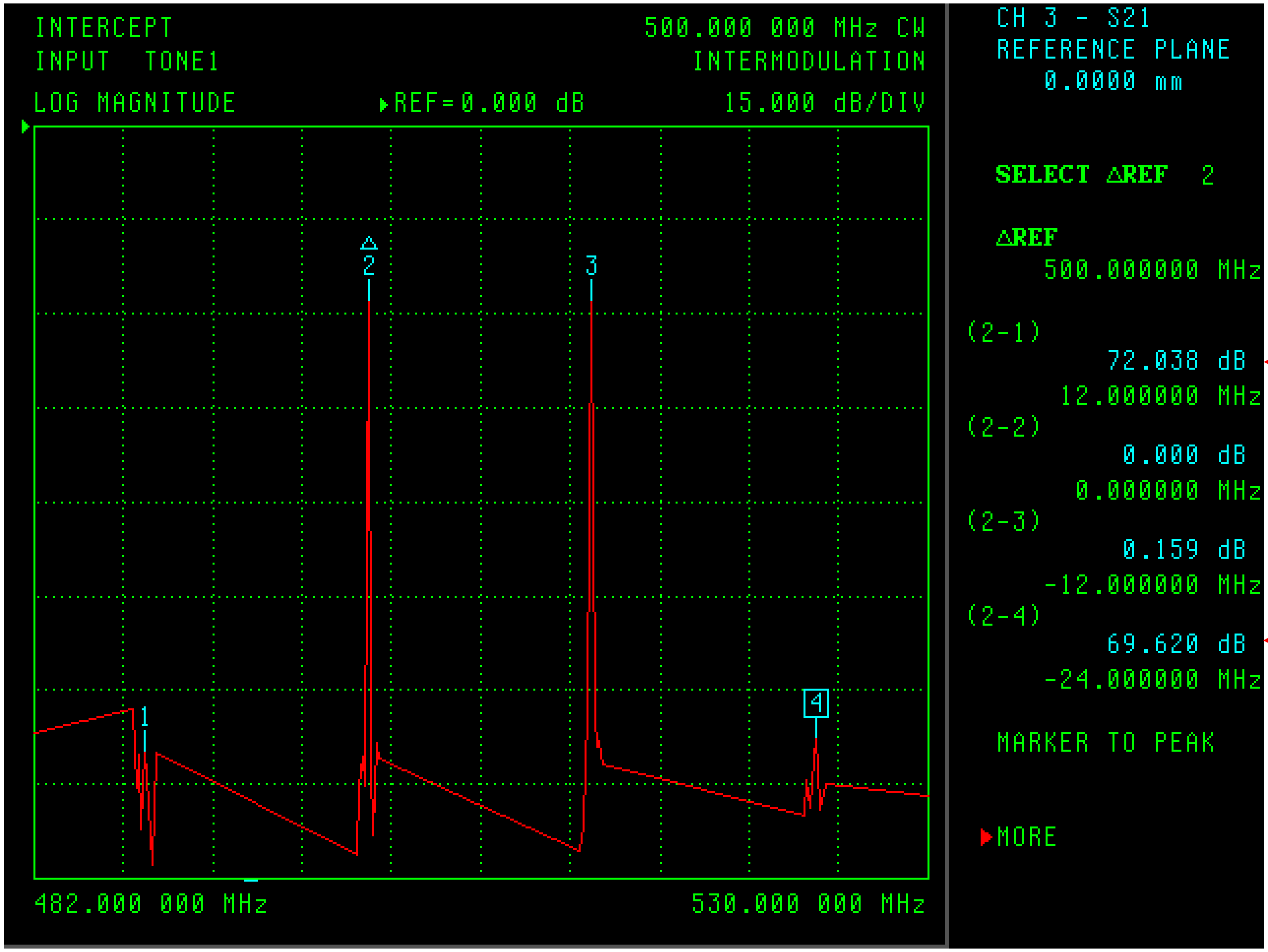
```
CH 3 - S21
REFERENCE PLANE
   0.0000 mm

SELECT ΔREF   2

ΔREF
   500.000000 MHz
(2-1)
        46.309 dB
     12.000000 MHz
(2-2)
         0.000 dB
      0.000000 MHz
(2-3)
         0.319 dB
    -12.000000 MHz
(2-4)
        46.470 dB
    -24.000000 MHz

MARKER TO PEAK

▸MORE
```

DFB Laser
1300 nm
Modulation
  Index: 50%
Coax Package

H = ~46 dB

H = ~46 dB

Vendor 2 Laser @ 1 mW



```
INTERCEPT                                500.000 000 MHz CW
INPUT  TONE1                             INTERMODULATION
LOG MAGNITUDE        ▸REF=0.000 dB        15.000 dB/DIV

482.000 000 MHz                          530.000 000 MHz
```

```
CH 3 - S21
REFERENCE PLANE
   0.0000 mm

SELECT ΔREF  2

ΔREF
   500.000000 MHz

(2-1)
        72.038 dB
     12.000000 MHz
(2-2)
         0.000 dB
      0.000000 MHz
(2-3)
         0.159 dB
    -12.000000 MHz
(2-4)
        69.620 dB
    -24.000000 MHz

MARKER TO PEAK

▸MORE
```

DFB Laser
1300 nm
Modulation
Index: 50 %
Mini-Dil Package

H = ~72 dB

H = ~69 dB

Linearity Calculation

- Linear operation on function X(t)
  $Y(t) = A + B\,X(t)$
  X=input, Y=output, A=Y-intercept, B=slope
- Nonlinear operation
  $Y(t) = A + B\,X(t) + C\,X(t)^2 + D\,X(t)^3 + \ldots$
  Assume non-linearity coefficients C and D << 1, neglect higher-order
- Error is $\Delta Y \approx C\,X(t)^2 + D\,X(t)^3$
- Maximum error is $E = (C/3)^3 / (D/2)^2$
- E.g. 1Ω Resistor: A=0, B=1 V/mA, C=0.001 V/mA^2, D=0.001 V/mA^3, then E=0.00067 V

Requirements Calculation

- Consider the nonlinear transfer function
  $Y(t) = A + B\ X(t) + C\ X(t)^2 + D\ X(t)^3$
  Assume coefficients C and D << 1
- Let $X(t) = \cos(\omega_1 t) + \cos(\omega_2 t)$ this generates
  $Y(t) = A + B\ X(t) + (C/2)\cos(2\omega_1 t) +$
  $(C/2)\cos(2\omega_2 t) + C\cos(\omega_1 - \omega_2)t +$
  $C\cos(\omega_1 + \omega_2)t$ which are the 2nd-order terms
- $+ (D/4)\cos(3\omega_1 t) + (D/4)\cos(3\omega_2 t) +$
  $(3D/4)\cos(2\omega_1 - \omega_2)t + (3D/4)\cos(2\omega_1 + \omega_2)t +$
  $(3D/4)\cos(2\omega_2 - \omega_1)t + (3D/4)\cos(2\omega_2 + \omega_1)t$

  which are the 3rd-order terms

Nonlinearity Characterization

- Laser vendors may specify the nonlinearity as:
  - Composite Second-Order (CATV)
  - Composite Triple-Beat (CATV)
    - Can relate CSO and CTB to the nonlinear coefficients C and D given the # of channels and intermodulation products/channel
  - 2-Tone test at the appropriate frequency is simpler
    - Use Vector Network Analyzer
    - For 2nd-order, 2-tone test, $C = H$
    - For 3rd-order, 2-tone test, $D \approx (4/3)\ H$
      - Assuming the coefficient $D << 1$
    - -20 dB requirement: $D = 0.013$, $C = 0.01$

Laser Linearity Summary

- Power penalty = 10 log [1-(N-1)E]
- Need linearity of -20 dB for <0.25 dB penalty
- Early analysis of a limited sample of standard digital (not CATV) OC-48 DFB class lasers indicate sufficient linearity performance.
- Kink-free lasers appear to be sufficient for MAS deployment.
- Large-signal linearity is a function of link design.
- Production testing for small-signal linearity may not be required.

Laser Noise

- RIN is a catch-all for Noise in a Laser Power
  - RIN = $\langle P^2 \rangle / \langle P \rangle^2$ = variance / $(\text{average})^2$
  - Back Reflections into the laser cavity can make noise very large and chaotic
  - Shot noise from quantum nature of photons and injected carriers (spontaneous emission)
  - Mixing of spontaneous emission with the lasing field
  - Thermal fluctuations
  - Mode-Partition noise, mostly in FP lasers, less problematic in DFB/DBR lasers

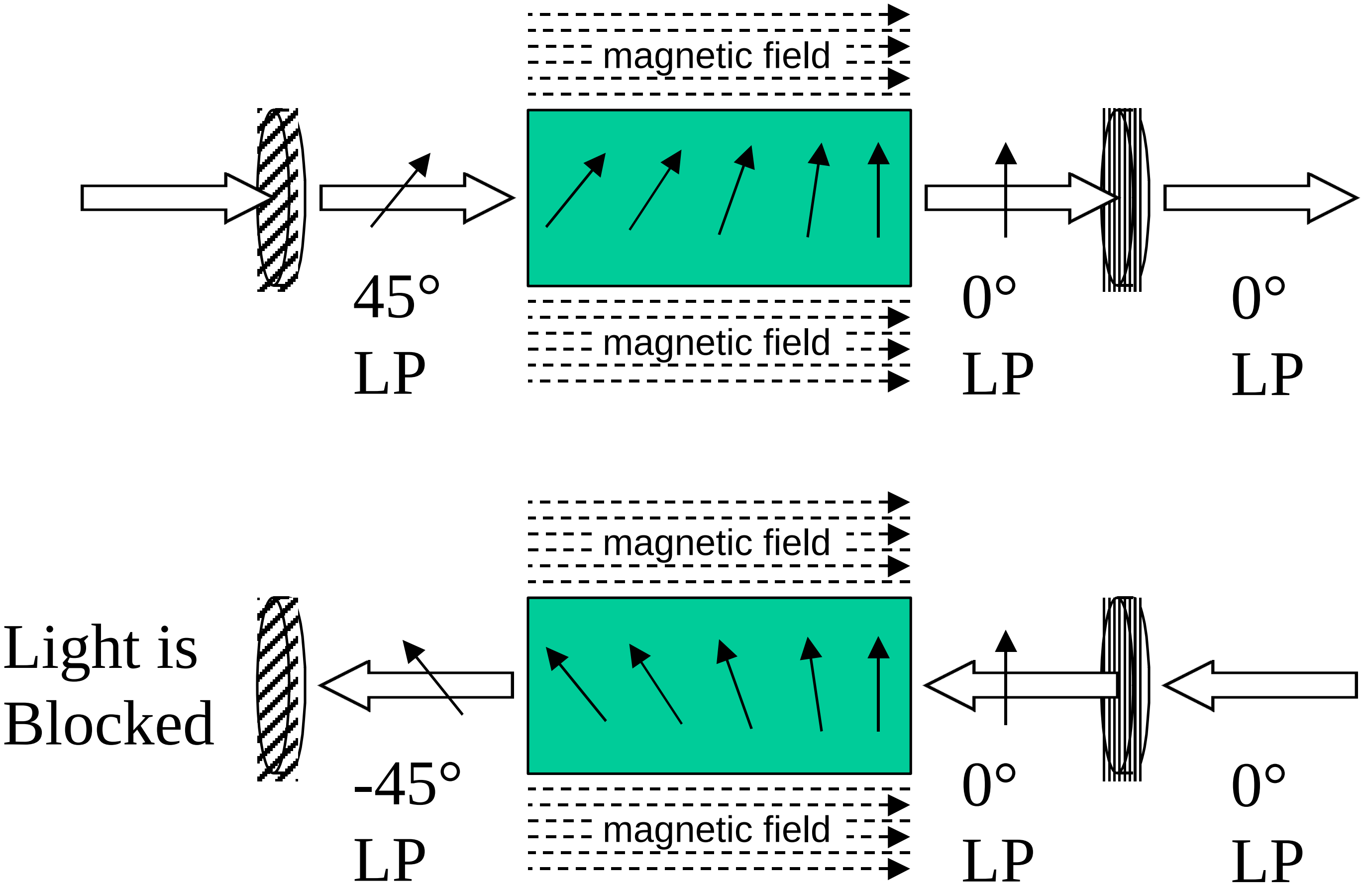
How to Reduce Laser Noise

- Reduce Line Rate and BW (MAS, scrambling)
- Implement FEC for coding gain to offset RIN
- Tighten RIN specification on lasers
    - For RIN-dominated systems, a 6 dB RIN decrease yields a 3 dB SNR improvement
- Optimize laser for low threshold, high carrier density and high relaxation oscillation frequency
- Cooling is not a cost-effective option
- Add an Optical Isolator

Optical Isolator

- An Isolator is a "check valve" for light
- Avoids Back Reflections from connectors
- Very compact device, easy to integrate
    - For a low-noise laser, an isolator preserves the intrinsic laser RIN in a system with large back reflections
- Cost is << 50% of a single DFB laser
- Small loss penalty < 0.5 dB
- Difficult to incorporate into multi-channel lasers
- Tradeoff Isolator cost against FEC silicon cost to achieve System BER Objective.
    - Suggested MAS Direction: Robust FEC

Optical Isolator Basics



LD Example Requirements, LX

- OC-48 class DFB/DBR laser
- 1310 nm wavelength
- 1 mW average power
- Nominal Linearity (-20dB ~ -30dB)
- RIN better than -125 dB/Hz
  - Tradeoff against FEC complexity, Isolator cost
- 5.5 GHz Bandwidth (<65 pSec)
- Carrier, Die, or other HF packaging

Note: Work in progress, not Absolute Requirements

Optical Receiver Attributes

- Wavelength
- Optical Power
- Bandwidth
- Linearity
- Noise

Receiver Wavelength and Power

- Rx saturation level is set by the best-case responsivity, headroom in the photodetector biasing and subsequent amplification stages.
- Cannot use traditional limiting post-amp
  - Requires linear post-amp
- LW Receiver is more sensitive than SW
- Receiver noise can dominate ultimate sensitivity at low power levels.

Receiver Bandwidth

- BW requirement diminished by half for PAM5 (encoded) relative to 10 GBaud (unencoded)
- BW Receiver ~ 0.75 Baud in GHz = 4.0 GHz
- Integrated PhotoDiode (PD) and Trans-Impedance Amplifier (TIA) component availability is much higher @ 4.0 GHz than >7.5 GHz (10 GBaud)
- Higher production yield for lower BW devices
- Lower packaging & integration costs for lower BW devices

Receiver Linearity

- PDs are intrinsically very linear
- Avoid saturation and compression regimes
- Gain of TIA and postamp sets AC/DC saturation
- Care in design of Rx electronics yields low NL

Receiver Noise Components

- Shot Noise: $\propto \sqrt{BW} \quad \propto \sqrt{Power}$
- Thermal Noise: $\propto \sqrt{BW}$
- Dark Current Shot Noise: $\propto \sqrt{BW} \quad \propto \sqrt{I_{DARK}}$
- 1/f Noise: at low frequencies
- Amplifier Noise: design & component selection
- Power Supply Rejection Ratio:
  design & component selection
- Uncorrelated crosstalk and EMI Susceptibility:
  layout and shielding

Optical Sub-Assembly Packaging

- MAS PHY is OSA and connector independent
- Supports MMF & SMF installed and new media
- Duplex-SC and Small Form Factor Integration
- OSA package independence
  - Pigtailed HF packaging, e.g. mini-DIL
  - Traditional coaxial OSA’s
  - V-groove, microbench, MT-type technology
- More flexibility for module implementation

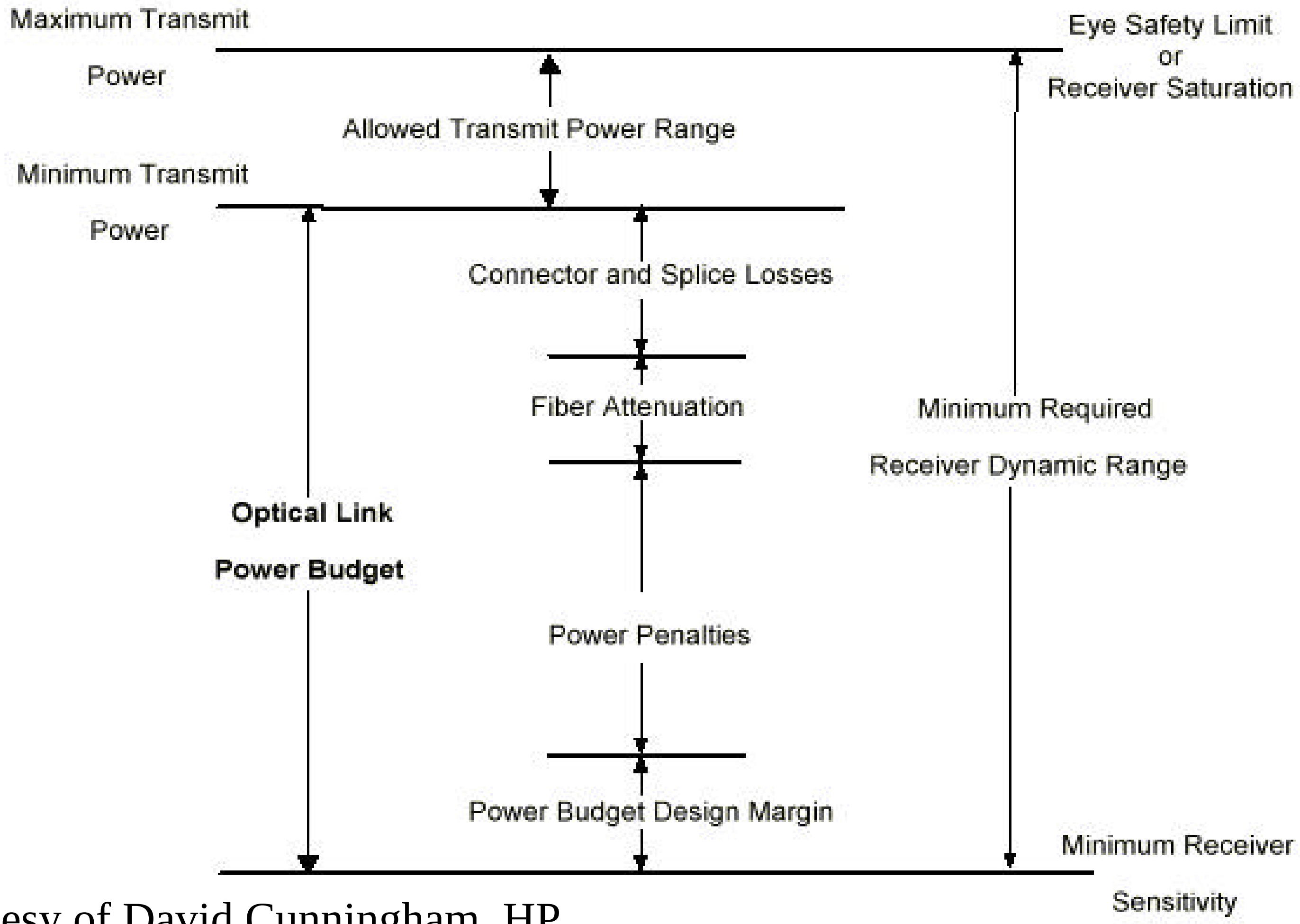
MAS Optical Non-Issues

- Receiver Nonlinearity
- Sidemode Supression Ratio
- Laser Absolute Wavelength
- Laser Temperature Control
- Photodetector linearity
- Skew
- Crosstalk

Optical Power Penalties

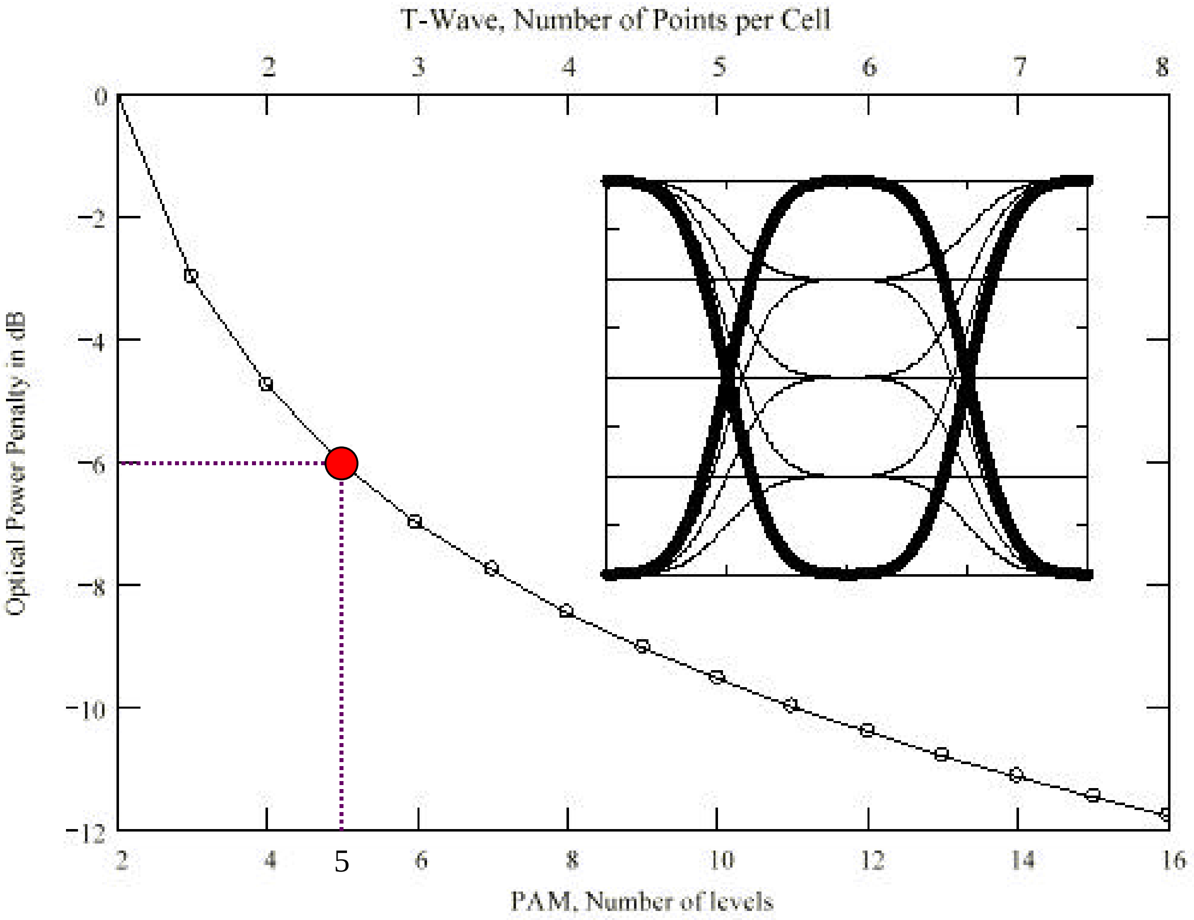
- Power Penalties need to be carefully re-examined for MAS
  - DFB lasers not covered in GbE link model
  - Model must be normalized for higher data rates/Baud according to the number of PAM levels
  - PAM power penalty $P_N = 10\log(N-1)$
- New Power Penalties also applicable to OOK
  - Laser Chirp penalty, if any
  - Polarization Mode Dispersion (long distance SMF)

Conceptual Optical Power Budget



Courtesy of David Cunningham, HP

PMA - PAM5 Optical Power Penalty



PAM5 penalty
6 dB

Note: Constant Symbol Rate Assumed

Courtesy of David Cunningham, HP

Beyond PAM5

- PAM5 significantly more cost effective than PAM2
  - FEC and Link Calibration offset PAM5 losses
  - Careful system design enables more PAM levels
  - For a 3 dB link penalty, PAM9, 3 bits/Baud, 3.33 GBaud, f_o 1.875 GHz, supporting MMF with 500 MHz•km/1.875 GHz ≈ 267 m
    - Only 5.6% higher Baud than 3.125 GBaud
    - Enables simpler CDR, DAC, ADC designs
    - Enables simpler equalization designs, longer distances
- The technology to go beyond PAM 5 is here now

PCS - Coding

- PAM5 systems have coding requirements similar to those of PAM2 (e.g. GbE’s 8B/10B) including:
  - Special Symbol support (SOP, EOP, etc.)
  - DC Balance (jitter containment)
  - Transition Density (CDR)
  - Error Containment (minimal error multiplication)
- PAM5 adds FEC to these requirements
  - Possible FEC codes include:
    - Trellis/Viterbi (e.g. 1000BASE-T)
    - Reed-Solomon
      - E.g. RS(255,239) code in 10^{-4} BER, out 10^{-14} BER

PAM5 Coding Direction

- One 1000BASE-T PCS octet maps to one symbol spread across 4 wire pairs (1 Baud interval).
- 10 GbE maps one 1000BASE-X equivalent octet to 4 consecutive Baud intervals.
  - PAM5 symbol = $5 \times 5 \times 5 \times 5$ = 625 code points
- 8B/10B supports 256 data codes, 12 special codes
  - 268 codes map to ~ 400/1024 total codes
- PAM5 goal is to map 625 code points to the 268 codes AND meet all other coding requirements including FEC.

FEC Coding Gain

- Redundancy is used by all Forward Error Correction (FEC) codes to perform Error Detection and Correction (EDAC).
- FEC codes allow a receiver in the system to perform EDAC without requesting a retransmission.
- FEC codes enable a system to achieve a high degree of data reliability, even in the presence of significant signal noise.
- FEC usage can offer significant effective SNR improvement in systems where improvement using any other means is very costly or impractical.
  - E.g. Increased transmit power, expensive lower noise components.
- FEC SNR improvement is sometimes called “coding gain”.

FEC Latency

- Worst case: A long block length Reed Solomon code, such as (255,239)
  - 255 bytes @ 100 ps/bit = 204 nsec @ 10 Gbps
  - Light travels through a fiber at a rate of ~5 ns/m
  - 204 ns/(5ns/m) = 40.8 m of fiber optic cable
  - Actual delay depends heavily upon the particular implementation (e.g. degree of parallelism, hardware vs. tables vs. firmware, etc.)
  - Negligible latency effects on full duplex links
  - SNR/BER gain of FEC vs. additional gates/latency is a good tradeoff

MAS PMD

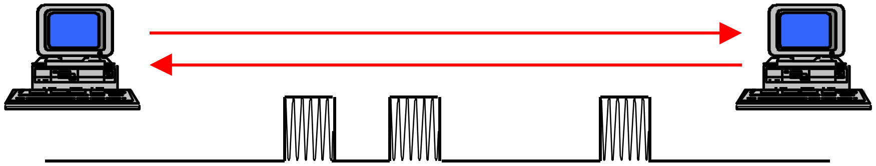
- PMD independent, supports SX, LX, EX, CX
- Supports the same media as 1000BASE-X
- Supports similar distances as 1000BASE-X
    - 62.5 µm MMF, 500 MHz•km, 1300 nm ≈ 200 m
    - 50 µm MMF, 1250 MHz•km LOF, 1300 nm ≈ 500 m
    - Even longer distances @ 850 nm with VCSELs and newer enhanced MMF, 2200 MHz•km ≈ 880 m
    - SMF 1300 nm ≈ 10-15 km

Auto-Negotiation (AN)

- Unrelated to MAS technology, distinct protocol
- Simplifies the 1/10 GbE integration task
- Uses Tone-based signaling akin to FLPs
    - New AN protocol for optical/copper serial links
    - Enables speed negotiation: 1/10 GbE operation
- Provides transport for MAS Link Calibration
- Leverages all of Ethernet AN except new Tones
- Achieves functional parity with UTP AN products
- Operational Benefit: Most useful to determine why two connected devices don’t work

Auto-Negotiation Review

- Method used to exchange information between 2 stations;
- Used to configure operating parameters such as speed, flow control;

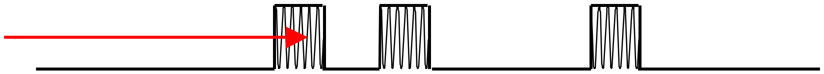


- An AN device advertises its abilities and detects the abilities of its Link Partner (remote device);
- AN information is exchanged using link pulses and acknowledged;
- AN compares the two sets of abilities and uses a priority resolution algorithm to establish the best mode of operation;
- The highest performance common technology is attached to the media;
- AN becomes transparent until reinvoked due to reset, power-on, link failure, etc.;
- Allows for automatic link establishment without user intervention.

Toning

- Serial Receivers include two receive circuits
  1) Data Acquisition logic   2) Signal Detect logic
- Data Acquisition logic limitations
  - Frequency response limitations
    - Prevents direct communication between 1X and 10X variants
- Signal Detect logic may be used to detect Tones
  - Tones may be used between 1× and 10× variants
- Existence Proof
  - P1394b startup protocol
- Use Toning as basis for Serial AN Signaling

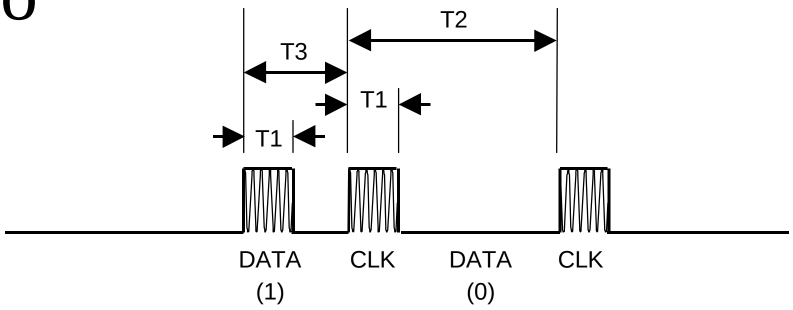
Tone Frequency



- Should support 1X - 10X or greater speed variants
  - Example Frequency: 625 MHz square wave
    - b’1010101010/0101010101’ 8B/10B D21.5 code @ 1X speed
    - b’1100110011/0011001100’ 8B/10B D24.3 code @ 2X speed
    - b’1100000111/0011111000’ 8B/10B K28.7 code @ ≥4X speed
- Probably invisible to interfaces less than 1 GbE
    - Tone frequency above Fast Ethernet & Ethernet filters
    - Propose that lower speed Ethernet variants are not interoperable
    - If AN is supported by only one link end, and AN fails, it is assumed that the link partner is a 1GbE device

Tone Pulse Timing

- Tone Pulses correspond to Fast Link Pulses (FLP)
- Pulse Timing basis is Signal Detect response
  - Specs may be derived from GBIC, GbE, P1394b
  - Transmit Disable pulsing possible, extends AN time



- Proposed Pulse and Pulse-to-Pulse timings
  - T1 - Pulse Duration: 50 µs
  - T2 - Clock-to-Clock/Data-to-Data Duration: 200 µs
  - T3 - Clock-to-Data/Data-to-Clock Duration: 100 µs

Tone Pulse/Burst Protocol

- Tone Pulses are arranged 17-33 Pulses to a Burst
- Tone Bursts are transmitted repeatedly until ACK’d by Link Partner
- Tone Burst Protocol includes Base Page and Optional Next Page Exchange
- Priority Resolution algorithm establishes best mode of operation
  - The highest performance common technology is enabled

or

  - Management can tell why the 2 devices don’t work

Link Calibration

- Uses information in Tone Pulses sent during AN to calibrate transmitter power and receiver levels
  - Executes simultaneously with AN protocol
  - Sets optimum transmit power for each link
  - Sets optimum receiver thresholds
  - Increases optical link budget
  - Eliminates optical compression penalty
  - Compensates for laser non-linearity
  - Similar in nature to, but much simpler than 1000BASE-T PHY-Startup

MAS Summary

- Digital grade lasers have sufficient linearity
- Provides two more variables, Baud & Number of Intensity Levels, for system tradeoff
- Is independent of PMD choices
- Scalable to even higher data rates

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