Multi-Level Analog Signaling Techniques for 10 Gigabit Ethernet
MAS Tutorial Presenters

• Rich Taborek - MAS PHY Architecture
  ◆ Principal Architect
    ■ 650 210 8800 x101, rtaborek@transcendata.com

• Bob Dahlgren - Fiber Optic Components
  ◆ Director, Fiber Optic R&D
    ■ 650 210 8800 x103, bob@transcendata.com

Transcendata, Inc.
1029 Corporation Way, Palo Alto, CA 94303
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

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

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 $3 \times$ 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
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, $10 \times$ 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 (Gbps)
- 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

• Example gate delay per inverter in ring oscillator

<table>
<thead>
<tr>
<th>Width (um)</th>
<th>Delay (ps)</th>
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<tbody>
<tr>
<td>0.35</td>
<td>55</td>
</tr>
<tr>
<td>0.25</td>
<td>40</td>
</tr>
<tr>
<td>0.18</td>
<td>30, 33 GHz</td>
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</table>

+ Low cost, High Density and readily available
MAS 10 GbE Technology Basis

**IEEE 1000BASE-X**
- PCS - 8B/10B
- AN - Link Test
- PMD - SX, LX, CX

**IEEE 1000BASE-T**
- PCS - Scrambling
- PCS - Trellis/Viterbi
- PMA - PAM5
- AN - Multi Speed

**10 Gigabit Ethernet**
- MAC
- PHY
  - PCS - Coding
  - PMA - MAS
  - PMA - Link Monitor
  - Auto-Negotiation
  - PMD - S,L,E,CX

**Other Technologies**
- PCS Reed-Solomon
- PMA - MAS
- PMA - Link Monitor
- AN - Serial
- AN Link Calibration
- PMD - EX 1550 nm
MAS Architecture

Media Access Control (MAC) - Full Duplex

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: Short Chip Interconnect/PCB Trace

10 Gigabit Transceiver
PAM5 - 5 GBaud
Media: Long PCB Trace/Short Coax

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

Device 1
Multiport 10GbE MAC
- Integrated GMII
- Integrated Partial PCS
- PCB mounted

Device 2
Singleport 10GbE MAC
- 8/16/32

MAS Transceiver
- Front Panel Mounted
- Quad-Serial interface
- 2.5 - 3.125 Gbps
- 2-24” nominal

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

PC/PM
- 10 GMII
- 4
- 4
- 4
- 4

MAS Transceiver
PMA - Binary vs. PAM5 Signaling

<table>
<thead>
<tr>
<th>Bit</th>
<th>Binary Signaling (a.k.a. PAM2, On-Off-Keying)</th>
<th>Logic Level</th>
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</thead>
<tbody>
<tr>
<td>0/1</td>
<td>0 -2</td>
<td>1</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Bit1: 0/1</th>
<th>Bit2: 0/1</th>
<th>Coding</th>
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<tbody>
<tr>
<td>+2</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>+1</td>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>-2</td>
</tr>
<tr>
<td>1000BASE-T</td>
<td>PAM5</td>
<td></td>
</tr>
</tbody>
</table>

Maximum Optical Power

Minimum Optical Power
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 ($N=\#\text{channels}$)
  - 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

Laser Power

\( I_{th} \)

\( I_{sat} \)

Current

\( \Delta y_{max} \)
Linearity Compensation

PD Voltage

LD Current

Light

I_{TH} I_2 I_1 I_0 I_1 I_2 I_{SAT}

V_2 V_1 V_0 V_{-1} V_{-2} 100% Noise

Vertical Eye Closure Penalty

100% Noise
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

\[ f_1 \]
488 MHz

\[ f_2 \]
512 MHz

\[ I_n \]

10 dB

Bias Tee

Laser 50Ω

Rx 1.5 GHz

Vector Network Analyzer (Anritsu)

Fiber
Time Domain Baseline
Frequency Domain Baseline

Test System Nonlinearity w/o LD/PD

H = \sim 104 \text{ dB}

H = \sim 98 \text{ dB}
Vendor 1 Laser @ 1 mW

DFB Laser
1300 nm
Modulation Index: 50%
Coax Package

H = ~46 dB

H = ~46 dB
Vendor 2 Laser @ 1 mW

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

H = ~72 dB
H = ~69 dB
Linearity Calculation

- Linear operation on function $X(t)$
  $$Y(t) = A + B \cdot X(t)$$
  $X$=input, $Y$=output, $A$=Y-intercept, $B$=slope

- Nonlinear operation
  $$Y(t) = A + B \cdot X(t) + C \cdot X(t)^2 + D \cdot X(t)^3 + \ldots$$
  Assume non-linearity coefficients $C$ and $D \ll 1$, neglect higher-order

- Error is $\Delta Y \approx C \cdot X(t)^2 + D \cdot X(t)^3$

- Maximum error is $E = (C/3)^3 / (D/2)^2$

- E.g. $1\Omega$ 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
  \[ Y(t) = A + B \cdot X(t) + C \cdot X(t)^2 + D \cdot X(t)^3 \]
  Assume coefficients C and D << 1

- Let \( X(t) = \cos(\omega_1 t) + \cos(\omega_2 t) \) this generates
  \[ Y(t) = A + B \cdot X(t) + \frac{C}{2} \cos(2\omega_1 t) + \frac{C}{2} \cos(2\omega_2 t) + C \cos(\omega_1 - \omega_2) t + C \cos(\omega_1 + \omega_2) t \]
  which are the 2nd-order terms

- \[ + \frac{D}{4} \cos(3\omega_1 t) + \frac{D}{4} \cos(3\omega_2 t) + \frac{3D}{4} \cos(2\omega_1 - \omega_2) t + \frac{3D}{4} \cos(2\omega_1 + \omega_2) t + \frac{3D}{4} \cos(2\omega_2 - \omega_1) t + \frac{3D}{4} \cos(2\omega_2 + \omega_1) t \]
  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, \( D \approx \frac{4}{3} H \)
      - Assuming the coefficient \( D \ll 1 \)
    - -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
  - \[ \text{RIN} = \frac{\langle P^2 \rangle}{\langle P \rangle^2} = \frac{\text{variance}}{(\text{average})^2} \]
  - 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 $\ll 50\%$ 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

Light is Blocked
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 \( \sim 0.75 \) 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: \( \propto \sqrt{BW} \propto \sqrt{\text{Power}} \)
- Thermal Noise: \( \propto \sqrt{BW} \)
- Dark Current Shot Noise: \( \propto \sqrt{BW} \propto \sqrt{I_{\text{DARK}}} \)
- 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 Suppression 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

Maximum Transmit Power

Allowed Transmit Power Range

Connector and Splice Losses

Fiber Attenuation

Power Penalties

Power Budget Design Margin

Minimum Transmit Power

Optical Link Power Budget

Minimum Required Receiver Dynamic Range

Eye Safety Limit or Receiver Saturation

Minimum Receiver Sensitivity

Courtesy of David Cunningham, HP
PMA - PAM5 Optical Power Penalty

Note: Constant Symbol Rate Assumed

PAM5 penalty
6 dB

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, $f_0$ 1.875 GHz, supporting MMF with 500 MHz•km/1.875 GHz $\approx$ 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
  - 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
Acknowledgements

• The rest of the Transcendata design team
  • Isaac Achler, Greg Blanck, Fred Buckley, Eric Edwards, Bill Ellersick, Peter Gunadi, Prof. Joseph Kahn, Mike Wincn
• IEEE members who have directly/indirectly contributed
  • Dr. Kameran Azadet, Lucent; Brad Booth, Level One; Ben Brown, Nortel; Ed Chang, Unisys; Po Chiu, Fujitsu; David Cunningham, HP; Piers Dawe, HP; Howard Frazier, Cisco; Tom Hansen, AHA; Larry Rubin, Level One.
  • Note that the inclusion of any material from external sources does not denote the endorsement of MAS technology by the source individual and/or company.