Welcome to

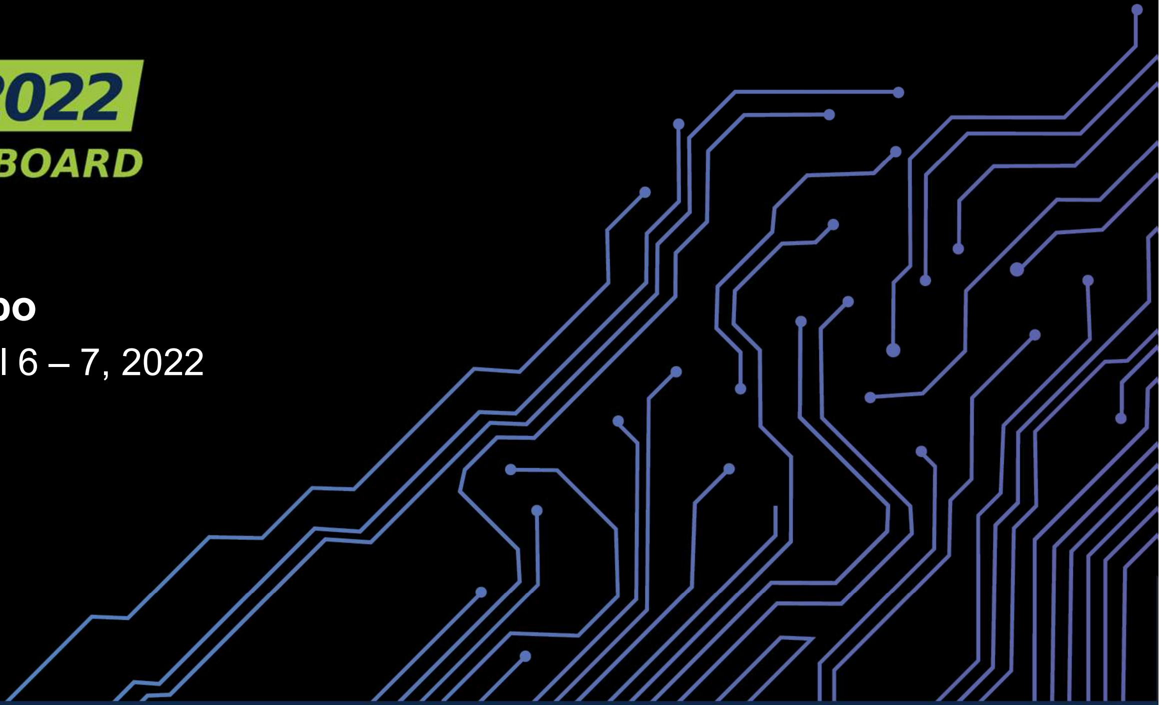
DESIGNCON® 2022

WHERE THE CHIP MEETS THE BOARD

Conference
April 5 – 7, 2022

Expo
April 6 – 7, 2022

Santa Clara Convention Center



How to optimize TxFFE and what we can learn from the optimization

Speakers: Ransom Stephens (BitifEye & Ransom's Notes)
Wolfgang Köbele (BitifEye)

Anton Unakafov (BitifEye), Wolfgang Köbele (BitifEye)
Hermann Stehling (BitifEye), Sergio Cina (BitifEye), (BitifEye),
Ransom Stephens (BitifEye & Ransom's Notes)

SPEAKERS

Ransom Stephens

Consulting Senior Scientist, BitifEye Digital Test Solutions,GmbH
ransom.stephens@bitifeye.com | ransomsnotes.com | @ransomstephens

Ransom Stephens is Consulting Senior Scientist at BitifEye where he provides insights when he can and wisecracks when he can't. Dr. Stephens helps engineers advance to higher data rates with targeted training, including the classes he teaches at Oxford University's Department of Continuing Education.

Wolfgang Köbele

Electrical Engineer, BitifEye Digital Test Solutions,GmbH
Wolfgang.koebele@bitifeye.com | bitifeye.com | @twitter

Wolfgang Köbele is an engineer at BitifEye. He earned his B.Eng. in electrical engineering at the DHBW (Baden-Wuerttemberg Cooperative State University) Stuttgart, campus Horb. Since 2016 he has been employed by BitifEye as a software engineer working on the development of the SAS, PCIe5, and PCIe6 solutions.

Agenda

< note: this draft of PPT slides will differ from those shown at the conference because I'm incapable of opening a PPT file without changing it – Ransom >

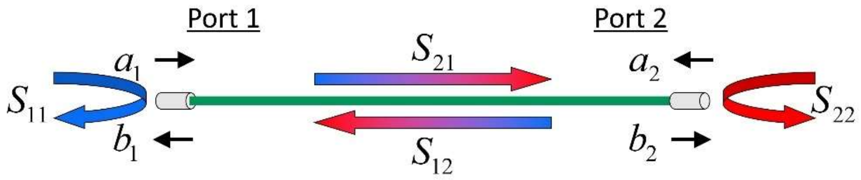
- **Transmitter Feed-Forward Equalization – TxFFE**
    - The principle of operation and a practical approach, FIR filters, and shift registers
    - Relationship between taps and waveforms: de-emphasis, boost, and pre-shoot
- **Optimizing TxFFE parameters in a complete, system-level, equalization scheme**
    - Combining Tx and Rx equalization
    - Maximizing different figures of merit, complications
- **Link Training**
- **Analysis of TxFFE signals**
    - Testing link training
    - Measurement and calibration of TxFFE signals
- **The problem of serdes DAC resolution for TxFFE and PAM*n***
- **Additional use cases for TxFFE**
    - TxFFE for noise estimation
    - TxFFE as a de-embedding tool

Introduction to TxFFE

- **Transmitter-based equalization is an attempt to**
  "Pre-distort the waveform in such a way that the frequency response of the channel removes that distortion, resulting in a signal that can be decoded by the receiver"
- **Equalization corrects inter-symbol interference (ISI)**
  - Consider the signal
    - *PAMn Signals are composed of hundreds of discrete frequencies, each with specific amplitudes*
  - Consider the channel
    - *Channel frequency response – loss, impedance mismatches – degrades the amplitude-frequency relationships of signal components → neighboring symbols interfere, ISI*
    - *Reflections cause echoes of previous symbols to interfere with the current symbol*
  - The length of the interfering symbol sequences = the duration of the pulse response

The Principle of Tx-based equalization

- **Recall: S-parameters**



$$\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}$$

$$S_{11}a_1 + S_{12}a_2 = b_1$$

$$S_{21}a_1 + S_{22}a_2 = b_2$$

$\mathbf{S}$ = the matrix of S-parameters, elements are functions of f and φ

$\mathbf{Tx}$ and $\mathbf{Rx}$ = transmitted and received signals in the frequency domain

$$\mathbf{S\,Tx} = \mathbf{Rx}$$

pre-distortion

distortion

- **The principle of Tx-based equalization**

  pre-distort with the inverse of the S matrix:

  then the channel removes the distortion:

$$\mathbf{TxFFE} = \mathbf{S}^{-1}\,\mathbf{Tx}$$

$$\mathbf{S\,TxFFE} = \mathbf{S\,S}^{-1}\mathbf{Tx} = \mathbf{Tx} = \mathbf{Rx}$$

The Principle of Tx-based equalization

- **Problem: identify the *n*th symbol, $\boldsymbol{Rx(n)}$**
  - Neighboring symbols interfere, so modify their amplitudes for each n

$$\mathrm{TxFFE}(n) = c_{-2}\mathrm{Tx}(n-2) + c_{-1}\mathrm{Tx}(n-1) + c_0\mathrm{Tx}(n) + c_{+1}\mathrm{Tx}(n+1) + c_{+2}\mathrm{Tx}(n+2)$$

  - The signal amplitudes, $\mathbf{Tx}(\boldsymbol{n})$, are called “**cursors**”
  - The constant coefficients, $\boldsymbol{c_i}$, are called “**taps**”
- **If we identify the taps with elements of the inverted S-parameter matrix, $\mathbf{TxFFE}(\boldsymbol{n})$ is a discrete, time-domain approximation to**

$$\mathbf{TxFFE} = \mathbf{S}^{-1}\,\mathbf{Tx}$$

But we can do better than this!

General, discrete form for TxFFE

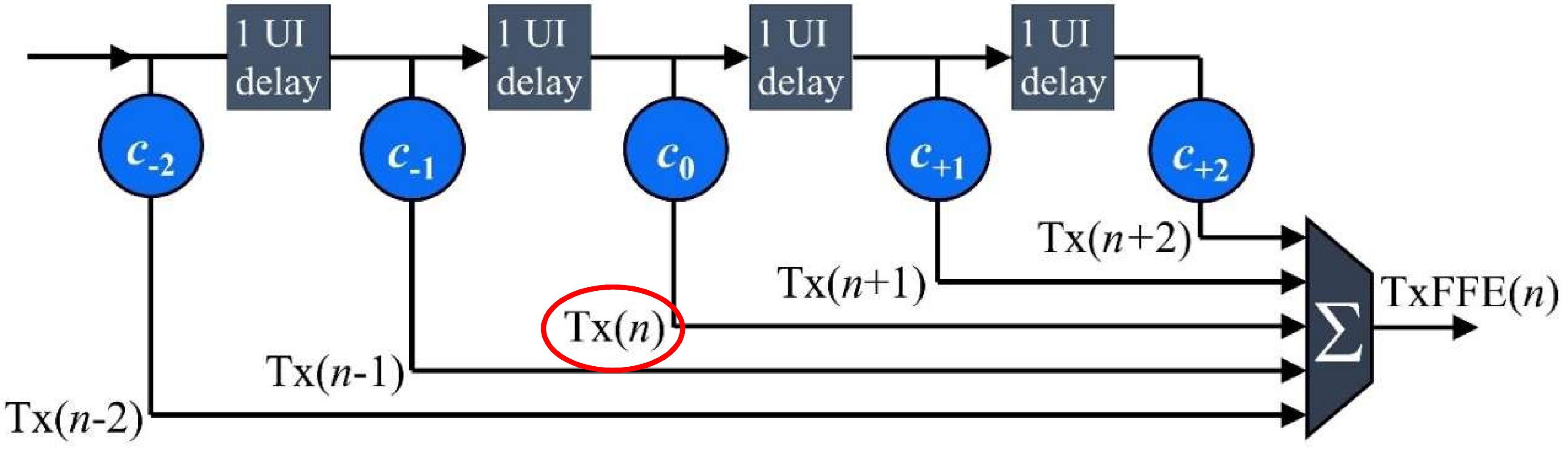
$$\boxed{\mathrm{TxFFE}(n) = \sum_{Taps,i} c_i \mathrm{Tx}(n+i)}$$

- Linear, accommodates any number of taps and cursors
- A **finite impulse response (FIR) filter**, feeds information “forward” – feed-forward, not feedback
  - *“FIR filter” is DSP (digital signal processing) see Ifeacher and Jervis,* Digital Signal Processing: A Practical Approach, 2nd Edition*, Addison-Wesley, 2001*
- Supports both “pre-cursors” that arrive at Rx prior to the *n*th symbol and “post-cursors” that arrive at Rx after the *n*th symbol
- **Constrain taps to fix the total power**

$$\sum_{Taps,i} |c_i| = 1$$

TxFFE implemented as a shift register

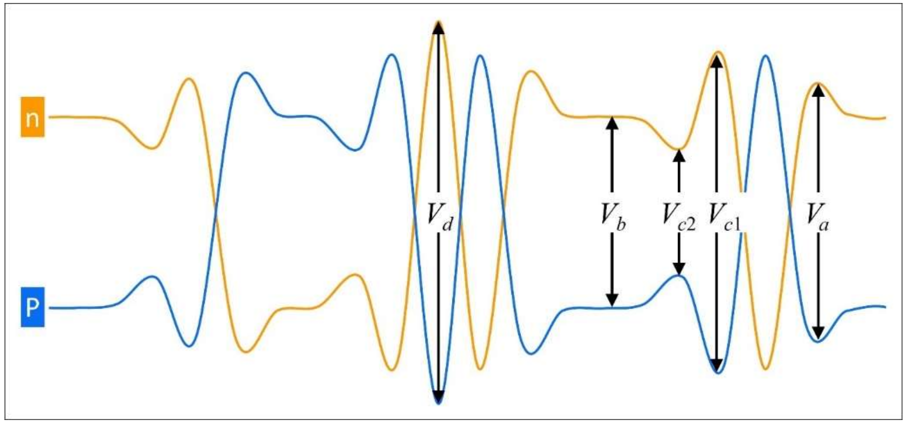
$$\sum_{i=-2}^{2} |c_i| = 1$$



Pre-cursors

Post-cursors

FFE waveforms: de-emphasis, boost, pre-shoot



example from PCIe 6

- **Constrain** $c_{+1} \le 0, \quad c_0 \ge 0, \quad c_{-1} \le 0 \quad c_{-2} \ge 0$ **get**
  - V_i represent voltage swings relative to the full-scale of the signal defined as dimensionless amplitudes

$$V_a = +c_{-2} + c_{-1} + c_0 - c_{+1}$$
$$V_b = +c_{-2} + c_{-1} + c_0 + c_{+1}$$
$$V_{c1} = +c_{-2} - c_{-1} + c_0 + c_{+1}$$
$$V_{c2} = -c_{-2} + c_{-1} + c_0 + c_{+1}$$
$$V_d = +c_{-2} - c_{-1} + c_0 - c_{+1}$$

- **The total power constraint becomes**

$$V_d = \sum_{i=-2}^{1} |c_i| = 1$$

Relate taps to the waveform

- **Define De-emphasis, Boost, and Pre-shoots**

$$\mathrm{DE} = 20\log\left({}^{V_b}\!/\!{}_{V_a} \right)$$

$$\mathrm{B} = 20\log\left({}^{V_d}\!/\!{}_{V_b} \right) = 20\log\left({}^{1}\!/\!{}_{V_b} \right)$$

$$\mathrm{PS1} = 20\log\left({}^{V_{c1}}\!/\!{}_{V_b} \right)$$

$$\mathrm{PS2} = 20\log\left({}^{V_{c2}}\!/\!{}_{V_b} \right)$$

Algebra . . .

$$\begin{pmatrix} c_{+1} \\ c_0 \\ c_{-1} \\ c_{-2} \end{pmatrix} = -\frac{1}{2}10^{-B/20} \begin{pmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & -1 & -1 \\ 0 & -1 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{pmatrix} \begin{pmatrix} 10^{-\mathrm{DE}/20} \\ 1 \\ 10^{\mathrm{PS1}/20} \\ 10^{\mathrm{PS2}/20} \end{pmatrix}$$

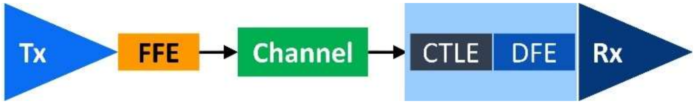
or

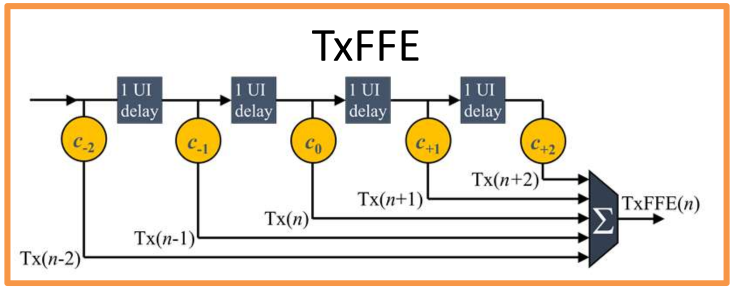
$$\begin{pmatrix} 10^{-\mathrm{DE}/20} \\ 1 \\ 10^{\mathrm{PS1}/20} \\ 10^{\mathrm{PS2}/20} \end{pmatrix} = -\frac{1}{c_{-2}+c_{-1}+c_0+c_{+1}} \begin{pmatrix} 1 & -1 & -1 & -1 \\ -1 & -1 & -1 & -1 \\ -1 & -1 & 1 & -1 \\ -1 & -1 & -1 & 1 \end{pmatrix} \begin{pmatrix} c_{+1} \\ c_0 \\ c_{-1} \\ c_{-2} \end{pmatrix}$$

Agenda

- Transmitter Feed-Forward Equalization – TxFFE
    - The principle of operation and a practical approach, FIR filters, and shift registers
    - Relationship between taps and waveforms: de-emphasis, boost, and pre-shoot
- **Optimizing TxFFE parameters in a complete, system-level, equalization scheme**
    - Combining Tx and Rx equalization
    - Maximizing different figures of merit, complications
- Link Training
- Analysis of TxFFE signals
    - Testing link training
    - Measurement and calibration of TxFFE signals
- The problem of serdes DAC resolution for TxFFE and PAM*n*
- Additional use cases for TxFFE
    - TxFFE for noise estimation
    - TxFFE as a de-embedding tool

Tap Optimization

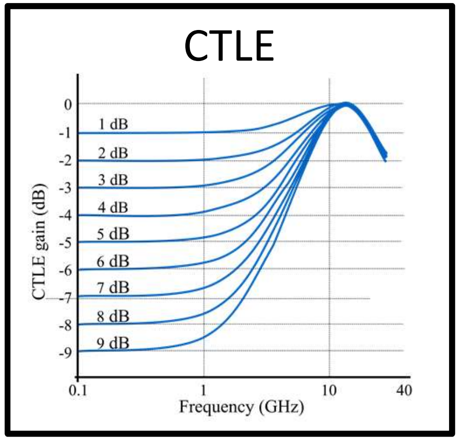




$$\mathrm{TxFFE}(n) = \sum_{N_{TxFFE}} c_i \mathrm{Tx}(n+i)$$

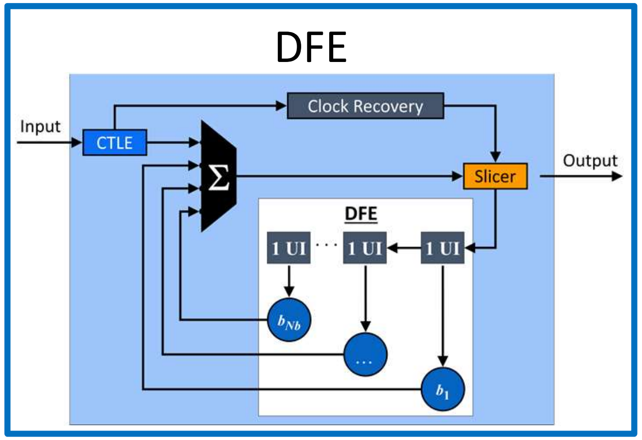
TxFFE

- is a source of high frequency noise
- has N_{TxFFE} taps/free parameters



CTLE

- amplifies high frequency noise
- has one free parameter, g_{CTLE}

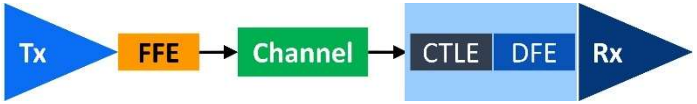


$$\mathrm{DFE}(n) = \sum_{k=1}^{N_b} b_k \mathrm{Sx}(n+k)$$

DFE

- affects all noise equally
- particularly effective against reflections
- has N_b taps/free parameters

Equalization must balance ISI and noise-gain



TxFFE
- is a source of high frequency noise
- has N_{TxFFE} taps/free parameters

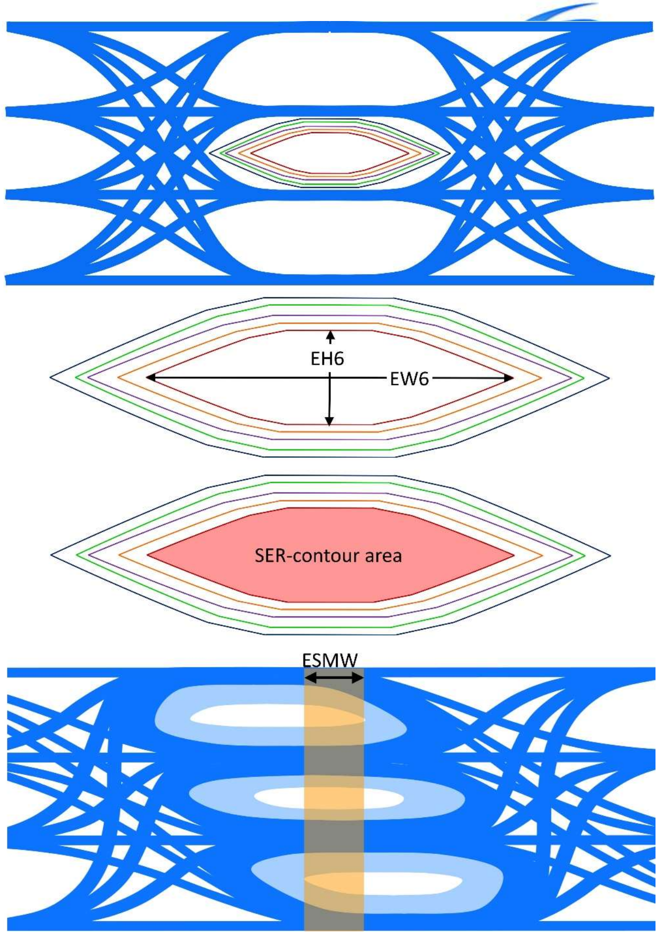
CTLE
- amplifies high frequency noise
- has one free parameter, g_{CTLE}

DFE
- affects all noise equally
- particularly effective against reflections
- has N_b taps/free parameters

- **The system equalization scheme must be optimized as a whole**
- **Define a Figure of Merit that indicates low BER or SER as a function of the equalization parameters**
  - e.g., typical 56 Gb/s PAM4 equalization scheme has
    - *5 TxFFE taps { c_i } + 1 CTLE gain g_{CTLE} + 20 or so DFE taps { b_k } = 26 equalization parameters*
  - A 26 dimensional optimization problem

Optimize a Figure of Merit

- **"FoM" – a function of free parameters that indicates good/bad**
- **Find the maximum of FoM({ c_i }, g_{CTLE}, { b_k })**
    - Determines the best taps and gain
- **FoM examples**
    - BER or SER
    - DDJ
    - Eye height, eye width
    - BER contour area
    - ESMW × VEC = Eye symmetry mask width × vertical eye closure
- **FoM calculation time**
    - Must span the parameter space → requires *many* calculations
        - *26 dimensions in this example, not atypical*
    - Use pulse response in models based on S-parameters with jitter, noise, xtalk,
        - *p(n) or SBR(n), single bit response*



Equalization optimization complications

- **Eq optimization can be complicated when FoM is influenced by processes that are assumed stable**
    - Long runs of consecutive identical symbols can cause the recovered clock to drift or lose lock
    - Imbalances in fractions of different symbols can cause the a DC offset at the symbol decoder input
    - Physical variations in shift register/filter implementations can affect the signal without affecting the calculation of the FoM

  (Thorough discussion in Telian, Steinberger, and Katz, “New SI Techniques for Large System Performance Tuning,” DesignCon 2016)

- **Complexity of Eq optimization increases with every additional tap and PAM*n* level**

Agenda

- **Transmitter Feed-Forward Equalization – TxFFE**
  - The principle of operation and a practical approach, FIR filters, and shift registers
  - Relationship between taps and waveforms: de-emphasis, boost, and pre-shoot
- **Optimizing TxFFE parameters in a complete, system-level, equalization scheme**
  - Combining Tx and Rx equalization
  - Maximizing different figures of merit, complications
- **Link Training**
- **Analysis of TxFFE signals**
  - Testing link training
  - Measurement and calibration of TxFFE signals
- **The problem of serdes DAC resolution for TxFFE and PAM*n***
- **Additional use cases for TxFFE**
  - TxFFE for noise estimation
  - TxFFE as a de-embedding tool

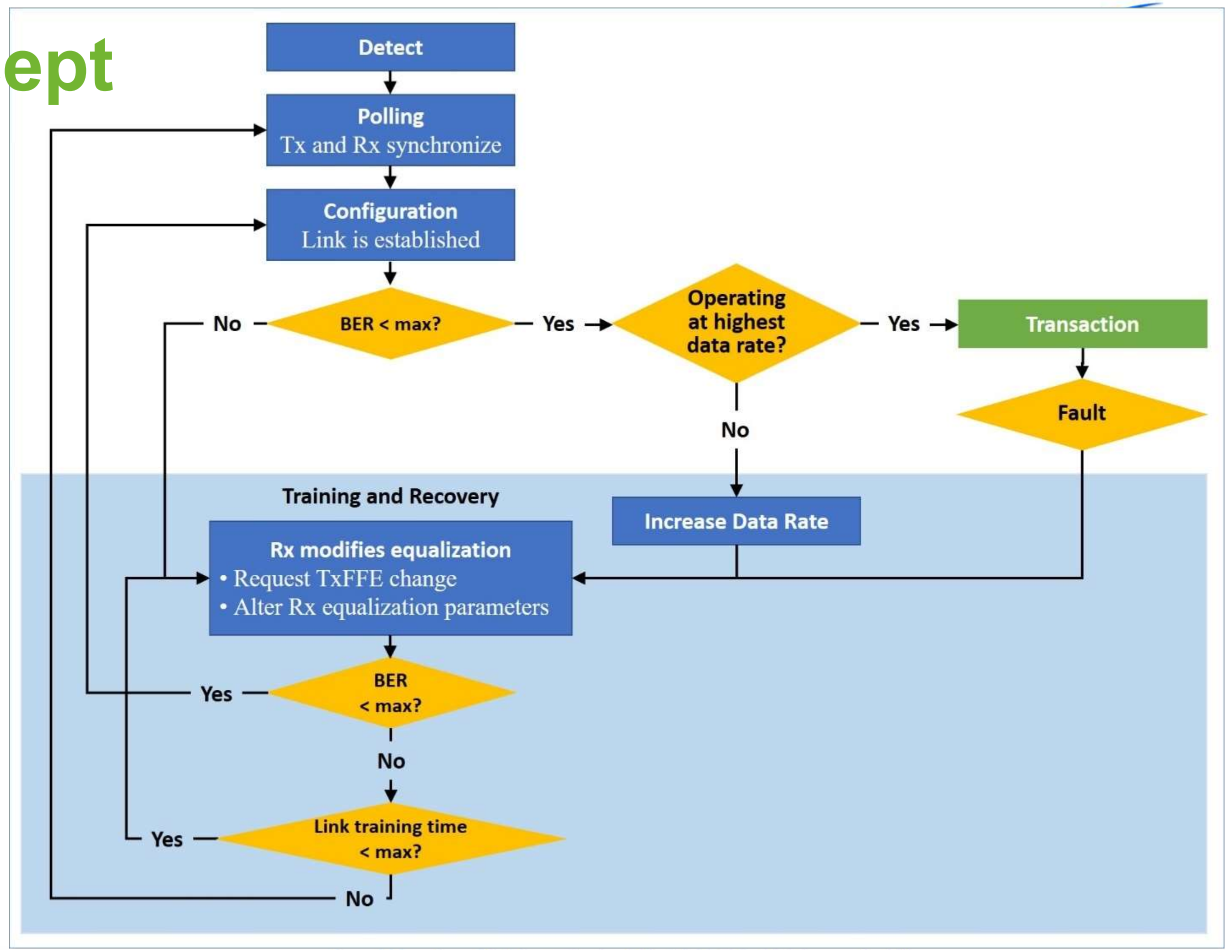
Link training

< disclaimer: link training requires exhaustive understanding of every possible case, they are spelled out in the Data Link Layer of the standards documentation that employ link training (e.g., PCIe, USB) >

- **Link training is an adaptive process for determining a compliant set of equalization parameters**
  - i.e., Eq scheme that operates at or better than the specified BER (FEC complicates things, of course)
- **The concept:**
  - Rx adjusts its own Eq scheme (CTLE gain and DFE taps) in conjunction with requests for TxFFE taps
    - *iterative process that adapts the system to specific operating conditions at power up and when faults occur*
  - Tx has a set of predetermined FFE “presets” = combinations of taps known to function well for common conditions
    - *PCIe has 11 presets, some standards up to 50*
    - *Rx can request presets*
    - *Or Rx can request the Tx increment/decrement specific taps or specific pre-shoot, boost, or de-emphasis values*

Link training concept

- **Power up → lowest data rate**
- **Synch Rx and Tx and establish link**
- **Request increased data rate**
- **Rx controls optimization of equalization parameters**
    - FoM is SER (symbol error ratio) or BER (bit error ratio)
    - Rx counts errors with error counting fchecksum or CRC (cyclic redundancy check)
- **Maximum link training time typically hundreds of ns**
- **Tx must not violate average and peak power requirements**



Detect

Polling
Tx and Rx synchronize

Configuration
Link is established

No — **BER < max?** — Yes → **Operating at highest data rate?** — Yes → **Transaction**

Fault

No

Training and Recovery

Increase Data Rate

Rx modifies equalization
- Request TxFFE change
- Alter Rx equalization parameters

Yes — **BER < max?**

No

Yes — **Link training time < max?**

No

Agenda

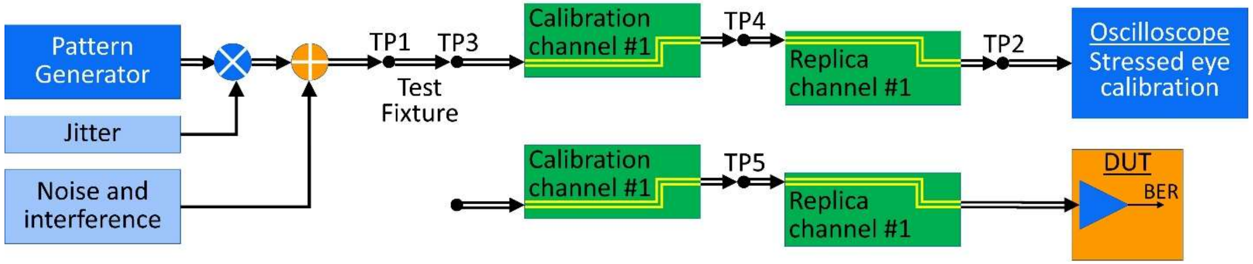
- **Transmitter Feed-Forward Equalization – TxFFE**
    - The principle of operation and a practical approach, FIR filters, and shift registers
    - Relationship between taps and waveforms: de-emphasis, boost, and pre-shoot
- **Optimizing TxFFE parameters in a complete, system-level, equalization scheme**
    - Combining Tx and Rx equalization
    - Maximizing different figures of merit, complications
- **Link Training**
- **Analysis of TxFFE signals**
    - Testing link training
    - Measurement and calibration of TxFFE signals
- **The problem of serdes DAC resolution for TxFFE and PAM*n***
- **Additional use cases for TxFFE**
    - TxFFE for noise estimation
    - TxFFE as a de-embedding tool

Testing link training

- **Link training tests require the DUT (device under test) serdes operate in loopback mode**
    - Rx *transmits* requests upstream that the Tx *receives*
- **For Tx testing, the role of "reference receiver" is played by an oscilloscope or BERT error detector**
    - Reference Rx must be able to send all permitted tap requests and a few violations
- **Transmitters must**
    - support all presets
    - verify that the TxFFE waveform doesn't violate the average and peak power constraints, etc
    - be capable of setting taps within the tolerances prescribed by standards
    - respond to requests within the specified response time
- **For Rx testing, the role of reference transmitter is played by a PG (pattern generator)**
    - PG must be able to respond to all requests for different FFE parameters
    - PG transmits a maximally stressed signal across a variable ISI board
- **The Rx test probes the receiver's ability to optimize the equalization scheme by modifying its own parameters and requesting TxFFE parameters**

Measurement and calibration of TxFFE signals

- **Rx test requires calibration of the TxFFE waveform at all required TPs (test points)**

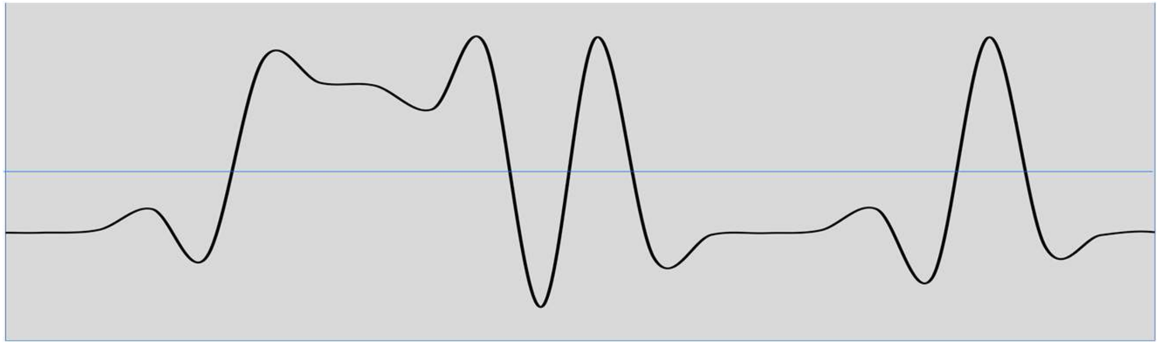


  - e.g., calibrate taps at TP3, the output of the test fixture to emulate the Tx
    - *measure taps at TP4 and TP2, determine effect of TxFFE for each channel and TP2 input to scope for calibration / DUT for test*

- **Calibrating taps is an iterative process**
  1. Set taps to nominal value at PG
  2. Measure at TP*n*
  3. Modify them at PG
  4. Return to step 2 until measured taps are within specified requirements at TP*n*

Techniques for measuring taps

1. **Extract the pulse response, *p*(*n*) or SBR(*n*), by fitting a waveform**
   - Waveform averaged over many repetitions to remove uncorrelated impairments but retain ISI

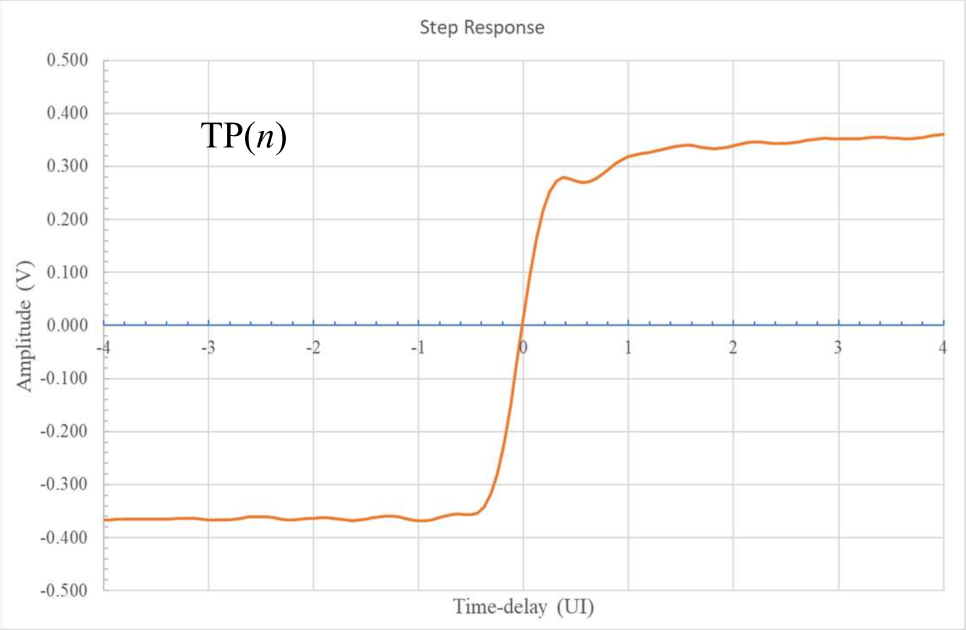


   - Measure taps by comparing pulse response with and without FFE

Techniques for measuring taps

2. **Measure taps from a time-averaged step response**
   - Simple waveform reduces uncertainties from choice of sampling point'
   - Easy to generalize to any number of taps
   - Time-averaged step of "long run" of S0s followed by "long run of S3s"
     - *"long run" >> duration of pulse response*

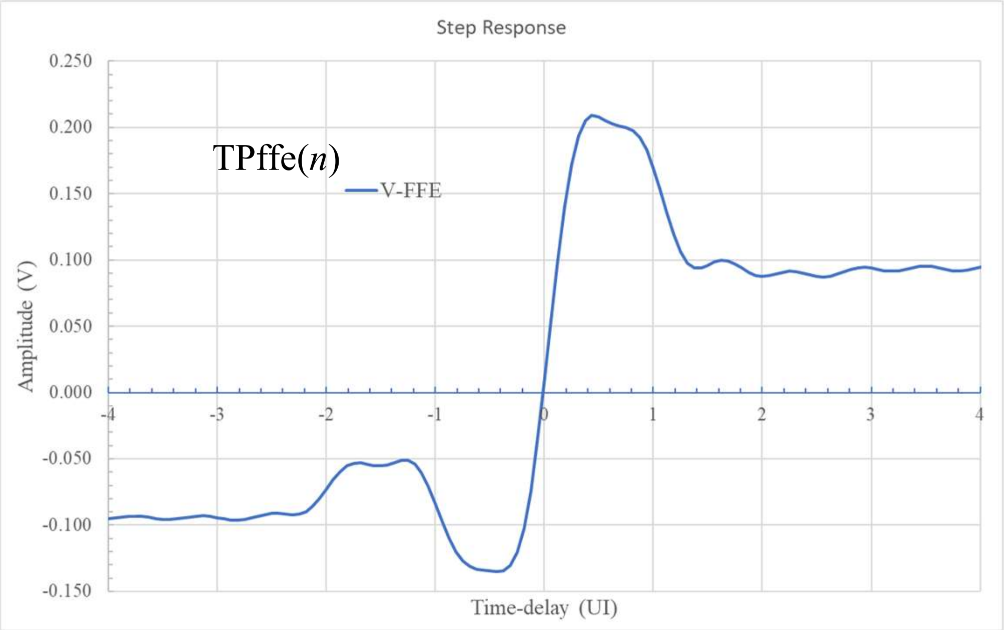
- **Determine FFE taps by comparing TP(*n*), the unequalized step at TP, to . . .**



Techniques for measuring taps

2. **Measure taps from a time-averaged step response**
   - Simple step waveform reduces uncertainties from choice of sampling point'
   - Easy to generalize to any number of taps
   - Time-averaged step of "long run" of S0s followed by "long run of S3s"
     - *"long run" >> duration of pulse response*

- **Determine FFE taps by comparing TP(n), the unequalized step at TP, to TPffe(n), the equalized step**



$$\mathrm{TxFFE}(n) = c_{-2}\mathrm{Tx}(n-2) + c_{-1}\mathrm{Tx}(n-1) + c_0\mathrm{Tx}(n) + c_{+1}\mathrm{Tx}(n+1)$$

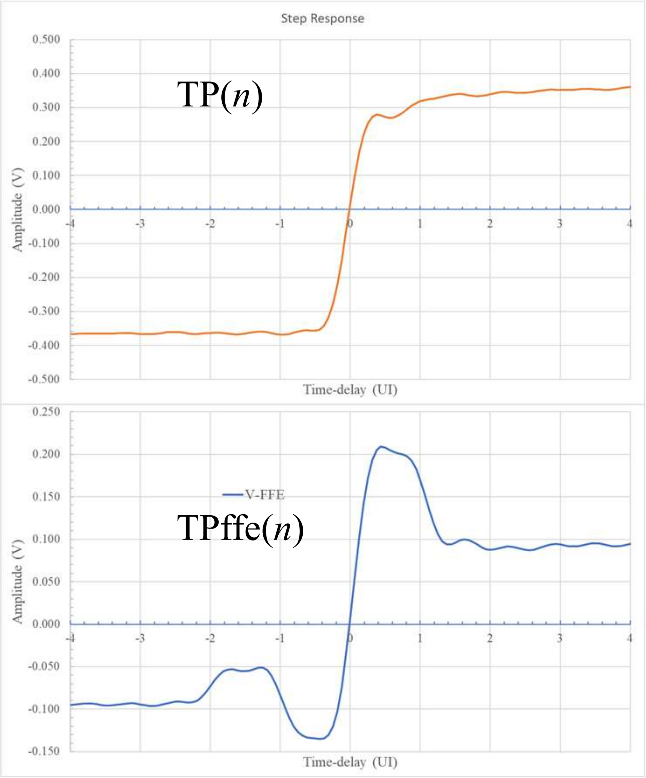
Measuring/calibrating taps

- **Example, four taps:**
  2 pre-cursors, the primary cursor, and 1 post-cursor

$$\mathrm{TxFFE}(n)=c_{-2}\mathrm{Tx}(n-2)+c_{-1}\mathrm{Tx}(n-1)+c_{0}\mathrm{Tx}(n)+c_{+1}\mathrm{Tx}(n+1)$$

- **Expect TP(*n*) to rise near *t* = 0 and converge to S3**

- **TPffe(*n*) deviates from S0 at *t* ≈ -2 UI and plateaus to the de-emphasis level at *t* > 1UI**



Measuring/calibrating taps

- **Oversample TP(*n*) and TPffe(*n*) to increase measurement precision**
  - *M* samples per UI → total number of samples = *NM*
    - *where* N *is the pulse response duration*
  - Switch to TP(*k*) and TPffe(*k*) to avoid confusion where *k* = 1, …, *MN*
- **Determine the tap values, $\{ c_{\mathrm{TP},i} \}$**
  - Applying FFE to TP(*k*) "by hand": $$\mathrm{TPfit}(k) = \sum_{i=-2}^{+1} \left(c_{\mathrm{TP},i} \mathrm{TP}(k + iM) \right)$$
  - Use least squares method to fit TPfit(*k*) to TPffe(*k*), i.e., find the minimum of

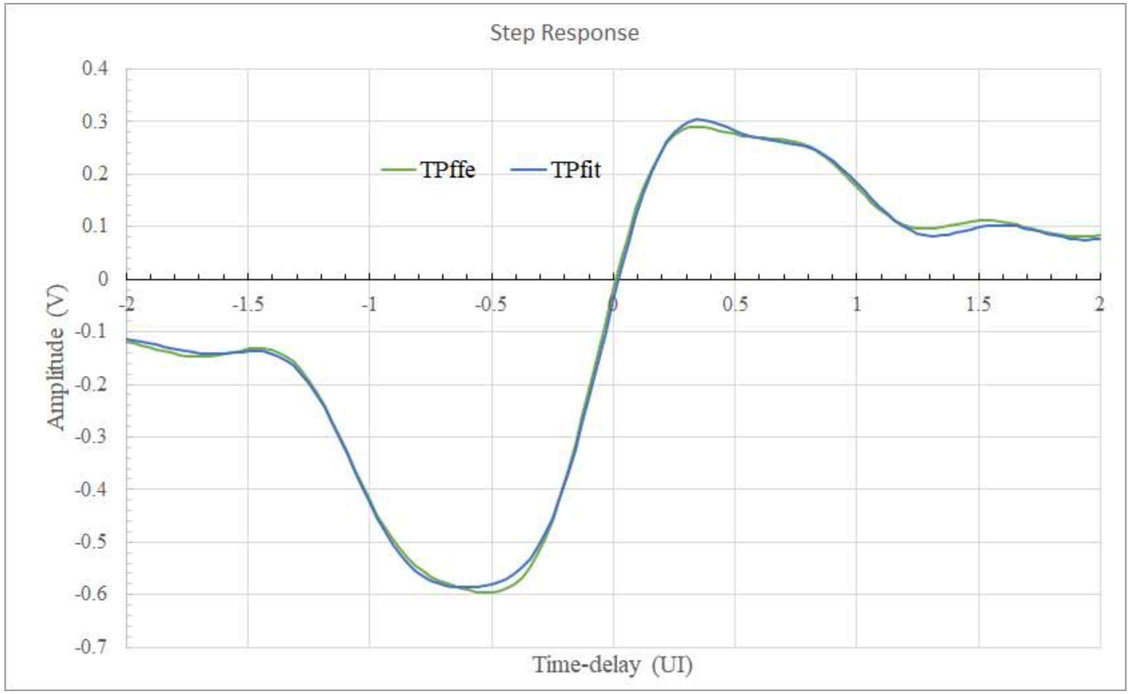
$$f(c_{\mathrm{TP},-2}, c_{\mathrm{TP},-1}, c_{\mathrm{TP},0}, c_{\mathrm{TP},+1}) = \sum_{k=1}^{NM} \left[\mathrm{TPfit}(k) - \mathrm{TPffe}(k) \right]^2$$

$$\boxed{\min \left\{ \sum_{k=1}^{NM} \left[\sum_{i=-2}^{+1} \left(c_{\mathrm{TP},i} \mathrm{TP}(k + iM) \right) - \mathrm{TPffe}(k) \right]^2 \right\} \xrightarrow{\text{Yields}} c_{\mathrm{TP},i}}$$

Measuring/calibrating taps

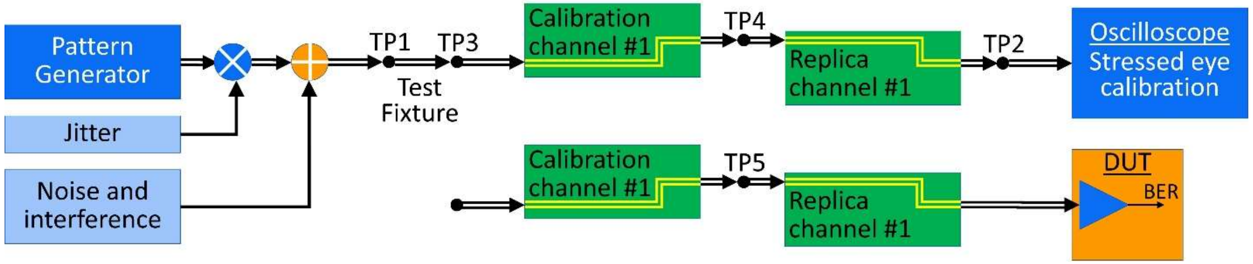
BitifEye
Digital Test Solutions

- **Comparison of observed FFE step response, TPffe(*k*), and fit, TPfit(*k*)**



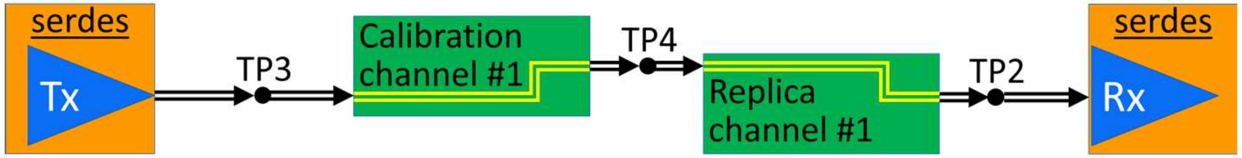
Calibrated taps

- **Think of $\{ c_{TP,i} \}$ as the taps that originate from the test point, TP**



  - ○ $\{ c_{TP,i} \}$ at TP3 are the calibrated values of FFE taps at the Tx, “reference transmitter,” output
  - ○ $\{ c_{TP,i} \}$ at TP2 are the remnants of the FFE taps at the Rx, “DUT,” input
    - *Ideal FFE taps would be exhausted at TP2:* $c_0=1,\ c_{i\neq 0}=0$

- **But there is a subtlety – serdes are not analog devices**

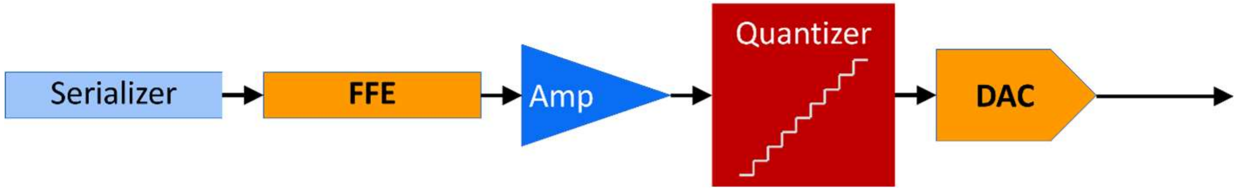


Agenda

- Transmitter Feed-Forward Equalization – TxFFE
  - The principle of operation and a practical approach, FIR filters, and shift registers
  - Relationship between taps and waveforms: de-emphasis, boost, and pre-shoot
- Optimizing TxFFE parameters in a complete, system-level, equalization scheme
  - Combining Tx and Rx equalization
  - Maximizing different figures of merit, complications
- Link Training
- Analysis of TxFFE signals
  - Testing link training
  - Measurement and calibration of TxFFE signals
- **The problem of serdes DAC resolution for TxFFE and PAM*n***
- Additional use cases for TxFFE
  - TxFFE for noise estimation
  - TxFFE as a de-embedding tool

The problem of serdes DAC resolution

Tx diagram:



- **A serdes' minimum amplitude variation, δV, is given by the DAC's (digital to analog convertor's) LSB (least significant bit):**

$$\delta V = \frac{V_{PP}^{Tx}}{2^N}$$

  - V_{PP}^{Tx} is the full scale range and *N* is the DAC resolution in bits
- **DAC granularity can limit a serdes' ability to pass compliance tests**
  - During link training, granularity can give unexpected results
    - *δV = minimum tap adjustment → affects values of pre-shoots and de-emphases*

Problematic serdes → a tough debug

BitifEye
Digital Test Solutions

- **We have tested serdes whose data sheets indicated TxFFE taps could be adjusted in 0.01 steps but, behind the data sheet had 6 bit DAC resolution**
  - 6 bit DAC ➔ 64 levels → 1/64 = 0.015625 steps
  - Link training thinks tap increments/decrements are in units of 0.01 but DAC “resamples” to 0.015625
- **Example:**
  - serdes increases pre- and post-cursor taps by one unit of resolution:

    data sheet values: $\{c_0 = 0.98,\ c_{+1} = -0.01,\ c_{-1} = -0.01\}$

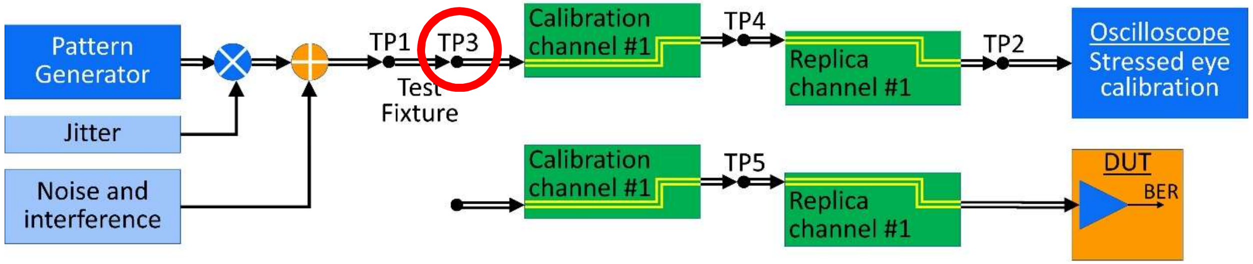
    actual DAC outputs: $\{c_0 = 0.984375,\ c_{+1} = -0.015625,\ c_{-1} = -0.\ 015625\}$

  - the actual output violates the power constraint $\sum_{Taps,i} |c_i| = 1$

    but the serdes transmitter doesn’t report it and the serdes fails compliance test
  - If we had known the DAC resolution, could have found the bug in minutes, but . .

DAC resolution and Rx testing

- The calibrated pre-shoot/de-emphasis are at the output of the test fixture, TP3



  - The *effective* granularity of voltage amplitudes, $\delta V_{Effective}$ includes the Tx DAC resolution and test fixture frequency response
  - The relationship between the DAC resolution, δV, the calibrated taps at TP3 and their granularity, $\delta c_{i,\ Effective}$, the resulting calibrated pre-shoot, boost, and de-emphasis levels at TP3 and their granularity δPS_i, δB, δDE_i is neither obvious nor linear

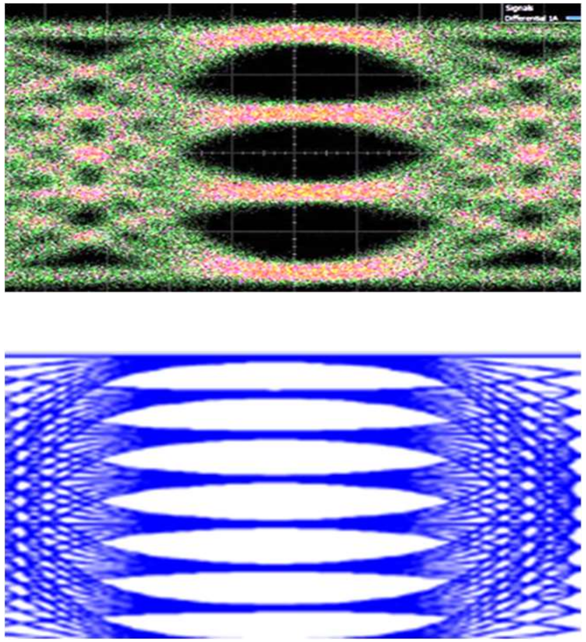
$$\delta V = \frac{V_{PP}^{Tx}}{2^N} \otimes \min\left\{ \sum_{k=1}^{NM} \left[\sum_{i=-2}^{+1} \left(c_{\mathrm{TP},i} \mathrm{TP}(k+iM) \right) - \mathrm{TPffe}(k) \right]^2 \right\} \xrightarrow{\text{Yields}} c_{\mathrm{TP},i} \otimes \begin{pmatrix} c_{+1} \\ c_0 \\ c_{-1} \\ c_{-2} \end{pmatrix} = -\frac{1}{2} 10^{-B/20} \begin{pmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & -1 & -1 \\ 0 & -1 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{pmatrix} \begin{pmatrix} 10^{-\mathrm{DE}/20} \\ 1 \\ 10^{\mathrm{PS1}/20} \\ 10^{\mathrm{PS2}/20} \end{pmatrix}$$

$$\delta V_{Effective}$$

DAC resolution and PAM*n*

- **Each symbol level requires a set of tap values that give pre-shoots and de-emphases that don't overlap other symbols**
  - PAM*n* requires higher serdes DAC resolution

    For 6 bit resolution
    - *PAM4 → ~ 30 levels between each symbol*
    - *PAM6 → ~ 11 levels between each symbol*
    - *PAM8 → ~ 8 levels between each symbol*



Agenda

- Transmitter Feed-Forward Equalization – TxFFE
    - The principle of operation and a practical approach, FIR filters, and shift registers
    - Relationship between taps and waveforms: de-emphasis, boost, and pre-shoot
- Optimizing TxFFE parameters in a complete, system-level, equalization scheme
    - Combining Tx and Rx equalization
    - Maximizing different figures of merit, complications
- Link Training
- Analysis of TxFFE signals
    - Testing link training
    - Measurement and calibration of TxFFE signals
- The problem of serdes DAC resolution for TxFFE and PAM*n*
- **Additional use cases for TxFFE**
    - TxFFE for noise estimation
    - TxFFE as a de-embedding tool

Additional uses for TxFFE

- **TxFFE as noise estimation tool**
  - The impact of high frequency, like crosstalk, vs ISI upsets the balance between TxFFE taps, CTLE gain, and DFE taps
  - High crosstalk pushes the channel response correction from CTLE gain to TxFFE pre-shoot and de-emphasis
    - *Compare the system-optimized TxFFE taps to the inverse S-parameter terms in* $\mathbf{TxFFE} = \mathbf{S}^{-1}\,\mathbf{TX}$
- **TxFFE as a de-embedding tool**
  - De-embedding uses the S-parameters of a trace or channel to remove its effects from a waveform and yield the waveform as it appears at some point within the system but
    - ***de-embedding raises a scope's noise floor*** *by the amount of signal de-embedded*
  - Using TxFFE to "de-embed" the response of a trace is less accurate than an S-parameter calculation, but doesn't raise the noise floor.

Conclusion

- **TxFFE is a crucial component of HSS technology not a supplement to Rx-based equalization**
  - Does not amplify high frequency (crosstalk) noise as RxFFE and CTLE do
- **TxFFE must be optimized in combination with Rx-based equalization**
  - Balance noise gain and DFE performance cancelling reflection-based ISI
  - Optimizing the right figure of merit can integrate different signal impairments, like PAM*n* eye compression and skew, in the EQ calculation
  - Link training adapts the equalization scheme to the operating conditions and requires communication between Tx and Rx
- **The values of taps and resulting pre-shoots and de-emphases are easily measured at any test point using a fitting technique and repeating step function**
- **The balance of TxFFE tap magnitudes, CTLE gain, and DFE tap magnitudes provide a way to gauge the impact of crosstalk.**
- **TxFFE is being used to partially “de-embed” test fixtures without raising test equipment noise floors**

More information

- **Tutorials and videos at www.bitifeye.com**
- **References**
  - The seminal DSP reference is Emmanuel C. Ifeachor and Barrie W. Jervis, *Digital Signal Processing: A Practical Approach, 2nd Edition*, Addison-Wesley, 2001.
  - PCIe Special Interest Group, PCI Express Base Specification Revision 6.0, Sections 7.5.3.6 to 7.5.3.8, January-2022, available at https://pcisig.com/pci-express-6.0-specification.
  - Kevin Zheng et al., “Feedforward Equalizer Location Study for High-Speed Serial Systems,” Signal Integrity Journal, 21-May-2019; and, “Partitioning of TX and RX Feedforward Equalizer for 112 Gbps Serial Links,” DesignCon 2019.
  - IEEE 802.3-2018, IEEE Standard for Ethernet, https://standards.ieee.org/standard/802_3-2018.html.
  - William H. Press, et al., *Numerical Recipes: The Art of Scientific Computing, Third Edition* Cambridge university Press, 2007.
  - Adam Healey and Cathy Liu, “100 Gb/s/lane chip-to-module interface simulation analysis,” IEEE P802.3ck 100 Gb/s, 200 Gb/s, and 400 Gb/s Electrical Interfaces Task Force, July 2018, available at https://www.ieee802.org/3/ck/public/18_07/healey_3ck_01b_0718.pdf.
  - Donald Telian, Michael Steinberger, and Barry Katz, “New SI Techniques for Large System Performance Tuning,” DesignCon 2016.
- **Speaker’s emails ransom.stephens@bitifeye.com or ransom@ransomsnotes.com**
  - Shameless plug: **Attend Ransom’s class “Mastering High-Speed Serial I/O Technology” at Oxford University May 23-25, 2022** https://www.conted.ox.ac.uk/courses/mastering-high-speed-serial-io-technology

Thank you!

—

QUESTIONS?