Proposal for 10Gb/s single-lane PHY using PAM-4 signaling

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* **This contributor supports multi-level signaling standardization for certain applications. This support does not necessarily reflect the support of PAM-4 over competing technology solutions.**

July 13, 2004 (r1.3)

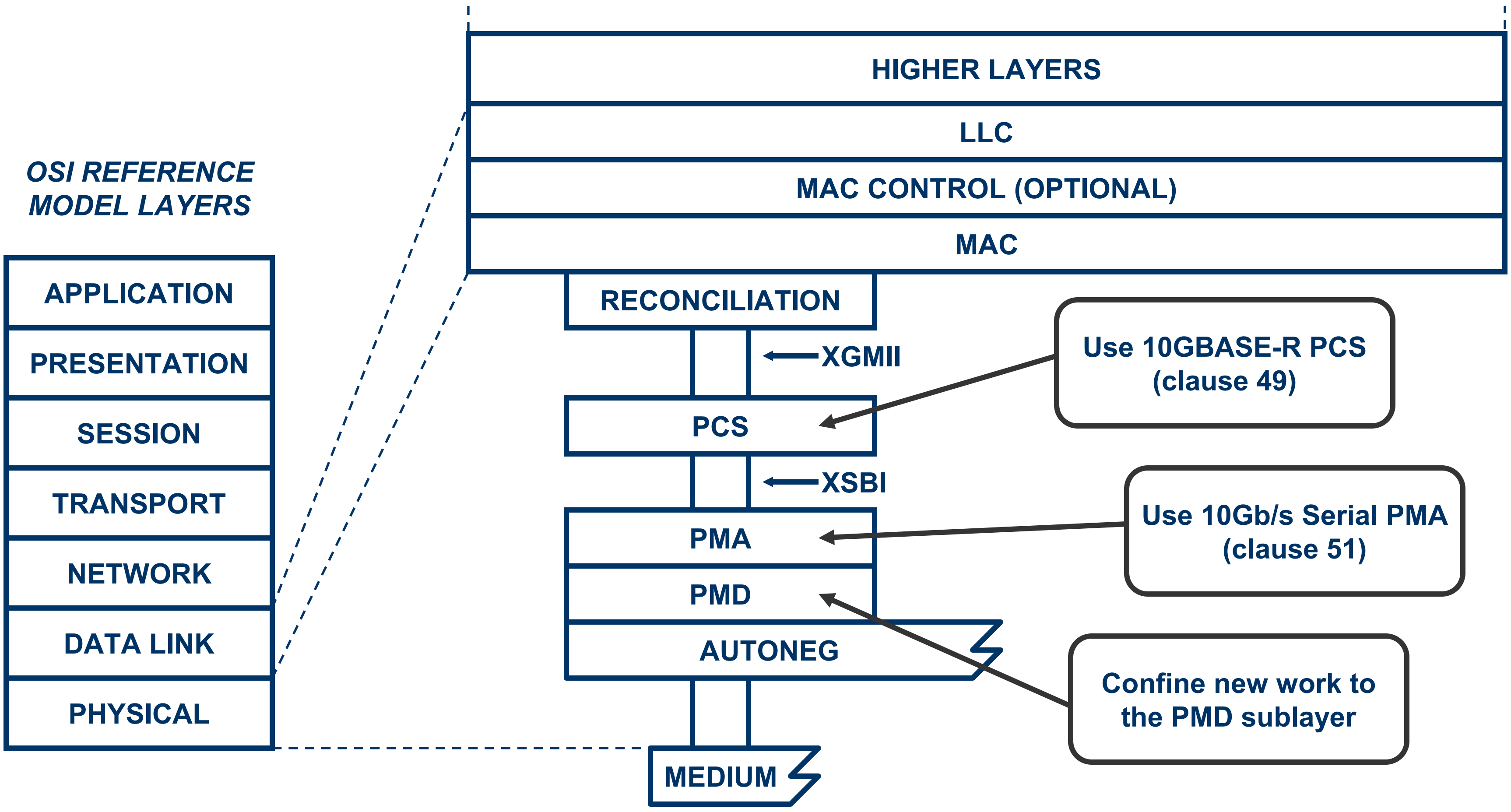
Scope and Purpose

- This presentation proposes a new PMD sublayer based on PAM-4 signaling.
- The new PMD leverages the 10GBASE-R PCS (clause 49) and 10Gb/s serial PMA (clause 51) to form a complete physical layer stack.
- This presentation describes the fundamental concepts behind the proposed PMD.
- This presentation describes how the proposed PMD satisfies the Task Force objectives for the single-lane 10Gb/s PHY.

Agenda

- **Proposal Overview**
- Link Simulations
- Link Initialization Protocol (LIP) Detail
- Conclusions

Layer Model

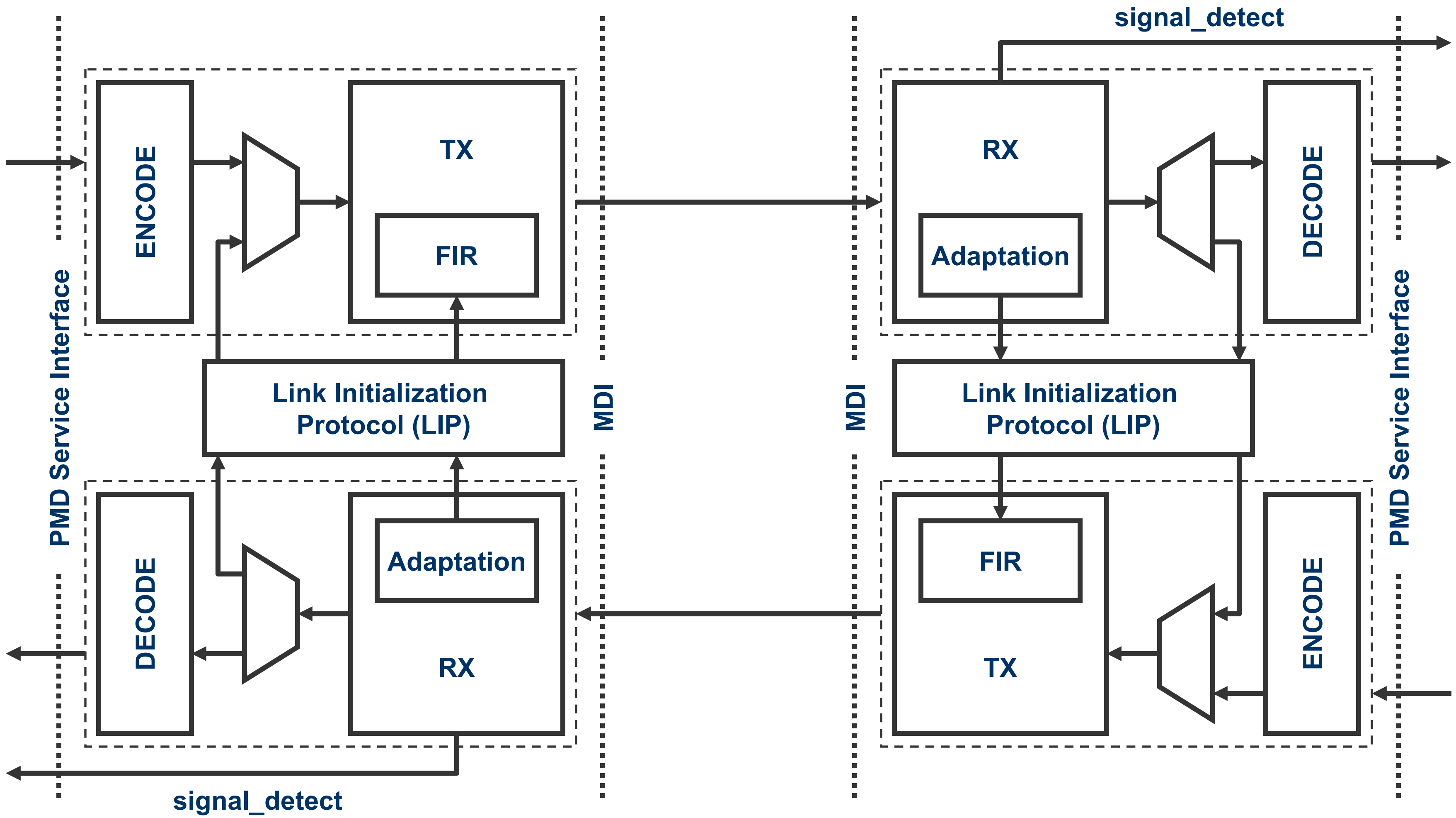


OSI REFERENCE MODEL LAYERS
APPLICATION
PRESENTATION
SESSION
TRANSPORT
NETWORK
DATA LINK
PHYSICAL
HIGHER LAYERS
LLC
MAC CONTROL (OPTIONAL)
MAC
RECONCILIATION
XGMII
PCS
XSBI
PMA
PMD
AUTONEG
MEDIUM
Use 10GBASE-R PCS (clause 49)
Use 10Gb/s Serial PMA (clause 51)
Confine new work to the PMD sublayer

Proposal Overview

- Reduce occupied bandwidth through the use of PAM-4 signaling.
  - Reduces required equalization effort.
  - SNR improvement for worst-case channel exceeds the 9.5dB lost to multi-level.
- Divide equalization effort between the transmitter and receiver.
- Define an adaptive transmitter.
  - Precise equalization is easier to implement at the transmitter.
  - Alleviates burden on receiver circuitry.
  - Transmitter is trained during link initialization, and then the settings are frozen.
  - Requires a receiver-to-transmitter communication path (but only during link initialization).
- Continuously adaptive receiver.
  - Simpler, lower power design due to pre-compensation at the transmitter.
  - Tracks time-variation due to temperature and humidity changes.

Link Model



signal_detect
PMD Service Interface
ENCODE
TX
FIR
Link Initialization Protocol (LIP)
DECODE
Adaptation
RX
signal_detect
MDI
MDI
RX
Adaptation
DECODE
Link Initialization Protocol (LIP)
FIR
TX
ENCODE
PMD Service Interface

Encoding/Decoding

- Each PAM-4 symbol carries two information bits.
  - 10.3125Gb/s → 5.15625Gbaud
- Simple linear encoding preserves DC balance.

Bits [MSB, LSB]	Symbol
00	-3
10	-1
01	+1
11	+3

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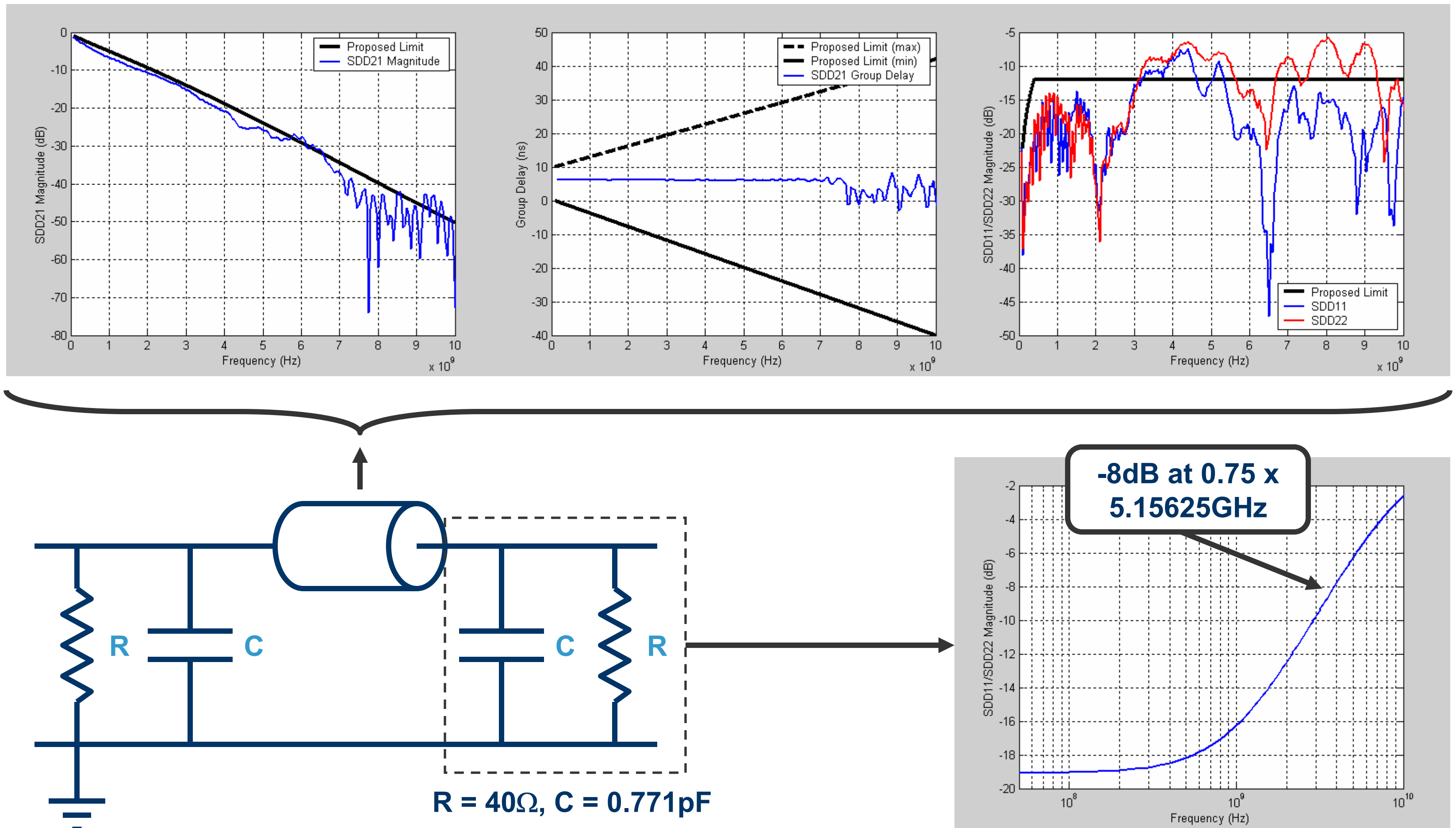
Link Simulations

- Basic premise and feasibility are demonstrated using channel data representative of the worst-case environment.
- Transmitter contains 5-tap adaptive finite impulse response (FIR) filter.
  - Filter is trained using only -3 and +3 symbols, as described later.
  - Training pattern is PN-7.
  - For the purpose of this simulation, LMS adaptation is employed.
- Receiver equalizer is modeled as a simple gain peaking amplifier.
  - No time varying element in this simulation.
- Following training, the PAM-4 eye is evaluated.
- Sample point is positioned at eye center.
- Vertical and horizontal eye opening is reported at 1E-15.

Test Channel



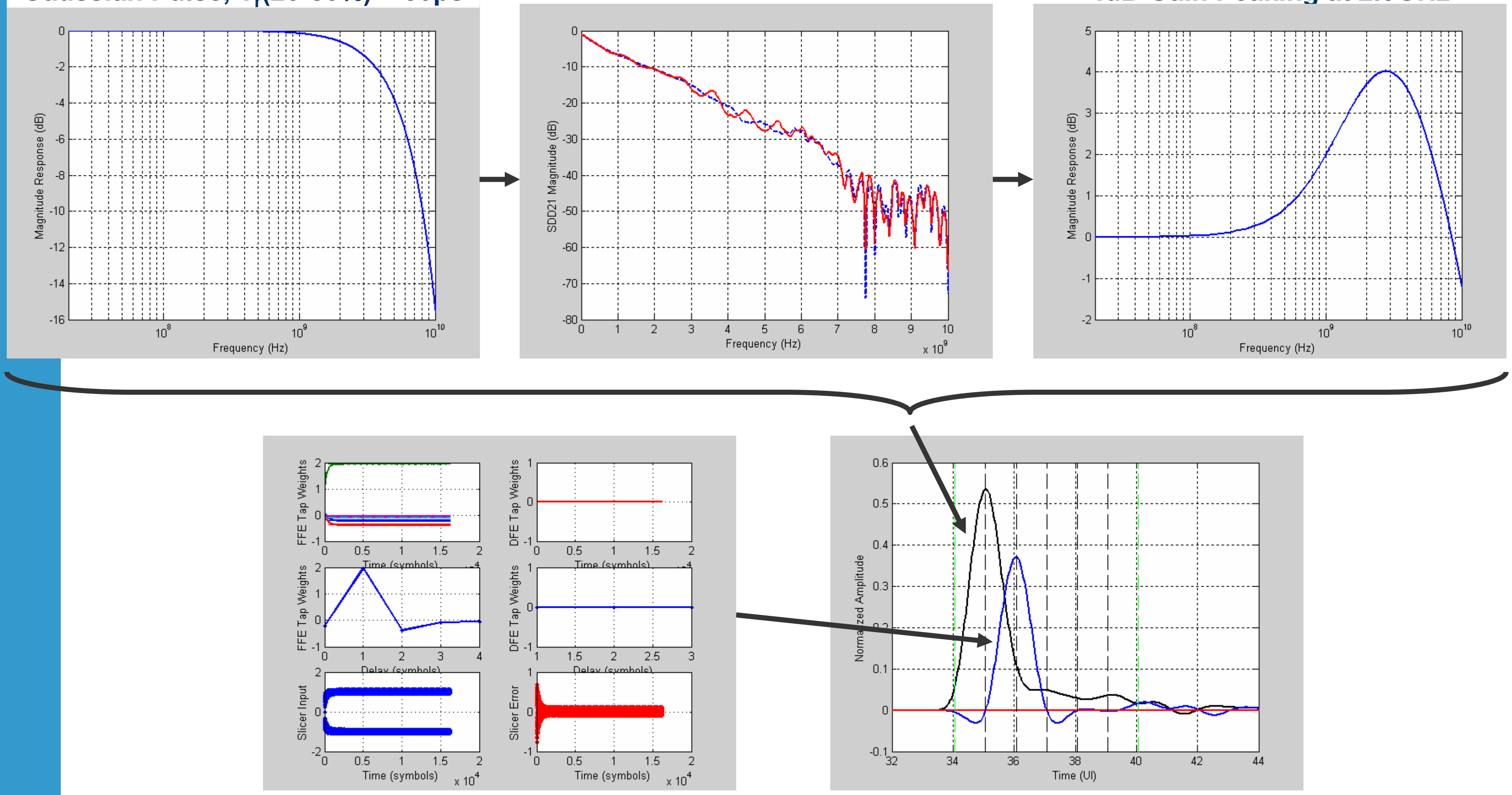
Note: Tx/Rx load model not intended to represent a specific implementation. Rather, its purpose is to ensure that mismatch effects are included in the simulation.

Equalizer Training

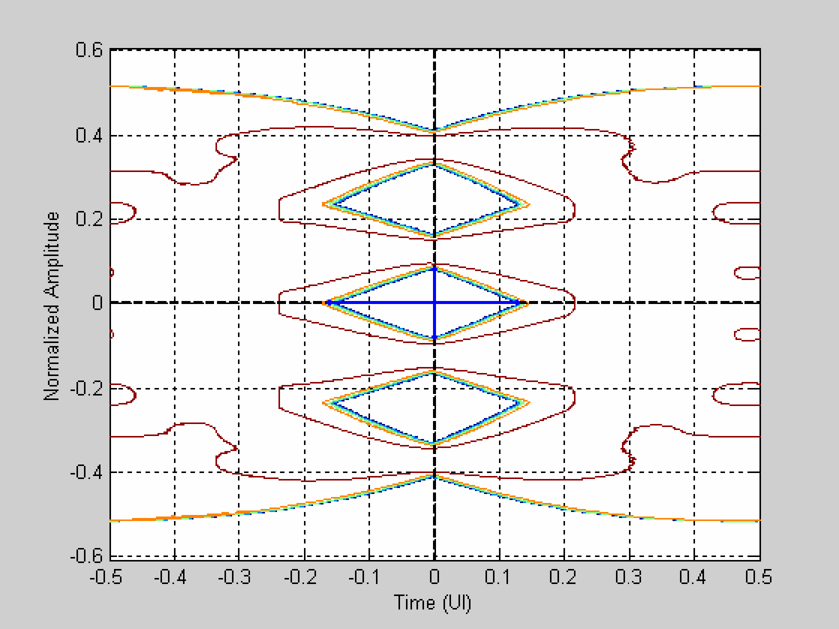
Transmitter
Gaussian Pulse, T_r(20-80%) = 50ps

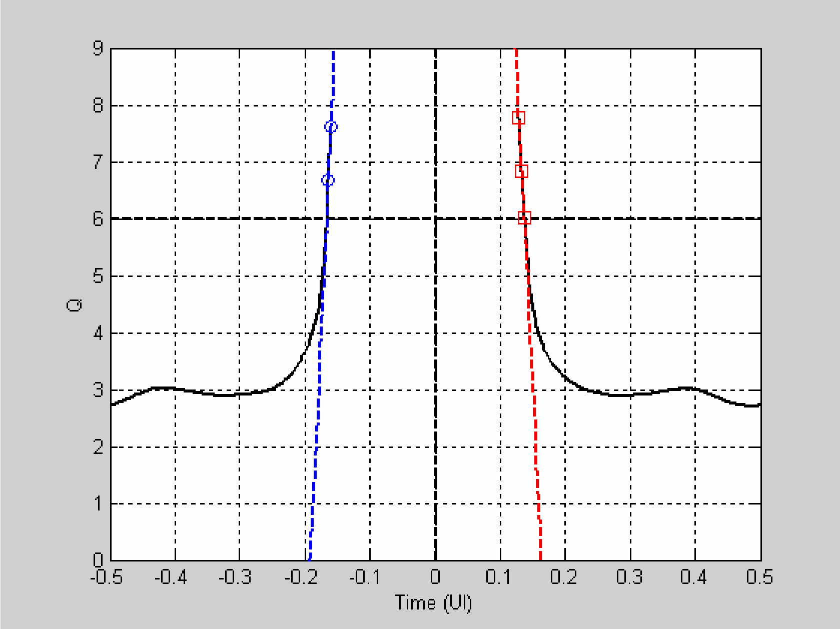
Channel

Receiver
4dB Gain Peaking at 2.5GHz



10Gb/s Operation (0.05UI$_{p-p}$ Tx RJ, no crosstalk)

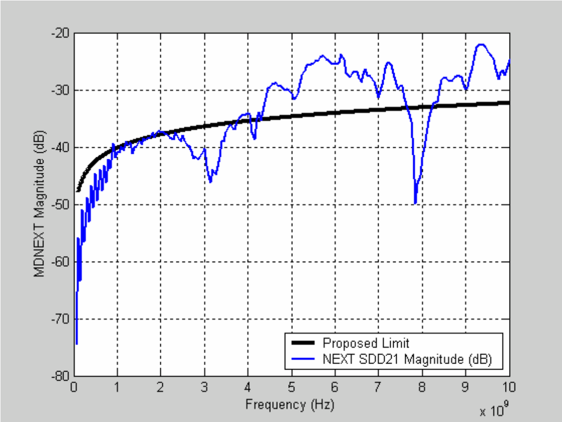


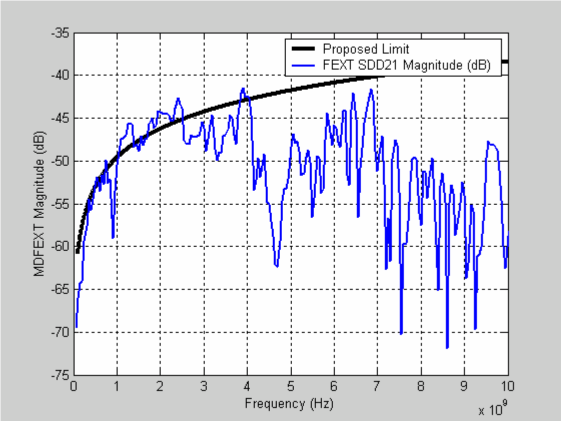


Vertical Eye Opening (at 1E-15)	0.16	au
Horizontal Eye Opening (at 1E-15)	0.28	UI
Effective DJ, Peak-Peak	0.65	UI
Effective RJ, RMS	0.004	UI

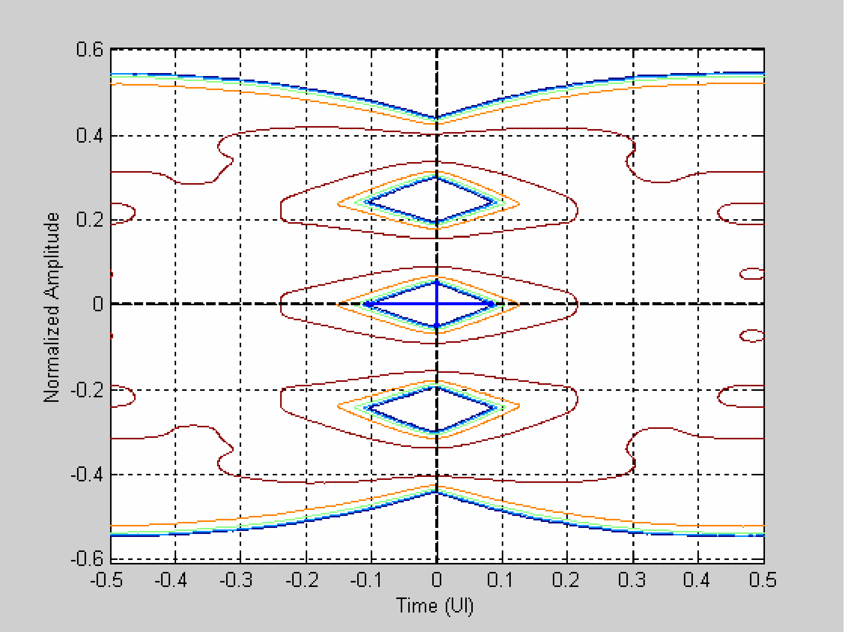
Crosstalk

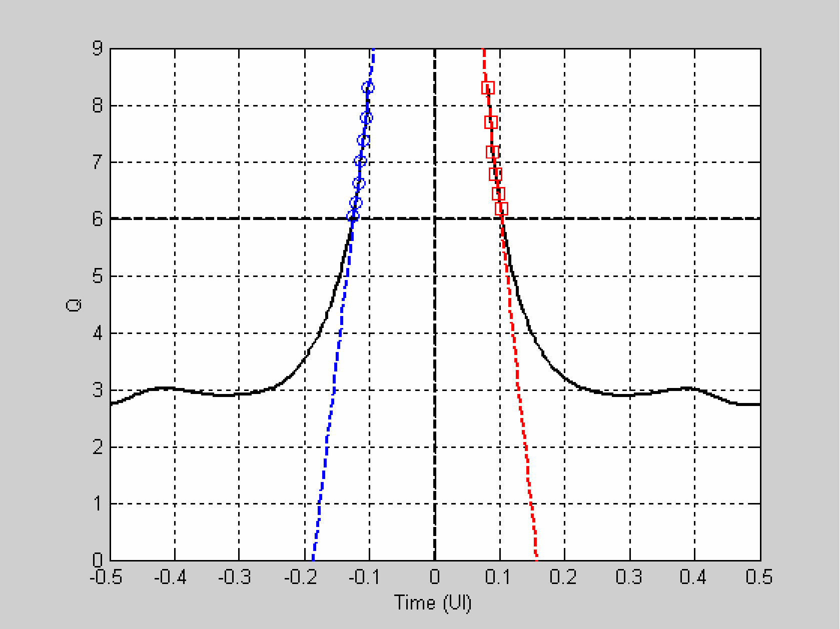
- Only single-aggressor NEXT and single-aggressor FEXT applied.
  - Exceeds proposed multi-disturber allocation.
- Near-end aggressors assumed to be asynchronous with respect to the signal of interest (±100ppm).
  - Peak value “walks” across eye.
- Far-end aggressors assumed to synchronous with respect to the signal of interest.
  - Peak value fixed at eye center (worst-case analysis).
- Near-end and far-end aggressors assumed to be similar transmitters driving similar channels.
  - Same output amplitude, rise time, and FIR tap settings.





10Gb/s Operation (0.05UI$_{p-p}$ Tx RJ, crosstalk)

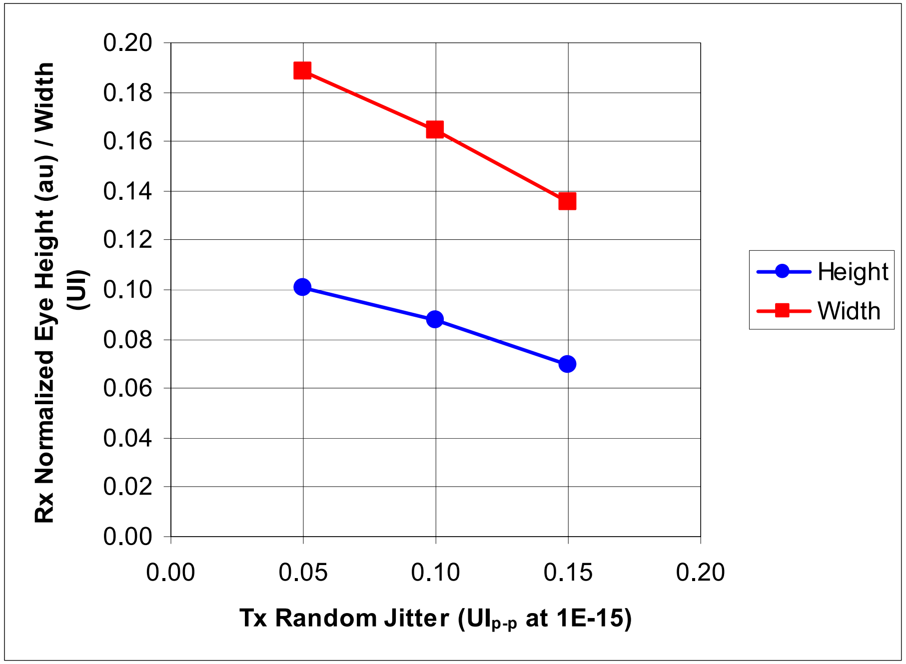




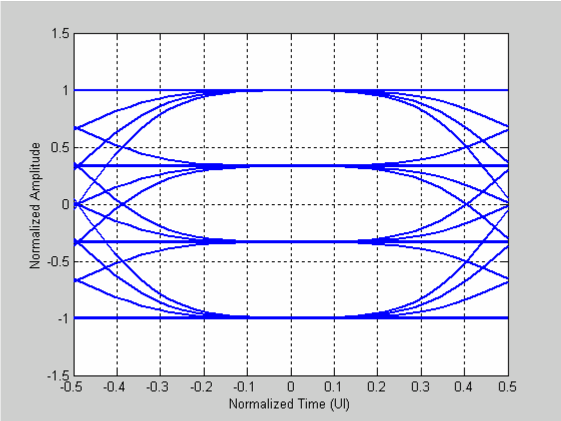
Vertical Eye Opening (at 1E-15)	0.10	au
Horizontal Eye Opening (at 1E-15)	0.19	UI
Effective DJ, Peak-Peak	0.66	UI
Effective RJ, RMS	0.010	UI

Jitter

- In this simulation, deterministic jitter is the intrinsic jitter due to unconstrained switching among PAM-4 levels.
- Random jitter is increased from base value 0.05 to 0.15UI_{p-p} (as measured at 1E-15).
- Note that at 0.10UI_{p-p}, a 1000mV_{ppd} output voltage will yield at 45mV_{ppd} eye opening at the slicer input.



NOTE: In this simulation, eye height is normalized to a 2V_{p-p} Tx output voltage. This does not imply that the solution requires 2V_{p-p}.

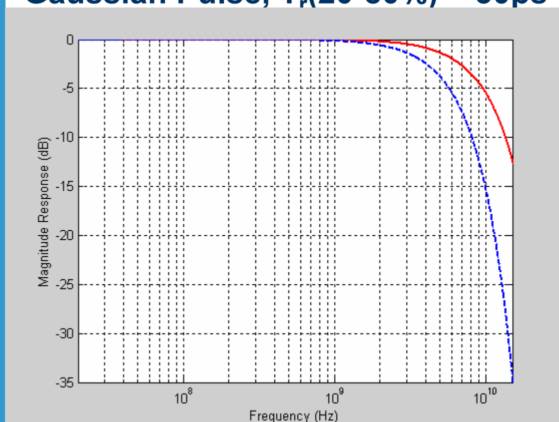


Aside: NRZ Link Simulations

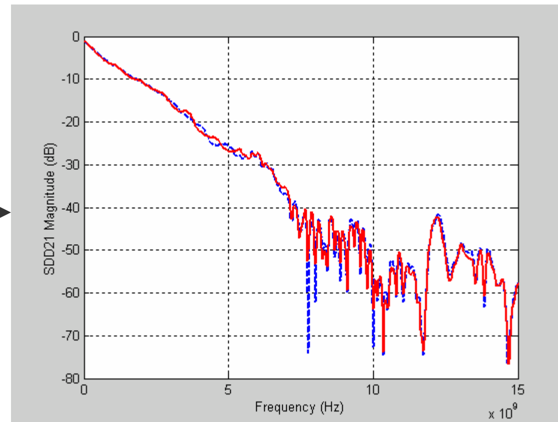
- Driver rise time and Tx / Rx termination models changed to be more appropriate for a 10Gb/s NRZ design.
- Transmitter contains 3-tap adaptive finite impulse response (FIR) filter (two pre-cursor taps).
- Receiver is modeled as a gain peaking filter followed by a 5-tap decision feedback equalizer.
  - Gain peaking at $f_{baud}/2$ is identical to PAM-4 gain peaking at $f_{baud}/2$.
- Transmit and receive equalizers are jointly trained.
  - Training pattern is PN-7, LMS adaptation is employed.
- Following training, the NRZ eye is evaluated.
- Sample point is positioned at eye center
  - …as seen at the output of the gain peaking filter.
- Vertical and horizontal eye opening is reported at 1E-15.

Equalizer Training (NRZ)

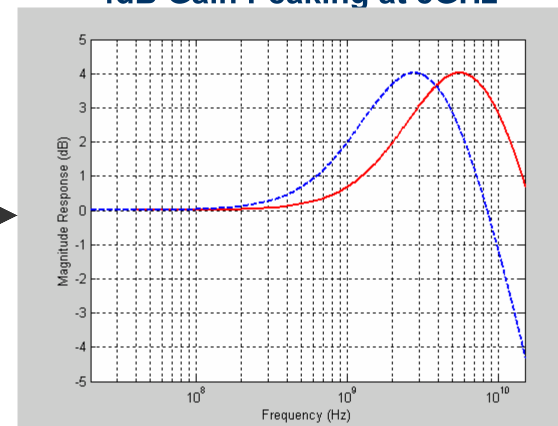
Transmitter
Gaussian Pulse, T_r(20-80%) = 30ps

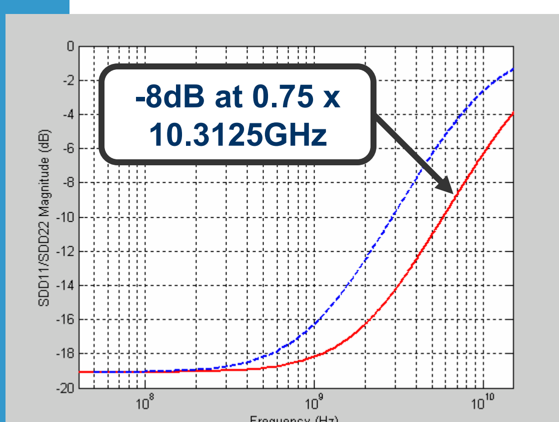


Channel

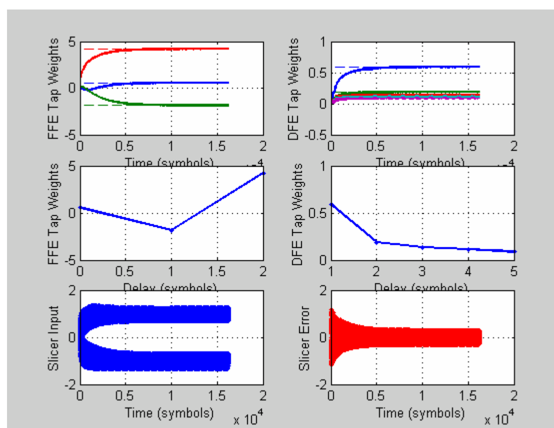


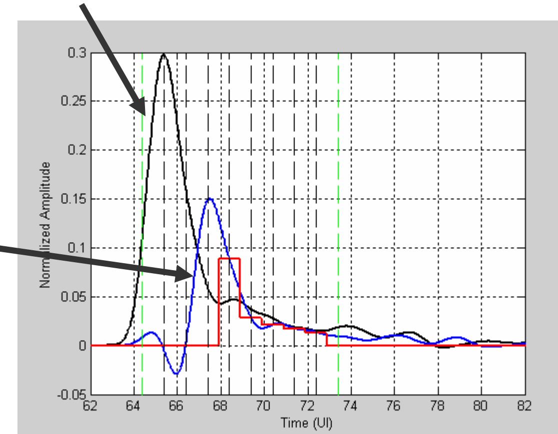
Receiver
4dB Gain Peaking at 5GHz



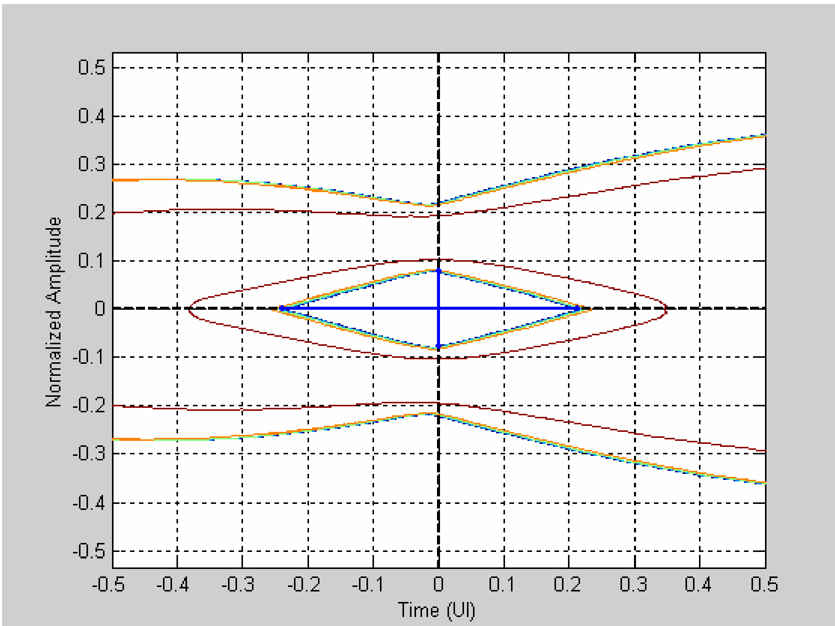


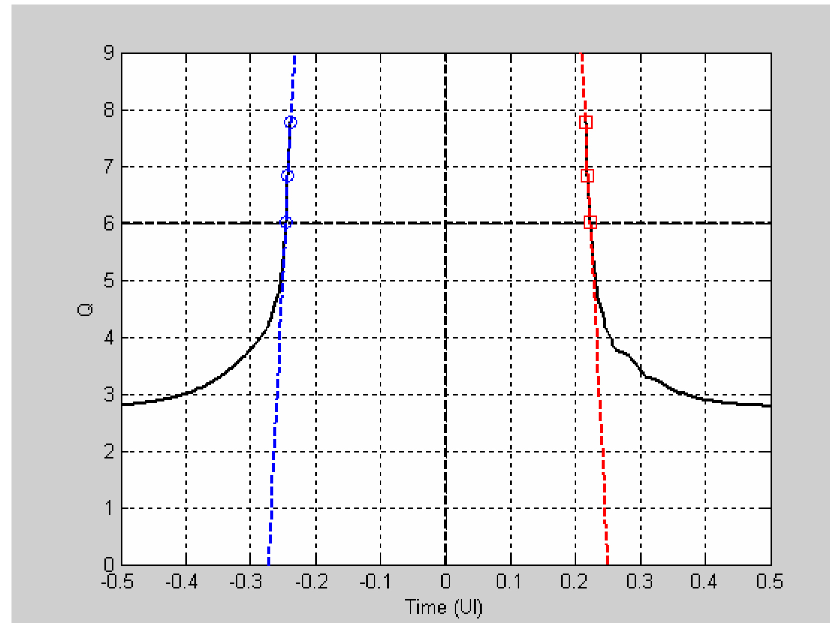
R = 40Ω, C = 0.385pF





NRZ Eye (0.05UI$_{p-p}$ Tx RJ, no crosstalk)

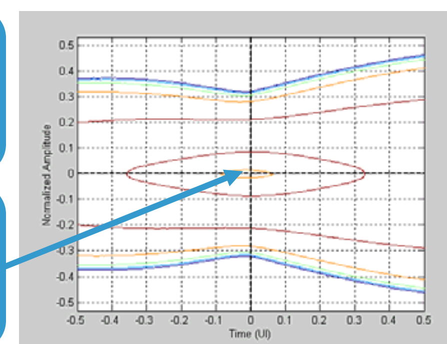




Vertical Eye Opening (at 1E-15)	0.16	au
Horizontal Eye Opening (at 1E-15)	0.45	UI
Effective DJ, Peak-Peak	0.48	UI
Effective RJ, RMS	0.004	UI

Identical to PAM-4 eye height!

Note: Crosstalk completely closes the eye at 1E-15



Agenda

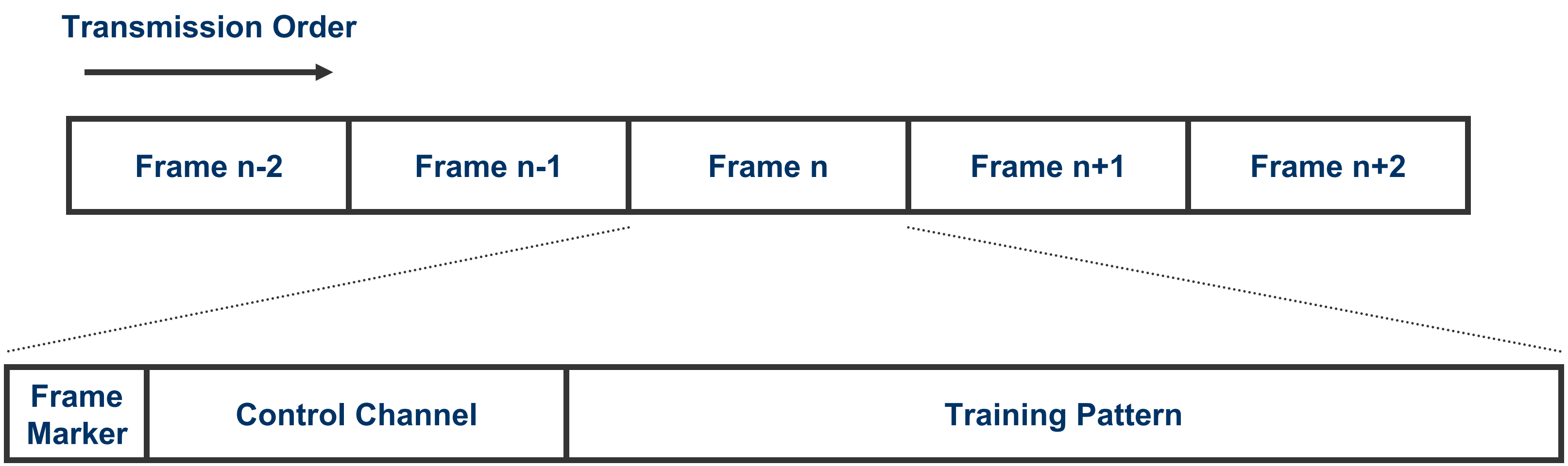
- Proposal Overview
- Link Simulations
- **Link Initialization Protocol (LIP) Detail**
- Conclusions

Link Initialization Protocol (LIP)

- Facilitates clock recovery.
- Optimizes transmitter FIR.
- Automatic power control.
  - Receiver may steer the transmitter output voltage to the minimum level required for acceptable performance.
- Optimize receiver equalizer.

LIP Frame Format

- Transmitted using only -3 and +3 symbols.
  - NRZ signaling at 5.15625Gb/s.
- Frame length is 560 bits.
  - Divisible by both 16 and 20.
  - 4-byte frame marker, 8-byte control channel, 58-byte training pattern



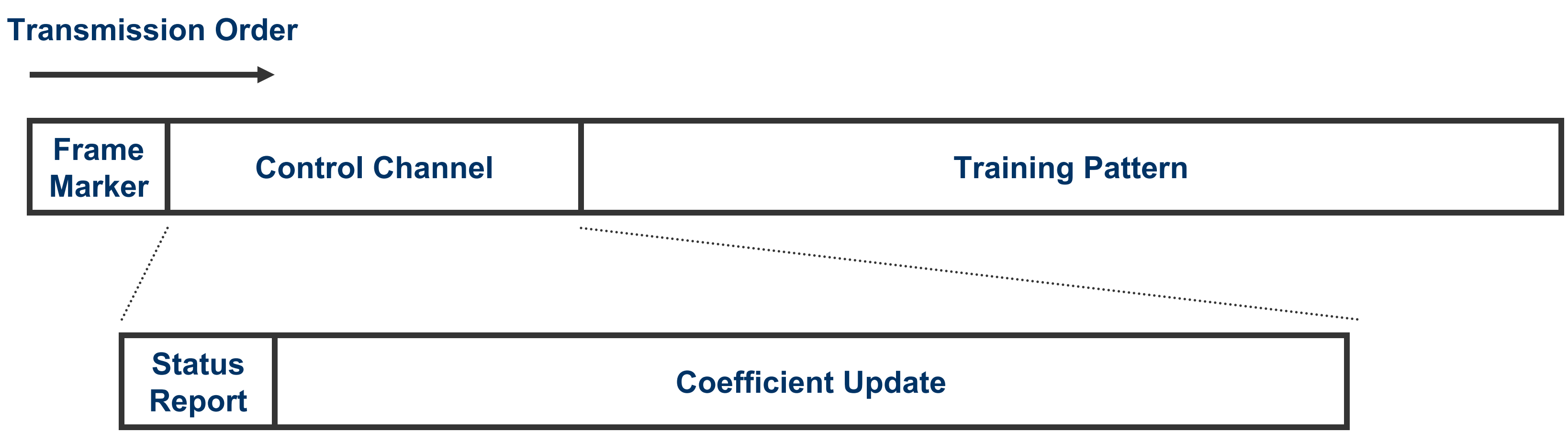
Frame Marker

- Delimits LIP frames.
- Fixed 4-byte pattern, 0xFFFF_0000
  - Detectable over unequalized or partially equalized channels.
  - Does not occur in control channel or training pattern.
  - Also may be used as a polarity check (reception of 0x0000_FFFF indicates polarity reversal).

Control Channel

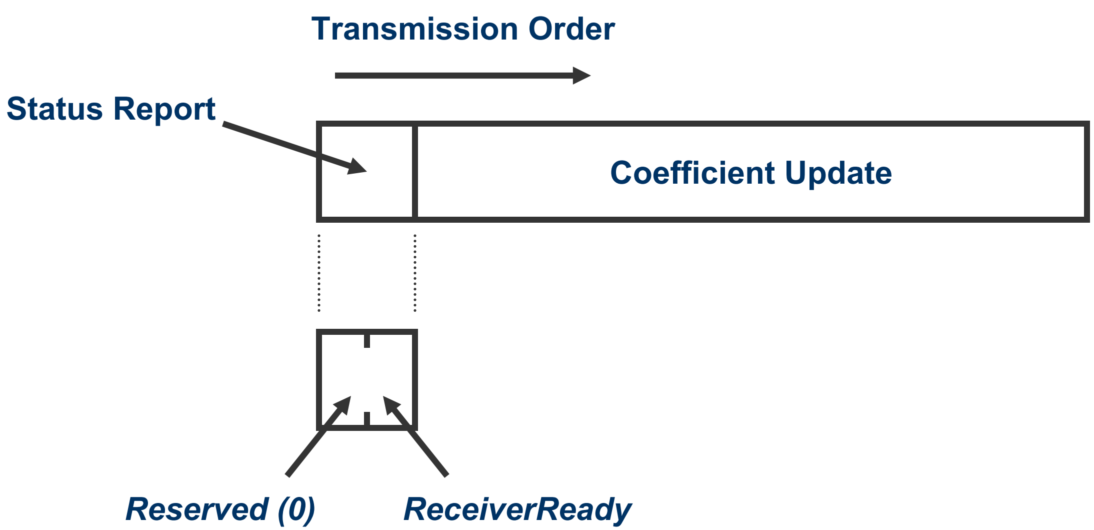
- 2-bytes of control information (8-bytes after encoding).
  - Status report.
  - Coefficient update.
- Double-Wide Manchester Coding
  - Guarantees 50% transition density.
  - Guarantees DC balance.
  - Prevents frame marker pattern from appearing in the control channel.
  - Detectable over unequalized or partially equalized channels.

Message Bit	Encoded Sequence
0	1100
1	0011



Status Report

- *ReceiverReady* indicator (1-bit).
  - Asserted (1) when receiver deems that equalization training (for both the transmitter and receiver) is complete.



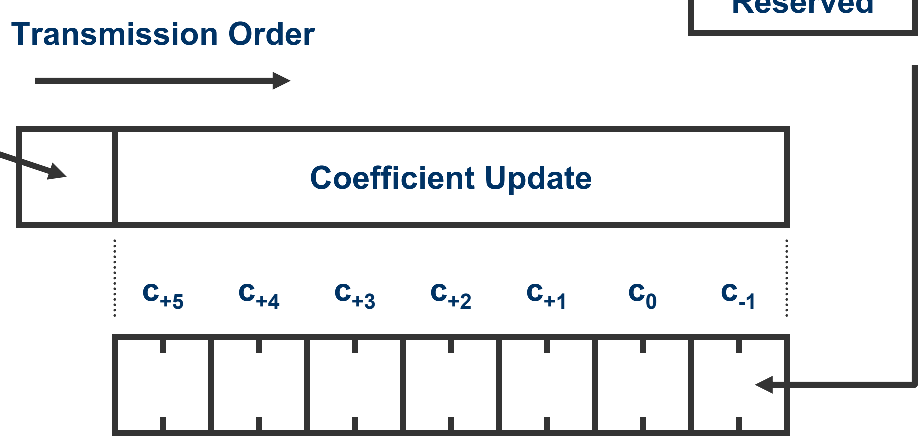
Notes

a) Fields shown prior to Manchester encoding.

Coefficient Update

- Supports parallel update of transmitter FIR coefficients to a maximum of 7 taps.
  - It is not necessary for an implementation to support all 7 taps.
- Each tap has an associated action.
  - Decrement / Hold / Increment
  - Agnostic to the supported tap weight resolution.
  - Tolerant of corrupted or lost coefficient updates.
  - Actions applied to unsupported taps are ignored.

Action	Encoding
Hold	00
Decrement	01
Increment	10
Reserved	11



<u>Notes</u>

a) Fields shown prior to Manchester encoding.

b) By convention, c_0 is the main (or gain) tap.

Training Pattern

- Any DC-balanced "random" pattern will suffice.
- One possibility is the 464-bit pattern consisting of the pattern shown below (232-bits) followed by its inverse.

Transmission Order →

Sync. Pattern [6-bytes]	00 FF 00 FF 00 FF
Impulse [3-bytes]	00 80 00
High-Speed Clock [4-bytes]	AA AA AA AA
1'b1 followed by $x^7 + x^6 + 1$ (all ones seed) [16-bytes]	FE 04 18 51 E4 59 D4 FA 1C 49 B5 BD 8D 2E E6 55

LIP Highlights (1/2)

- LIP frames are signaled continuously using only -3 and +3 symbols.
  - Absence of -1 and +1 symbols for an extended period indicates that the remote PMD wishes to re-initialize.
- Local receiver adaptation process sends FIR tap weight updates to the remote transmitter via the coefficient update field.
  - The adaptation process itself is beyond the scope of the standard.
  - A variety of algorithms may be employed.

LIP Highlights (2/2)

- When the local adaptation process determines that the local Tx and remote Rx a fully trained, it sets the ReceiverReady bit on outgoing LIP frames.
  - The LIP state machine must see the ReceiverReady bit asserted three consecutive times before it concludes that remote receiver is ready to received data (no hair triggers).
- When the LIP state machine determines that the local and remote receivers are ready to receive data, it sends a fixed number of LIP frames to ensure that the remote receiver properly detects the ReceiverReady bit.

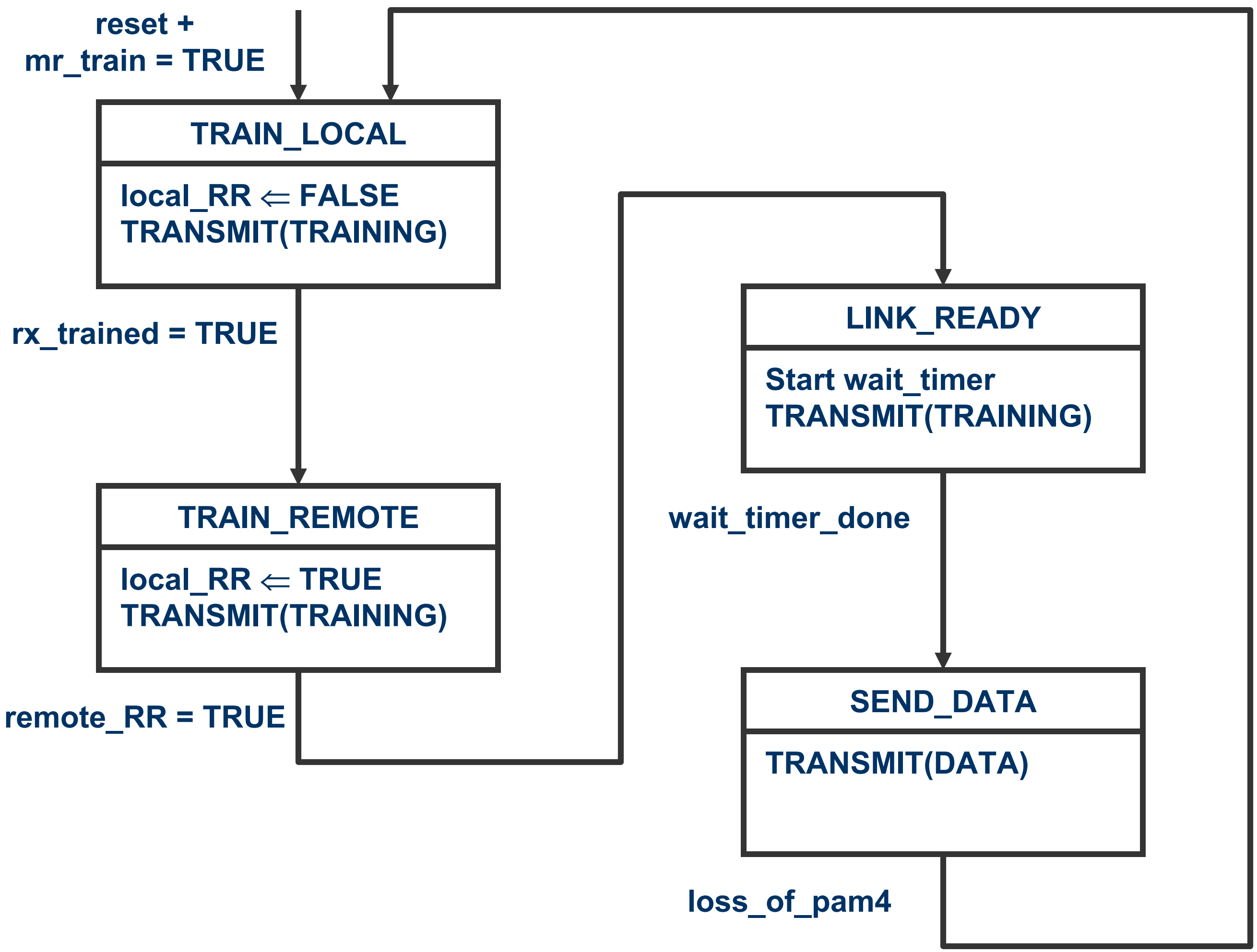
LIP State Diagram (1/3)

- Variables
  - reset: Condition that is true until such time as the power supply for the device has reached its specified operating region.
  - mr_train: Asserted by system management to initiate training.
  - local_RR: Asserted by the link initialization protocol state machine when rx_trained is asserted. This value is transmitted as the *ReceiverReady* bit on all outgoing LIP frames.
  - remote_RR: The value of remote_RR shall be set to FALSE upon entry into the TRAIN_LOCAL state. The value of remote_RR shall not be set to TRUE until no fewer than three consecutive LIP frames have been received with the *ReceiverReady* bit asserted.
  - rx_trained: Asserted when the transmit and receive equalizers have been optimized and the normal data transmission may commence.
  - loss_of_pam4: Asserted when X consecutive symbols are received without the presence of –1 or +1 symbols. This is an indication that the remote transmitter has reverted to LIP frames. The value of X shall be between 500 and 1500 PAM-4 symbols

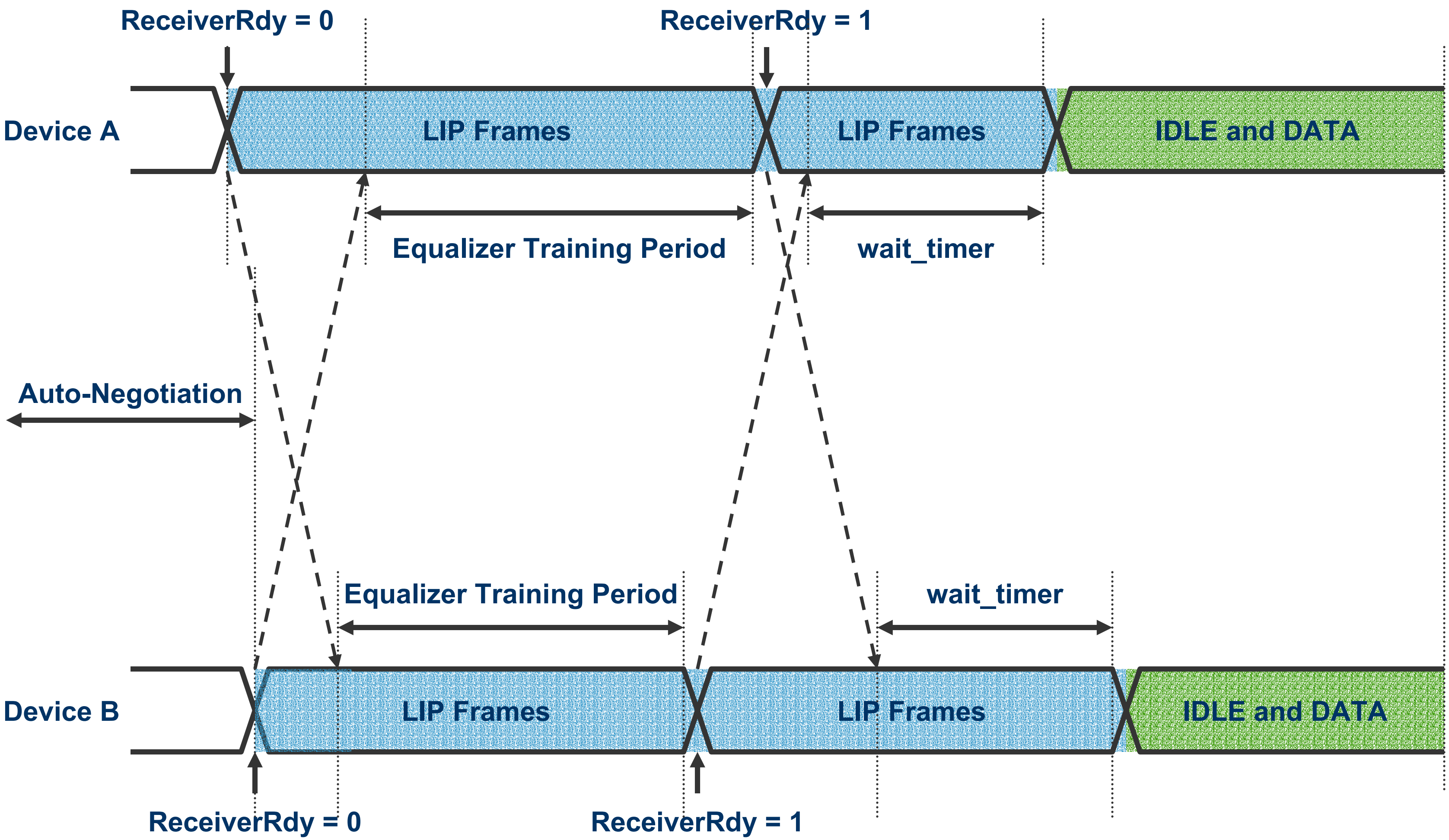
LIP State Diagram (2/3)

- Timers
  - wait_timer: This timer is started when the local receiver detects that the remote receiver is ready to receive PAM-4 data. The local transmitter will deliver wait_timer additional LIP frames to ensure that the remote receiver correctly detects the *ReceiverReady* state. The value of wait_timer shall be between 100 and 300 LIP frames.
- Messages
  - TRANSMIT( )
    - TRAINING: Sequence of LIP frames. The status report and coefficient update fields are defined by receiver adaptation process.
    - DATA: Sequence of PAM-4 symbols as defined by the output of the PAM-4 encoding block.

LIP State Diagram (3/3)



Example LIP Timing Diagram

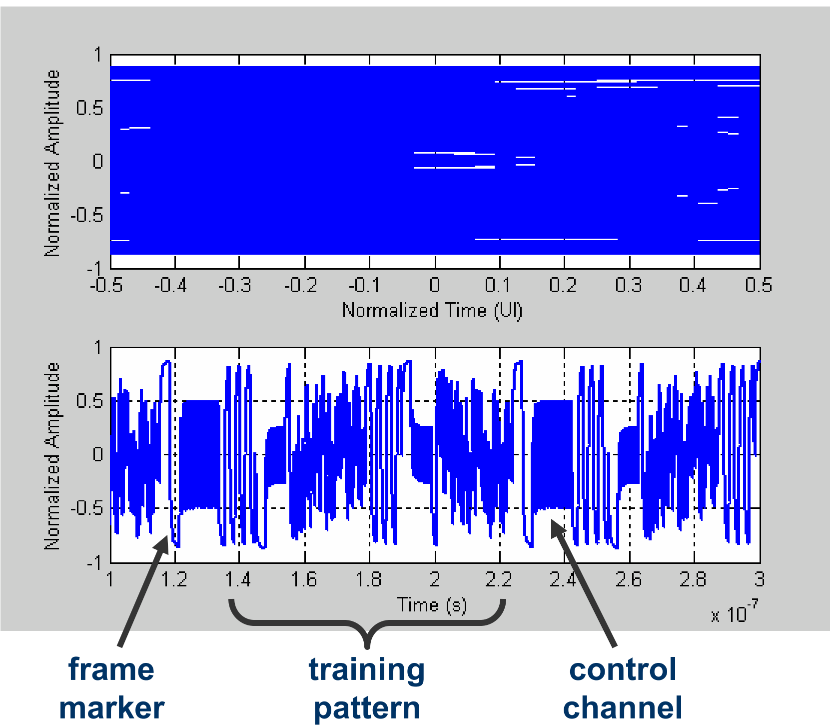


Robust Reception of LIP Frames

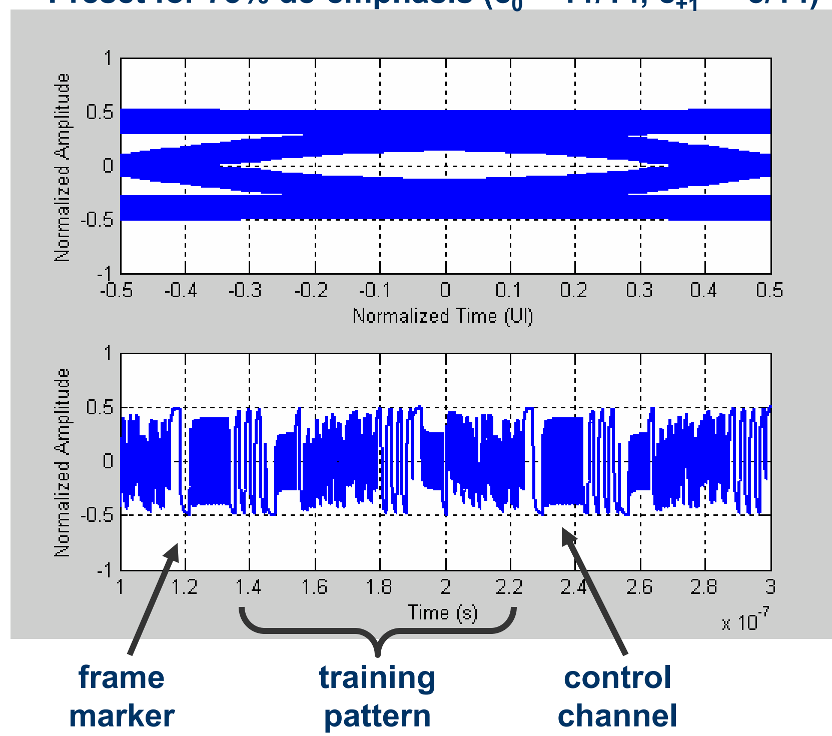
Note: Simulations use same worst-case channel studied earlier.

- LIP Frames are transmitted using PAM-2 at 5Gbaud for more reliable reception over unequalized channels.
- Robustness may be improved through the use of simple equalizer pre-sets.

No Preset



Preset for 75% de-emphasis (c_0 = 11/14, c_{+1} = -3/14)



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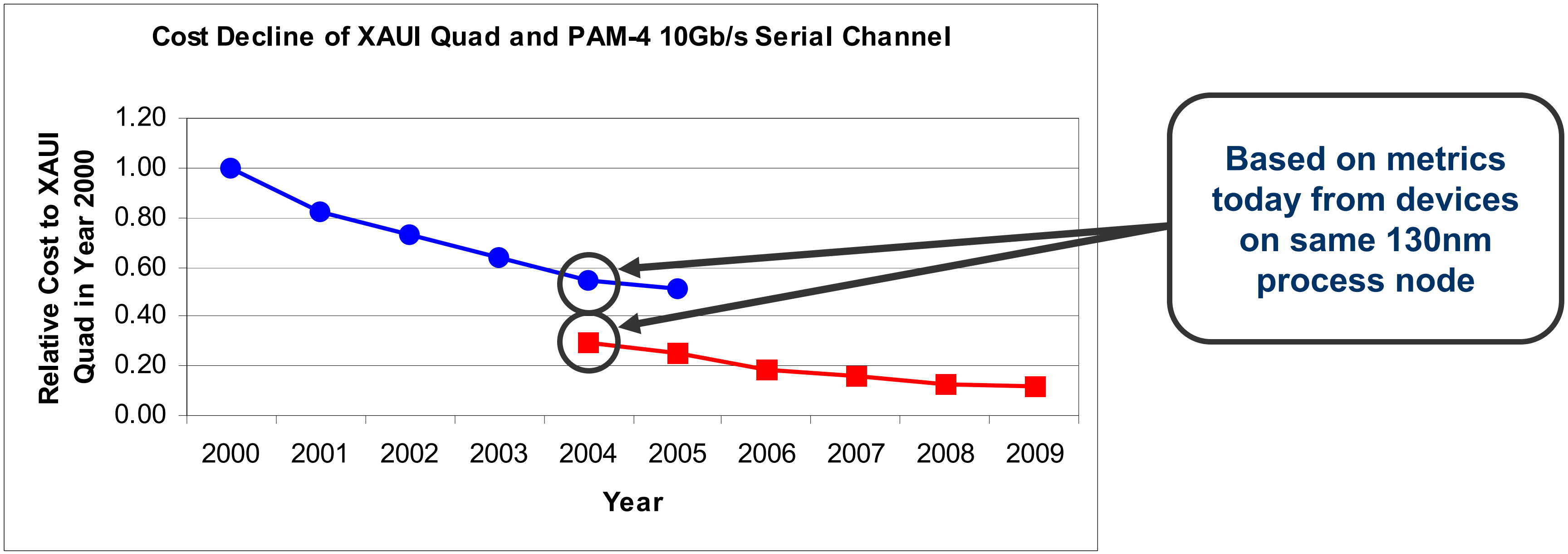
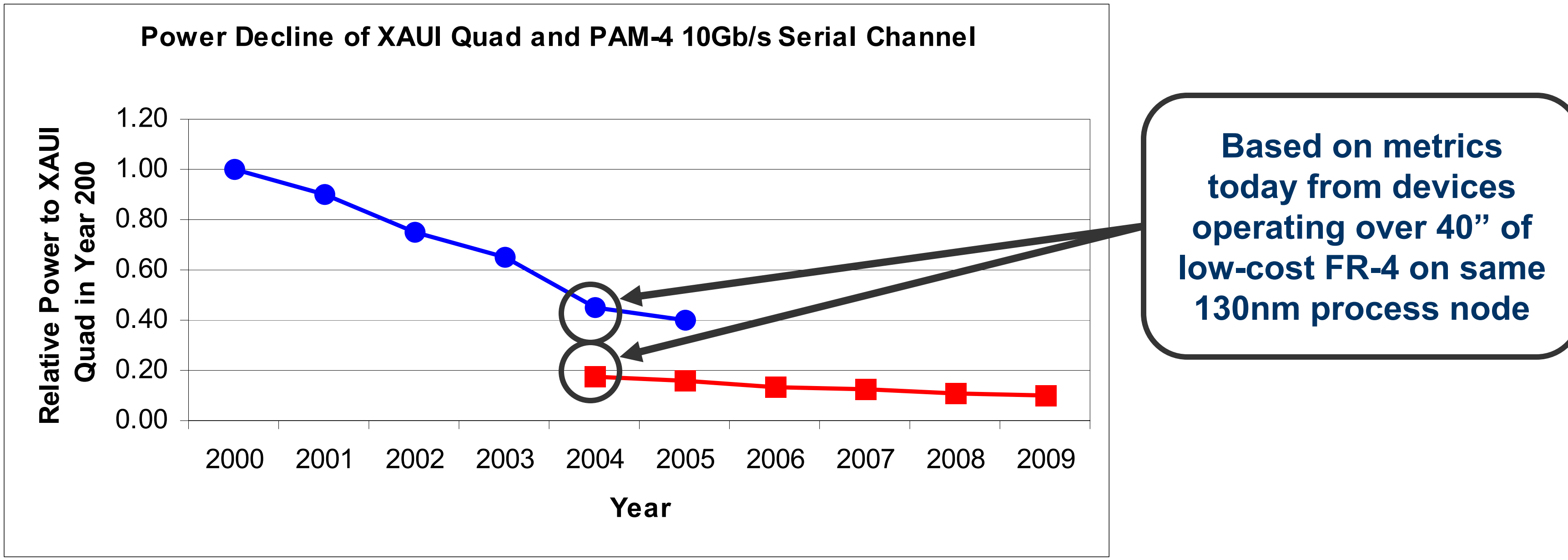
PAM-4 Silicon Complexity and Cost



- Single lane of 10Gb/s PAM-4 is less than ½ die area of a typical 10Gb/s XAUI quad today.
  - Will follow similar XAUI cost declines going forward.
  - Total Cost = Chip Test + Yield + Packaging as well as Backplane Interconnect.
- 10Gb/s PAM-4 is technically feasible and demonstrated in 130nm today.
  - Extensive data for operation over 40” low-cost FR-4 backplane with two connectors.

PAM-4 Power Considerations



- Single lane of 10Gb/s PAM-4 is less than ½ the power of a typical 10Gb/s XAUI quad **today**.
  - Will follow additional power decline curve moving to smaller geometries.
  - This estimates includes higher voltage supplies for I/O (however, it is possible that the higher output voltage is not required for the targeted channels).

Objectives Check

- Preserve the 802.3/Ethernet frame format at the MAC Client service interface. [Yes]
- Preserve min. and max. frame size of current 802.3 Std. [Yes]
- Support existing media independent interfaces. [Yes, XGMII via the 10GBASE-R PCS]
- Support operation over a single lane across 2 connectors over copper traces on improved FR-4 for links consistent with lengths up to at least 1m. [Yes, 10Gb/s operation simulated and demonstrated]
  - Define a 1 Gb/s PHY
  - Define a 10 Gb/s PHY
- Consider auto-negotiation.
- Support BER of 10^-12 or better. [Yes, 10Gb/s operation simulated and demonstrated to BER better than 10^-12]
- Meet CISPR/FCC Class A. [Automatic power control and reduction in occupied bandwidth help meet this requirement]

Conclusions

- A new PMD sublayer based on PAM-4 signaling is proposed.
- Use of transmitter pre-compensation greatly reduces receiver complexity.
- Link Initialization Protocol (LIP) maintains plug-and-play feel.
  - Simple and robust.
- Methodology proven in simulation and in measurement.
  - http://ieee802.org/3/bladesg/public/jan04/hoppin_01_0104.pdf
  - http://ieee802.org/3/bladesg/public/mar04/hoppin_01_0304.pdf
- Proposed PMD satisfies the 5 Criteria and all Task Force objectives related to the 10Gb/s serial backplane PHY.

Thank You