Multilevel Analog Signaling

- Technology & Applications -

IEEE 802.3 HSSG - Coeur d'Alene, ID

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Technology Requirements

- Derived from customer requirements, Reconciled in PAR
- Survey Said: Cost is #1 Priority, Raw Bandwidth was #2
  - GbE survey ANgigsur.txt ranked implementation cost highest (26%) as Technology Selection Criteria
  - Raw Bandwidth got 20% of the vote
  - Preserve existing cabling plant was included in ‘other’.
- Derived Requirements:
  - Low Cost
  - 10 Gbps (not 2, 2.5, 4, 5 or 8)
  - Support of the existing cable plant (LAN / MAN / WAN)
  - Only the PHY and MAC interface need be changed to support 10 GbE

Signal Design Challenges

- 10 GbE serial data stream transmission presents several design challenges. The challenges are due to:
  - High speed logic requirements, 10X GbE
  - Attenuation Fiber Copper
  - Dispersion / Group Delay Fiber / Copper
  - Return Loss Fiber Copper
  - Transceiver Crosstalk Fiber / Copper and Cable Crosstalk Copper
  - Electromagnetic Emissions and Susceptibility Copper
- Solution: Leverage the best of Ethernet and Cost-Effective State-of-the-Art technologies to address these challenges.
- 1000BASE-T / X provide a solid technology base for 10 GbE.
- A 10 GbE MAS-based PHY uses digital communications techniques to cost effectively meet 10 GbE objectives.

Technology Justification

- Goal: Specify 10 GbE with technologies which meet cost and performance requirements.
- Direction: Maximize the use of silicon-based technologies best meet this goal (i.e. chips are cheap).
  - Reduce cost / complexity by using a single channel
    - Fiber has the bandwidth, unlike UTP
    - One channel is cheaper / more reliable than 4 (or 2 or 8…)
  - Use PAM signaling to increase #bits per Baud.
  - Use coding techniques to offset PAM SNR loss, control DC balance, provide high transition density, etc.
    - Scrambling and Trellis / Viterbi vs. 8B / 10B+ vs. others
  - Use compensation techniques to achieve BER requirements in 'difficult' environments (e.g. low BW fiber, long haul) including:
    - Receive Equalization and Transmit Pre-Distortion

Signal-to-Noise Ratio (SNR)

- Signal power is decreased by channel attenuation.
- Noise power is the sum of the following (and more):
  - Laser chirp
  - Inter-Symbol Interference (ISI) due to the dispersion / group delay
  - Transceiver, connector and cable crosstalk
- SNR is the ration of signal power to noise power
- SNR is related the Bit Error Ratio (BER)
  - A higher SNR generally allows a lower BER to be maintained
- SNR margin:
  - The amount of additional signal loss or noise that the system can tolerate before the BER increases above a given level

Bit Error Ratio (BER)

- The ratio of the number of bits received in error to the total number of bits received
- Objectives for Ethernet variants:
  - 10BASE2, 10BASE-T BER objective is 10^{-8}
  - 10BASE5 BER objective is 10^{-9}
  - 1000BASE-T BER objective is 10^{-10}
  - 100BASE-X, 1000BASE-X BER objective is 10^{-12}
- BER Performance:
  - BER of 10^{-10} @ 10 Gbps = a bit error every 1 sec.
  - BER of 10^{-12} @ 10 Gbps = a bit error every 1 min, 40 sec.
  - BER of 10^{-13} @ 10 Gbps = a bit error every 16 min, 40 sec.
  - IMHO, 10 GbE the BER objective should be at least 10^{-12}, perhaps 10^{-13} for parity with GbE link reliability.

Single vs. Multiple Channels

- Single Channel transmission systems are inherently simpler than their Multiple Channel counterparts. Some advantages:
  - No multiplexing / demultiplexing of data streams
  - No skew management and associated delay
  - No attenuation due to wavelength multiplexing / demultiplexing
  - No requirement for multiple / ribbon fibers (installed cable plant)
  - No multiple optics precision alignment issues and variance
  - No reliability issues associated with individual channel failures
  - Direct drive of WDM optics including strategic DWDM systems
- MAS employs **one low-cost** laser
  - Serial TDM requires a much faster laser, more expensive
  - WWDM requires 4 lasers similar to MAS lasers
  - Parallel Optics requires 4 similar lasers to MAS or >4 cheaper ones
- MAS uses **1, inexpensive,** laser backed-up by **cheap silicon**

Pulse Amplitude Modulation

- Provides better bandwidth utilization than binary signaling
  - Binary signaling: a.k.a. On-Off-Keying (OOK), PAM-2, Serial TDM
  - Each transmitted symbol represents just one bit (0 or 1.)
- PAM-n, where n>2, affects Signal-to-Noise ratio
  - Adding just one level, PAM-3 (e.g. MLT-3), decreases signal by 3 dB
  - Splitting the signal in half again (6 dB) provides 5 levels (4 'eyes')
    - 1000BASE-T employs PAM-5, loses 6 dB, and gains it all back
    - PAM-5 symbols represents one of five different levels (-2, -1, 0, + 1, +2)
    - Each symbol can represent two bits (4 levels) plus one extra level
    - Extra levels provide FEC, special codes, DC balance, transition density
    - SNR increased though Forward Error Correction coding & equalization
  - Net result: PAM-5 is **250%** more efficient than OOK & 8B/10B
- For 10 GbE: PAM-5 @ 5 GBaud = binary signaling @ 12.5 GBaud

PAM-5 and Beyond

- PAM-5 provides a cost effective gain over binary signaling
  - But it leaves us at 5 GBaud for 10 GbE vs. 1.25 GBaud for GbE (4X)
  - Dispersion effects for SMF / 1300 nm are minimal (to ~15 km)
  - MMF modal dispersion is 4X GbE resulting in shorter links
    - Link distances for typical MMF are 500 MHz • km / 2.5 GHz = 200 m
    - Link distances for LOF MMF are 1250 MHz • km / 2.5 GHz = **500 m**
- PAM-5 technology provides the simplest, 1 channel, 10 GbE solution but falls short of addressing the installed base.
- The following PAM extensions can address the installed LAN / MAN / WAN cable plant:
  - T-Wave signaling for sophisticated dispersion compensation
  - Additional PAM levels to reduce signaling rate / dispersion effects
- The technology to go beyond 5 level PAM is feasible

Beyond PAM-5

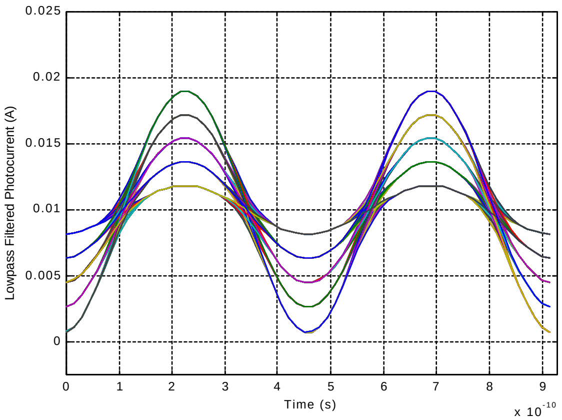
- Linear Quiet lasers are the key to using more levels
  - Laser linearity is proving to be a second order concern
  - SNR is proving to be the first order concern
  - Uncooled, unisolated standard DFB lasers are prime choices
    - Need to identify the quiet ones (i.e. low RIN, etc.)
- PAM-8 or 9 provides 33% efficiency gain over PAM-5
  - For a 3 dB link penalty, PAM-8/9, 3 bits/Baud, 3.33 GBaud, f_o 1.875 GHz, supporting MMF with 500 MHz•km/1.875 GHz = 267 m
  - Note that this exceeds GbE minimum link distances of 220 m
  - Link distances for LOF MMF are 1250 MHz•km/1.875 GHz = **667 m**
- SNR takes a beating at PAM-8/9 (9 dB over OOK)
  - Best to focus on dispersion compensation, WDM after PAM 8 /9
  - Follows WAN strategy, except WANs don't use PAM… **yet**

T-Waves

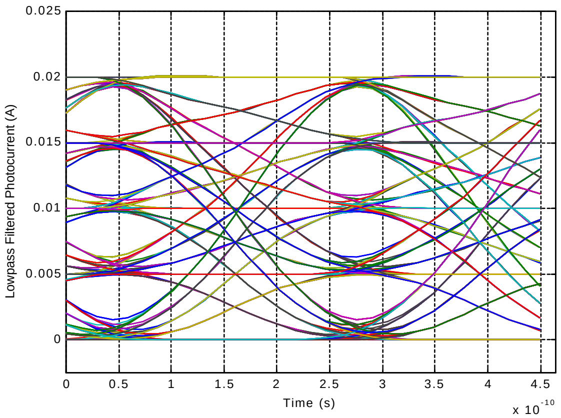
- Synthesized, Multilevel, Intensity Modulation
  - Waveform synthesis/laser drive by high-speed D/A conversion
- Significant Link Penalty compared to PAM
  - 4.5 dB penalty for an equivalent number of levels since only half of available levels minus average power are used.
- Narrowband Frequency Spectrum
  - Approximately *f*/2 to 1.5*f*
  - Reduced spectrum compared to OOK (on-off keying) and PAM
- High Resistance to Dispersion and Nonlinearity
  - System is loss-limited, not dispersion-limited
  - Ability to characterize and compensate for dispersion
- PAM is more efficient, simpler in ‘easy’ environments
- T-Waves may be more efficient in ‘difficult’ environments

MAS Signaling Simulation

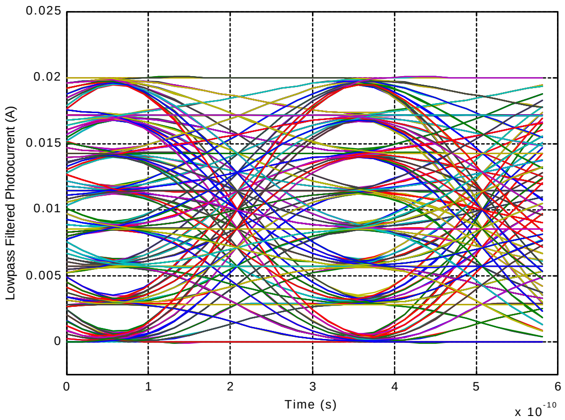
- Constructed a model to analyze MAS optical signaling
  - One purpose of the model is to analyze dispersion / compensation
  - Laser and fiber model included
  - Fiber model is SMF now, MMF being added
  - Following details are at 10 Gbps, SMF, 1550 nm lasers
  - Dispersion is worse at 1550 nm than 1300 nm



5 Level T-Wave



5 Level PAM



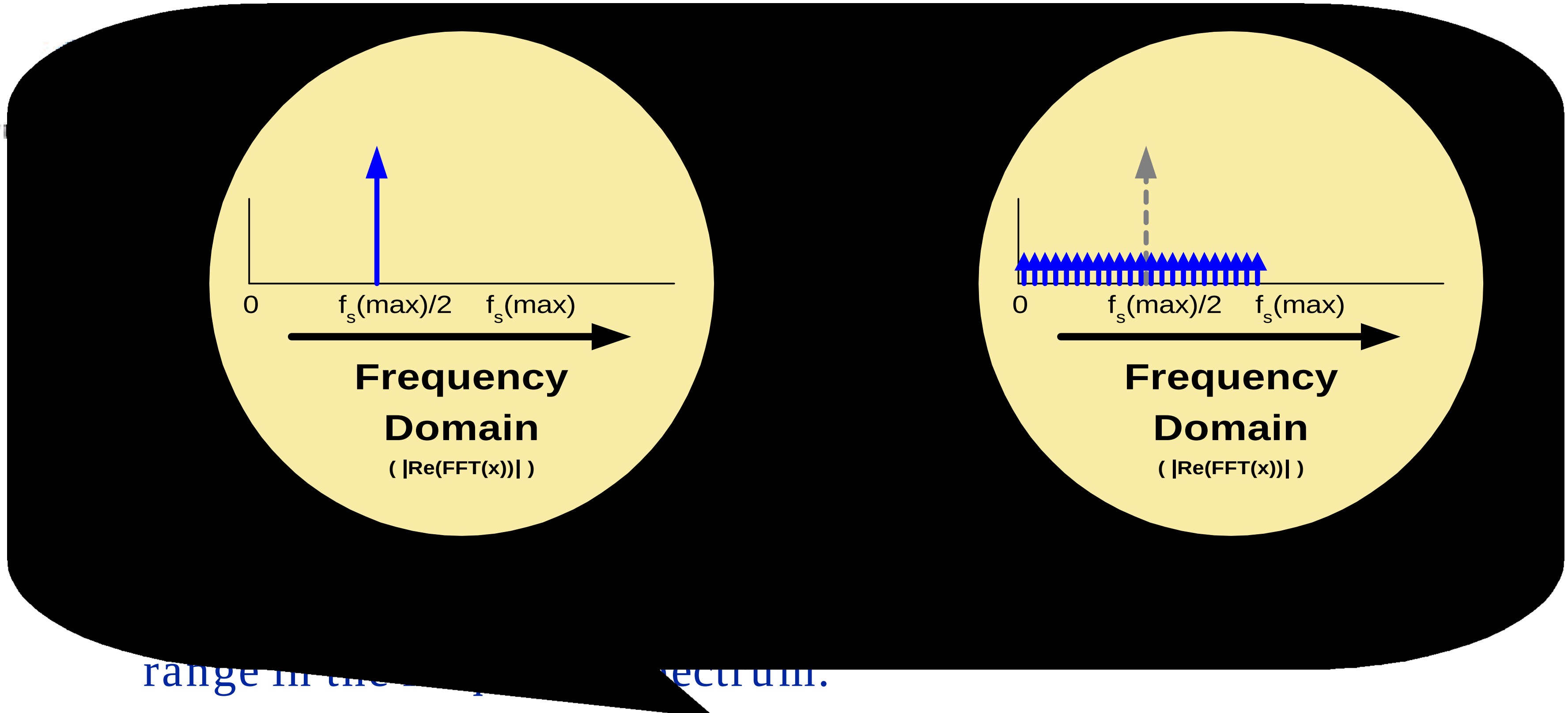
8 Level PAM

Coding

- 8B/10B, 1000BASE-T PCS or other
- Great 1000BASE-T PCS presentation by Bob Noseworthy of UNH IOL
  - ftp://ftp.iol.unh.edu/pub/gec/training/pcs.pdf
  - Much of the following coding tutorial material is 'pilfered' from the above presentation (thanks Bob, I owe you one or three!)

Scrambling Basics

- Used to randomize the sequence of transmitted symbols and avoid the presence of spectral lines in the transmitted signal spectrum.
  - Scrambling creates essentially uncorrelated data symbols, which assists the receiver in distinguishing the desired signal from the background noise.
  - When data is scrambled, no single frequency is sent for any significant period of time, thus the power is spread out over a range in the frequency spectrum.
  - This technique also makes more efficient use of the available bandwidth (as the entire band may be utilized).
  - Data is scrambled by taking each symbol and altering it by a pseudo-random value.
  - A Linear Feedback Shift Register (LFSR) is commonly used to implement a pseudo-random number generator.



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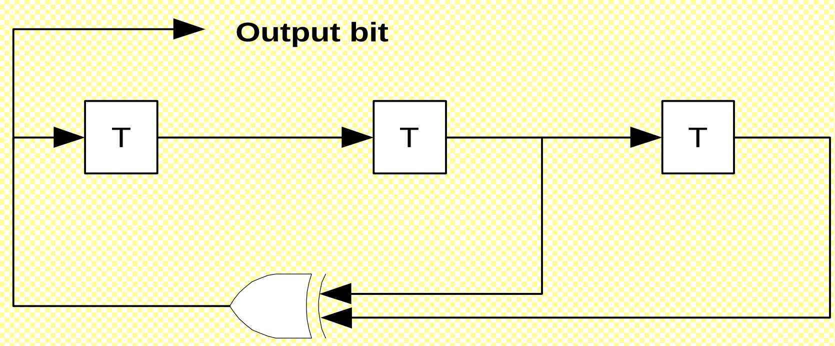
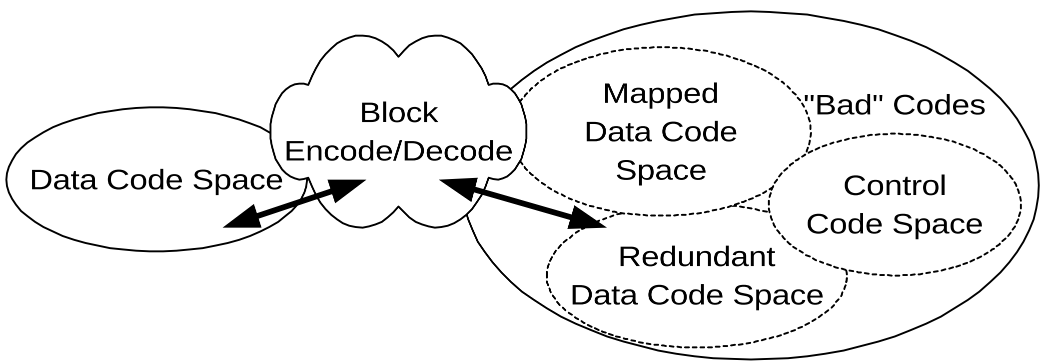


The repeating 7-code pattern for this LFS is

0010111 (1 = 1 0 = -1)

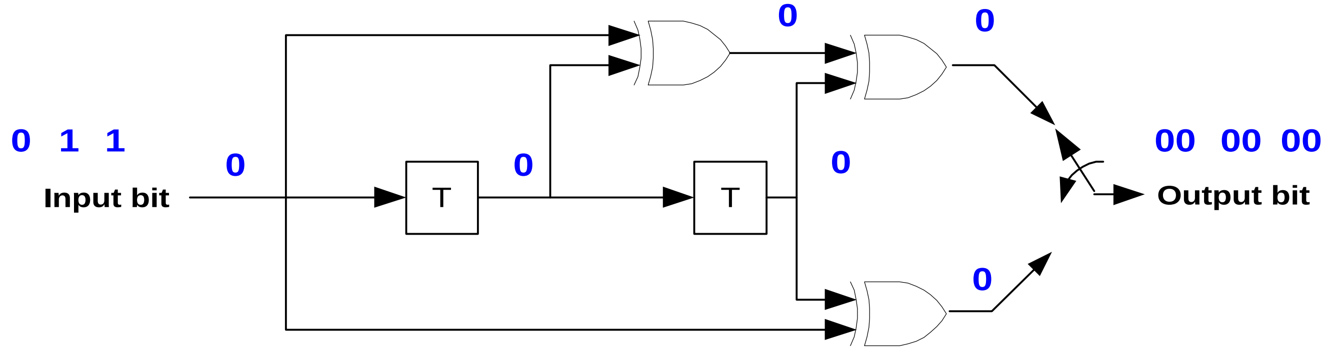
Block Coding

- Expands the code space of the data being transmitted.
- Typical Benefits of Block Codes
  - Allows an intelligent selection of channel symbols from the desired block of data being sent.
  - Permits rich transition densities (allows for easier clock recovery)
  - Permits DC Balanced codes to be used
  - Permits non-data (control) codes, such as IDLE, Start of Frame, etc.
- Some Ethernet Block Codes: 4B/5B, 8B/10B, 6B/3T



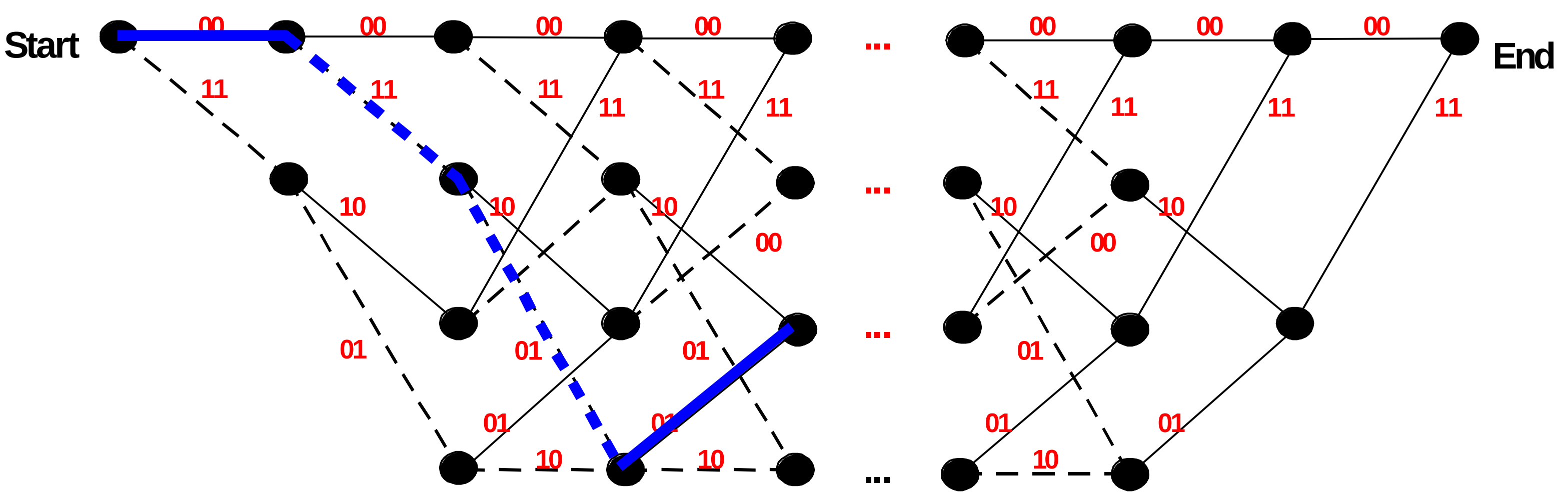
Convolutional Codes

- Convolutional Codes are a special class of Block Codes
  - A convolutional code may simply be the result of XOR'ing the transmit data with the output of a scrambler.
- A Simple Convolutional Encoder example:
  - The sequence $0_n\ 1_{n-1}\ 1_{n-2}\ 0_{n-3}$ is fed into the encoder, consisting of the time delay blocks, and XOR blocks.
  - Note the output $00_n\ 11_{n-1}\ 01_{n-2}01_{n-3}$ is at twice the input rate.



Trellis Coding

- The preceding convolutional encoder can be represented in another form - a Trellis Diagram.
  - A simple trellis provides a structure to the transmitted data stream. Only valid transitions through the trellis may be transmitted!
  - In this example of encoding 0110 to 00,11,01,01, after the code-group 11 is sent, only the code-groups 01 or 10 are permissible.



If data to send is ‘0’, follow solid line from state and output code-group in **red**.

If data to send is ‘1’, follow dashed line from state and output code-group in **red**.

Viterbi Decoding

- A Viterbi Decoder provides Error Correction. Not just Error Detection like most other block codes.
  - The Forward Error Correction mechanism provided by a Trellis Encoder / Viterbi Decoder results in a measurable BER tolerance.
  - Therefore, the overall system performance, oft expressed in terms of the systems SNR is effectively increased.
- The Viterbi structure provided to the underlying symbols transmitted is analogous to spelling and grammar rules. consider:

  "I coldn't wait til it was over"

  "I can't believe their still awake"

  - Both symbol sequences are erred, but the knowledge of the structure of the transmission, allows the receiver to properly decode the sequence.

TRANSCENDATA

Signal Compensation

- Used to compensate for signal distortion introduced by the communication channel in order to maximize SNR.
  - Achieved with a combination of analog and digital filtering elements used at the transmitter, at the receiver, or both.
- Compensation is used to:
  - Minimize or counteract the effects of dispersion / pulse spreading;
  - Minimize the transmitted signal energy at frequencies where distortion and disturbances are significant;
  - Reduce both low and high frequency signal components;
  - Reject high-frequency external noise components.
- Silicon-based compensation techniques are a cost-effective way to utilize lower cost components, support longer link lengths as well as the installed base of LAN ⇔ WAN fiber.

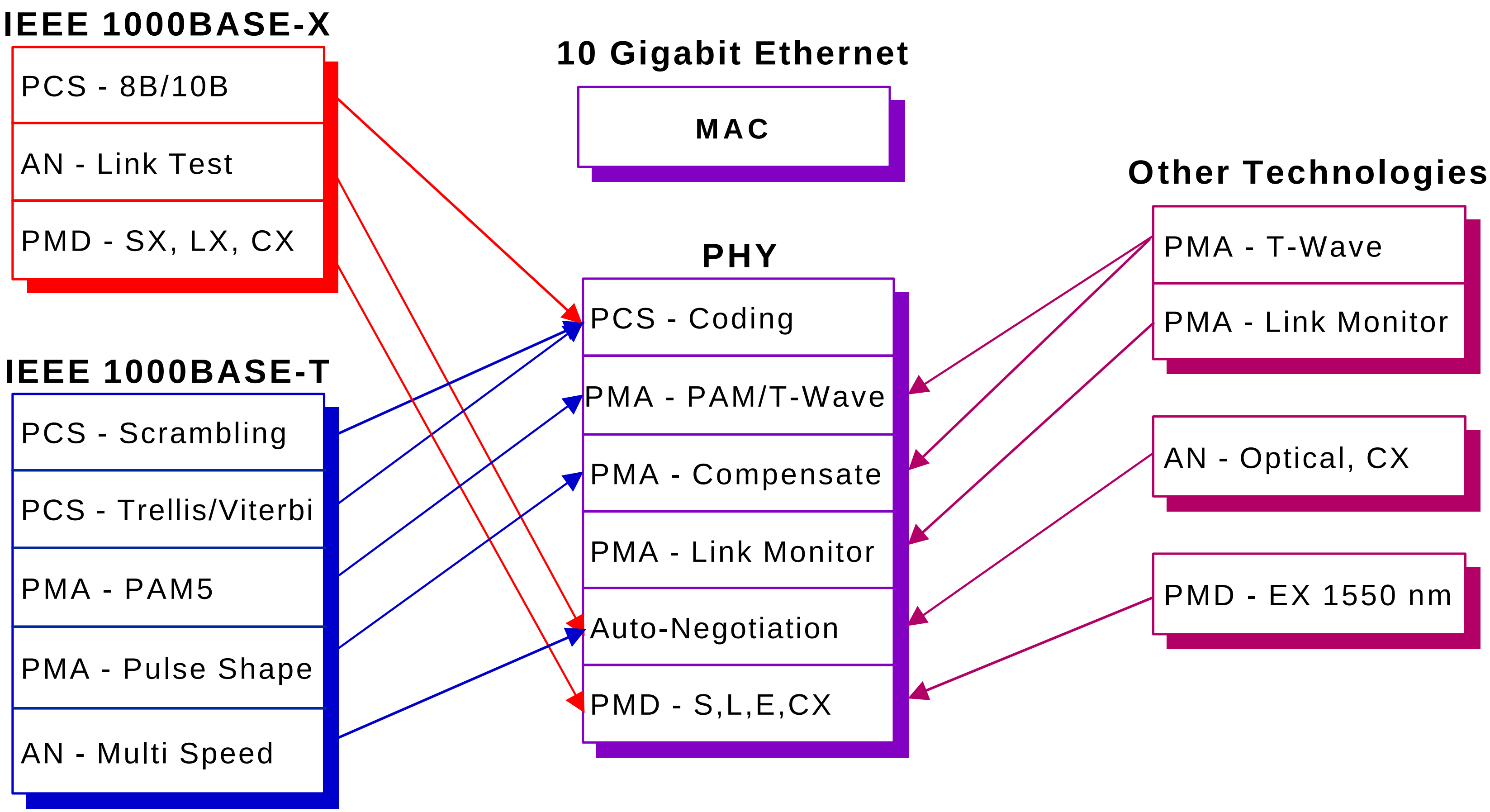
MAS Technologies

- T-Wave™ & Pulse Amplitude Modulation (PAM)
  - T-Waves are special PAM variant
  - Differences include sine-wave carrier, periodic zero-crossings
- PAM technology is well understood and widely deployed
  - Specify PAM-5 systems first for use in 'easy' environments
    - SMF with 1300 nm DFB lasers to 15 km
    - LOF 50 µm MMF to 500 m
    - 50/62.5 µm MMF @ 500 MHz•km to 200 m
- PAM-5 covers **most** environments
- Dispersion compensation required in **other** environments
- Addressable by T-Waves or more PAM levels
  - Auto-Negotiation can insure MAS PHY compatibility

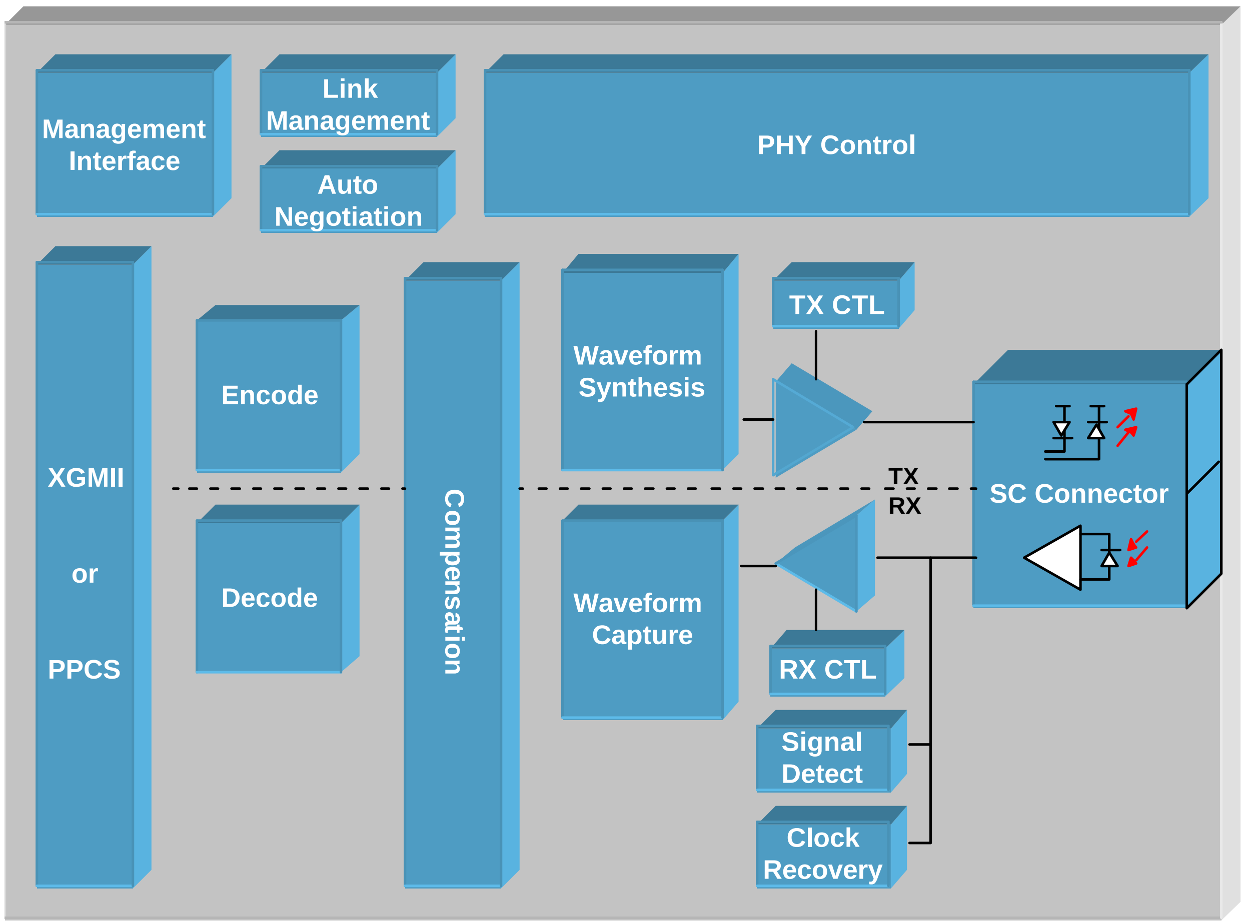
MAS-Based PHY

- MAS forms the foundation of efficient PHY signaling
- Leverages Ethernet MAS-based PHY constructs
  - 100BASE-T4 MLT-3
  - 100BASE-T2 PAM5x5
  - 1000BASE-T 4D-PAM5
- Complete PHY combines other elements / technologies
  - Single / Multiple Channels
  - Coding: Scrambling, Encoding / Decoding, Error Correction
  - Signal Compensation
  - Media Independence (e.g. SMF, MMF, Twinax, UTP, STP, etc.)

MAS 10 GbE Technology Basis



Optical MAS Block Diagram



TRANSCENDATA

PCS & PMA

- Physical Coding Sublayer (PCS)
  - Framed, pre-encoded 8B/10B input (data + D/K bit)
  - Scrambling to provide uncorrelated data and DC Balance
  - Trellis encoding for Forward Error Correction
  - 2+ bits/Baud from 5 levels, 4 Baud/byte @ 2.5 GHz for 10 Gbps
  - PAM-5 4 Baud code-groups yield 625 (5x5x5x5) codes for 256 data + 12 special codes.
    - Ref: 8B/10B yields 1024 codes for 256 data + 12 special codes
  - Viterbi decoding for Error Correction, 6 dB SNR gain
- Physical Media Attachment (PMA)
  - Xmit: Conversion of code-groups to analog waveforms (DAC)
  - PAM-5 ⇒ 2 levels above/below, 1 at average optical power
  - Rcv: Conversion of analog waveforms to code-groups (ADC)

Auto-Negotiation (AN)

- Unrelated to MAS technology, distinct protocol
- Simplifies the 1/10 GbE integration task
- Uses Tone-based Link Code Words for signaling
  - New AN protocol for optical/copper serial links (SX/LX/EX/CX)
  - Enables 1/10 GbE operation, may extend to 10 & 100 Mbps optical
  - May extend to other protocols (e.g. FC, P1394b, NGIO, FIO, etc.)
- Provides transport for MAS compensation to optimize PHY performance
  - Required for best use of the existing cable plant (LAN ⇔ WAN)
- Leverages standard Ethernet AN management, local device and link partner information, protocol
  - Allows 1/10 GbE devices to be managed like their 10/100/1000 UTP-based counterparts

MAS PMD

- SX, LX, EX, CX variants; same media as 1000BASE-X
- Similar optical components as 1000BASE-X, a bit faster
  - OC-48 uncooled, unisolated 1300 nm DFB lasers are sufficient
  - **PAM-5:** Need to generate 2.5 GHz AM pulses
  - **T-Waves:** Need to generate 2.5 GHz AM sinusoids
  - **PAM-8/9:** Need to generate 1.67 GHz AM pulses
- PAM-5: Similar distances to 1000BASE-X
  - 62.5 µm MMF, 500 MHz•km, 1300 nm ≈ 200 m
  - 50 µm MMF, 1250 MHz•km LOF, 1300 nm ≈ 500 m
  - SMF 1300 nm ≈ 15 km
- T-Waves: Extended distances, Dispersion Compensation
  - 50/62.5 µm MMF 1300 nm ≈ 1 km
  - SMF 1550 nm ≈ 60-80 km

Addressing PAR Criteria

1) Broad Market Potential

- Next in the line of scalable 802.3 solutions 10 Mbps   10 Gbps
- High-end Backbone, Server and Gateway connectivity
- Aggregation of GbE switches
- NEW Potential new applications in Carrier Access and WAN space

2) Compatibility with IEEE 802.3

- Ignoring CSMA/CD ...
- MAC conformance, with 10 Gbps authorized extensions
- NEW New Physical Layer, deemed conformant

3) Distinct Identity

- MAS enables a single PHY solution
- Applicable to MMF, SMF @ 1310/1550 nm, CX copper
- GbE AN capable   WDM compatible

Addressing PAR Criteria 2

4) Technical Feasibility

- MAS/PAM technology used in 100BASE-TX, T2 and 1000BASE-T
- MAS spreads implementation difficulty among all PHY elements
- Re-use of existing MMF cable plant is feasible
  - T-Wave dispersion compensation, Laser Optimized Fiber (LOF)
- PAM technology reliable, T-Wave feasibility ongoing

5) Economic Feasibility

- MAS solution driving towards low-cost monolithic **CMOS**
- MAS complete **PHY integrated transceiver** feasible
- MAS employs **one low-cost** laser

  Serial TDM ➢ 1 $$$laser, WWDM ➢ 4, Parallel Optics ➢ 4+
- Reduce optics cost, increase system reliability in **silicon**

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- T-Waves may do much better due to dispersion compensation potential
- More PAM levels are possible, PAM 8 or 9 is feasible

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- T-Waves may do much better due to dispersion compensation potential
- More PAM levels are possible, PAM 8 or 9 is feasible
- Specify PAM-5 **now**, add T-Waves and/or more PAM levels later.
  - Use AN for compatibility.