Benefits of Transmitter Adaptation for Optical Links

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IEEE 802.3dj Task Force

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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.**

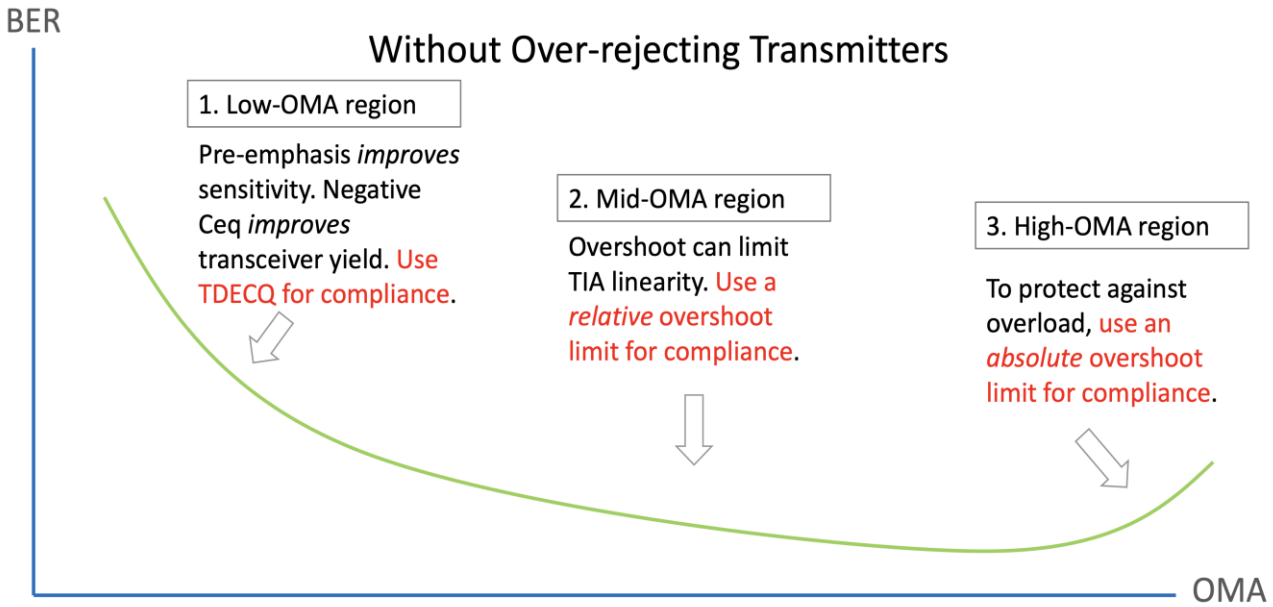
Benefits of Optical Link Training

- **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 Impact on 400GBASE-FR4 Links

- **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
    - https://grouper.ieee.org/groups/802/3/cu/public/March20/rodes_3cu_01a_031720.pdf

Achieving Robust Transmitter Compliance



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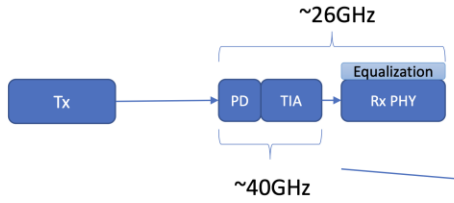
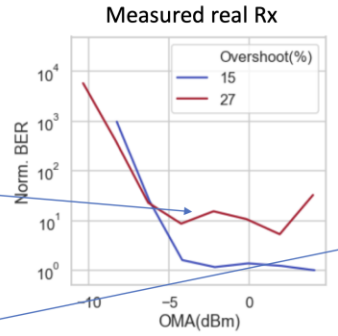
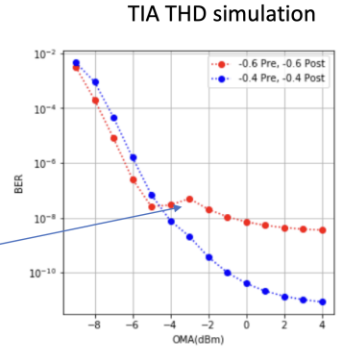
Mid-OMA region: use overshoot for compliance

Why control relative overshoot?

Overshoot triggers TIA nonlinearities that limit Error floor







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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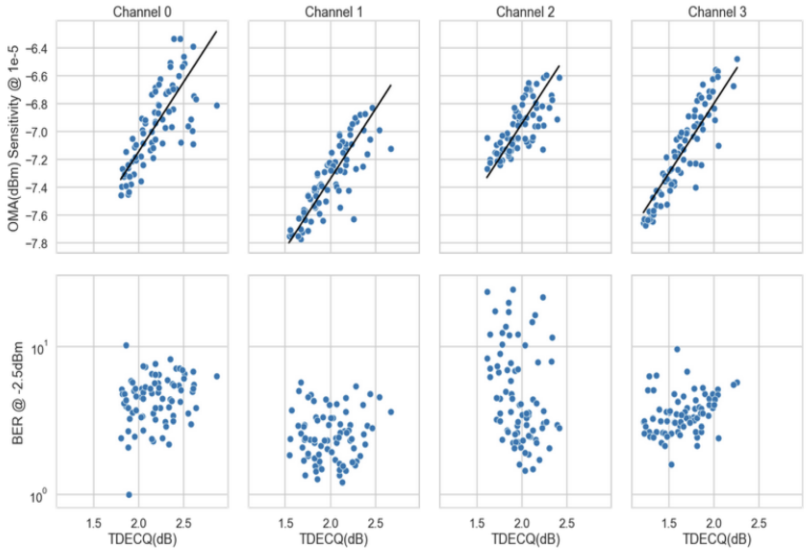
Pre-Emphasis Generally Improves TDECQ

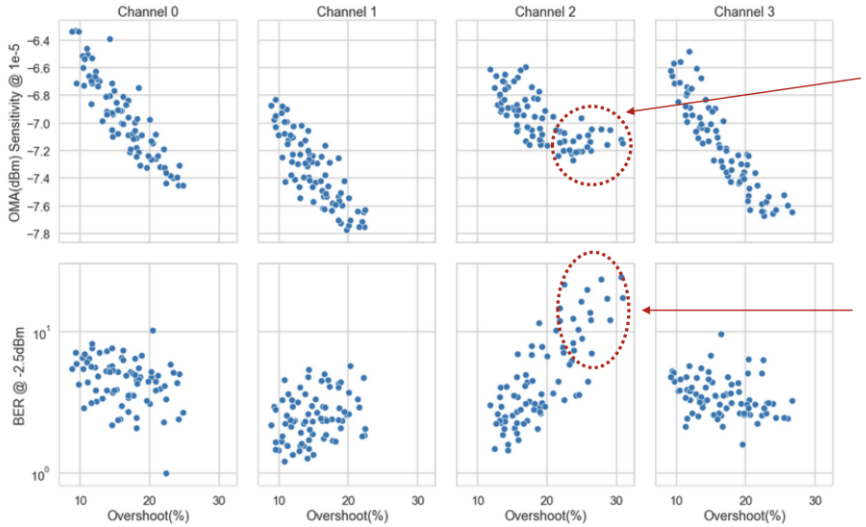
- **But may result in overload and error floor as shown below for 802.3cu transmitters!**
  - https://www.ieee802.org/3/cu/public/cu_adhoc/cu_archive/rodes_3cu_adhoc_030520_v2.pdf
    - Background presentation https://www.ieee802.org/3/cu/public/Jan20/cole_3cu_01b_0120.pdf.

TDECQ vs Rx performance



- TDECQ vs Sensitivity shows good agreement with 1:1 linear fit

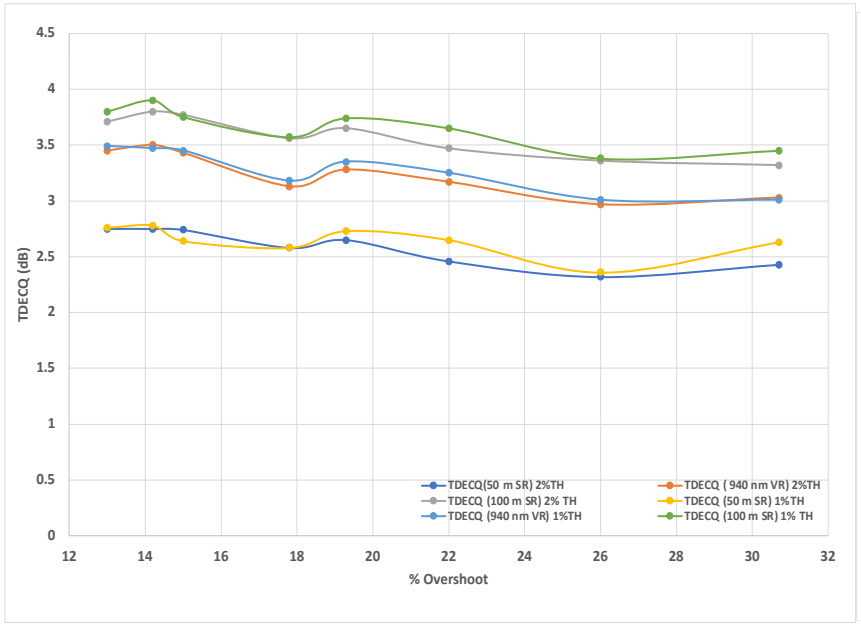
Overshoot vs Rx performance

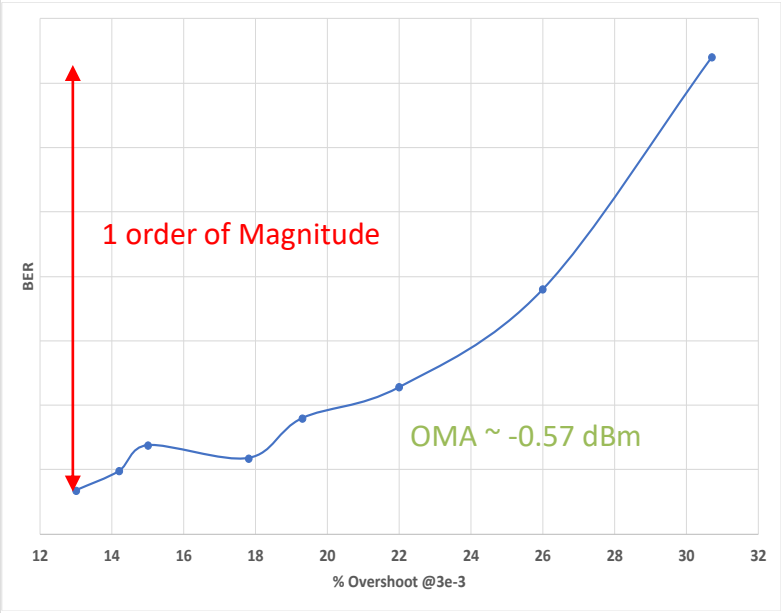


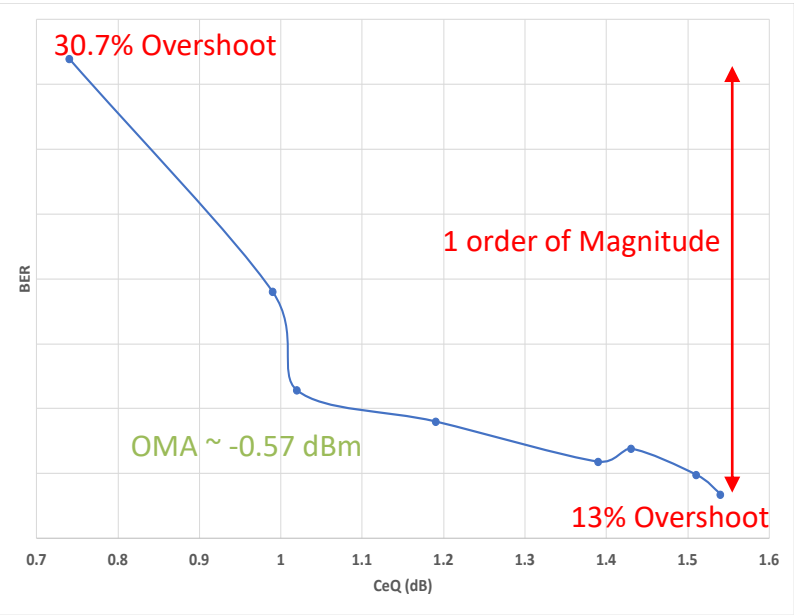
- Overshoot tends to improve sensitivity. It saturates for values larger than 22%
- **Overshoot values larger than 22% increase error floor significantly**

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.





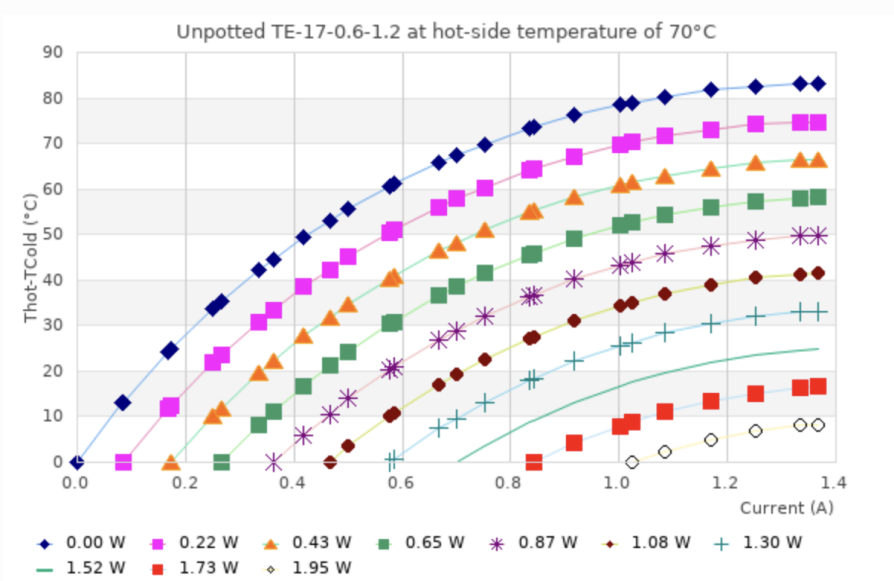


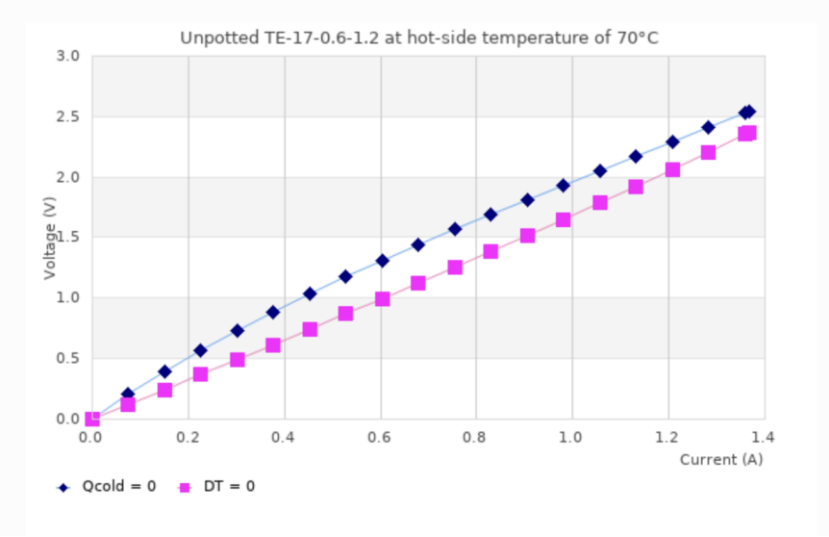
Potential Energy Efficiently

- 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 consummation with DFB at max current 120 mA 0.8A*(2x1.5)[1] V= 2.4 W
  - TEC power consummation with DFB at ½ the current 60 mA 0.4A*(2x0.75) [1] 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 AN and Link Training

- **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.

Original KR CL72 LT Frame

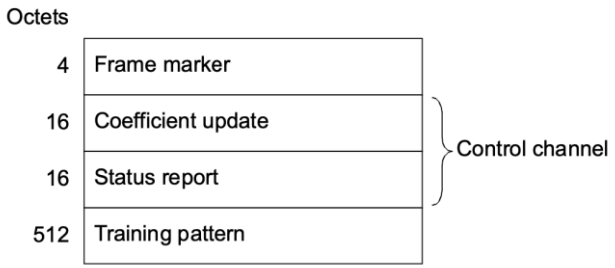


Figure 72–2—Training frame structure

Expanded CL136 LT Frame Supporting PAM4

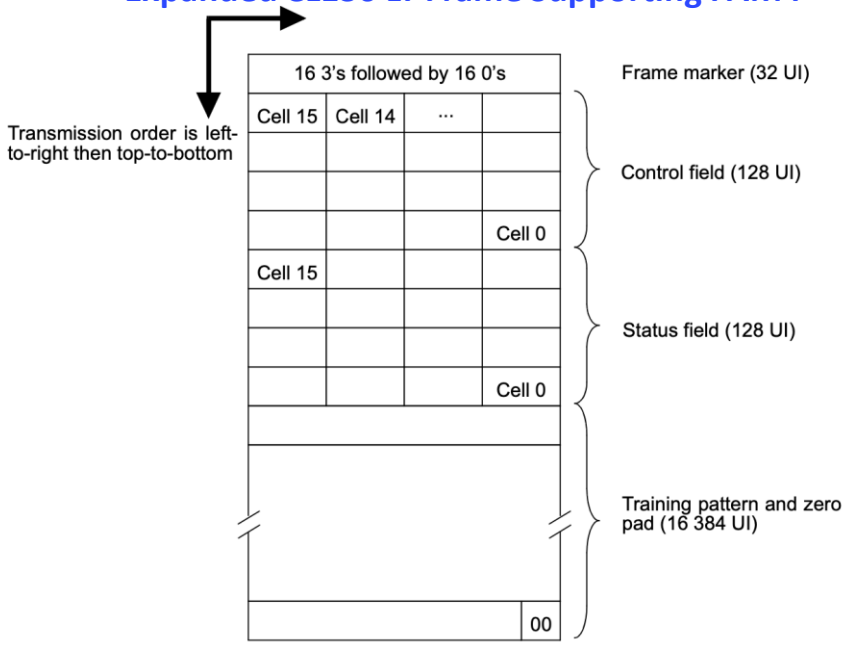
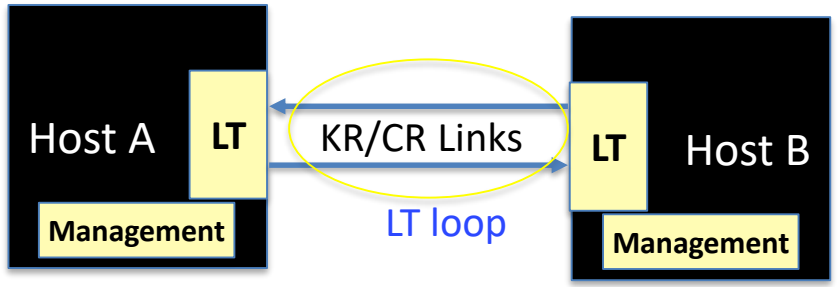


Figure 136–3—Training frame structure



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.

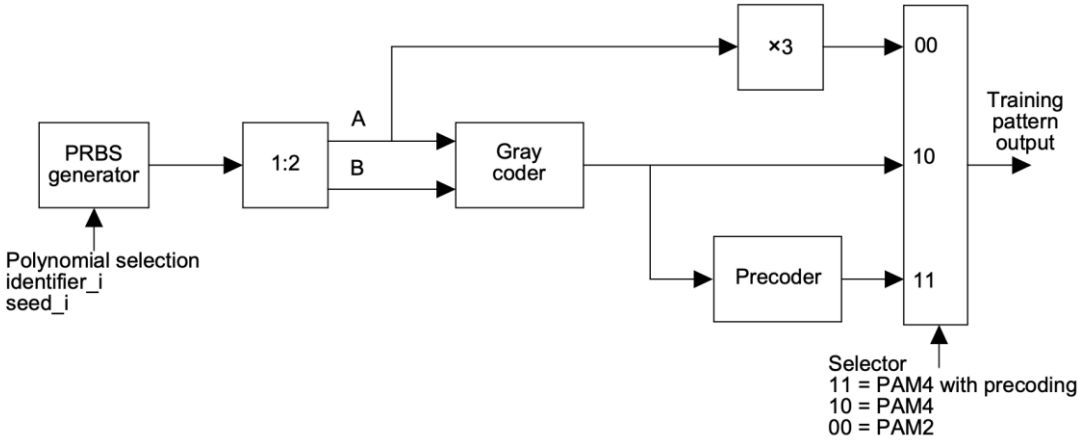


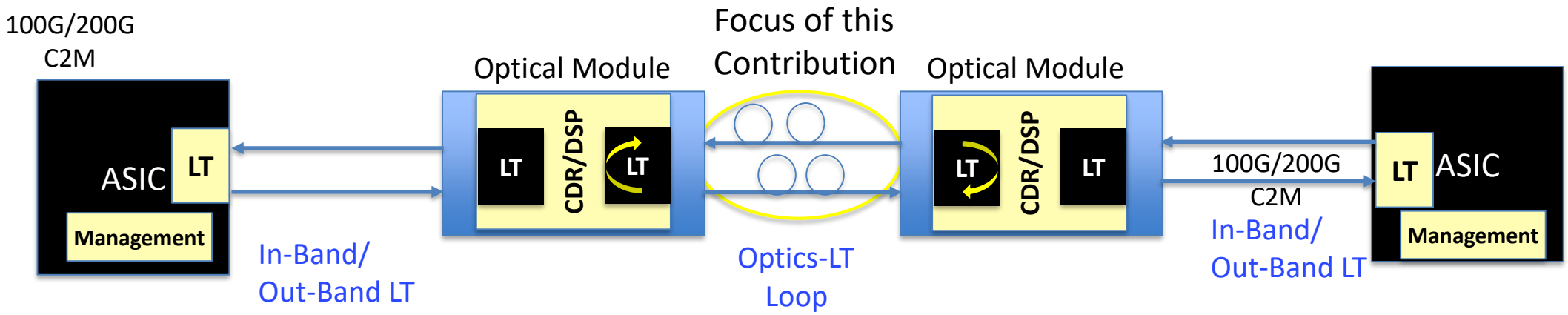
Figure 136–4—Training pattern generator

Table 136–8—Training patterns

p	Polynomial_*p*, *G*(*x*)	Default seed bits[a]	Initial output, PAM2	Initial output, PAM4	Initial output, PAM4 with precoding
0	$1+x+x^2+x^{12}+x^{13}$	0000010101011	0030330330000	10313202201111[b]	1301200200101
1	$1+x^2+x^3+x^7+x^{13}$	0011101000001	3030303030333	3030213021333	3122012201212
2	$1+x^2+x^4+x^8+x^{13}$	1001000101100	0303333033030	1212332133031	1102120121301
3	$1+x^2+x^5+x^9+x^{13}$	0100010000010	3330300030330	2231210121221	2032013201110

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.



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 meets 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-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 162–9—Control field structure

Bit(s)	Name	Description
15:14	Reserved	Transmit as 0, ignore on receipt
13:11	Initial condition request	13 12 11 1 1 1 = 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
10	Reserved	Transmit as 0, ignore on receipt
9:8	Modulation and precoding request	9 8 1 1 = PAM4 with precoding 1 0 = PAM4 0 1 = Reserved 0 0 = PAM2
7:5	Reserved	Transmit as 0, ignore on receipt
4:2	Coefficient select	4 3 2 1 0 0 = Reserved 1 0 1 = $c(-3)$ 1 1 0 = $c(-2)$ 1 1 1 = $c(-1)$ 0 0 0 = $c(0)$ 0 0 1 = $c(1)$ 0 1 x = Reserved
1:0	Coefficient request	1 0 1 1 = No equalization 1 0 = Decrement 0 1 = Increment 0 0 = Hold

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.