CDAUI-8 Chip-to-Module (C2M) System Analysis

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Introduction (1)

- Follow-up to previous ad hoc contribution on the merits of various reference receiver architectures for 26.5625GBaud PAM4 C2M

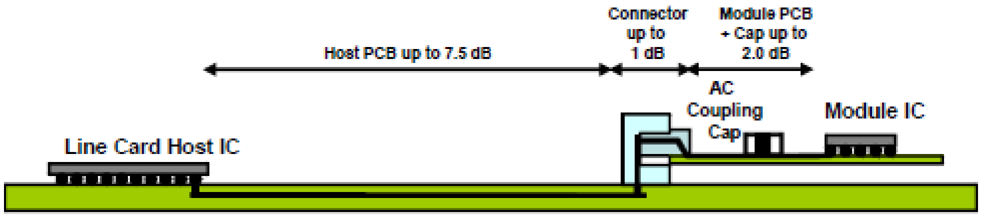
- LFEQ:
  - We quantified the benefit of a (1z,1p) low-frequency linear equalizer
    - Brooks (mazzini_01_082415_elect_ad_hoc) also discussed benefits of a low-frequency equalizer; Hedge (hegde_3bs_01_0715) previously did so for DFE-less C2C proposal
  - We didn't provide results for LFEQ+CTLE in the absence of a TXFIR
    - In this contribution, we show that the LFEQ isn't "enough" to remove the need for a TXFIR to close higher loss links

Introduction (2)

C2M Link Margins

- Several contributions have been made, each using a different model and a different quantification of performance. Some results seem more optimistic than others—what gives??
- **EH6**:
  - EH6 spec in OIF draft (and baseline .bs) is unattainably high for high loss channel
- **SNDR**:
  - At 29 dB (peak-to-rms, as in .bj KP4), transmitter noise is a large impairment
    - But it seems clear that different contributions have made different assumptions about the definition (and modelling) of TX SNDR
    - Current 56G VSR OIF draft does not provide a definition of TX SNDR, even though an informative TP0a value is provided
- **Package Model**
  - As seen in several C2C contributions (healey_3bs_01_0315, hegde_3bs_01_0715), the package model has a significant influence on PAM4 margins

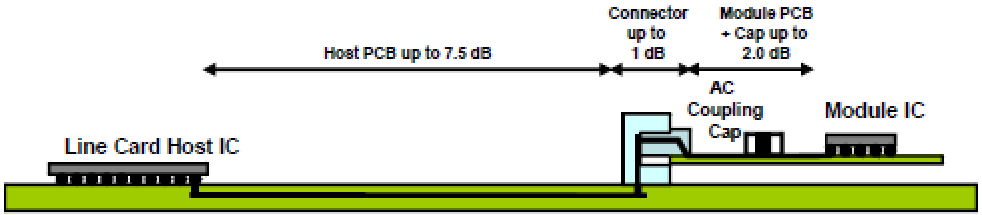
System Model



- TX and RX package models (.s4p file) each add ~1dB of IL @ 13.28125 GHz
- Die Termination with 120fF parasitic capacitance
- Module RX model:
  - (1z,1p) low-frequency equalizer (zero & pole ~1GHz)
  - (1z, 2p) reference CTLE (from OIF-VSR-56G PAM-4 and CAUI-4 C2M):

Peaking (dB)	G	P1/2π (GHz)	P2/2π (GHz)	Z1/2π (GHz)
1	0.891	18.6	14.1	8.31
2	0.794	18.6	14.1	7.10
3	0.708	15.6	14.1	5.68
4	0.631	15.6	14.1	4.98
5	0.562	15.6	14.1	4.35
6	0.501	15.6	14.1	3.82
7	0.447	15.6	14.1	3.43
8	0.398	15.6	14.1	3.00
9	0.355	15.6	14.1	2.67

System Model



- Host TX model:
  - 750 mV differential peak-to-peak
  - SNDR = 29 dB (peak-to-rms)
  - RLM = 0.9
  - RJ = 0.01 UIrms
  - DJ = 0.05 UI peak-to-peak
  - 2-tap TXFIR (i.e., pre+cursor)

Channel Models

CHANNEL	FEXT	NEXT	IL @ 13.28125 GHz (dB)	ILD (dBrms)
From IEEE 802.3bs shanbhag_3bs_14_0623:				
(1) Nelco 4000-13SI Host PCB + next gen 28Gb/s high density SMT IO	5	0	8.7	0.110
(2) EM-888 Host PCB + next gen 28Gb/s press-fit stacked IO	7	0	8.9	0.051
From IEEE 802.3bs shanbhag_3bs_01_1014:				
(3) 4in Megtron6 Host PCB + next gen 28Gb/s high density SMT IO	5	0	4.3	0.110
(4) 10in Megtron6 Host PCB + next gen 28Gb/s high density SMT IO	5	0	8.8	0.106
(5) 4in Megtron6 Host PCB + next gen 28Gb/s press-fit stacked IO	7	0	4.5	0.051
(6) 10in Megtron6 Host PCB + next gen 28Gb/s press-fit stacked IO	7	0	9.0	0.052
Cisco Channels:				
(7) Cisco 2in Stacked	0	0	8.5	0.237
(8) Cisco 5in Stacked	0	0	11.3	0.245

Link Margin Calculation

- The COM definition of margin is a quantification of the Vertical Eye Opening (VEO)
  - $\text{COM} \equiv \text{VEO} \triangleq 20\log_{10}\left(\min\left\{\frac{Av_{upp}}{Av_{upp}-v_{upp}}, \frac{Av_{mid}}{Av_{mid}-v_{mid}}, \frac{Av_{low}}{Av_{low}-v_{low}}\right\}\right)$
  - Eye contours are measured for a target symbol error rate $\mathbf{DER_0}$

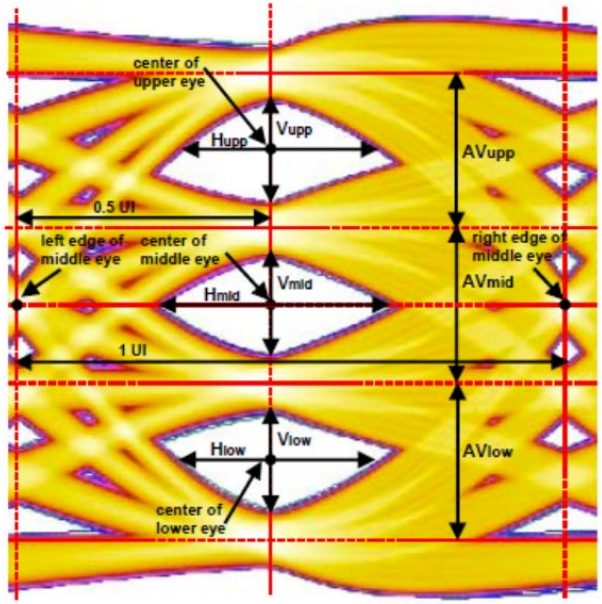


Figure 16-9. TP1a and TP4 jitter and Eye Height parameters

Baseline Results

- Reference CTLE Receiver
  - No TXFIR, No LFEQ, DER_0=1E-6

Channel	1	2	3	4	5	6	7	8
COM (dB)	-0.07	-0.04	1.01	-0.45	1.24	-0.13	-1.37	-2.65

- **Only the ~4dB channels have positive margin**

Improvements (1)

- Reference CTLE + LFEQ
  - COM program optimizes LFEQ: $0.5 \text{ GHz} \leq z \leq 2.5 \text{ GHz}, 0.5 \text{ GHz} \leq p \leq 2.5 \text{ GHz}$
  - **No TXFIR, DER_0=1E-6**

Channel	1	2	3	4	5	6	7	8
CTLE	-0.07	-0.04	1.01	-0.45	1.24	-0.13	-1.37	-2.65
CTLE + LFEQ	0.45	0.50	1.39	-0.14	1.92	0.27	-1.37	-2.49

  - LFEQ improves COM margin by 0.4 to 0.5 dB in most cases

Improvements (2)

- Reference CTLE + TXFIR
  - COM program optimizes TXFIR: $|C_{-1}| \leq 0.15, |C_{-1}| + |C_0| = 1$
  - **No LFEQ, DER_0=1E-6**

Channel	1	2	3	4	5	6	7	8
CTLE	-0.07	-0.04	1.01	-0.45	1.24	-0.13	-1.37	-2.65
CTLE + TXFIR	1.47	1.53	1.43	0.84	2.08	1.35	0.84	0.55

- A 2-tap TXFIR brings significant improvement on higher loss channels
  - Improvement is > 1dB for high loss channels

Improvements (3)

- Reference CTLE + TXFIR + LFEQ
  - COM program optimizes TXFIR and LFEQ : $0.5\ \mathrm{GHz} \leq z \leq 2.5\ \mathrm{GHz}$, $0.5\ \mathrm{GHz} \leq p \leq 2.5\ \mathrm{GHz}$
  - **DER_0=1E-6**

Channel	1	2	3	4	5	6	7	8
CTLE	-0.07	-0.04	1.01	-0.45	1.24	-0.13	-1.37	-2.65
CTLE + TXFIR	1.47	1.53	1.43	0.84	2.08	1.35	0.84	0.55
CTLE + LFEQ	0.45	0.50	1.39	-0.14	1.92	0.27	-1.37	-2.49
CTLE + TXFIR + LFEQ	2.26	2.50	2.13	1.28	2.95	2.14	1.43	0.84

- The combination of the CTLE, LFEQ and 2-tap TXFIR provides substantial improvement over a CTLE-only system
  - CTLE+TXFIR or CTLE+LFEQ do not provide sufficient margin
  - For high loss channels, adding TXFIR and LFEQ improves COM margin by 2dB or more

An Improved Reference RX/TX

- **The following (crudely) improved reference RX/TX provides nearly all of the gain:**

TX FIR	LFEQ: (Z1,P1) (GHz)	CTLE: (Z1,P1,P2) (GHz)
[-0.05,0.95]	(1,1.2)	(8.31,14.1,18.6)
[-0.05,0.95]	(1,1.2)	(7.10,14.1,18.6)
[-0.05,0.95]	(1,1.2)	(5.68,14.1,15.6)
[-0.05,0.95]	(1,1.2)	(4.98,14.1,15.6)
[-0.1,0.9]	(1,1.2)	(4.35,14.1,15.6)
[-0.1,0.9]	(1,1.2)	(3.82,14.1,15.6)
[-0.1,0.9]	(1,1.2)	(3.43,14.1,15.6)
[-0.1,0.9]	(1,1.2)	(3.00,14.1,15.6)
[-0.1,0.9]	(1,1.2)	(2.67,14.1,15.6)

Channel	1	2	3	4	5	6	7	8
CTLE	-0.07	-0.04	1.01	-0.45	1.24	-0.13	-1.37	-2.65
CTLE + TXFIR	1.47	1.53	1.43	0.84	2.08	1.35	0.84	0.55
CTLE + LFEQ	0.45	0.50	1.39	-0.14	1.92	0.27	-1.37	-2.49
CTLE + TXFIR + LFEQ	2.26	2.50	2.13	1.28	2.95	2.14	1.43	0.84
Reference RX/TX	2.22	2.47	2.13	1.28	2.95	2.14	1.18	0.19

- The degradation on channels 7 and 8 is due to insufficient pre-cursor equalization in the reference TX FIR

C2M Link Margins: EH6

- In 802.3bj, a COM margin of 3 dB was considered sufficient for channel compliance
- In 802.3bm, a COM margin of 2dB was considered sufficient
- In current OIF draft, EH6 is set to 50mV
  - This is **stringent** for high loss channels, corresponding to a COM much larger than 3dB
    - Example 1:
      - TX Output: 900 mV pk-to-pk; R_{LM}=0.9; PAM levels: (+/-180 mV,+/-450 mV)
      - Equalization of 10dB channel loss (plus TX package losses) scales TX levels by factor of ~2.5
      - Received levels (with perfect TX linearity): (+/- 72, +/- 180)
        - A 50 mV eye opening corresponds to a COM of $20\log_{10}\frac{54}{54-25} = 5.4$ dB
- For reference, the same calculation for 28G-VSR results in a COM of $20\log_{10}\frac{180}{180-47.5} = 2.7$ dB

C2M Link Margins: SNDR

- TX SNDR is one of the largest impairments, but it has not even been defined for C2M (or for 56G VSR)
  - KP4 COM
    - At the transmitter output, TX SNDR is defined as ratio of peak transmitter level to rms noise+distortion at transmitter output (in practice, as measured by a 33GHz BT4 reference receiver)
    - PSD of noise/distortion is not explicitly constrained
      - COM assumes that this noise is "passed through" to the slicer, in the sense that it is modelled as a slicer-referred peak-to-rms noise
        - This is reasonable for CTLE-based systems, as long as the bandwidth of the noise at the TX output is approximately limited to the RX bandwidth, and the receiver approximately inverts the channel

C2M Link Margins: SNDR

- For the previous model (i.e., an effective slicer-referred noise), a 29dB SNDR results in ~50% eye closure @1E-6 for PAM4, in absence of other impairments
  - Calculation:
    - Normalized PAM levels = [+/-1/3,+/-1]
    - RMS noise = 10^(-29/20) = 0.0355
    - 1E-6 contour is approximately 4.75-sigma of a Gaussian
    - Relative Eye Opening = 1- (2*4.75*0.0355)/(2/3) = 0.49
- Semtech results (frlan_01_082415_elect) showed EH6 > 50mV in several cases, but seemingly used a different model (or definition) for TX noise and distortion
    - For example, Slide 16 shows eye opening of ~75mV, which is well beyond the 50% opening for the stated TX/RX parameters, without even accounting for contribution of residual ISI
      - The same conclusion can be made for the other Semtech results, where residual ISI is an additional significant contributor to eye closure
    - Note that Semtech results assumed perfect eye linearity and no xtalk

C2M Link Margins: Eye Linearity (~RLM)

- We modelled non-uniform PAM4 level spacing via RLM
  - Eye Linearity (56G VSR) is similar, although different waveforms are used to measure the values, and different test points are defined
  - For MSB/LSB TX skew less than ~10%, the two definitions are essentially the same

- Current (OIF) maximum Eye Linearity spec is 1.5, which corresponds to $\mathrm{RLM} \leq \frac{3}{2+1.5} = 0.857$
- Returning to our SNDR example:
  - Normalize PAM Levels=[+/-0.429,+/-1]
  - Relative Eye Opening=1-(2*4.75*0.0355)/(1-0.429) = 0.41

- For link margin calculations, we have assumed RLM=0.9
  - RLM=0.857 seems too pessimistic

Recommendations

- LFEQ+CTLE is **not enough** to close the link for higher loss channels
  - TXFIR is required to provide >2dB link margin
- We are proposing:
  - Reference Receiver: VSR-56G CTLE + Fixed LFEQ
  - Reference Transmitter: 2-tap TX FIR with 3 coarse settings; 0%, 5%, 10% pre-emphasis
- EH6
  - Discussions about link closure are centered around eye height requirements
  - Current EH6 requirements are unreasonably large for high loss channels
- TX SNDR
  - We need an agreed upon definition and model
  - At 29dB, it's a (potentially) large impairment, so it's critical that we model it consistently
- Eye Linearity (RLM)
  - We should consider tightening the requirement from current OIF value
- ILD
  - A suitable limit on ILD needs to be agreed upon