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.
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

**Layers Diagram**

- Higher Layers
  - LLC
  - MAC Control (Optional)
  - MAC
- Reconciliation
  - XGMII
  - XSBI
  - PCS
    - XGMII
  - PMA
  - PMD
  - AUTONEG
    - XGMII
    - XSBI
  - 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
Encoding/Decoding

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

<table>
<thead>
<tr>
<th>Bits</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>-3</td>
</tr>
<tr>
<td>10</td>
<td>-1</td>
</tr>
<tr>
<td>01</td>
<td>+1</td>
</tr>
<tr>
<td>11</td>
<td>+3</td>
</tr>
</tbody>
</table>
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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.

IEEE P802.3ap Task Force

July 13, 2004 (r1.3)
Equalizer Training

Transmitter
Gaussian Pulse, $T_{90\%} = 50$ ps

Channel

Receiver
4 dB Gain Peaking at 2.5 GHz
10Gb/s Operation (0.05UI_{p-p} Tx RJ, no crosstalk)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Eye Opening (at 1E-15)</td>
<td>0.16 au</td>
</tr>
<tr>
<td>Horizontal Eye Opening (at 1E-15)</td>
<td>0.28 UI</td>
</tr>
<tr>
<td>Effective DJ, Peak-Peak</td>
<td>0.65 UI</td>
</tr>
<tr>
<td>Effective RJ, RMS</td>
<td>0.004 UI</td>
</tr>
</tbody>
</table>

July 13, 2004 (r1.3)
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 be 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)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Eye Opening (at 1E-15)</td>
<td>0.10</td>
</tr>
<tr>
<td>Horizontal Eye Opening (at 1E-15)</td>
<td>0.19</td>
</tr>
<tr>
<td>Effective DJ, Peak-Peak</td>
<td>0.66</td>
</tr>
<tr>
<td>Effective RJ, RMS</td>
<td>0.010</td>
</tr>
</tbody>
</table>

IEEE P802.3ap Task Force

July 13, 2004 (r1.3)
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 0.15\(U_{p-p}\) (as measured at 1E-15).
- Note that at 0.10\(U_{p-p}\), 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 2\(V_{p-p}\) Tx output voltage. This does not imply that the solution requires 2\(V_{p-p}\).
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 $f_{\text{baud}}/2$ is identical to PAM-4 gain peaking at $f_{\text{baud}}/2$.
- 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, $T_{(20-80\%)} = 30\text{ps}$

Receiver
4dB Gain Peaking at 5GHz

Channel
-8dB at $0.75 \times 10.3125\text{GHz}$

$R = 40\Omega$, $C = 0.385\text{pF}$
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

Note: Crosstalk completely closes the eye at 1E-15
Identical to PAM-4 eye height!
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.

### Table: Encoding Sequences

<table>
<thead>
<tr>
<th>Message Bit</th>
<th>Encoded Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1100</td>
</tr>
<tr>
<td>1</td>
<td>0011</td>
</tr>
</tbody>
</table>

### Transmission Order

- Frame Marker
- Control Channel
- Training Pattern
- Status Report
- Coefficient Update
**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.

<table>
<thead>
<tr>
<th>Action</th>
<th>Encoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hold</td>
<td>00</td>
</tr>
<tr>
<td>Decrement</td>
<td>01</td>
</tr>
<tr>
<td>Increment</td>
<td>10</td>
</tr>
<tr>
<td>Reserved</td>
<td>11</td>
</tr>
</tbody>
</table>

Notes:

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

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

TRAIN_LOCAL
local_RR ← FALSE
TRANSMIT(TRAINING)

TRAIN_REMOTE
local_RR ← TRUE
TRANSMIT(TRAINING)

LINK_READY
Start wait_timer
TRANSMIT(TRAINING)

SEND_DATA
TRANSMIT(DATA)

rx_trained = TRUE
reset +
   mr_train = TRUE

remote_RR = TRUE
wait_timer_done
loss_of_pam4
Example LIP Timing Diagram

Device A
- ReceiverRdy = 0
- LIP Frames
- Equalizer Training Period
- wait_timer
- LIP Frames
- ReceiverRdy = 1
- IDLE and DATA

Device B
- ReceiverRdy = 0
- LIP Frames
- Equalizer Training Period
- wait_timer
- LIP Frames
- ReceiverRdy = 1
- IDLE and DATA
Robust Reception of LIP Frames

- 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.

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

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- Conclusions
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.
- Proposed PMD satisfies the 5 Criteria and all Task Force objectives related to the 10Gb/s serial backplane PHY.
Thank You