Benefits of Transmitter Adaptation for Optical Links

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Overview

- **Benefits of optical link training**
  - Optimum transmit configuration providing improved BER
  - Energy efficiency

- **Why optics link training challenging**

- **Background on Ethernet link training**

- **Proposed optics link training**
  - Limited to preset initially but with ability to extend to full autonomous tuning

- **Optics link training process and flow**

- **Summary.**
Benefits of Optical Link Training

- **Benefits of adjusting pre-emphasis/boost**
  - Transmitter with large amount of pre-emphasis used with high BW receiver may result in clipping
    - Some transmitters that meet TDECQ may have excess boost at expense of sub-optimum receive BER
  - Slow transmitters with low distortion meeting TDECQ may benefit from extra boost used with low BW receivers

- **Increase ratio of outer/inner eyes**
  - MZM modulators have compression of outer eyes that may benefit from adjusting inner/outer eye
  - Receivers may have some compression that benefits from adjusting outer eyes
  - EA modulators can also take advantage of this with applied bias/signal are adjusted for EA non-linear response

- **OMA control**
  - Optical transmitters are designed to operate over maximum loss cable plant and launch condition
  - Reducing OMA increases energy efficiency
  - Reducing OMA may also mitigate overload and improve BER

- **Chirp and dispersion control**
  - Beneficial for >2 km links to mitigate dispersion penalty, most noticeably on outer wavelengths L0 and L3

- **An optical transmitter with the above preset controls more likely may operate with FECi bypassed and/or operate with lower transmit power.**
Pre-emphasis/overshoot can both improve and degrade the link BER

- Generally increasing overshoot (reducing Ceq) improves TDECQ
- In the example below overshoot resulted in error floor in the TIA
  
  ![Image](https://grouper.ieee.org/groups/802/3/cu/public/March20/rodes_3cu_01a_031720.pdf)

Achieving Robust Transmitter Compliance

**Without Over-rejecting Transmitters**

1. Low-OMA region
   - Pre-emphasis improves sensitivity. Negative $Ceq$ improves transceiver yield. Use TDECQ for compliance.

2. Mid-OMA region
   - Overshoot can limit TIA linearity. Use a *relative overshoot limit for compliance.*

3. High-OMA region
   - To protect against overload, use an *absolute overshoot limit for compliance.*

**Mid-OMA region: use overshoot for compliance**

![Diagram](IEEE P802.3cu)

**Why control relative overshoot?**

Overshoot triggers TIA nonlinearities that limit Error floor

- Measured real Rx
- TIA THD simulation

**Why do we think this is TIA related?**
1. We can simulate a similar error bump with a simple logistic function (S-shaped) to model TIA saturation
2. Manual gain control of TIA eliminates the error bump

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Pre-Emphasis Generally Improves TDECQ

- But may result in overload and error floor as shown below for 802.3cu transmitters!

TDECQ vs Rx performance

- Overshoot tends to improve sensitivity. It saturates for values larger than 22%
- Overshoot values larger than 22% increase error floor significantly
TDECQ is not Always a Good Indicator of Link BER

- The 802.3db transmitters below TDECQ improves with increasing overshoot (decreasing Ceq), but for overshoot >~20% (~<1.1 dB) the link develops an error floor!
  - [https://www.ieee802.org/3/db/public/September-09-September-29-2021/ghiasi_802.3db_01_092321.pdf](https://www.ieee802.org/3/db/public/September-09-September-29-2021/ghiasi_802.3db_01_092321.pdf)
Potential Energy Efficiently

What is the potential for energy efficiency if OMA and CW is reduced by ½ with link training?

800G-FR4 links with semi-cooled EMLs
- EML with max Iop=120 mA, Vop(max)=1.9 V, operating from 3.3 V supply, min EA driver amplitude 1.25 V single ended into 50 Ω
  - Power saving due to CW reduction by ½ per DFB ~1 pJ/bit
  - Power saving due to CMOS driver swing reduction to keep constant ER ~0.2 pJ/bit
  - Power saving due to TEC heat load reduction ~2.25 pJ/bit (see the next page)
- Power saving with no TEC: ~1pJ/bit
- Power saving with TEC: ~3 pJ/bit

800G-DR4 link with Si MZM and one high power uncooled DFB CW source
- DFB with max Iop=300 mA, Vop(max)=1.9 V, operating from 3.3 V supply, min MZM drive amplitude 2.5 V Diff(p-p)
- Power saving due to CW reduction by ½ per 200G lane: ~0.6 pJ/bit
- Power saving due to non-CMOS driver swing reduction to keep constant ER: ~0.5 pJ/bit
- Power savings: ~1 pJ/bit
Reducing TEC Heat Load

- Semi-cooled EML at 50 °C with case temperature of 75 °C and max heat load for 4 DFB/EA (4x1.9V*0.12 A)=0.91 W but rounded to 1 W
  - Link to online TEC product and calculator
    https://tetech.com/peltier-thermoelectric-cooler-modules/micro/
  - TEC power consumption with DFB at max current 120 mA 0.8A*(2x1.5) V= 2.4 W
  - TEC power consumption with DFB at ½ the current 60 mA 0.4A*(2x0.75) V= 0.6 W
  - The TEC power saving by reducing DC light by ½ is 0.45 W/DFB or 2.25 pJ/bit!

1. Assumes TEC driver supply is 2x TEC voltage drop and supply voltage is reduced when thermal load is smaller thermal load.
Why Optical TX Link Training is Challenging

- Unlike CR/KR optical devices may require specific adjustment based on the device type
  - VCSEL/DML – asymmetrical turn-on/off
  - MZM – cosine compression – minor effect for IMDD applications
  - Electro-absorption (EA) – non-linear transfer response
  - Combination of chirp and dispersion on SMF - may create pulse compression

- Transmit FFE adjustment only provides linear frequency compensation
  - Proposed Optic-LT will not provide non-linear adjustments specific to different class of optics
  - Different presets may include aspect of non-linear compensation based on device type
  - But all presets must be known good setting that operate with the reference equalizer otherwise receiver may lose lock

- Optical link training may provide significant benefit for some optical PMDs
  - Need to quantify the benefit of optics training for the adopted SMF PMDs
  - Need to define the presets and the FFE tap ranges/step/weight for each of the optical PMDs.

Optics-LT – Ghiasi, et. al.
IEEE 802.3dj Task Force
For proposed optics AN, see Brown_3dj_01_2311

Optics LT leverages 802.3 CL 136/162 LT link to operating as point-point
  - Optics LT exchange is between the two modules
  - CL136/162 Control/status fields are transmitted with DME (Differential Manchester Encoding) at 1/8 the Baudrate followed by PRBS13Q as PAM4 training pattern
    - FECo DME control/status operates at 1/8 of 106.25 GBd (13.28 GBd) with training pattern at full rate
    - FECi DME control/status operates at 1/8 of 113.4375 GBd (14.18 GBd) with training pattern at full rate.

**Figure 72-2—Training frame structure**

**Figure 136-3—Training frame structure**
Leveraging CL136 Link Training for Optics-LT

- Training frame structure based on 136.8.11.1
- Training pattern and training PRBS pattern based on 136.8.11.1.3
- Control field structure and status field structure generally follows 162.8.11 with the difference captured in this contribution
  - If 802.3dj modifies KR/CR PMD control then will follow those changes when possible.

![Diagram](image.png)

**Table 136–8—Training patterns**

<table>
<thead>
<tr>
<th>$p$</th>
<th>Polynomial $p$, $G(x)$</th>
<th>Default seed bits$^a$</th>
<th>Initial output, PAM2</th>
<th>Initial output, PAM4</th>
<th>Initial output, PAM4 with precoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$1 + x + x^2 + x^6 + x^{12} + x^{13}$</td>
<td>00000101010111</td>
<td>00303303300000</td>
<td>10313202201111$^b$</td>
<td>1301200200101</td>
</tr>
<tr>
<td>1</td>
<td>$1 + x^2 + x^3 + x^7 + x^{13}$</td>
<td>0011101000001</td>
<td>3030303030333</td>
<td>3030213021333</td>
<td>3122012201212</td>
</tr>
<tr>
<td>2</td>
<td>$1 + x^2 + x^4 + x^8 + x^{13}$</td>
<td>1001000101100</td>
<td>0303333033030</td>
<td>1212323130331</td>
<td>1102120121301</td>
</tr>
<tr>
<td>3</td>
<td>$1 + x^2 + x^5 + x^9 + x^{13}$</td>
<td>0100010000010</td>
<td>3330300030330</td>
<td>2231210121221</td>
<td>2032013201110</td>
</tr>
</tbody>
</table>

*IEEE 802.3dj Task Force*
Proposed Optical Link Training

The link training leverages 802.3 CL136/162 for Optics-LT on a single point-point optical segment

- Proposal makes minor modification to CL136/162 to support Optics-LT by segmenting optical link in a similar manner to CR/KR point-point link with repeaters
- Electrical link training on AUIs are outside the scope of Optics LT
- Optics DME/training can be driven by recovered clock from the host or the module reference clock
- Link training proposal for currently proposed SMF PMDs is limited to presets only to mitigate any risk
  - Future PMDs may choose to extend the Optics LT to autonomous FFE adjustment.

Focus of this Contribution

Optics-LT – Ghiasi, et. al. IEEE 802.3dj Task Force
Proposed Optics Link Training Limited to Transmit Presets

- **Leverage CL162 control field Modulation-Precoder to enable pre-coder (see back up)**
- **Preset1** is the default setting that TDECQ must be met
  - Preset 2-10 are allowed 40% excursion above the TECQ/TDECQ limit to minimize additional testing
  - Preset 2-10 meeting a TDECQ with guard-band prevents misbehaving transmitters where CDR loses lock
- **Optics LT limited to presets and not full autonomous FFE tuning**
  - Potential proposed presets address BW limitation/over emphasis, compression, power, chirp/dispersion control
  - Preset1 – Default setting only needs to meet TDECQ
  - Preset2 - Increase pre-emphasis +7.5%
  - Preset3 - Decrease pre-emphasis -7.5%
  - Preset4 - Increase ratio of outer/inner eye Y%
  - Preset5 - Decrease ratio of outer/inner eye Y%
  - Preset6 – Positive CD
  - Preset7 – Negative CD
  - Preset8 – Decrease OMA by 1 dB
  - Preset9 – Decrease OMA by 2 dB
  - Preset10 - Decrease OMA by 3 dB.
  - Bandwidth compensation
  - Compression/non-linear compensation
  - To manage CD dispersion on 10 km links
  - Optical signal power control
Link Training Process

- Proposed link training for 802.3dj PMDs limited to presets (under study)
  - Presets are additive and are applied in sequential order Preset[2:10] unless skipped
  - Default preset only need to meet TDECQ limit
  - Preset [2:10] are allowed to have 40% excursion in TDECQ limit to minimize test time
  - Pre-emphasis, compression, and chirp/carrier frequencies are adjusted at constant average power
  - If the link has sufficient margin last step is to reduce OMA at constant ER to maximize the energy efficiency (decreases average power)
  - Need to devise a method for modules advertisement that don’t support all the presets
  - Given that optics presets are additive to better preserve CL162 training different type of controls (pre-emphasis, OMA, etc.) can be fitted to an FFE coefficient select

- How a fully autonomous link training may look like (under study)
  - Start with default preset conditions, including CW source power and FFE gain
  - Converge TX FFE coefficients based on far end error signal instead of utilizing preset 2/3
    - Go through compression presets and chirp preset (if applicable)
  - If the link has sufficient margin OMA is reduced at constant ER to maximize the energy efficiency
  - Fine tune TX FFE coefficients based on far end error signal.
Summary

- **Why task force should consider optical transmit adaption**
  - Optical transmitters are tuned with higher emphasis to get the best TDECQ, but for many links/receivers lower TDECQ not always equates with better link BER
    - Some of the transmitters with excess emphasis for the given link/receiver may have orders of magnitude worse BER
    - But a low BW link/receiver almost always will benefit from higher emphasis
  - Optics is consuming over 50% (~2000 W or 39 pJ/bit) of 51.2 Tb switch power and data centers operators are demanding better optics energy efficiency
    - Optical links are designed for maximum power launch condition into cable plants with maximum loss
    - Majority of optical links have excess optical power, which may degrade the BER
    - For SMF uncooled PMDs ~ 1pJ/bit and for cooled PMDs ~ 3 pJ/bit energy can be saved which is significant considering 102.4 Tb system

- **Assuming optical automatic link configuration for optics (AN), Brown_3dj_01_2311 is adopted the DME facility will exist to perform transmitter adaption for optical links**
  - Optics LT will leverage as much as possible proven Clause 136/162 training and flow

- **Consider this proposal as a work in progress for optical link adaption with feedback appreciated!**
CL 162 PMD Control Function (backup)

<table>
<thead>
<tr>
<th>Bit(s)</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:14</td>
<td>Reserved</td>
<td>Transmit as 0, ignore on receipt</td>
</tr>
<tr>
<td>13:11</td>
<td>Initial condition request</td>
<td>11 12 13 = Reserved 1 0 1 = Reserved 0 1 1 = Preset 5 0 0 1 = Preset 4 1 1 0 = Preset 3 1 0 0 = Preset 2 0 1 0 = Preset 1 0 0 0 = Individual coefficient control</td>
</tr>
<tr>
<td>10</td>
<td>Reserved</td>
<td>Transmit as 0, ignore on receipt</td>
</tr>
<tr>
<td>9:8</td>
<td>Modulation and precoding request</td>
<td>1 1 = PAM4 with precoding 1 0 = PAM4 0 1 = Reserved 0 0 = PAM2</td>
</tr>
<tr>
<td>7:5</td>
<td>Reserved</td>
<td>Transmit as 0, ignore on receipt</td>
</tr>
<tr>
<td>4:2</td>
<td>Coefficient select</td>
<td>4 3 2 = Reserved 1 0 0 = $c(1)$ 1 1 0 = $c(0)$ 1 1 1 = $c(1)$ 0 0 0 = $c(1)$ 0 0 1 = $c(1)$ 0 1 1 = $c(1)$ 0 1 0 = $c(1)$</td>
</tr>
<tr>
<td>1:0</td>
<td>Coefficient request</td>
<td>1 0 = No equalization 1 1 = Increment 0 1 = Decrement 0 0 = Hold</td>
</tr>
</tbody>
</table>

CL162 Presets are not additive and would require some modification to the CL136/162 to make the presets additive!

By leveraging coefficient select field instead for Pre-emphasis, compression, CD control, and OMA with 2 or 4 settings the effects are additive and existing CL136/162 training can be reused!
High Level Link Training Process (backup)

- **Electrical AUIs and optical segments are trained as point-point segments**
  - This approach simplifies electrical and optical link training and backward compatible 100G-AUIs
  - With AUI trained the optics LT starts with known good clock (same as clock mission mode)

- **Module data path is initialized**

- **Local AUI trained**
  - Wait till remote AUI trained
  - Completion of remote AUI status through Optics AN

- **Leverage CL 136/162 training as much as possible**
  - With caveat that the current proposal is limited to presets only with ability to expand as needed

- **After optics LT is completed the module through CMIS inform the host**
  - Host configure the module for mission mode.