A closer look at effective return loss

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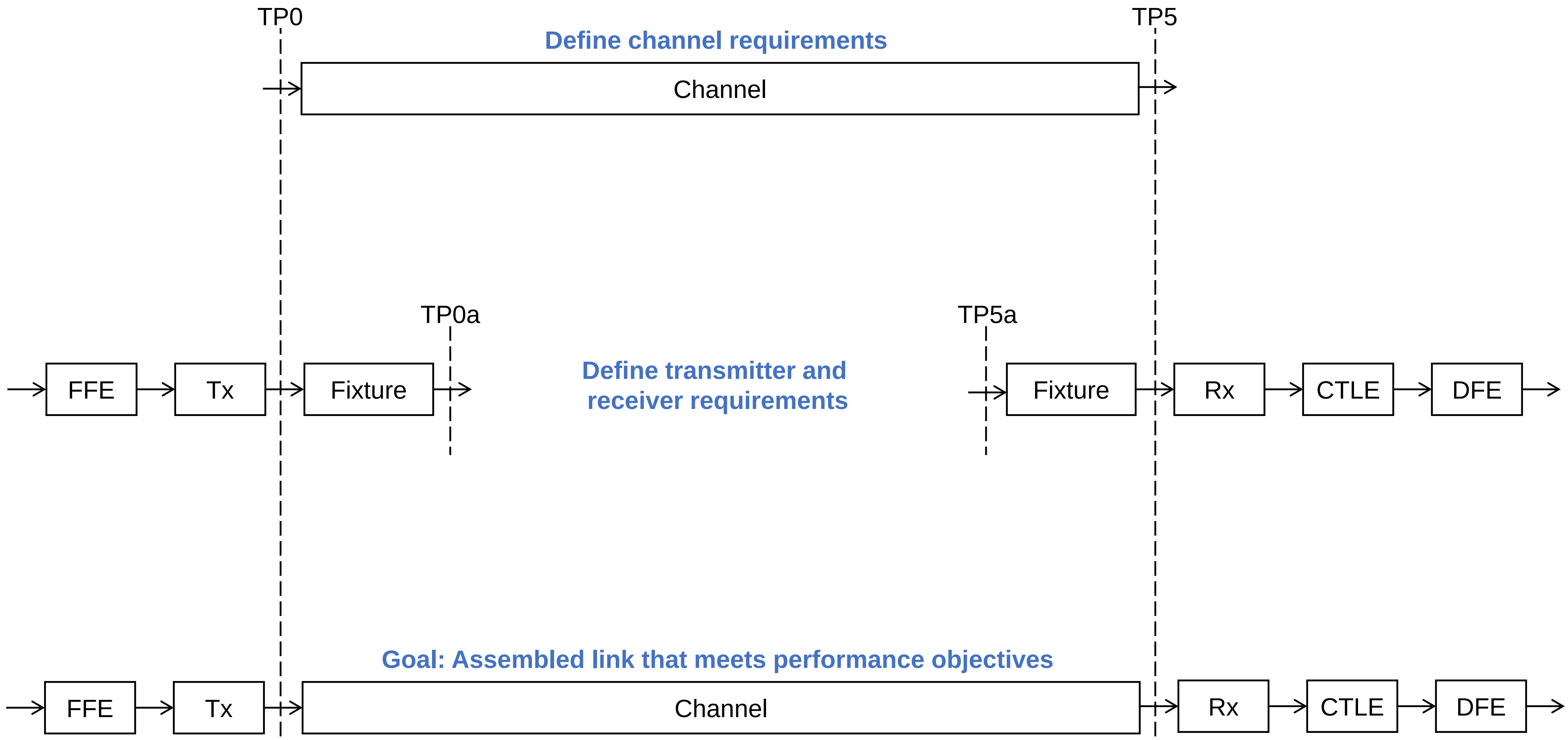
Introduction

- Effective return loss (ERL) has been a topic of recent discussions and a number of initial Task Force review comments
- This presentation takes a closer look at the underlying concepts of ERL
- It clarifies the role of ERL in the compliance methodology for backplane PHYS and chip-to-chip interfaces
- The impact of test fixtures is also considered

Backplane (and chip-to-chip) reference model



Transfer function of the assembled link

- The transfer function from the transmitter input to the receiver output is the following

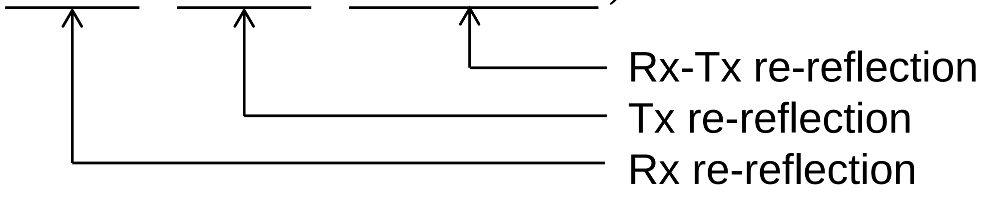
$$H_{21} = \frac{s_{21}^{(t)} s_{21} s_{21}^{(r)}}{1 - s_{22} s_{11}^{(r)} - s_{11} s_{22}^{(t)} + s_{11}^{(r)} s_{22}^{(t)} \Delta S}$$

$$\Delta S = s_{11} s_{22} - s_{21} s_{12}$$

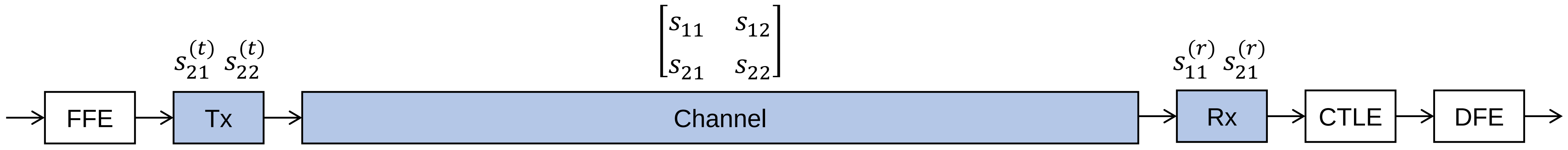
$$s_{21} = s_{12}$$

- Note that $1/(1-x) \cong 1 + x + x^2 + \cdots$ for $|x| < 1$

$$H_{21} \cong s_{21}^{(t)} s_{21} s_{21}^{(r)} \left(1 + \underline{s_{22} s_{11}^{(r)}} + \underline{s_{11} s_{22}^{(t)}} + \underline{s_{21} s_{21} s_{11}^{(r)} s_{22}^{(t)}}\right)$$



- Constraints on s_{11}, s_{22}, $s_{11}^{(r)}$, and $s_{22}^{(t)}$, e.g., ERL, are imposed to limit the re-reflection terms



Link equalization

Assume finite rise time and bandwidth from the Tx and Rx analog front-ends

- Let the bandwidth-limiting filters be H_t and H_r respectively

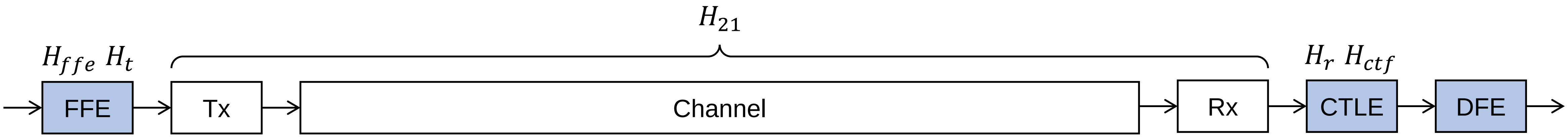
The transmitter and receiver cooperate to equalize the channel

- The transmitter includes a feed-forward equalizer (FFE) with transfer function H_{ffe}
- The reference receiver includes a continuous time linear equalizer (CTLE) with transfer function H_{ctf}
- H_{ffe} and H_{ctf} may only partially equalize the link in anticipation of further processing by a decision feedback equalizer (DFE)

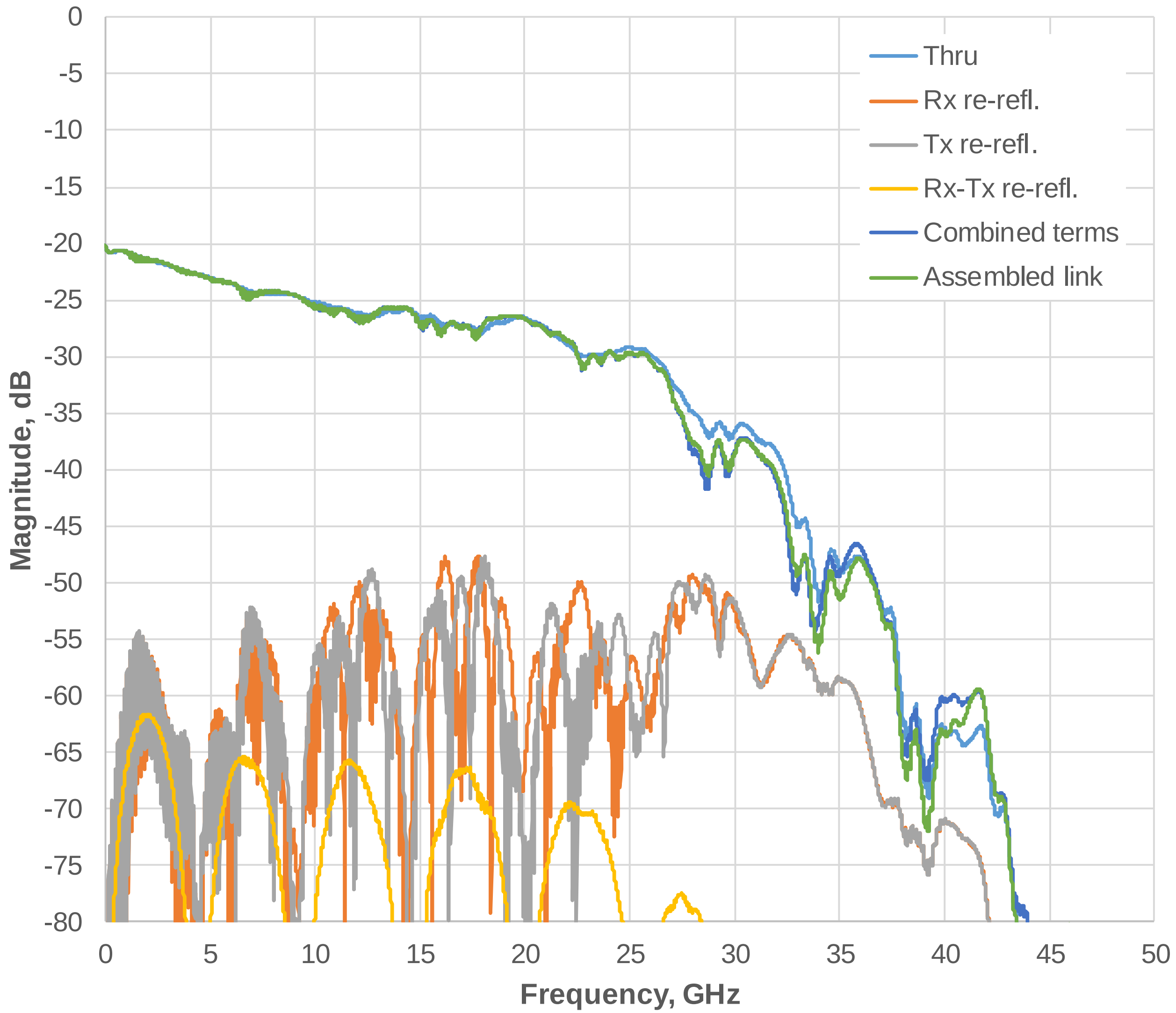
Stimulate the channel with a pulse with height A_v and width T_b (unit interval)

$$P = A_v T_b \mathrm{sinc}(f T_b) H_{ffe} H_t H_{21} H_r H_{ctf}$$

$$P \cong A_v T_b \mathrm{sinc}(f T_b) H_{ffe} H_t s_{21}^{(t)} s_{21} s_{21}^{(r)} H_r H_{ctf} \left(1 + s_{22} s_{11}^{(r)} + s_{11} s_{22}^{(t)} + s_{21} s_{21} s_{11}^{(r)} s_{22}^{(t)}\right)$$



Example



Channel information

- "Heck2" as defined in heck_3ck_01b_0719.pdf
- Loss is approximately 15.2 dB
- Effective return loss is approximately 13.6 dB for port 1, 12.7 dB for port 2
- Case 1 package model (z_p = 12 mm for Tx, Rx)
- Linear equalization determined using COM

Time-domain view

Notes

- Convert frequency-domain results from the prior slide to the time domain
- $t = 0$ corresponds to t_s as determined by COM
- Results are normalized to pulse amplitude at t_s

Observations

- Math works! Combination of terms agrees with the transfer function of the assembled link
- Only Rx and Tx re-reflection terms need to be considered (except, perhaps, for very low-loss channels)
- Re-reflection terms constructively/destructively combine with s_{21} product ($s_{21}^{(t)} s_{21} s_{21}^{(r)}$) and each other
- The s_{21} product includes a significant portion of the "tail" information

ERL and re-reflection interference

For the moment, ignore test fixture effects…

ERL calculation begins with calculation of the pulse time-domain reflectometry (PTDR) response

- Response of the filtered reflection coefficient to a pulse with height 1 and width T_b
- $p_{tdr}^{(r)} = \mathcal{F}^{-1}\left\{T_b sinc(fT_b) H_t s_{11}^{(r)} H_r\right\}$ where $\mathcal{F}^{-1}\{x\}$ is the inverse Fourier transform of x

Recall the Rx re-reflection interference term calculated earlier

- $H_{rr}^{(r)} = A_v T_b sinc(fT_b) H_{ffe} H_t s_{21}^{(t)} s_{21} s_{21}^{(r)} H_r H_{ctf} s_{22} s_{11}^{(r)}$
- It is clear that an impulse response can be derived that converts the PTDR to re-reflection interference
- $h_{rr}^{(r)} = \mathcal{F}^{-1}\left\{A_v H_{ffe} s_{21}^{(t)} s_{21} s_{21}^{(r)} H_{ctf} s_{22}\right\}$ is a function of the channel output reflection coefficient

Instead, ERL approximates the re-reflection interference by…

- “Gating and weighting” the PTDR response to yield R_{eff}
- Sampling R_{eff} at T_b-spaced intervals (at the phase corresponding to the largest RMS value)
- Constructing the cumulative distribution function (CDF) of the sampled terms (for i.i.d. PAM-L symbols)
- Finding the amplitude for which the area under the tail of the CDF equals the target detector error ratio

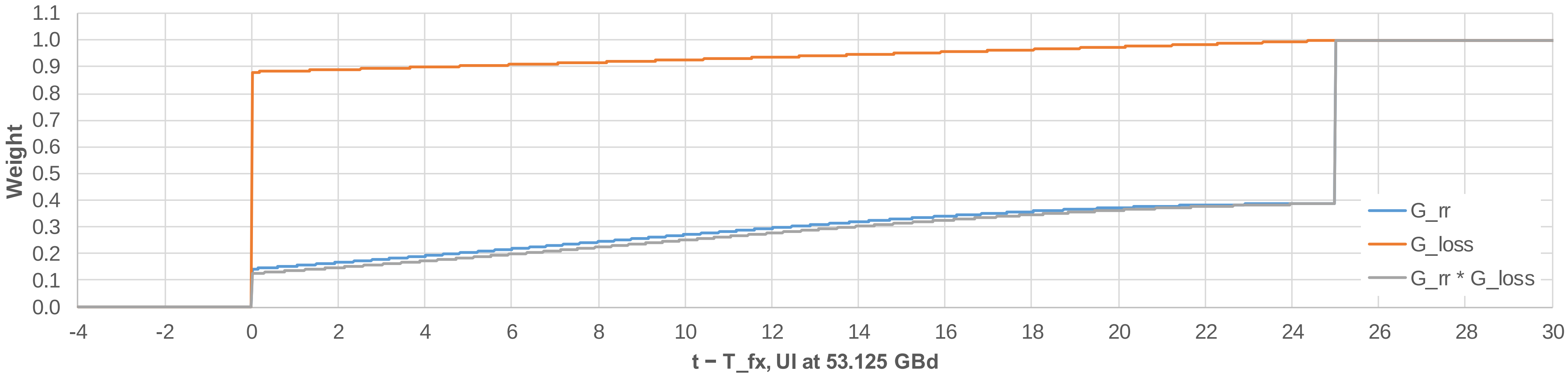
ERL “gating and weighting”

“Gating”

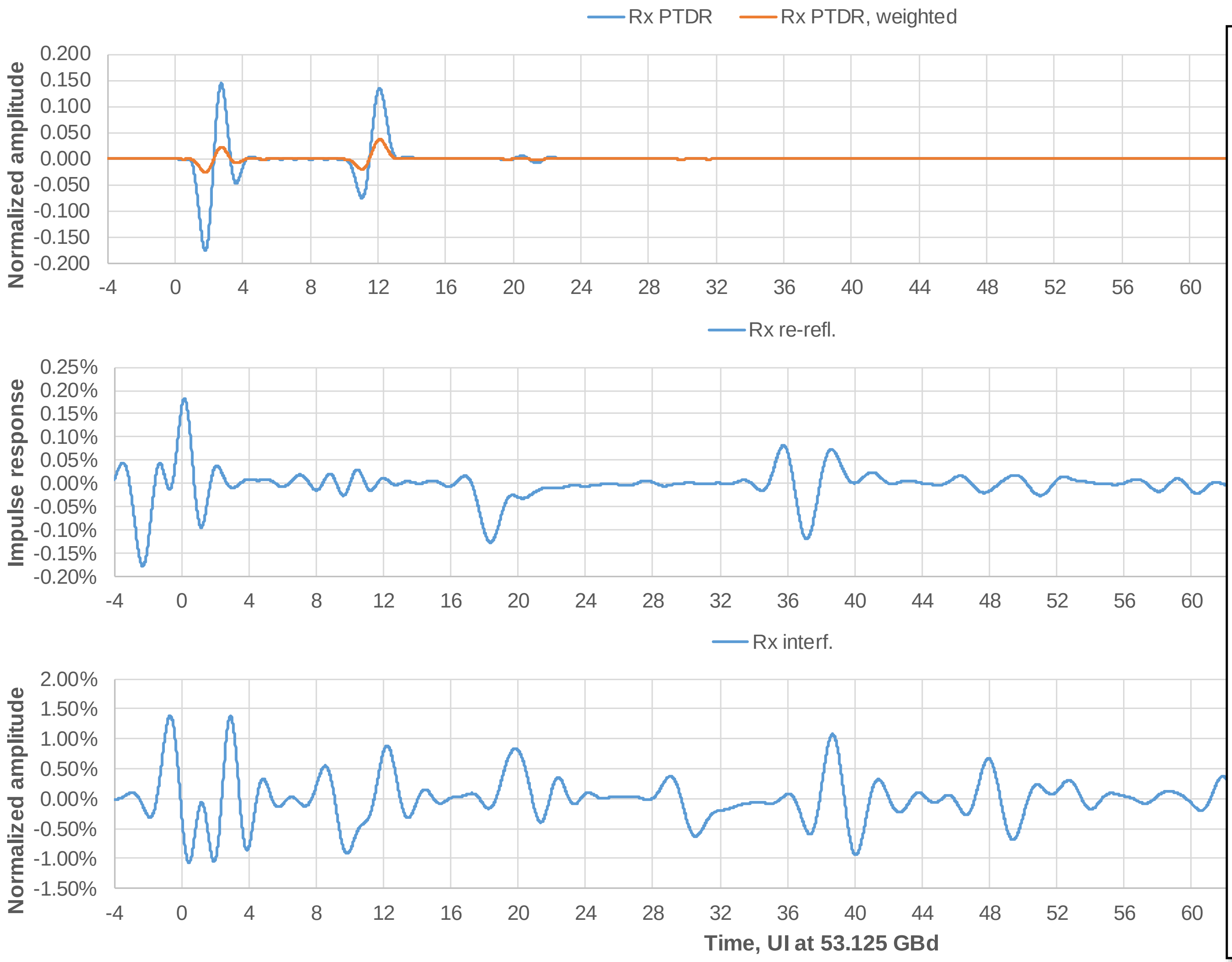
- PTDR response for time less than round-trip test fixture delay T_{fx} has weight 0
- Removes a portion of text fixture effect

“Weighting”

- G_{rr} (re-reflection) is a function of the minimum effective return loss allowed for connected channel, Tx, or Rx
- G_{loss} is not a significant factor (its value is close to 1)
- Significant discontinuity at $N_{bx} + 1$ unit intervals from T_{fx} (related to the expected Rx equalization capability)



Rx re-reflection example, part 1



Pulse time-domain reflectometry (PTDR)

- $t = 0$ is the round-trip test fixture delay T_{fx}
- Weighted PTDR (a.k.a. R_{eff}) is also shown

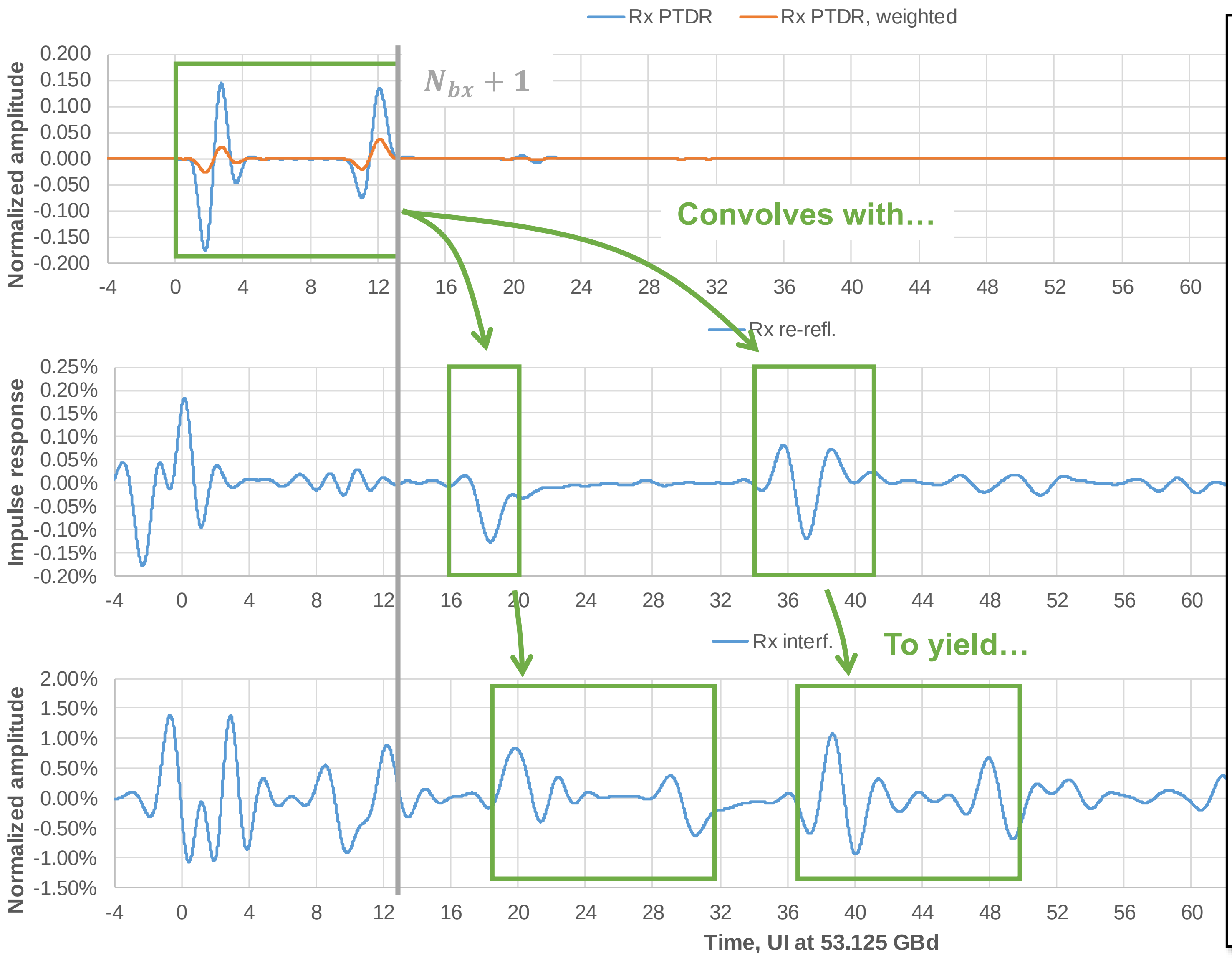
Re-reflection impulse response

- Normalized to pulse amplitude at t_s

Rx re-reflection interference

- Convolution of PTDR response (not weighted) and re-reflection impulse response $h_{rr}^{(r)}$
- This is what the receiver would actually "see"

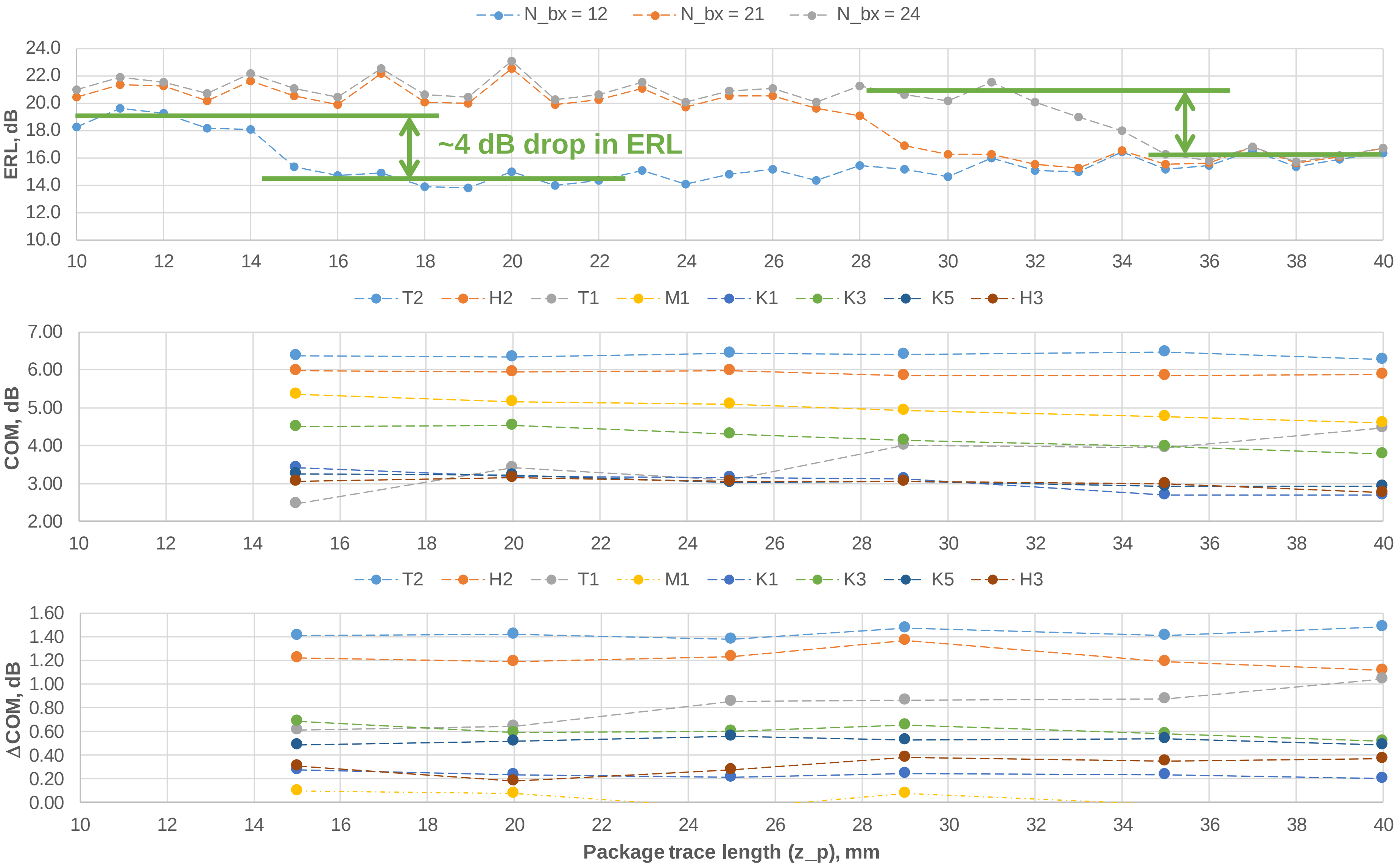
Rx re-reflection example, part 2



Observations

- Weighting implies the PTDR response for time $[0, N_{bx} + 1)$ UI is not as impactful
- Weighting implies the impact gets progressively smaller as t approaches 0
- But the receiver "sees" the convolution of the PTDR response and the re-reflection impulse response
- This "low impact" region of the PTDR response can generate interference terms later in time
- Some of these terms can be beyond the reach of the assumed DFE
- The interaction between the Rx (or Tx) and the channel is not fully described by the weighting function (and the ρ_x parameter)

Re-reflection impact on channel operating margin (COM)



ERL

- Sweep package trace length and calculate ERL
- Multiple values of N_{bx}

COM

- Computed using parameter values from Table 163–10
- Rx package trace length is swept (z_p = 31 mm for Tx)

Remove re-reflection

- Force s_{11}, s_{22}, $s_{11}^{(r)}$, $s_{22}^{(t)}$ to zero
- Measure improvement in COM (the equalizers are re-optimized)

Re-reflection impact on COM, continued

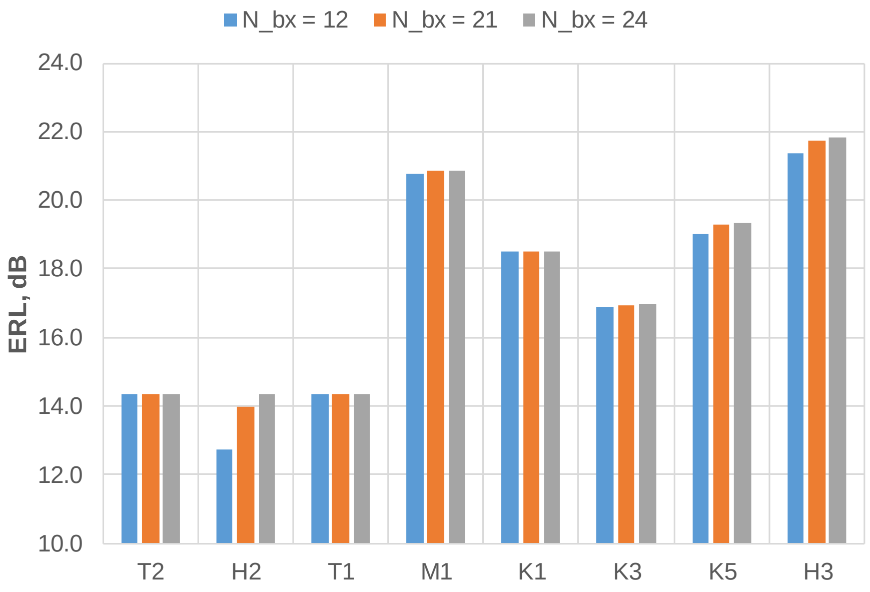
For the channels considered…

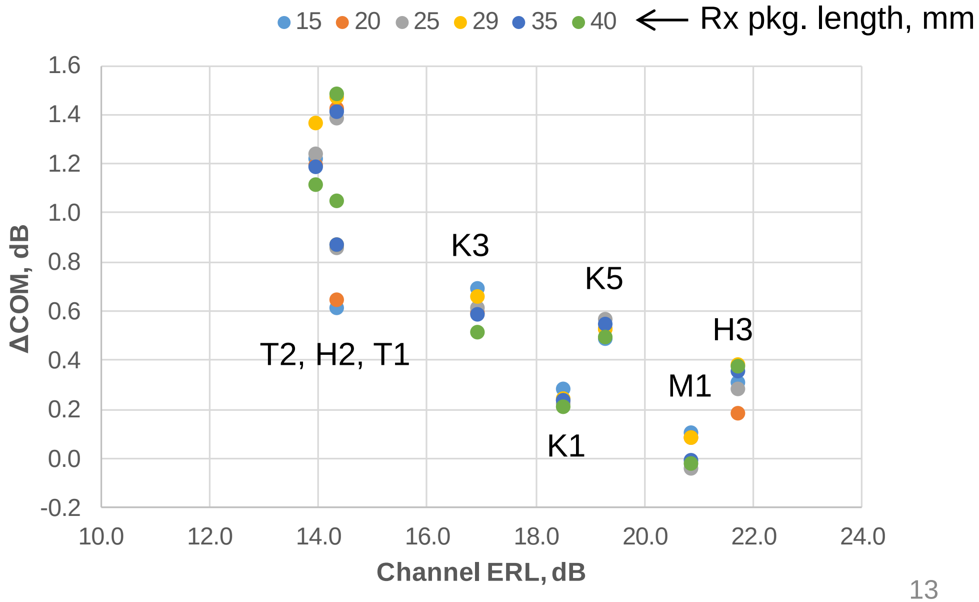
There is no clear justification for sharp decrease in ERL when Tx or Rx reflections are later than $N_{bx} + 1$ UI

- No corresponding increase in re-reflection interference (as indicated by ΔCOM)

Some correlation observed between channel ERL and re-reflection interference

- May be some relationship between re-reflection impulse response and channel PTDR response
- But channel ERL does not appear to be sensitive to N_{bx}





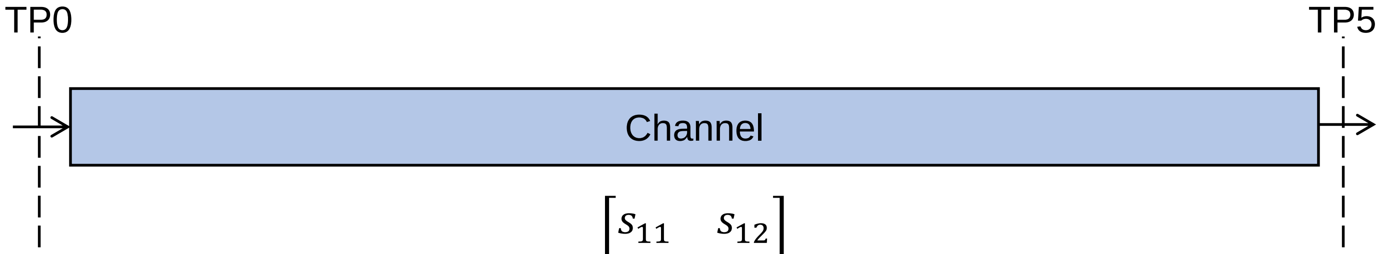
Things to consider for ERL, part 1

- ERL limits the additional re-reflection interference that the Rx needs to tolerate
- It captures the difference between component behavior measured with reference terminations and the expected behavior in an assembled link
- It ignores features that will not matter considering the capabilities of the reference equalizer
- But is it correctly discriminating between what matters from does not?

Things to consider for ERL, part 2

- Application of an equalization "window" to an individual PTDR response is not appropriate
- The PTDR response is not the interference "seen" by the Rx
  - The G_{rr} term does not appear to reconcile this difference
- Also recall that the interference is a combination of at least three terms
  - How to choose tap positions (for floating-tap equalizer)?
  - How to verify the correction is within the tap coefficient (or total energy) limit?
- While it is understood that the problem is complex and approximations can not be avoided…
- …the PTDR weighting (not gating) function should be revised/replaced
  - Goal is to protect the Rx from interference while enabling implementation flexibility

Backplane and chip-to-chip channel measurements

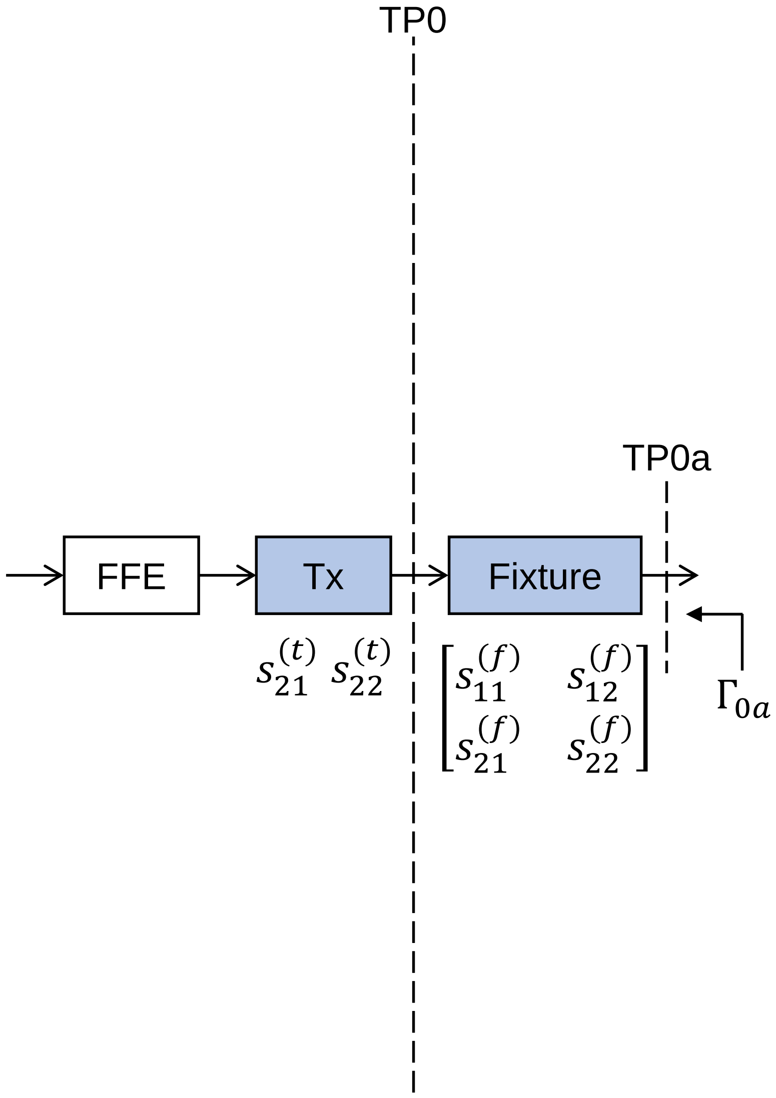


$$\begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix}$$

Direct measurement of channel s-parameters between TP0 and TP5

- No test fixture impact to consider

Transmitter measurements



Transmitter transfer function

- We want to know $s_{21}^{(t)}$ but we can only measure $s_{21}^{(0a)}$ (via linear fit pulse)
- The measurement is impacted by the properties of the test fixture

$$s_{21}^{(0a)} = \frac{s_{21}^{(t)} s_{21}^{(f)}}{1 - s_{22}^{(t)} s_{11}^{(f)}}$$

$$s_{21}^{(0a)} \cong s_{21}^{(t)} s_{21}^{(f)} \left(1 + s_{22}^{(t)} s_{11}^{(f)}\right)$$

Transmitter effective return loss

- We want to know $s_{22}^{(t)}$ but we can only measure Γ_{0a}

$$\Gamma_{0a} = s_{22}^{(f)} + \frac{s_{12}^{(f)} s_{22}^{(t)} s_{21}^{(f)}}{1 - s_{22}^{(t)} s_{11}^{(f)}}$$

$$\Gamma_{0a} \cong s_{22}^{(f)} + s_{22}^{(t)} s_{21}^{(f)} s_{21}^{(f)} \left(1 + s_{22}^{(t)} s_{11}^{(f)}\right)$$

Receiver measurements

Receiver transfer function

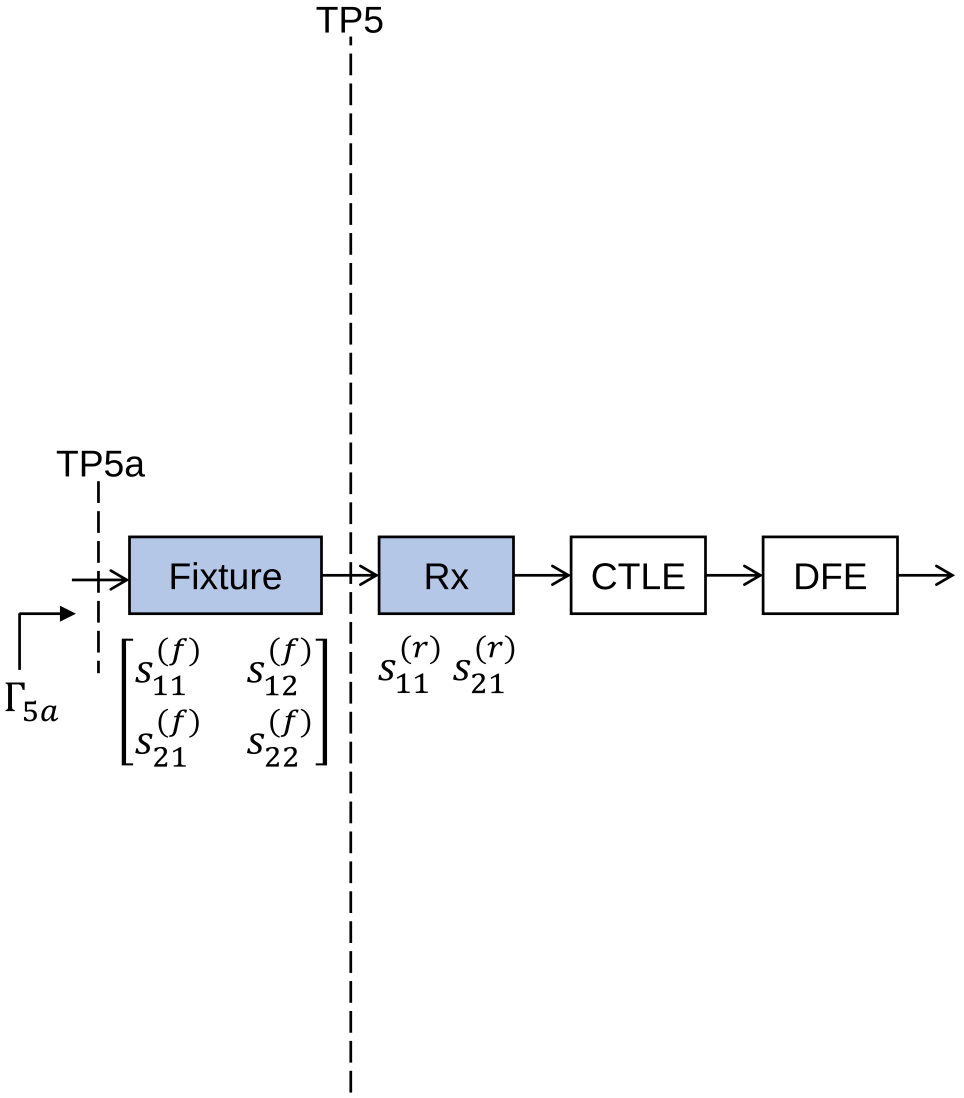
- $s_{21}^{(r)}$ is not measured or estimated (unclear how this might be done)
- Impairments related to $s_{21}^{(r)}$ must be tolerated by the receiver (this is evaluated via the receiver interference tolerance test)

Receiver effective return loss

- We want to know $s_{11}^{(r)}$ but we can only measure Γ_{5a}

$$\Gamma_{5a} = s_{11}^{(f)} + \frac{s_{21}^{(f)} s_{11}^{(r)} s_{12}^{(f)}}{1 - s_{22}^{(f)} s_{11}^{(r)}}$$

$$\Gamma_{5a} \cong s_{11}^{(f)} + s_{11}^{(r)} s_{21}^{(f)} s_{21}^{(f)} \left(1 + s_{22}^{(f)} s_{11}^{(r)}\right)$$



Things to consider for test fixtures, part 1

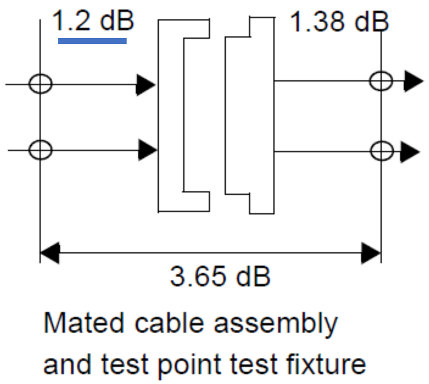
- If test fixtures can be built with very low insertion loss and high return loss, they could be ignored
- If the loss is not low enough to be ignored, but it is consistent, the impact can be considered when the compliance limits are set
- Pro-rating specifications for test fixture return loss deficiencies is trickier

Component	What we would like to know…	What we measure…
Tx	$s_{21}^{(t)}$	$s_{21}^{(t)} s_{21}^{(f)} \left(1 + s_{22}^{(t)} s_{11}^{(f)}\right)$
	$s_{22}^{(t)}$	$s_{22}^{(f)} + s_{22}^{(t)} s_{21}^{(f)} s_{21}^{(f)} \left(1 + s_{22}^{(t)} s_{11}^{(f)}\right)$
Channel	$\begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix}$	$\begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix}$
Rx	$s_{11}^{(r)}$	$s_{11}^{(f)} + s_{11}^{(r)} s_{21}^{(f)} s_{21}^{(f)} \left(1 + s_{22}^{(f)} s_{11}^{(r)}\right)$
	$s_{21}^{(r)}$	Interference tolerance

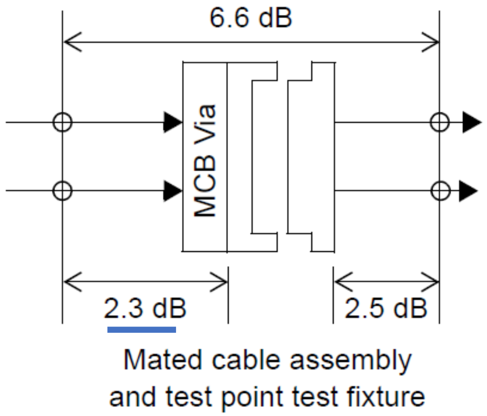
Things to consider for test fixtures, part 2

- It is not yet clear whether low and/or consistent losses will be achievable for this signaling rate
  - Thinking ahead, whatever is defined should enable a break-out of 8 Tx and 8 Rx pairs
- Module compliance board (cable assembly test fixture) loss allocation has increased almost 100% from 26.5625 to 53.125 GBd
- Doesn’t this imply that the transmitter/receiver test fixture loss allocation should also be increased?

From IEEE Std 802.3cd-2018
Figure 136A–1



From IEEE P802.3ck/D1.0
Figure 162A–1



Things to consider for test fixtures, part 3

- "The effects of differences between the insertion loss of an actual test fixture and the reference insertion loss are to be accounted for in the measurements"
- Overly aggressive test fixture targets will make this the norm rather than the exception
- If compensation becomes routine, the value of compensating to some reference loss is questionable
- Note that a lower loss test fixture for 100 Gb/s/lane testing will require loss to be embedded in test results for lower rates
  - Tx/Rx test fixtures are not expected to be pluggable
- Should the fixture loss simply "be accounted for in the measurements"?

Summary and recommendations

- Link between ERL and re-reflection interference seen by the Rx seems tenuous
- Application of an “equalization” exception window to PTDR response is incorrect
  - Recommend to not extend the window to reflect floating-tap capability at this time
  - Seek better ways to convert PTDR response to [equalized] re-reflection interference
- Need to decide on test fixture methodology and requirements in order to set specification limits
  - Reference loss of test fixture should be readily achievable
  - If not, recommend that test fixture insertion loss be “accounted for” in measurements
  - In either case, it is important to have good test fixture return loss

Reference

- Moore and Healey, "A Method for Evaluating Channels", IEEE 100 Gb/s Backplane and Copper Cable Study Group, March 2011.

Back-up

Channel information

Label	IL, dB at 26.6 GHz	Reference
T2	12.2	DPO_IL_12dB from tracy_3ck_02_0119_orthoBP.zip
H2	15.2	Cable_BKP_16dB_0p575m_more_isi from heck_3ck_01a_1118_cable_BKP_16dB.zip
T1	15.7	Std_BP_12inch_Meg7 from tracy_3ck_03_0119_tradBP.zip
M1	26.3	CaBP_BGAVia_Opt2_28dB from mellitz_3ck_adhoc_02_081518_cabledbackplane.zip
K1	27.6	OAch4 from kareti_3ck_01a_1118_orthoUpdated.zip
K3	28.4	CAch3_b2 from kareti_3ck_01_1118_cabledBP.zip
K5	28.9	Bch2_b7p5_7 from kareti_3ck_01_1118_backplane.zip
H5	29	Cable_BKP_28dB_0p575 from heck_3ck_01a_1118_cable_BKP_28dB.zip