EMBEDDING & EQUALIZATION
EMULATION OF SIGNAL DISTORTION & SIGNAL RECOVERY

Guido Schulze, Product Manager Oscilloscopes
Johannes Ganzert, Senior Application Engineer Oscilloscopes

ROHDE&SCHWARZ

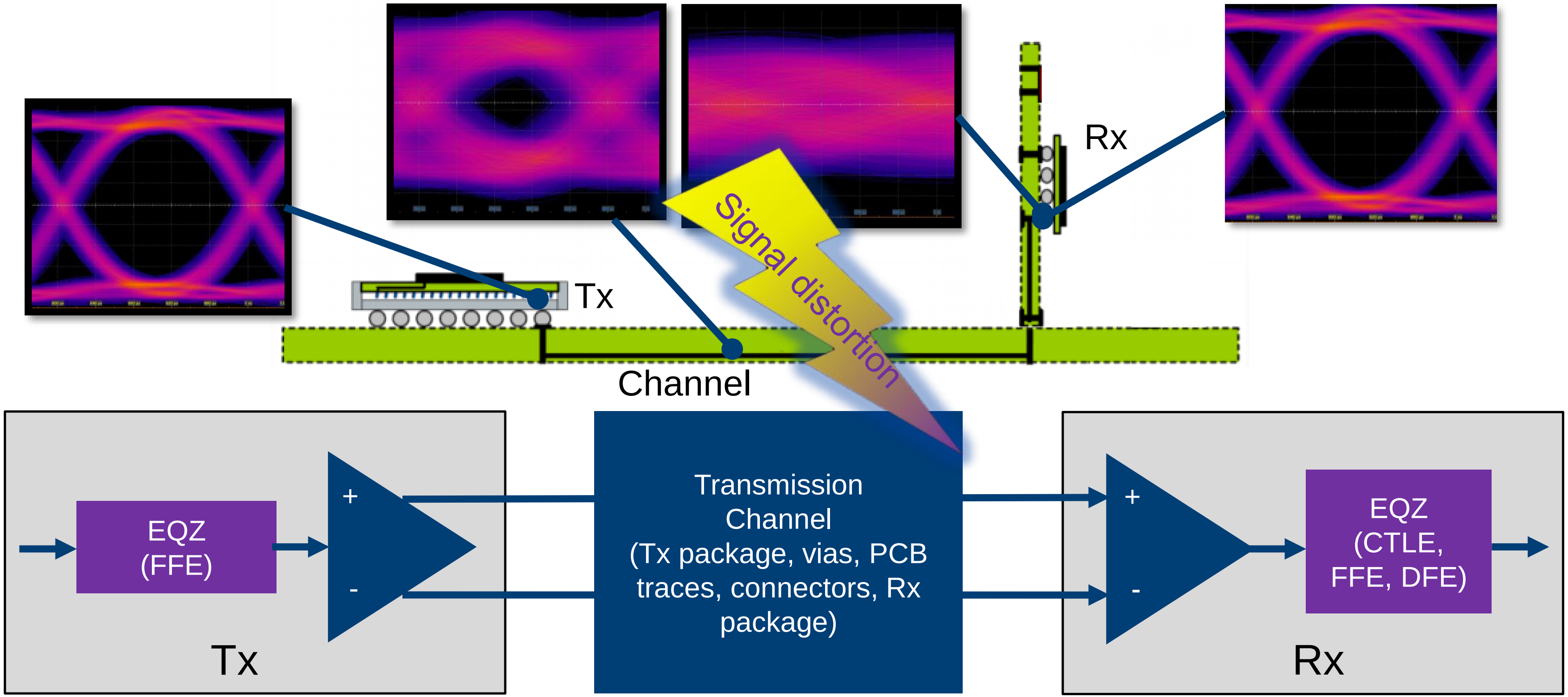
Make ideas real

OUTLINE

- ► Motivation
- ► Application example USB 3.2
- ► Introduction to Embedding / Equalization
- ► R&S implementation
- ► Demo
- ► Summary

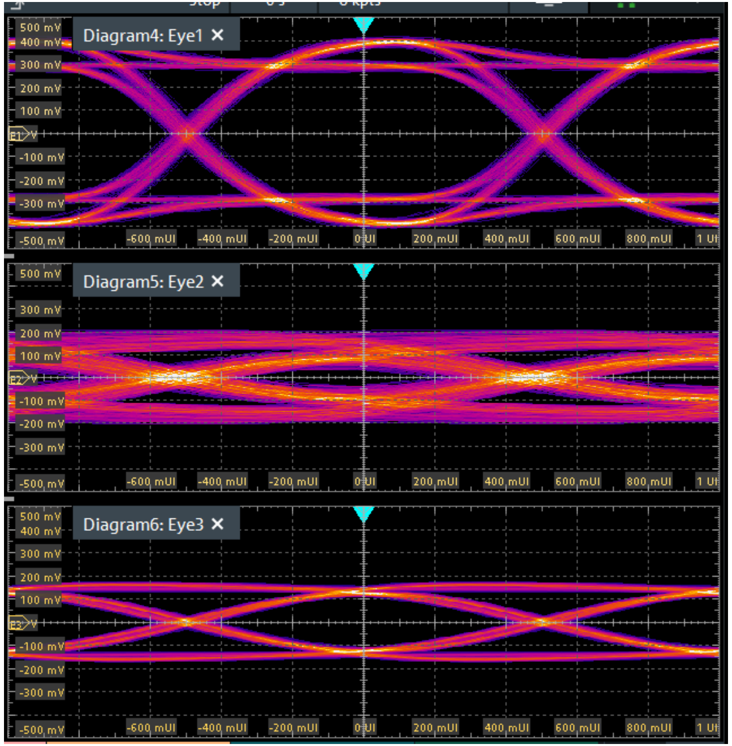
MOTIVATION

TRANSMISSION CHANNEL AND SIGNAL IMPAIRMENTS



INTER-SYMBOL-INTERFERENCE (ISI)

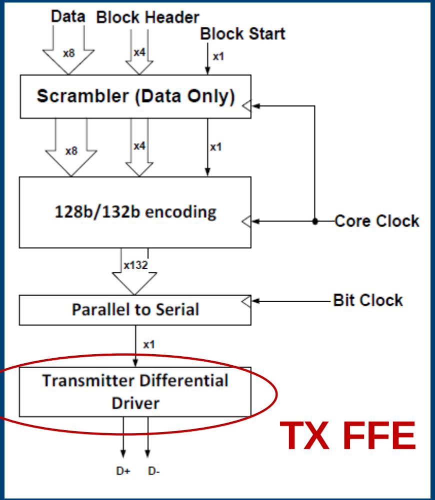
- **ISI**
  - Waveforms of adjacent symbols overlap in time due to dispersion or other impairments
  - Pattern dependent
  - ISI jitter & level distortion
- **Root causes:**
  - **Bandwidth limitation** of the channel
  - **Reflections** at impedance discontinuity in the channel
  - **Rise-time** degradation
- **Solution:**
  - Equalization compensates frequency-dependent channel losses by adjusting the signal's frequency response



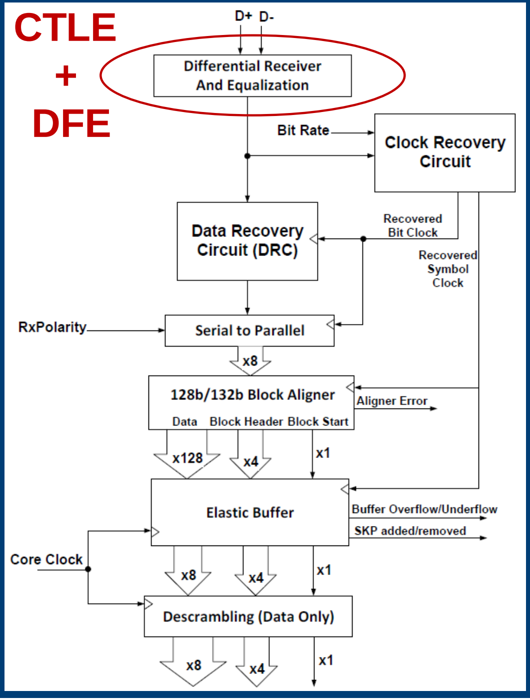
TYPICAL APPLICATIONS: USB 3.2 GEN2 SPECIFICATION

USB 3.2 SPECIFICATION
GEN2 - PHYSICAL LAYER

▶ Transmitter



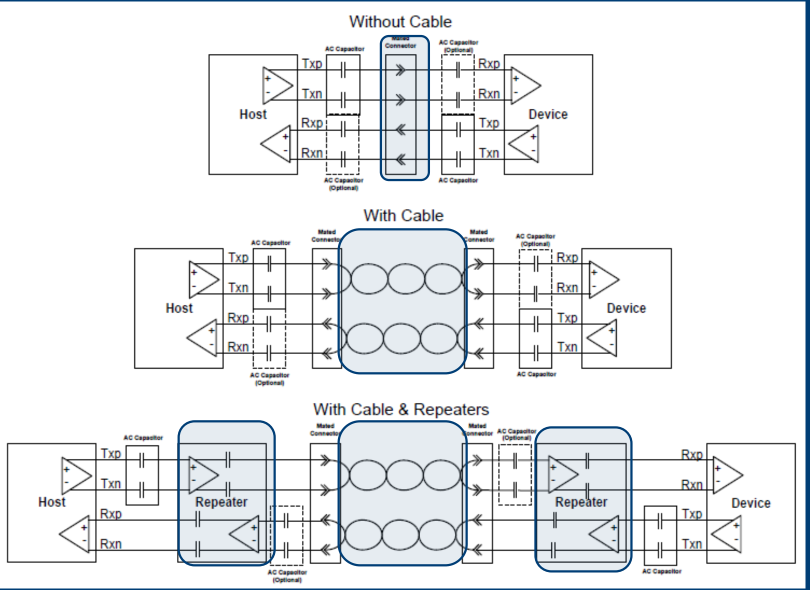
▶ Receiver



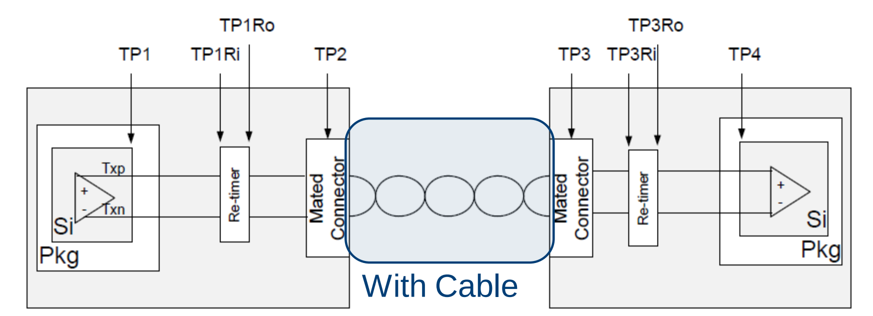
Source: USB 3.2 specification

USB 3.2 SPECIFICATION
GEN2 - PHYSICAL LAYER

▶ Channel Models

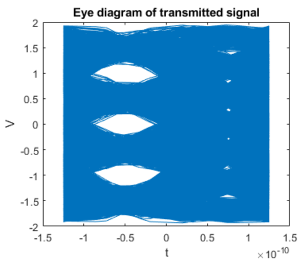


▶ Electrical Test Points



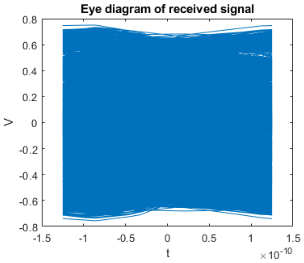
Source: USB 3.2 specification

HOW TO TEST CHANNEL LOSS & EQUALIZATION?



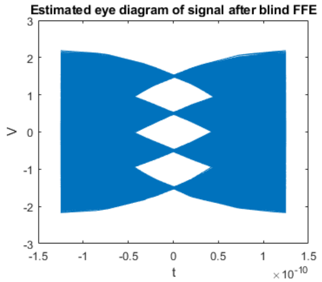
TX signal at oscilloscope input

Channel Embedding



RX signal after channel

Equalizer Emulation



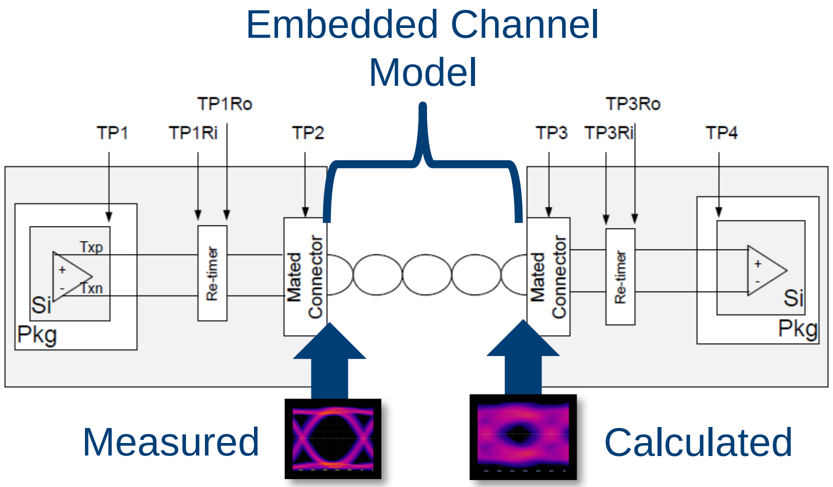
RX signal after equalization

Post-processing

INTRODUCTION TO EMBEDDING

EMBEDDING

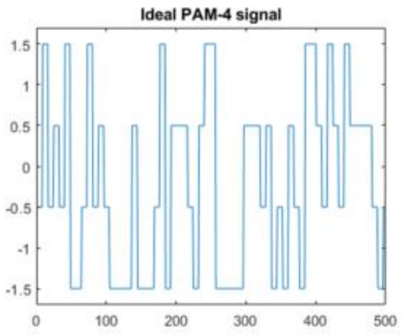
- ► Emulates additional signal distortion by adding mathematically „lossy“ components (e.g. cable)
- ► Components are expressed by S-parameters (typically 2-port or 4-port)
- ► Several components can be cascaded
- ► FIR filter gets designed to simulate respective frequency response

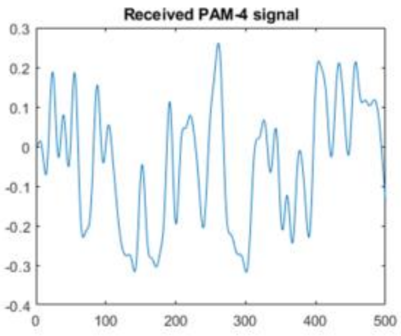


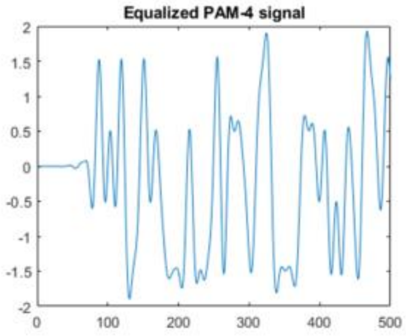
INTRODUCTION TO EQUALIZER

WHAT IS EQUALIZATION

- Operation that is applied to a pulse-amplitude modulated (PAM) signal that has been distorted by a channel (such as a cable).
- Equalizer compensate for some of the distortions introduced by the channel and can recover the transmitted PAM symbols:
  - + can compensate inter-symbol interferences
  - – can not remove noise or delays







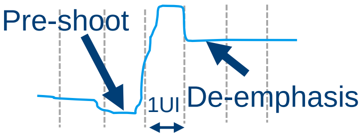
TYPES OF EQUALIZER

- Common Equalizer:
  - Transmitter side: **TX FFE** (pre-distortion / pre-emphasis / de-emphasis)
  - Receiver side: **CTLE** / **FFE** / **DFE**
- ***Note:*** *In a communications system, the output of the equalizer are generally the estimated PAM symbols, sampled at symbol rate. For debugging applications in the oscilloscope, we develop equalizers that output waveforms at the same sampling rate of the input waveform. This allows the computation of eye diagrams or jitter analysis.*

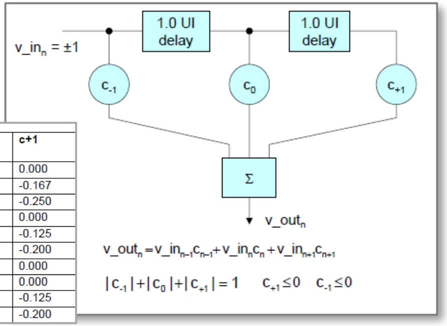
TX FFE (TRANSMITTER FEED-FORWARD EQUALIZATION)

Source: PCI Sig, PCIe Gen4 Base Specification for 8.0 GT/s

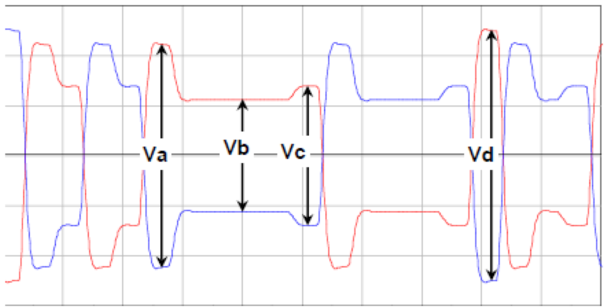
- ► Boosts the high-frequency energy on transitions in the data stream:
  - – Modifies the amplitudes of symbols around transitions while keeping the transmitted power constant
- ► Typically FIR filter with 3 taps (UI delays):
  - – Pre-cursor (Vc) is referred to as pre-shoot
  - – Post-cursor (Vb) is referred to as de-emphasis



  - – Standards typically provide values for the coefficients (c_N)
- ► Application:
  - – Compensation of “simple” low-pass filtering effect of the channel
  - – Cannot compensate discontinuity along the channel



Preset #	Preshoot (dB)	De-emphasis (dB)	c-1	c+1
P4	0.0	0.0	0.000	0.000
P1	0.0	-3.5 ± 1 dB	0.000	-0.167
P0	0.0	-6.0 ± 1.5 dB	0.000	-0.250
P9	3.5 ± 1 dB	0.0	-0.166	0.000
P8	3.5 ± 1 dB	-3.5 ± 1 dB	-0.125	-0.125
P7	3.5 ± 1 dB	-6.0 ± 1.5 dB	-0.100	-0.200
P5	1.9 ± 1 dB	0.0	-0.100	0.000
P6	2.5 ± 1 dB	0.0	-0.125	0.000
P3	0.0	-2.5 ± 1 dB	0.000	-0.125
P2	0.0	-4.4 ± 1.5 dB	0.000	-0.200

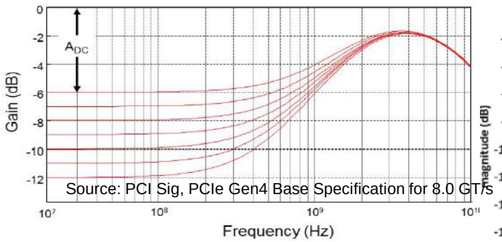


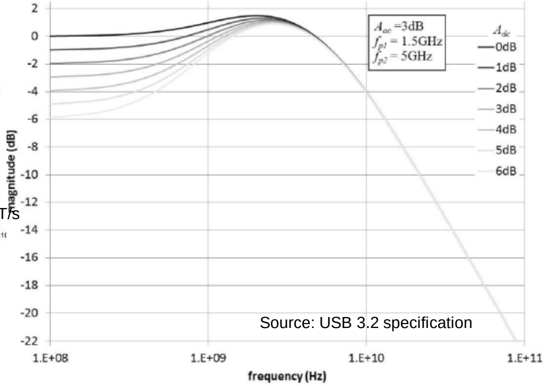
De-emphasis = $20 \log_{10} Vb/Va$
Preshoot = $20\log_{10} Vc/Vb$
Boost = $20\log_{10} Vd/Vb$

CTLE (CONTINUOUS TIME LINEAR EQUALIZATION)

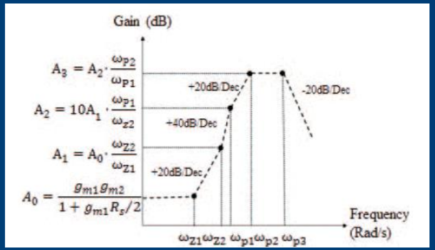
- ► CTLE is a continuous-time linear filter
  - – Inverts a channel's low pass characteristic
    - – attenuates low-frequency signal components
    - – amplifies higher frequency components
    - – filters off highest pole frequency
  - – Usually 1st order CTLE
  - – Specified by:
    - – a list of "zero frequencies" $f_{\mathrm{zero},m}$
    - – a list of "pole frequencies" $f_{\mathrm{pole},n}$
    - – and a DC gain A_{DC}
  - – Digitally realized as a real FIR filter

- ► Application
  - – Compensation of "simple" low-pass filtering effect of the channel



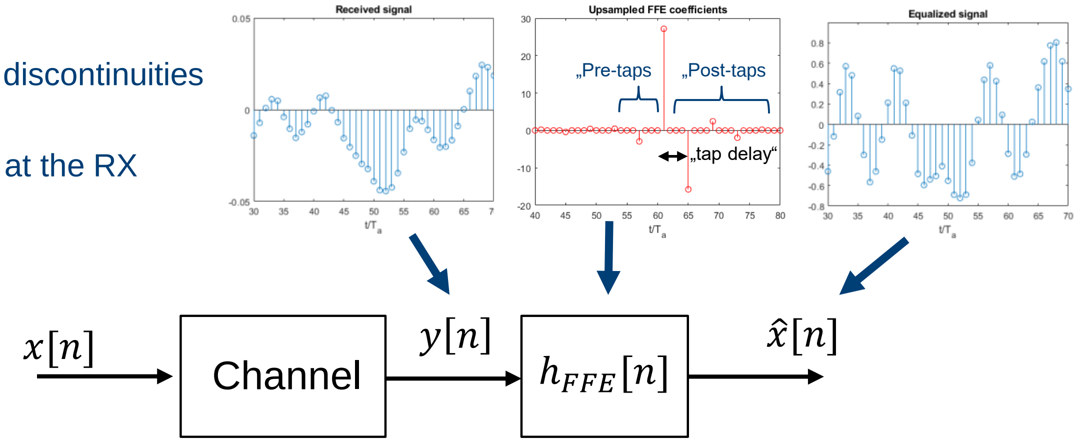


$$H_{\mathrm{CTLE}}(f) = A_{\mathrm{DC}} \cdot \frac{\prod_{m=1}^{M}\left(1 + j\frac{f}{f_{\mathrm{zero},m}}\right)}{\prod_{n=1}^{N}\left(1 + j\frac{f}{f_{\mathrm{pole},n}}\right)}$$



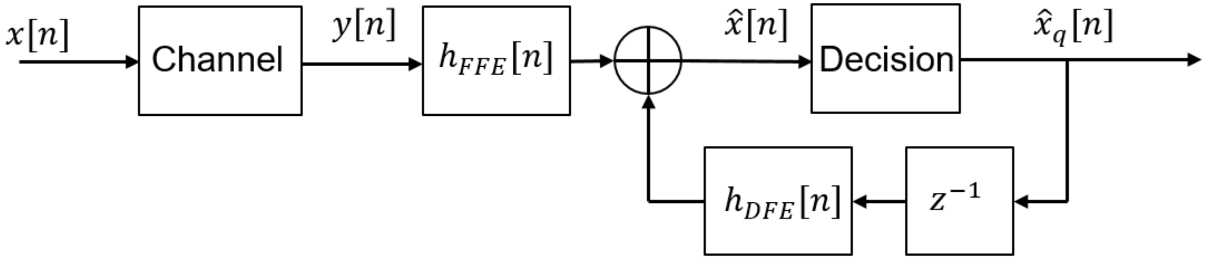
FFE (FEED-FORWARD EQUALIZER)

- Linear filter that creates similar to TX FFE a number of delayed versions of the input signal that are added back to the signal with the proper weights
- FIR filter works at symbol rate f_s (one tap per symbol), or at an integer multiple of it
  - for analysis at the oscilloscope, the FFE taps are up-sampled internally and applied to the waveform.
  - more taps are available than with TX FFE
- Application:
  - can reduce effects caused by to impedance discontinuities and reflections
  - be careful with amplifying input noise power at the RX (boosting high frequency noise)



DFE (DECISION-FEEDBACK EQUALIZER)

- DFE is nonlinear and has feedback loop that uses decisions on previous symbols to equalize the current symbol
  - "Decision" means finding the closest constellation point to each equalized symbol
- DFE is often combined with CTLE / FFE
- DFE required a CDR
- Application
  - DFE is better at compensating zeros or large dips in the frequency response of the channel without enhancing the noise. (For standard cables with a gradually falling frequency response, the advantage of a DFE is small)



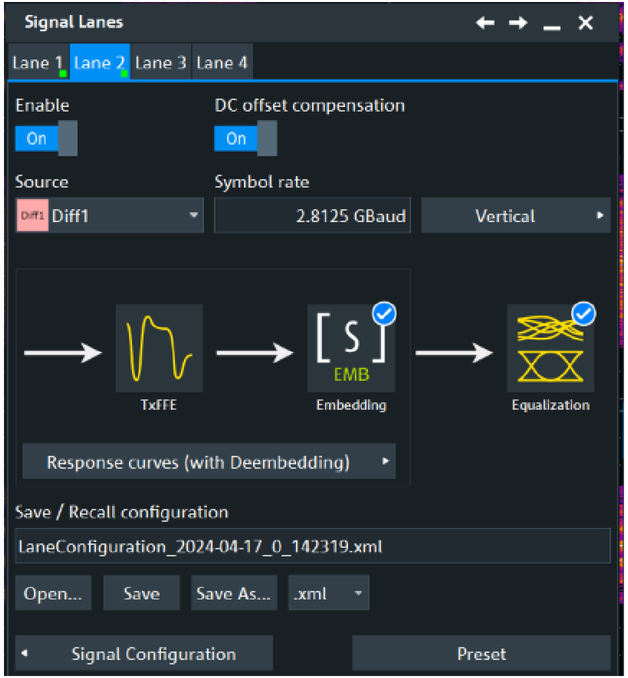
SUMMARY OF EQUALIZER TYPES

Feature	CTLE	FFE	DFE
Type	Linear	Linear	Nonlinear
Effectiveness at removing ISI	Moderate	Good	Excellent
Effectiveness at noise	Poor	Poor	Good

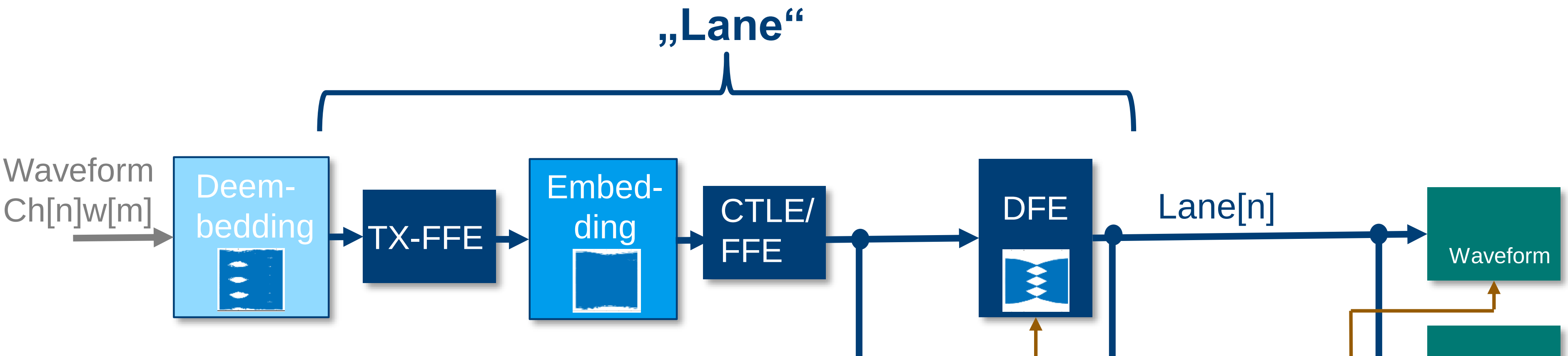
R&S IMPLEMENTATION: RTx-K126 EMBEDDING & EQZ

RTX-K126 EMBEDDING AND EQUALIZATION OPTION
AT A GLANCE

- **Options:** RTO/RTO6/RTP-K126
- **Functions:**
  - Embedding:
    - up to 5 user-configurable components
  - Equalization:
    - Pre-distortion at TX via FFE filter
    - Combine CTLE, FFE or DFE filters at RX
    - Training for FFE or FFE+DFE tap coefficients
  - Full PAM-N support w/ option RTx-K135
- **User Benefits:**
  - High flexibility in defining a signal path
  - Pre-defined filter coefficients for common interface standards
  - Advanced signal integrity analysis tools incl. adv. eye and adv. jitter

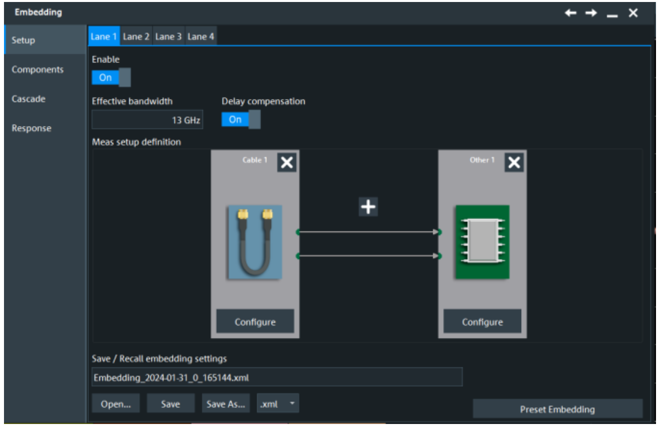


SYSTEM VIEW

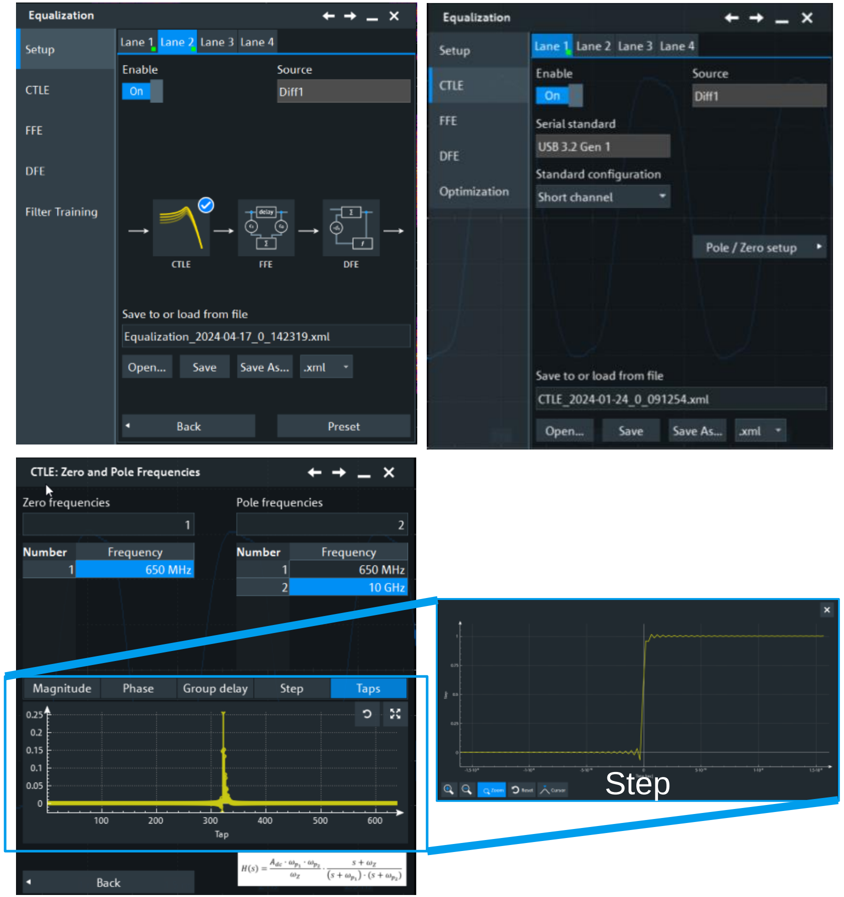

„Lane“
Waveform
Ch[n]w[m]
Deem-
bedding
TX-FFE
Embed-
ding
CTLE/
FFE
DFE
Lane[n]
Clock
SW
CDR[n]
Lane[n](pre-DFE)
SW
CDR[n]
Lane[n]
Waveform
Data eye
Jitter

EMBEDDING
R&S APPROACH

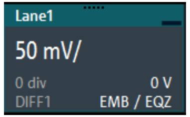
- Define up to 5 components
  - Configured by S-parameters
    - Extrapolation to DC
    - Extrapolation from max provided freq. to 0.5*sampling frequency (keep magnitude constant and phase linear)
- Support of 2-port and 4-ports depending on selected source
- Automatically designed FIR filter
- Similar GUI and features as for De-embedding
- Embedding processing in post-processing



EQUALIZATION
R&S APPROACH

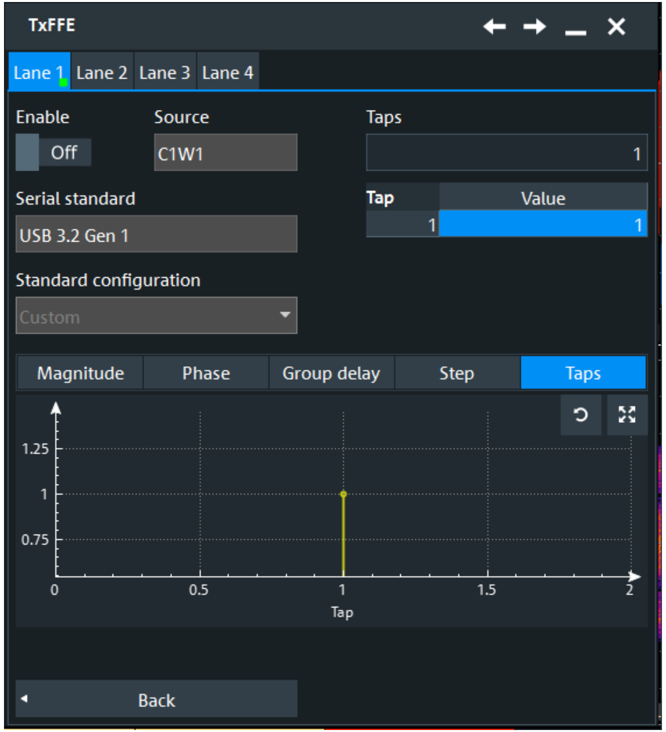


- **Easy Setup**
  - Pre-configuration for many interface standards
  - Define your own Taps
  - Filter training for “FFE” and “FFE+DFE”
  - Enable dedicated Equalizer first, then Enable overall Equalization
  - Save / Load of Lane Equalization setup
- **High confidence**
  - Filter diagram view (Magnitude, Phase, Group delay, Step, Taps)
- **High Accuracy**
  - Processing in all filters in SW post-processing
- **Good overview**
  - Emb and Eqz in Signal icons



TX-FFE
R&S APPROACH

- Pre-configuration for many interface standards
- Define up to 4 Taps
  - 1 pre-cursor, up to 2 post-cursor

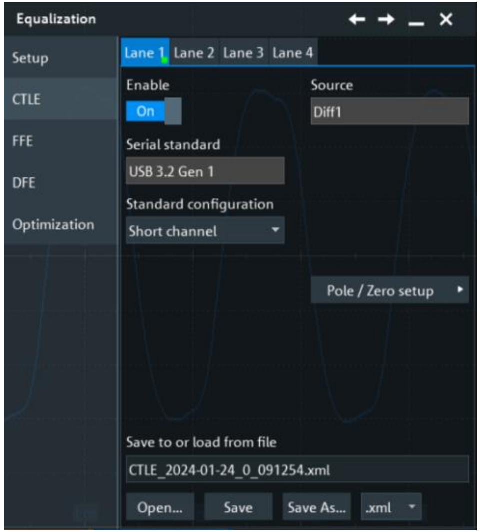


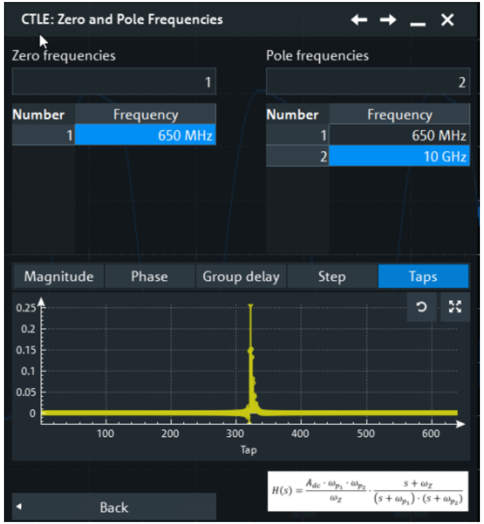
CTLE
R&S APPROACH

- ► Pre-configuration for many interface standards
- ► Define your own filter
  - – Zero frequencies (max 6)
  - – Pole frequencies (max 6)
  - – DC gain

$$H(s) = \frac{A_{dc} \cdot \omega_{p_1} \cdot \omega_{p_2}}{\omega_Z} \cdot \frac{s + \omega_Z}{(s + \omega_{p_1}) \cdot (s + \omega_{p_2})}$$

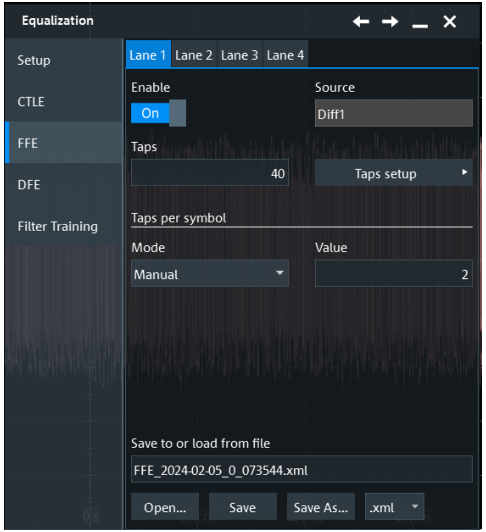
- ► Save / load of individual filter settings

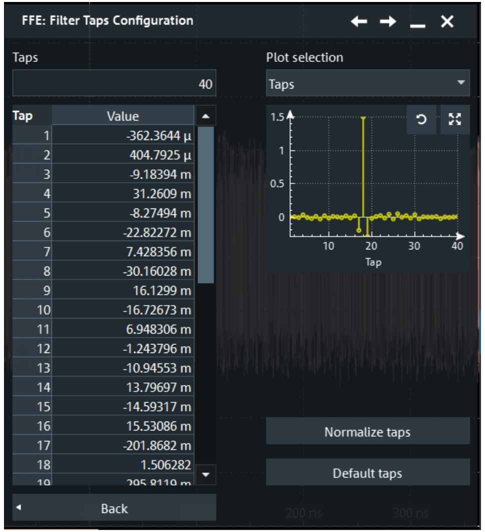




FFE
R&S APPROACH

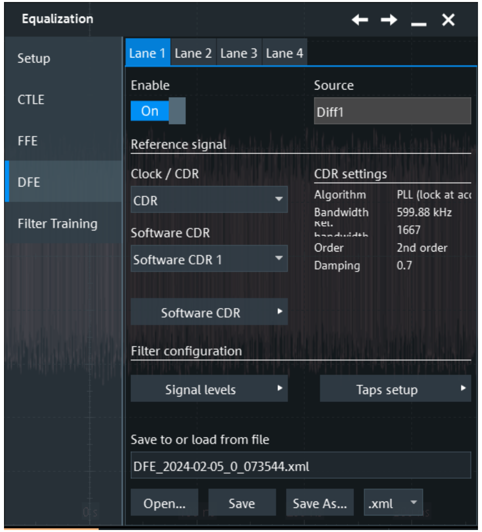
- ▶ Pre-configuration for many interface standards
- ▶ Define up to
  - – **Number of taps:** 1 .. 40
  - – **Number of taps per symbol:** 1 .. 8
  - – **FFE delay:** between 0 .. #FFE taps – 1 (only in Training configuration)
- ▶ Filter Training for FFE
- ▶ Save / load of individual filter settings

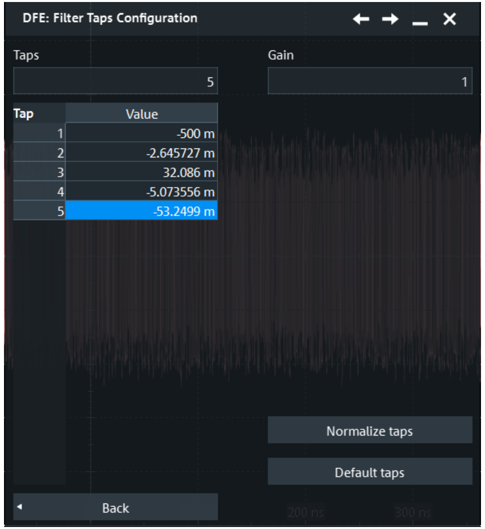




DFE
R&S APPROACH

- Pre-configuration for many interface standards
- DFE requires CDR
- Tap setup:
  - **Number of taps:** integer between 1 and 5
  - **Tap limits:** per DFE tap or globally a min/ max limit for the DFE training can be defined **(**-1 .. 1)
    (for training configuration)
- Filter training: FFE + DFE
- Save / load of individual filter settings

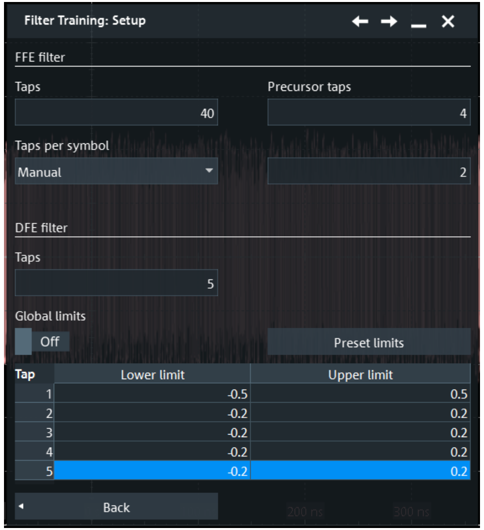




FFE/ DFE TRAINING

▶ MMSE method to train the EQZs for a given waveform

1. Filter selection: FFE or FFE+DFE
2. Setup Training: define Equalizer details
3. Normalize gain
4. Start training
5. Review Results
6. Apply tap values



PAM SIGNALS SUPPORT

DEMO

SUMMARY

SUMMARY

- Emulation of signal channel and equalizer is required for thourough testing
- R&S K126 Embedding & Equalization option:
  - high flexibility to define a signal path
  - built cascade of equalizer filter
  - predefined filter for common technologies
- Powerful analysis tool for Eye and Jitter & Noise analysis
- PAM-N support

Find out more

www.rohde-schwarz.com

ROHDE&SCHWARZ

Make ideas real