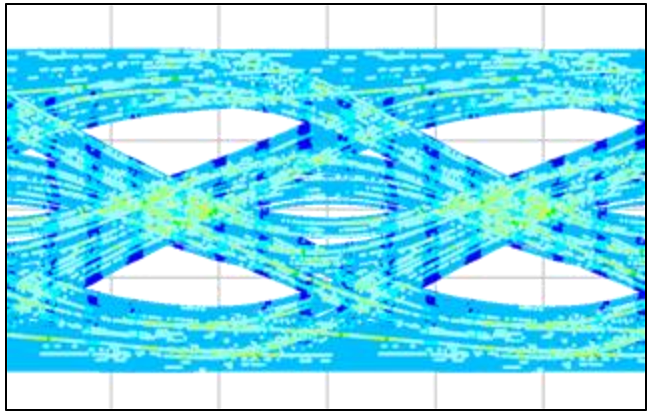
KEYSIGHT

Signal Integrity in Action: Practical Insights for High-Speed Design

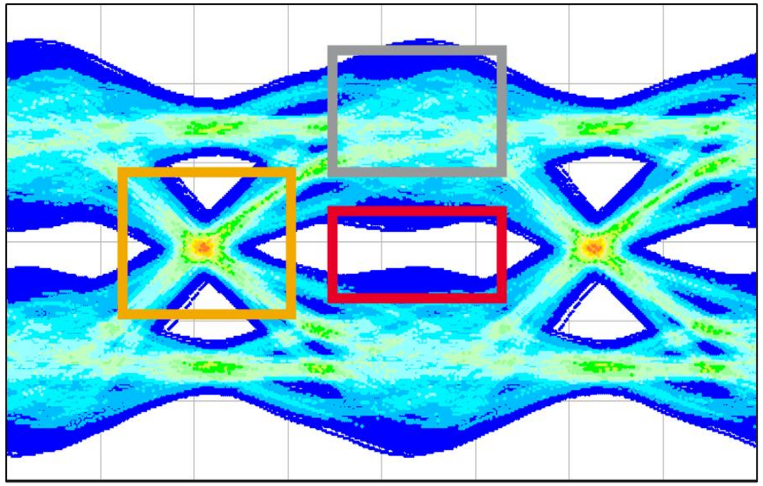
[Your Name | Title]

Agenda



How to solve **ALL** the signal integrity problems

Identifying the root causes of the problem

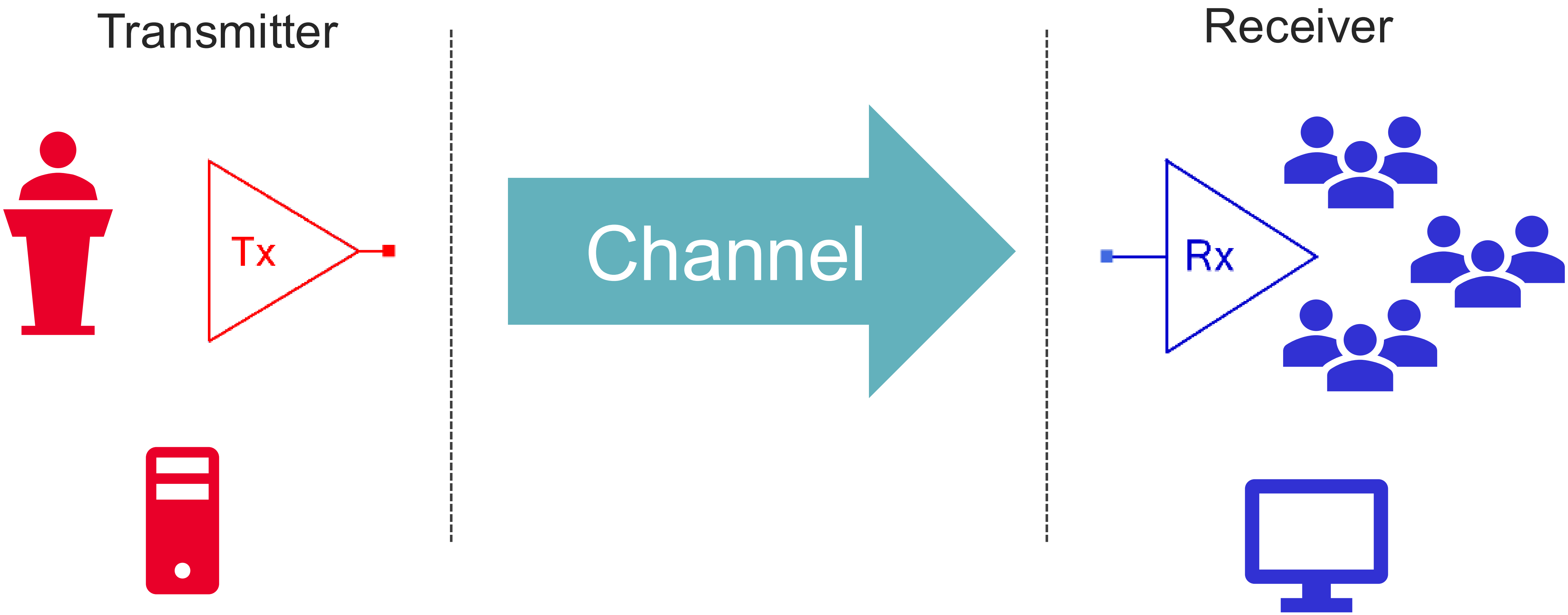


1. Signs of reflection
2. Signs of crosstalk
3. Signs of frequency-dependent loss

How Keysight EDA helps make your signal integrity analysis easier

Signal Integrity Overview

Signal Integrity Is All Around Us



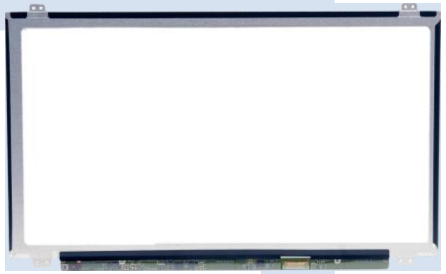
Signal Integrity in Digital Communication Channel

CPU (Tx)

Graphic card

Cable

Onboard video processor



LED display (Rx)

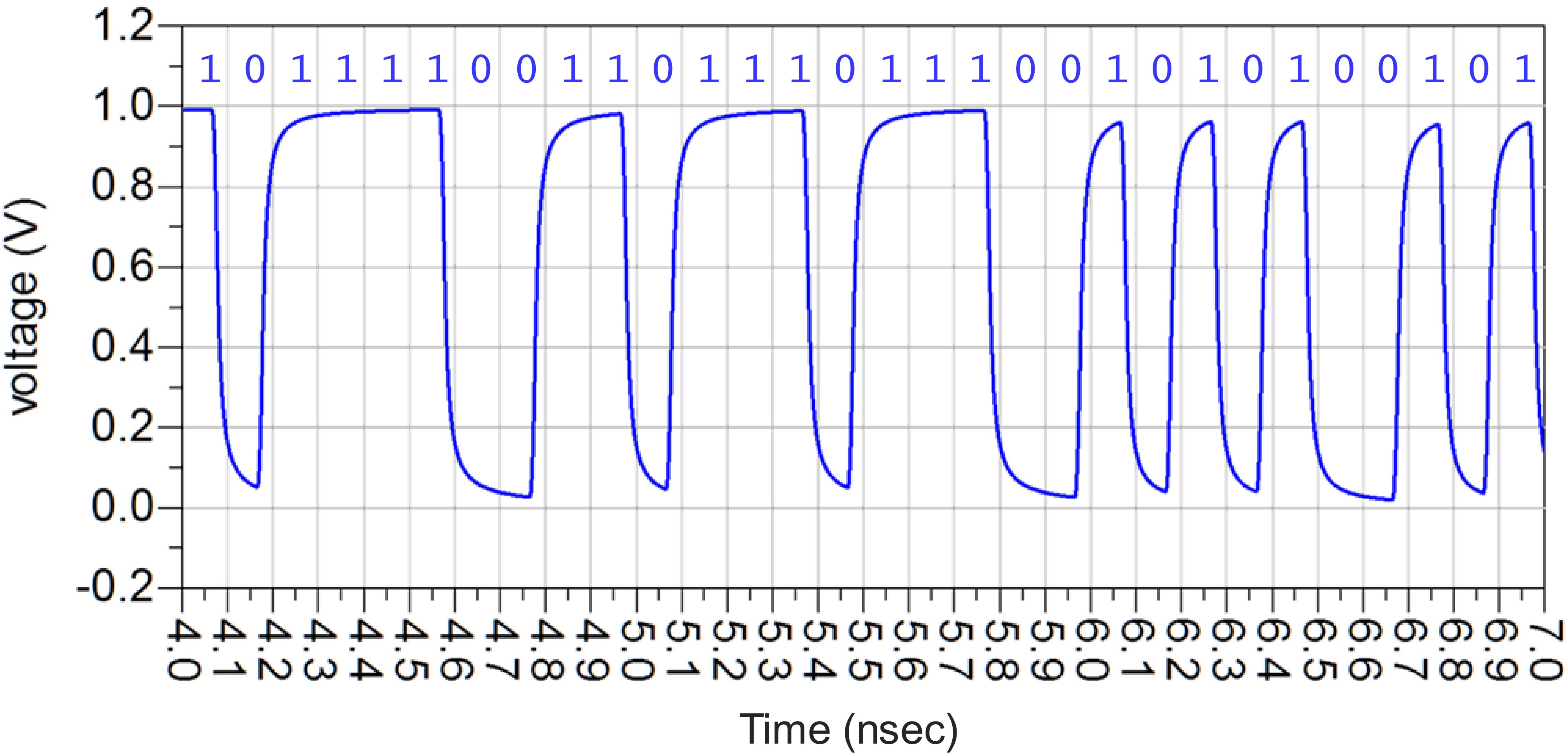
Interconnects (channel)

> “ Signal integrity is about the problems interconnects introduce and how to avoid them.
>
> – Dr. Eric Bogatin

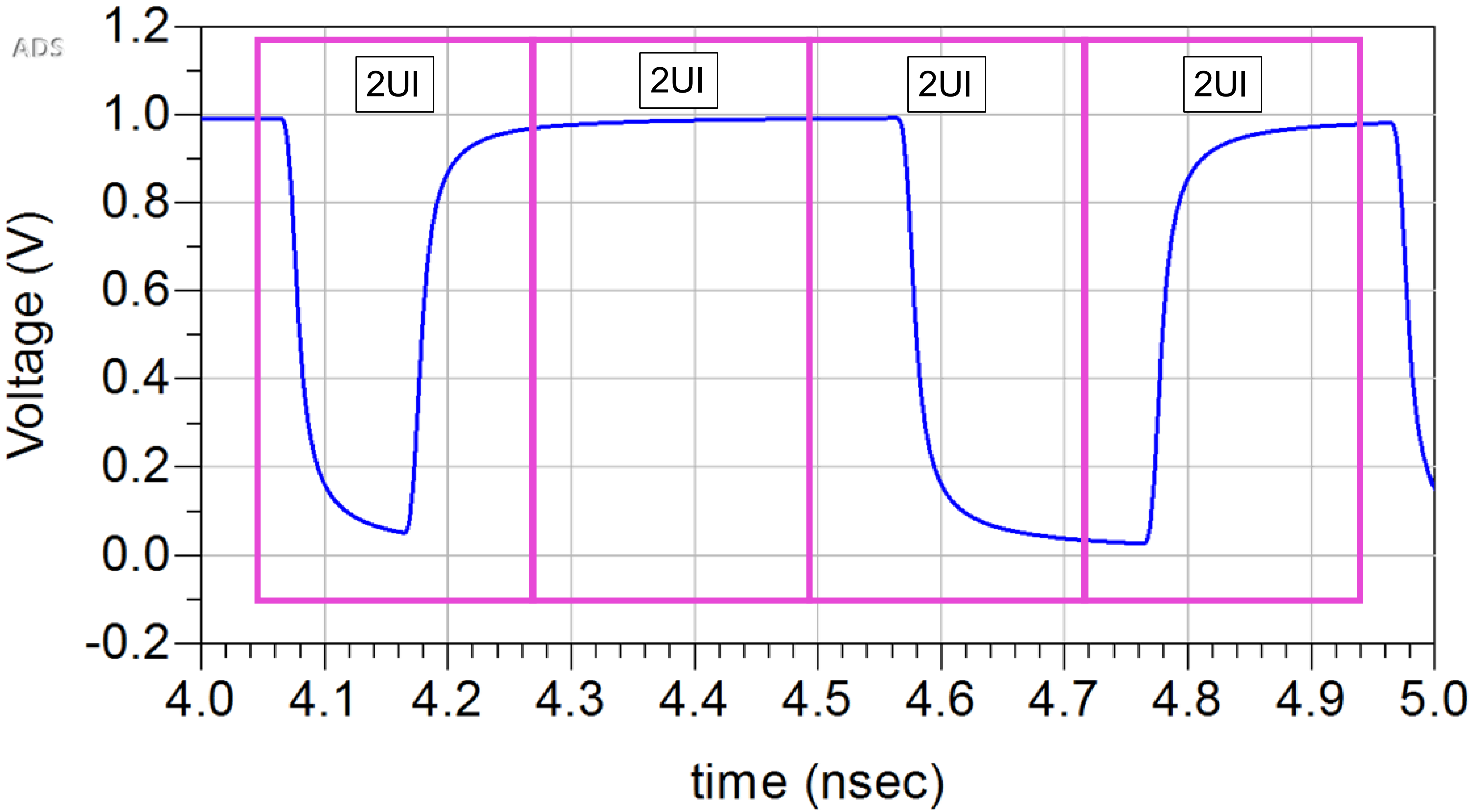
Eye Diagram From PRBS as the Main Diagnostic Tool

<u>PRBS: Pseudo-Random Binary Sequence</u>
By sending PRBS, we are testing how the channel affects all the possible transmitted data patterns.

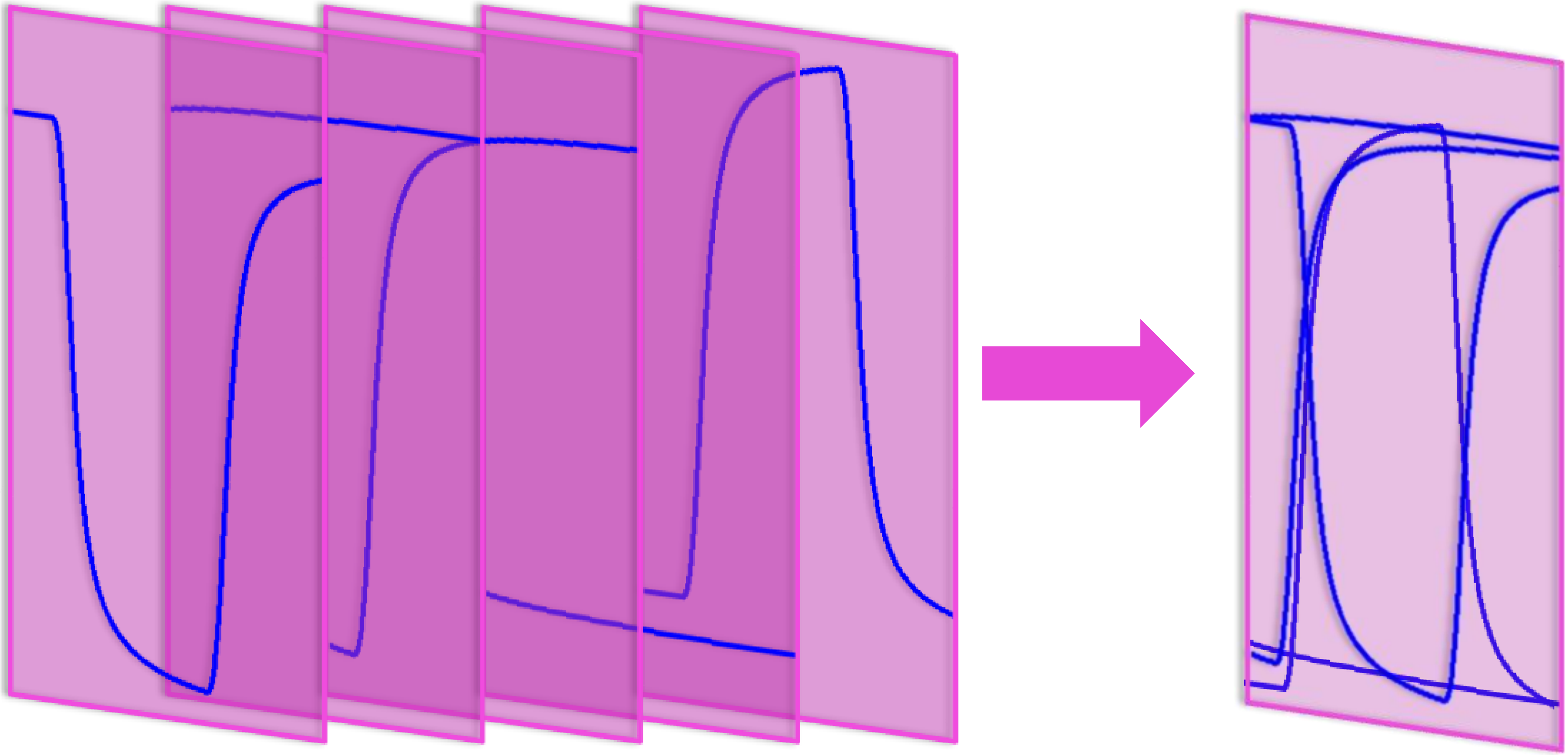
<u>Key terms:</u>
Data Rate: 10 Gbps
Unit Interval: 1/Data Rate (0.1 nsec)



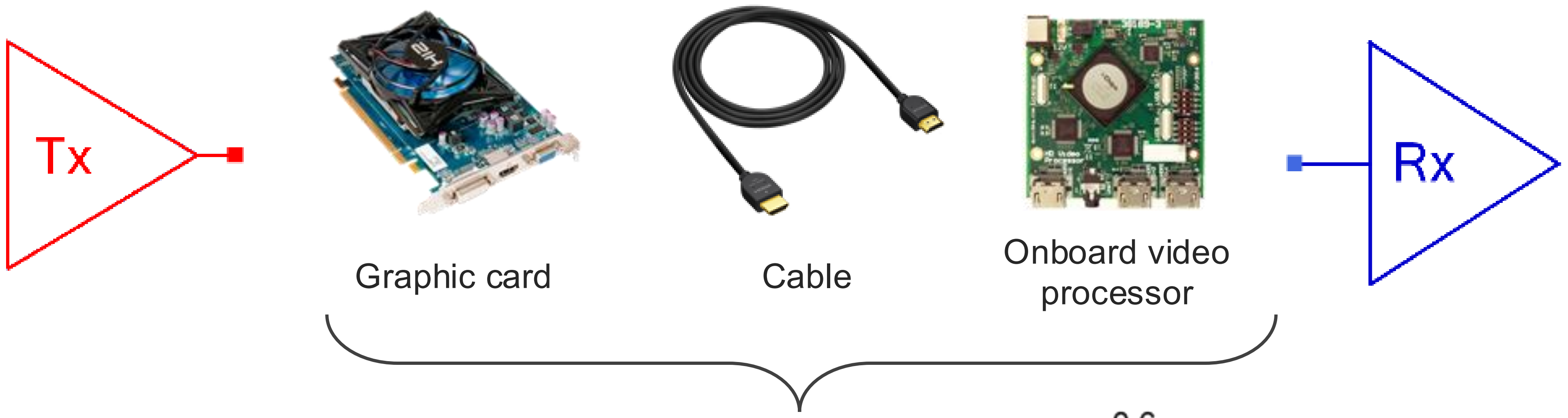
Partition PRBS Pattern by Unit Intervals

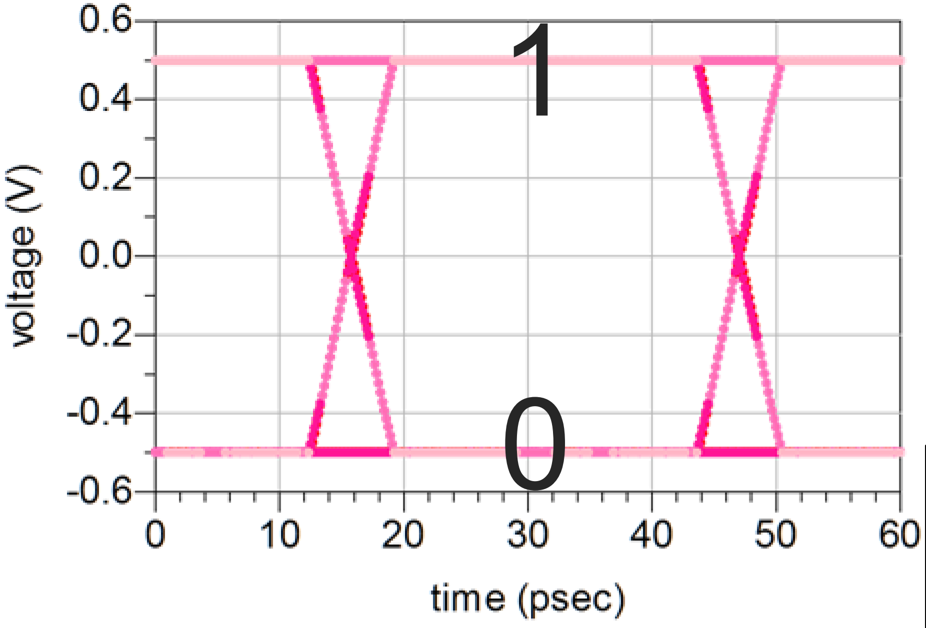


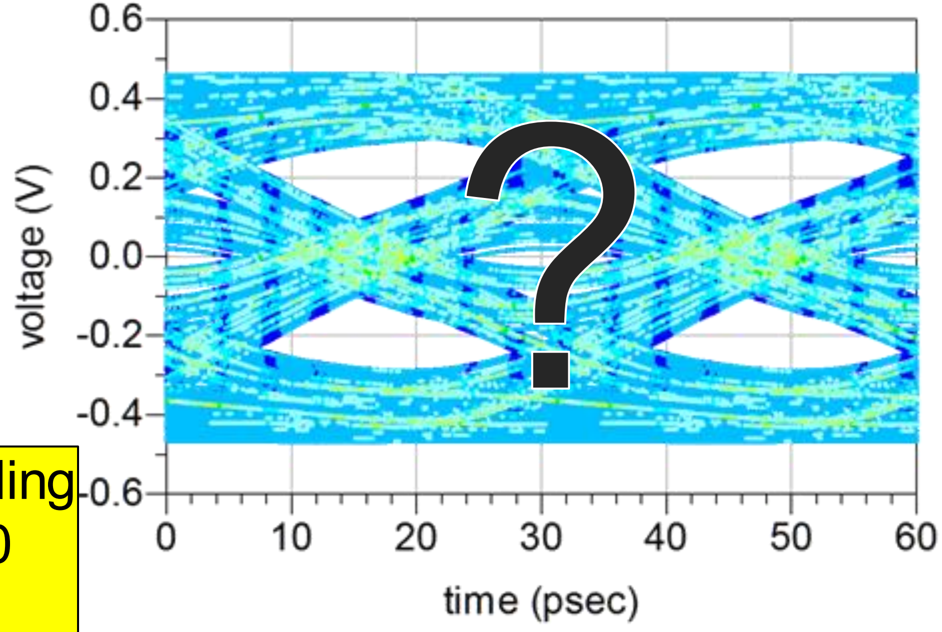
Overlay Partitioned PRBS Slices to Create the Eye



Use Eye Diagram Simulation to Evaluate a Channel





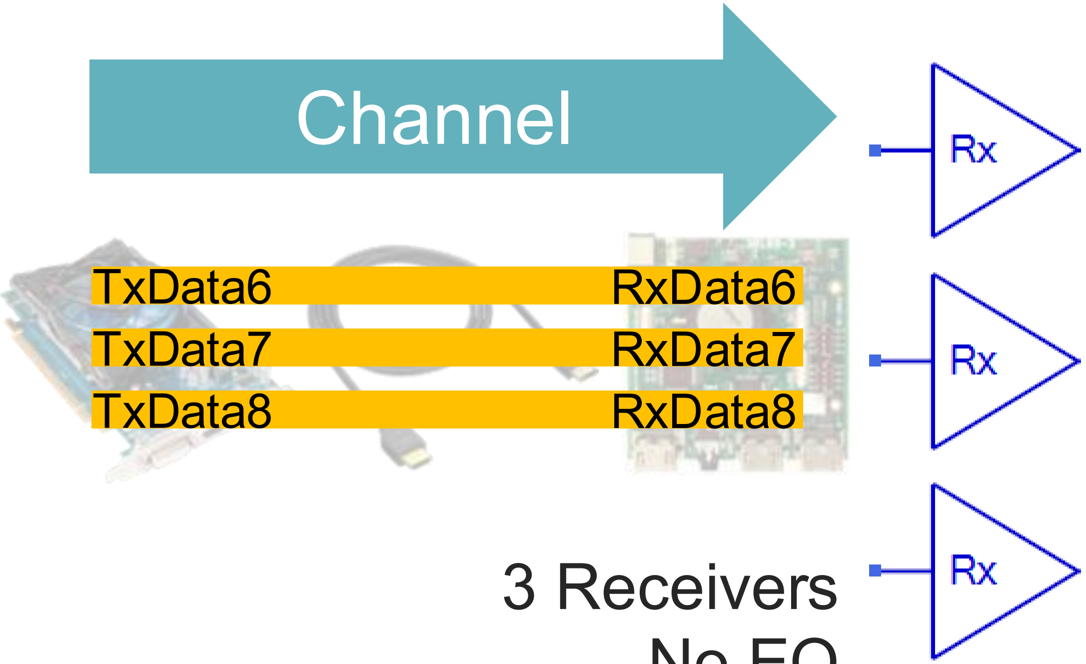


A closed eye indicates a failing channel because 1 and 0 cannot be distinguished

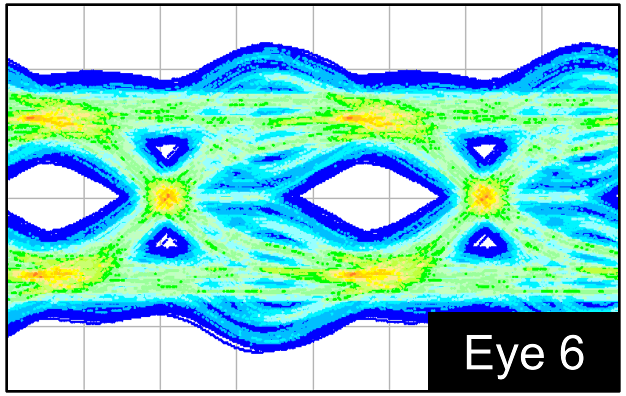
Gain SI Insights from the Broken Channel

Qualitative Assessment of the Eye Diagram Is Not Positive

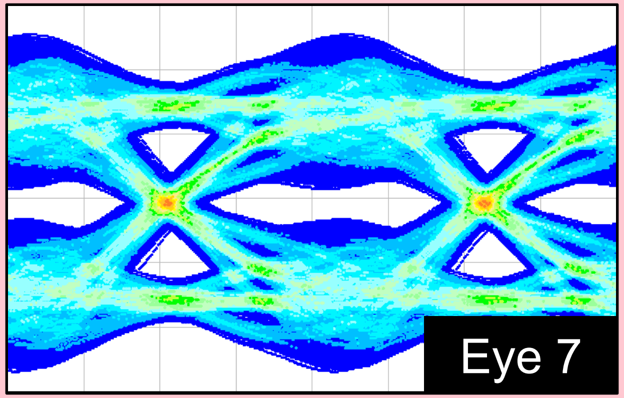
3 Transmitters
24 GT/s



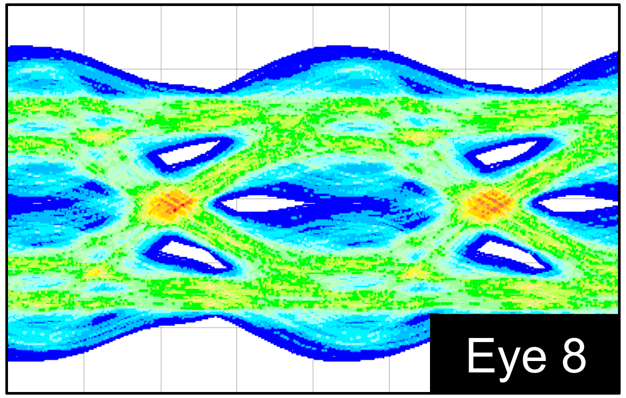
3 Receivers
No EQ
Terminated



Not good



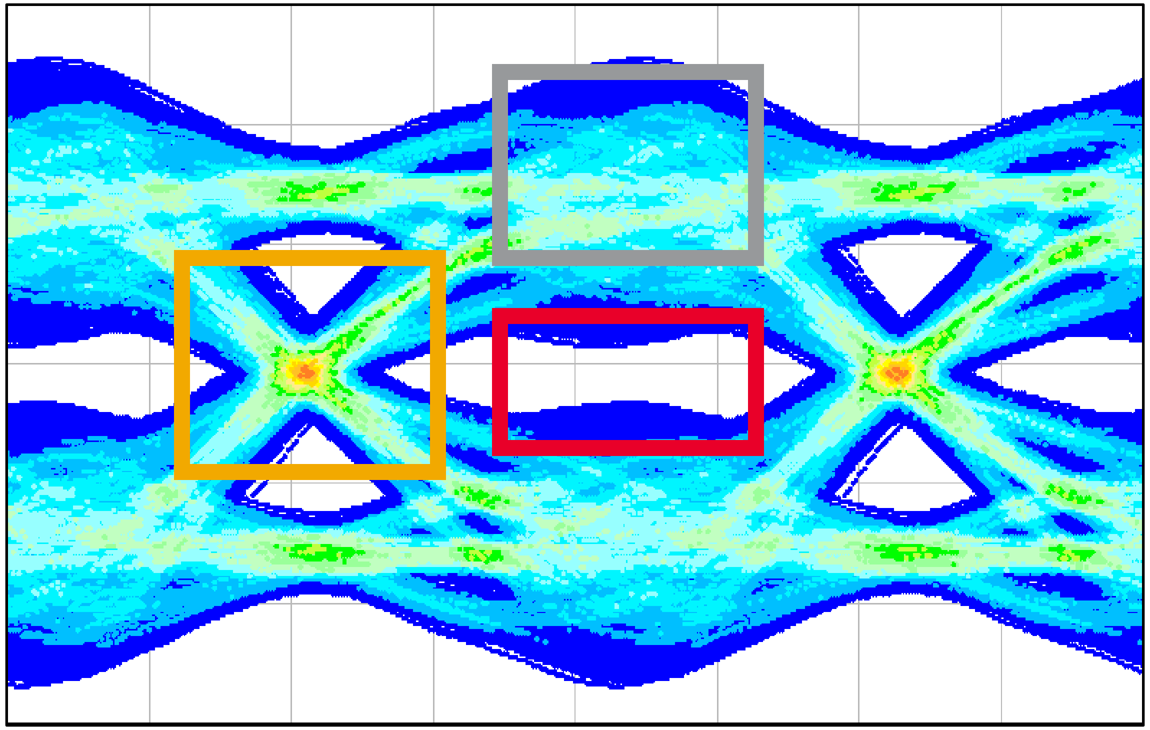
Bad



Very bad

Eye Shows Reflection, Crosstalk, and Considerable Loss

Received eye at RxData7 without equalization



1. Signs of reflection
2. Signs of crosstalk
3. Signs of frequency-dependent loss

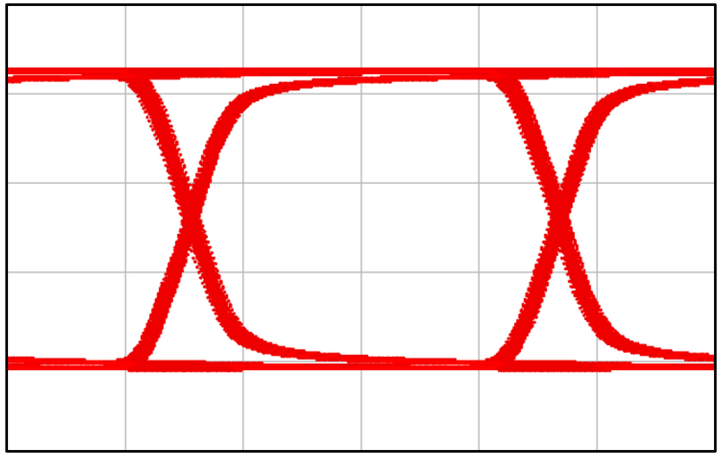
Rule Number 9: Anticipate Before You Measure or Simulate*

*E. Bogatin, "Bogatin's 20 Rules for Engineers," Signal Integrity Journal, [Online]. Available: https://www.signalintegrityjournal.com/blogs/4-eric-bogatin-signal-integrity-journal-technical-editor/post/1539-bogatins-20-rules-for-engineers

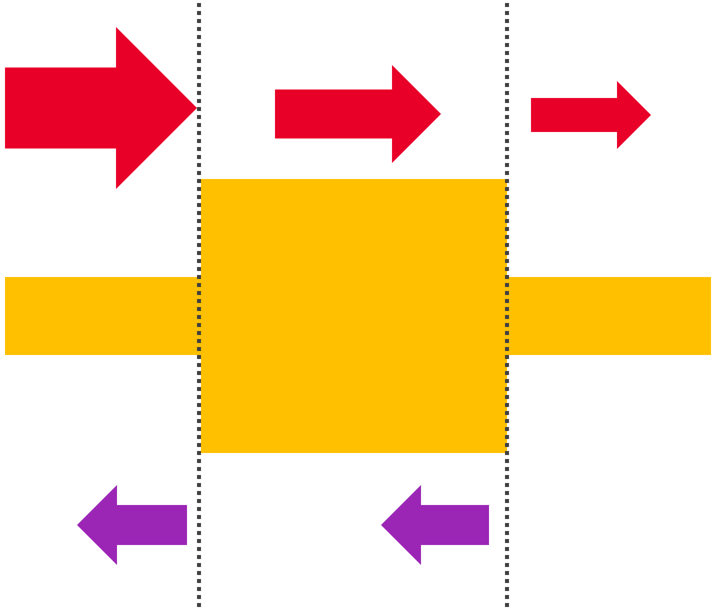
KEYSIGHT

Reflection Degrades the Amplitude of the Transmitted Signal

Moderate loss channel
With no discontinuities



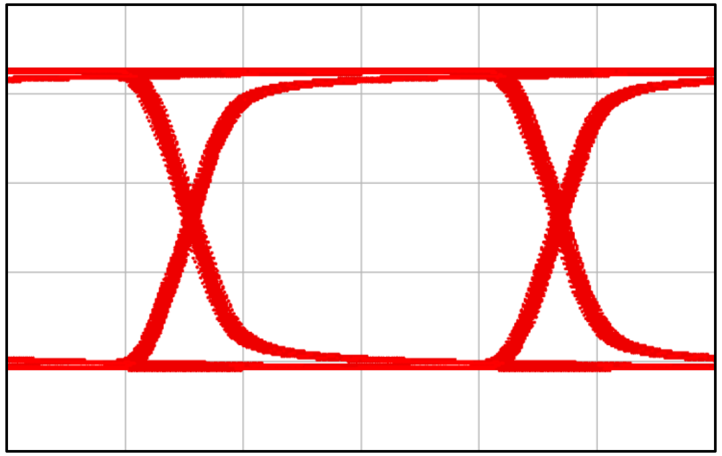
Moderate loss channel
With impedance discontinuities



One expects the received amplitude to be smaller than intended because part of the transmitted amplitude is reflected.

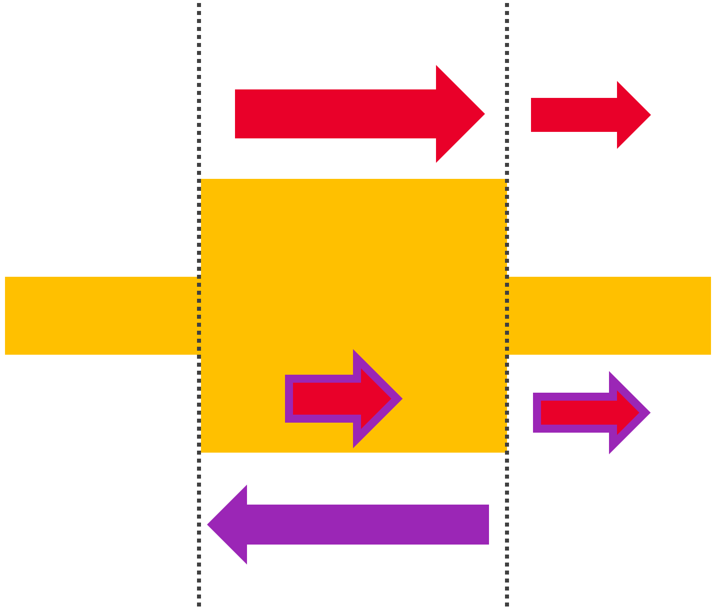
Reflections in the System Deform the Received Eye Shape

Moderate loss channel
With no discontinuities



Moderate loss channel

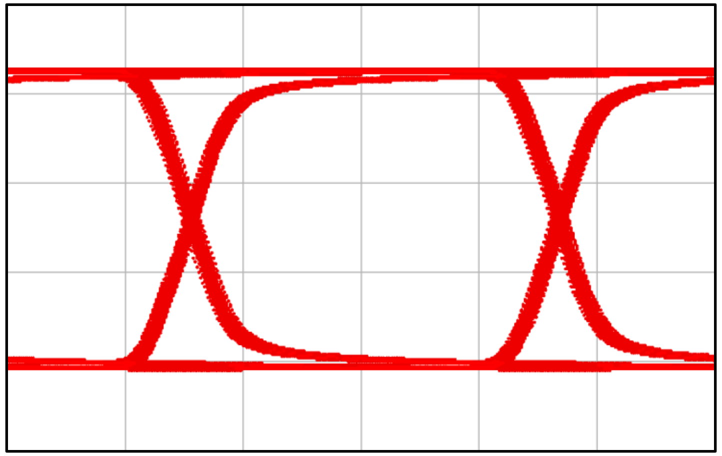
With impedance discontinuities



One expects the received eye shape to be deformed by the multiple reflections in the system.

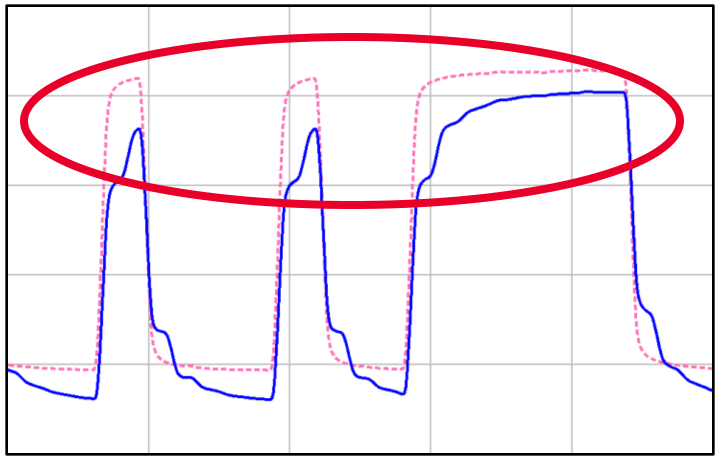
Reflections in the System Deform the Received Eye Shape

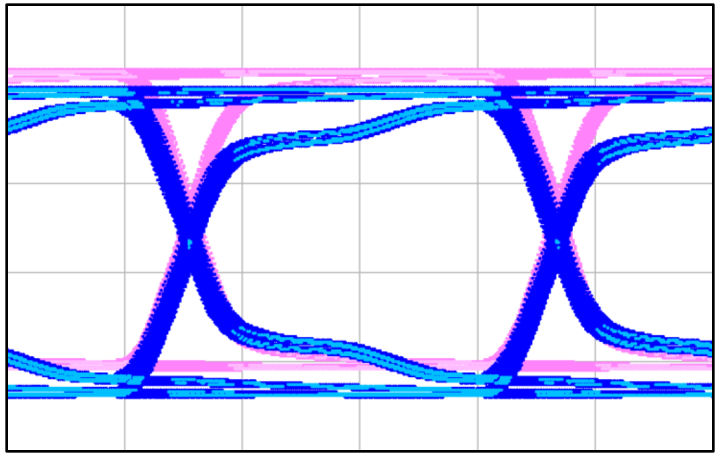
Moderate loss channel
With no discontinuities



Moderate loss channel

With impedance discontinuities



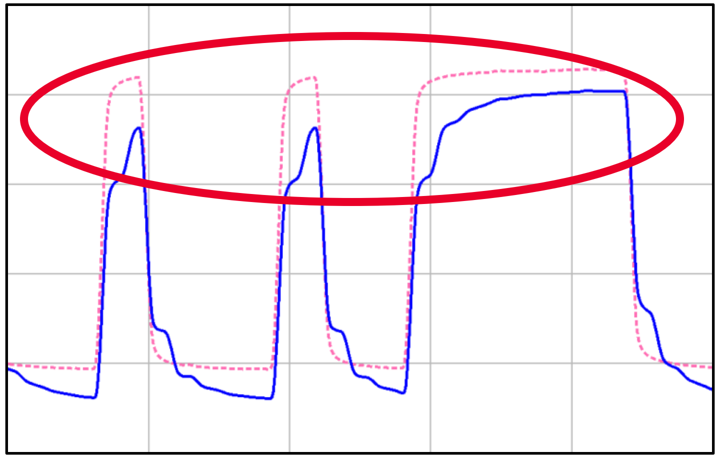


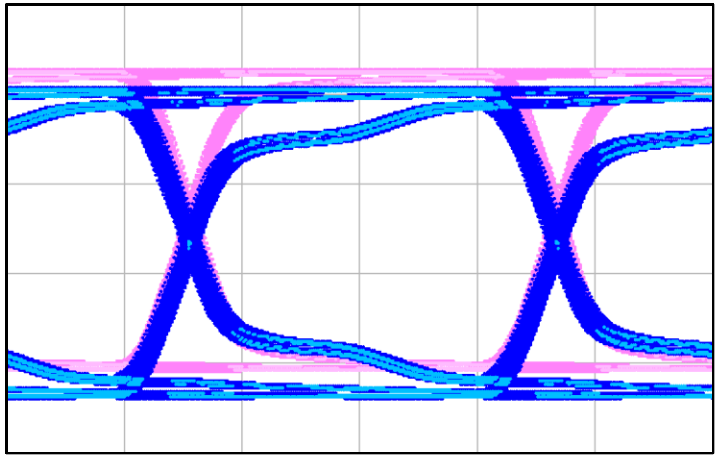
As expected, impedance discontinuity degrades both the eye amplitude and shape.

Fix Eye Closure by Removing Impedance Discontinuities

Moderate loss channel

With impedance discontinuities

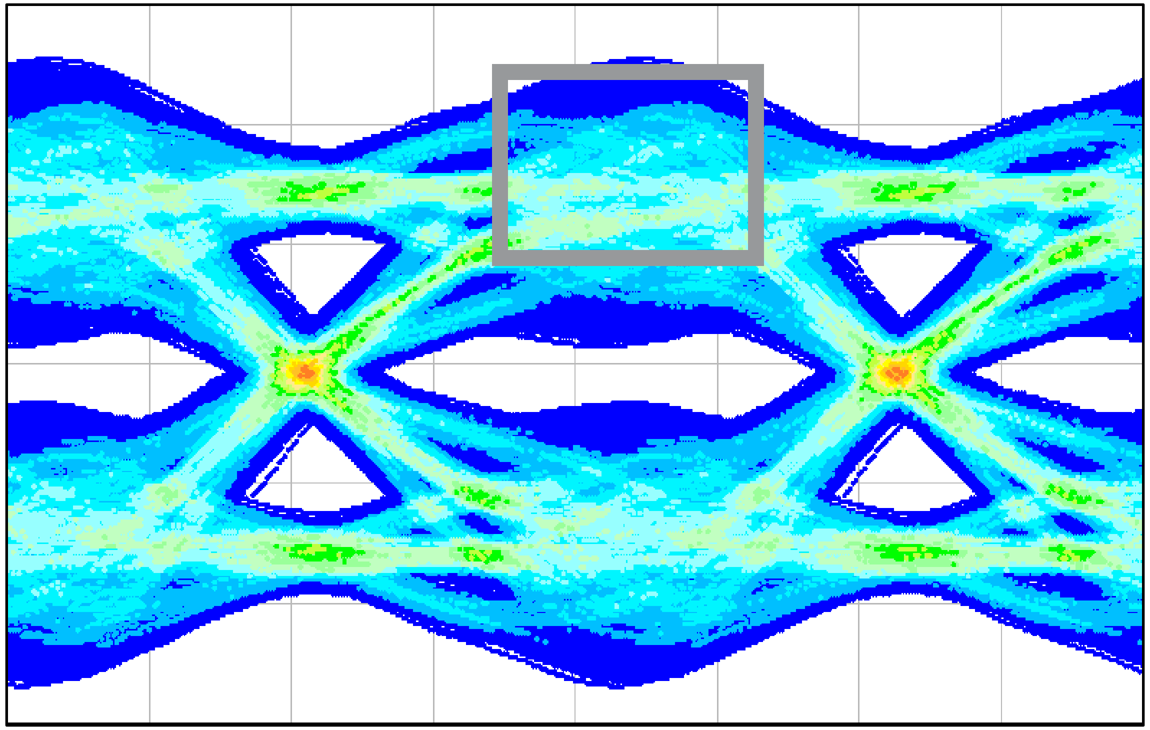




Signs in the Eye	Root cause	Fixes
• Deformed eye shape • Reduced eye amplitude	Impedance discontinuities	• Locate impedance discontinuity and match it with channel impedance

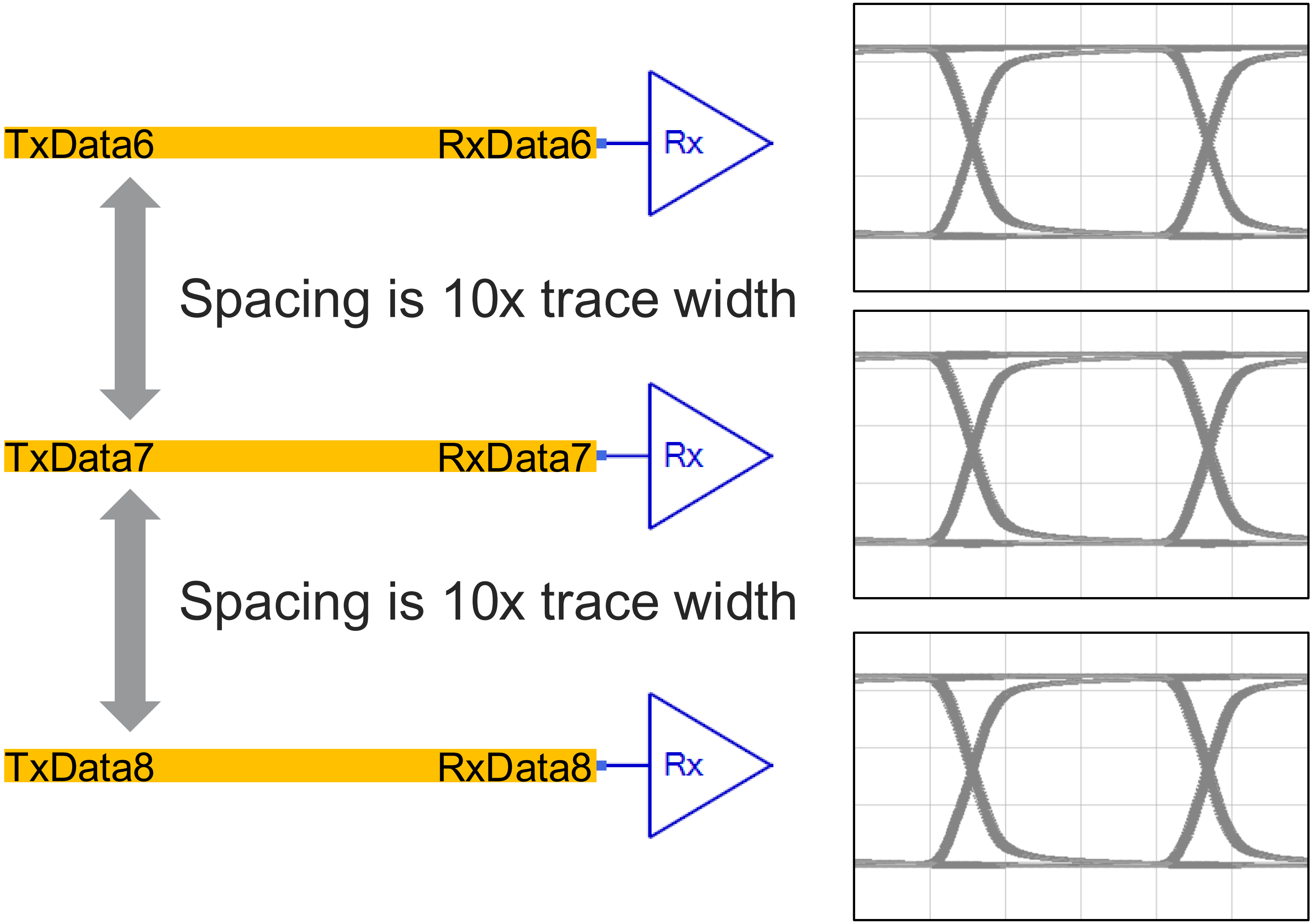
Eye Shows Reflection, Crosstalk, and Considerable Loss

Received eye at RxData7 without equalization



2. Signs of crosstalk

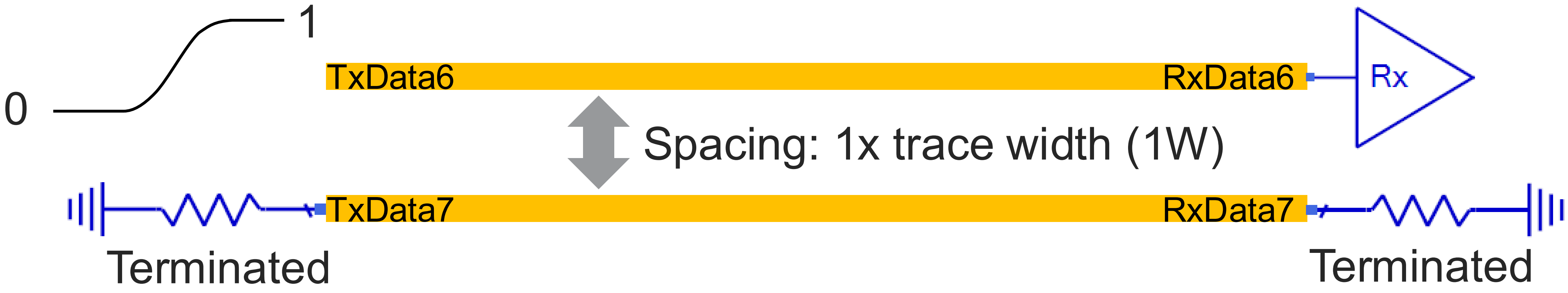
Eyes Are Open When the Channel Are 10 Trace-width Apart

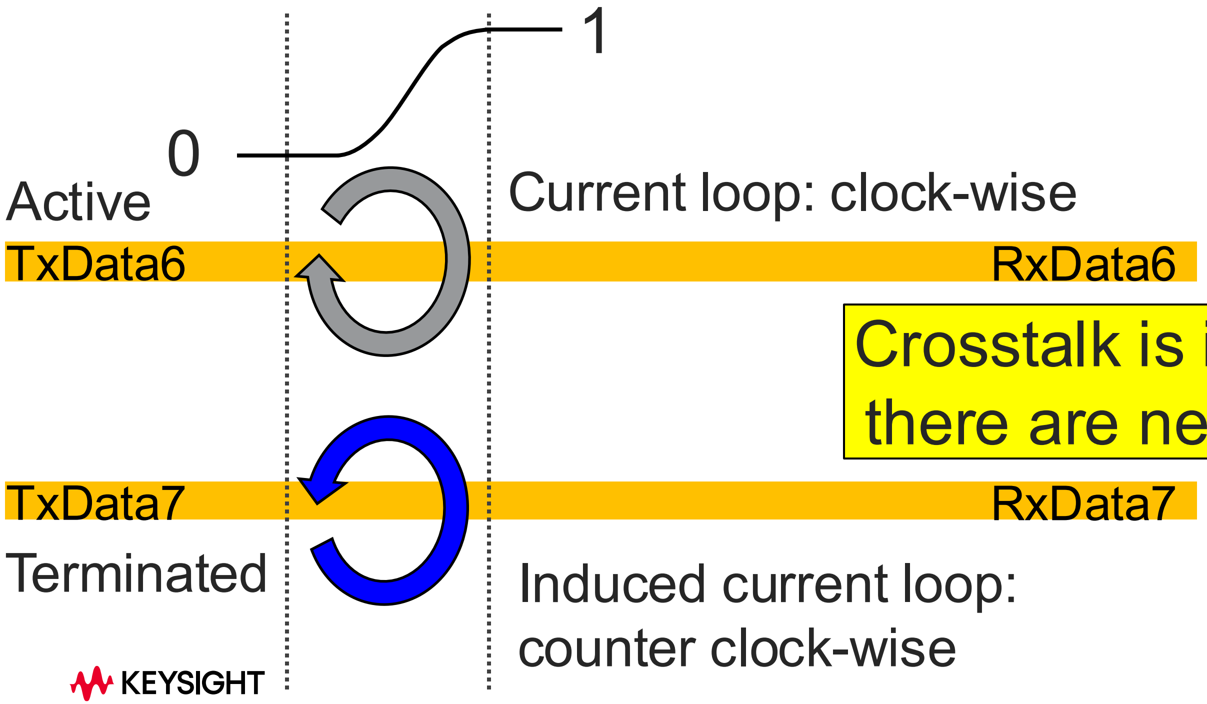


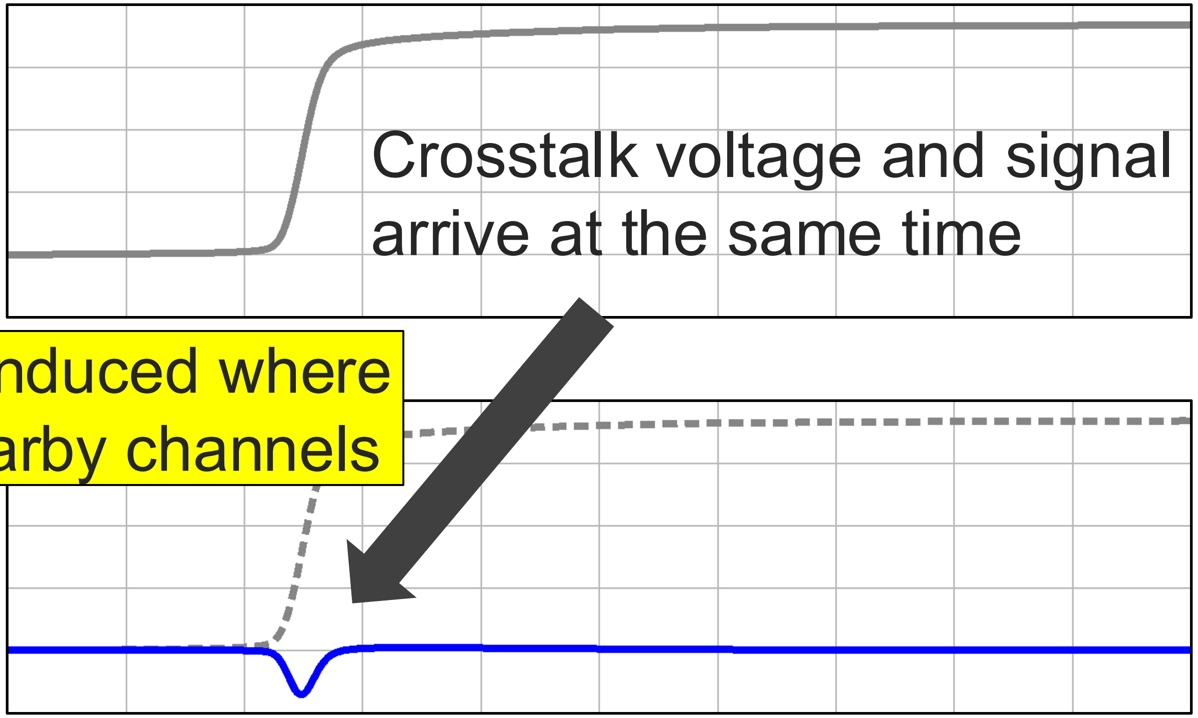
Eyes are open when the channels are 10 trace width apart.

There is no crosstalk when the channels are far from each other.

Expect Far-end Crosstalk When Channels Are Close

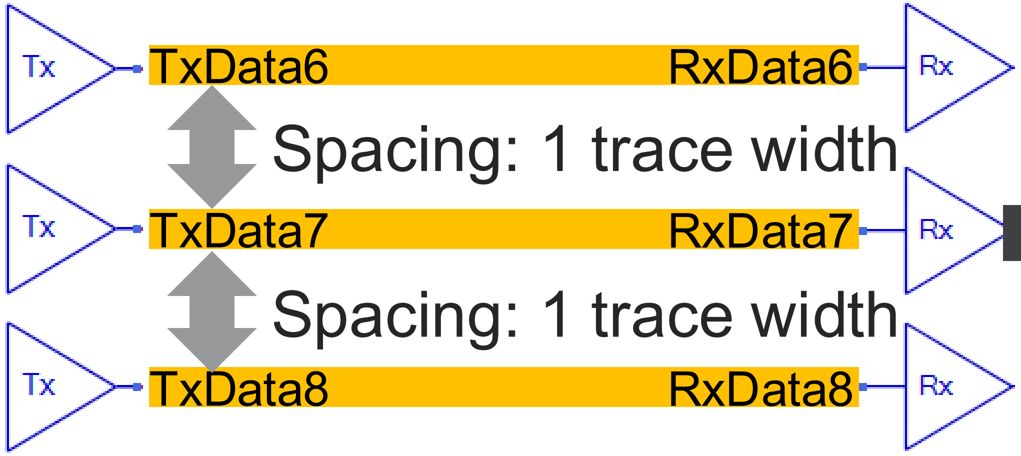




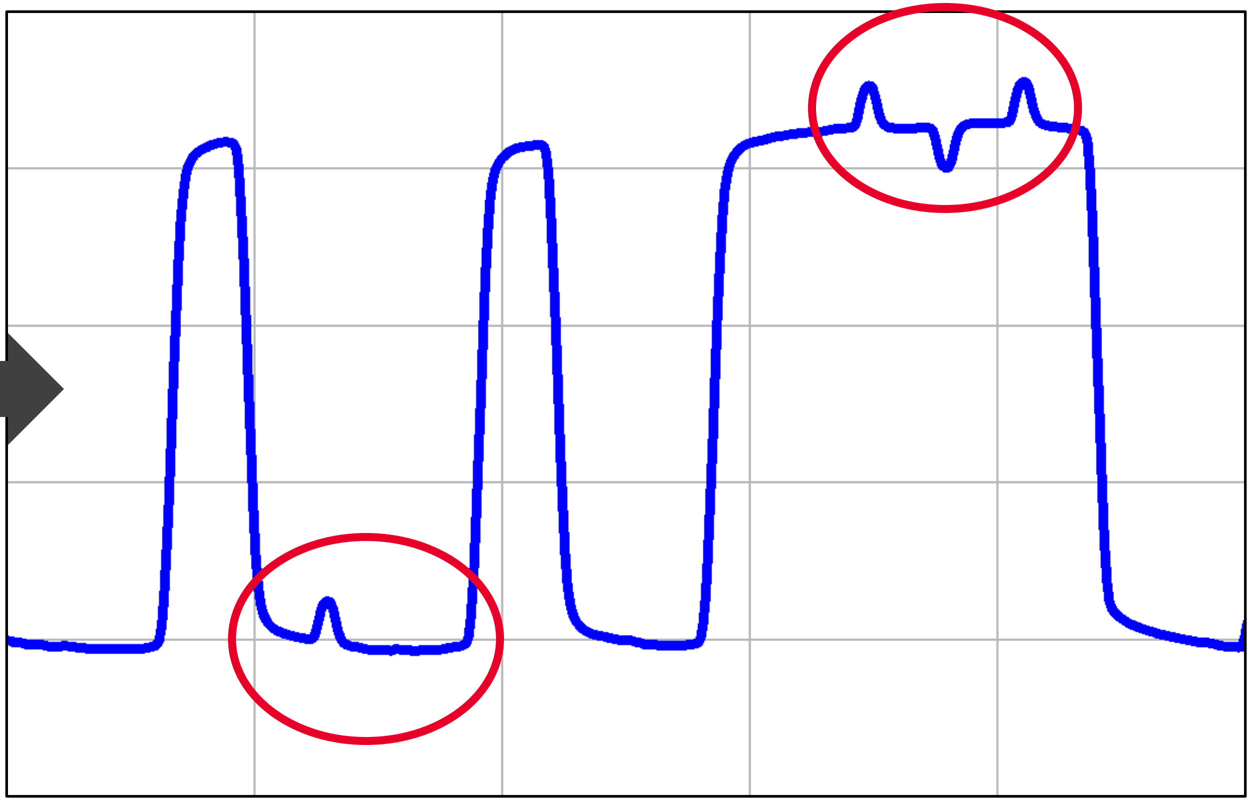


Far-end Crosstalk Signatures in the Waveform

Channels are close and they are all active

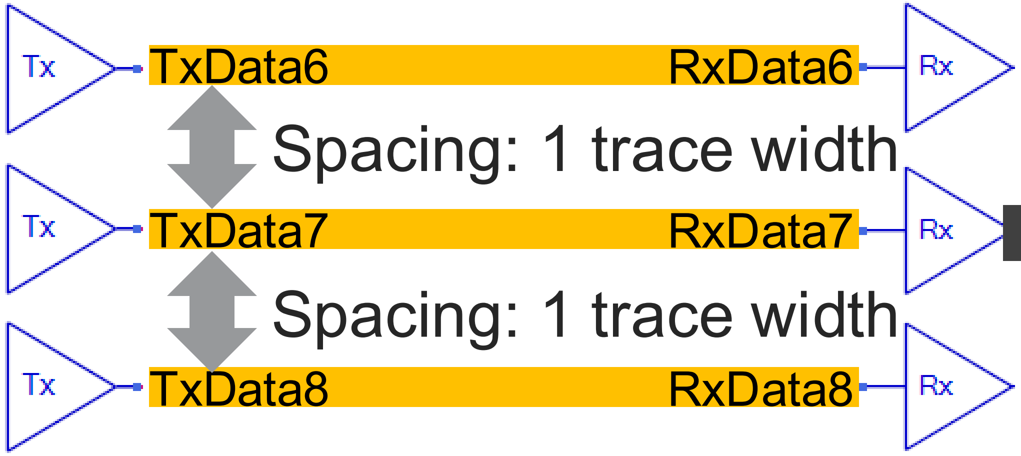


Crosstalk voltage signature in RxData7's waveforms

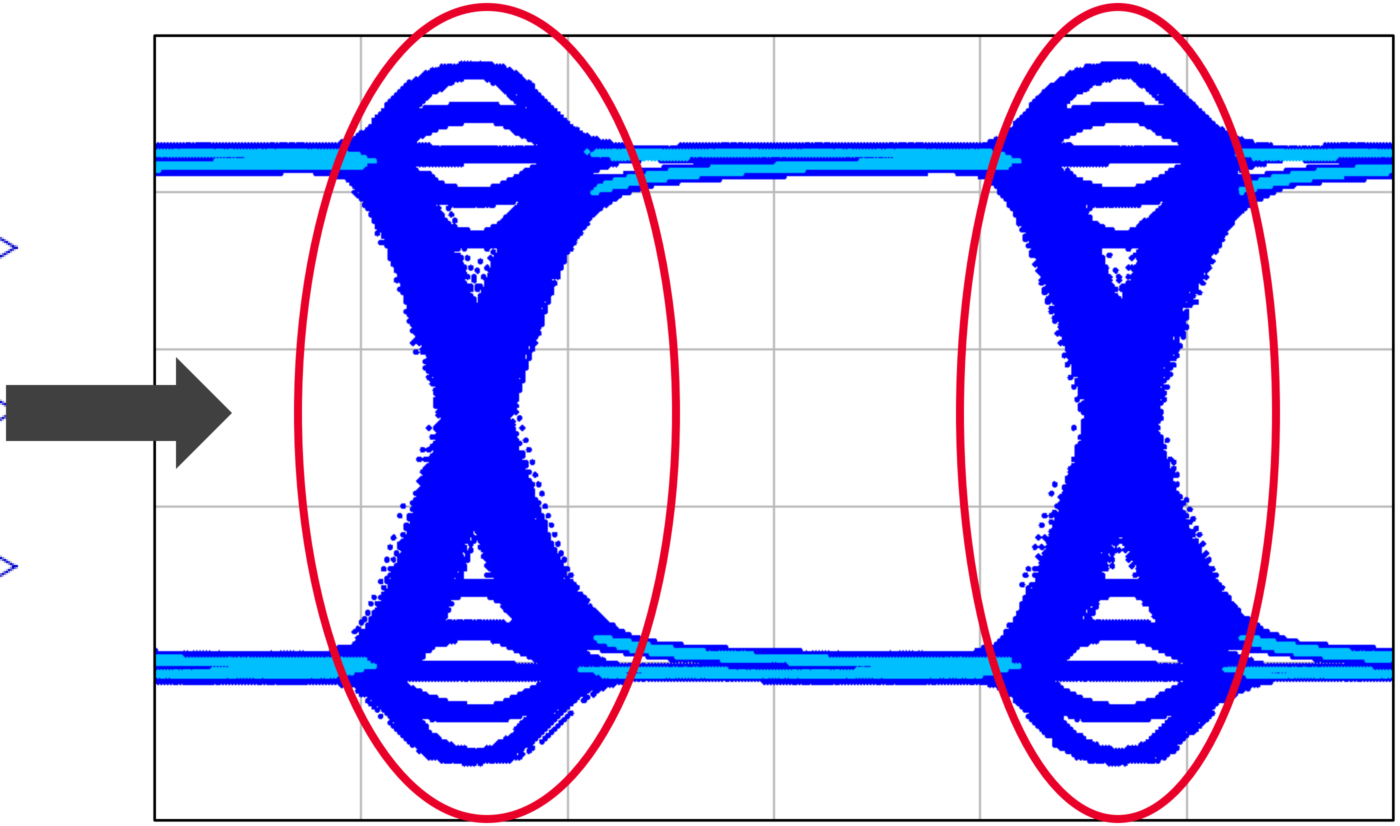


Far-end Crosstalk Signatures in the Eye

Channels are close and they are all active



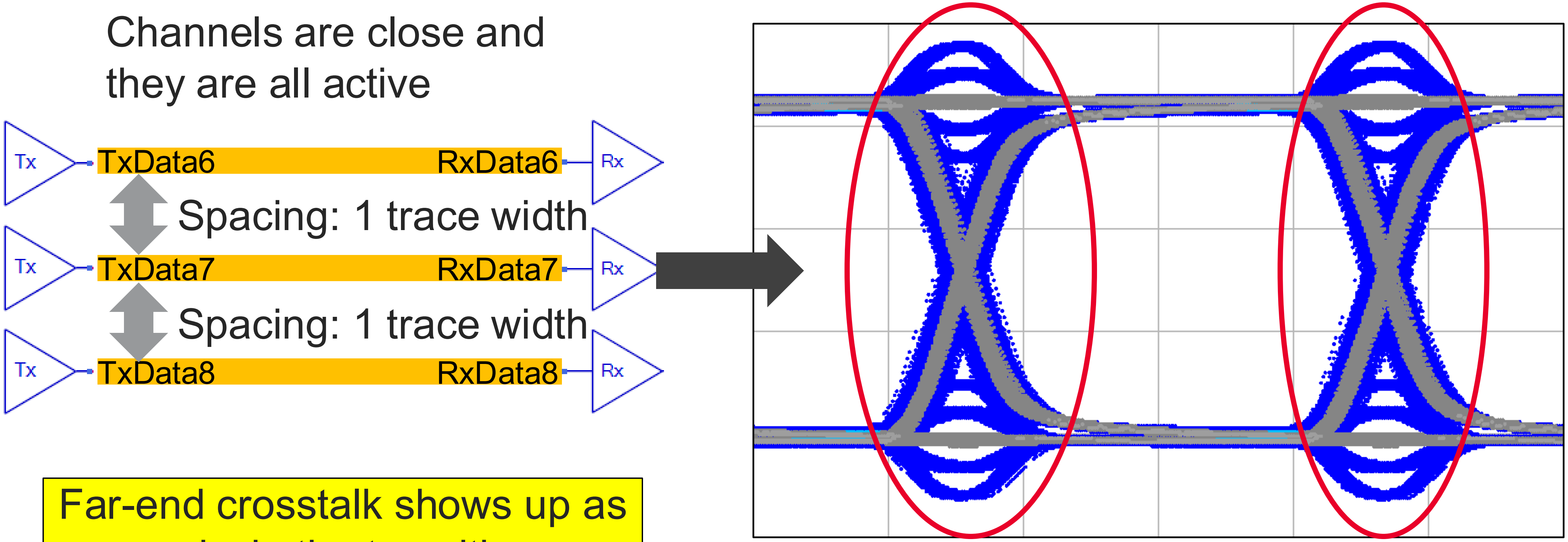
Crosstalk voltage signature in RxData7's waveforms



Far-end Crosstalk Signatures in the Eye

Channels are close and they are all active

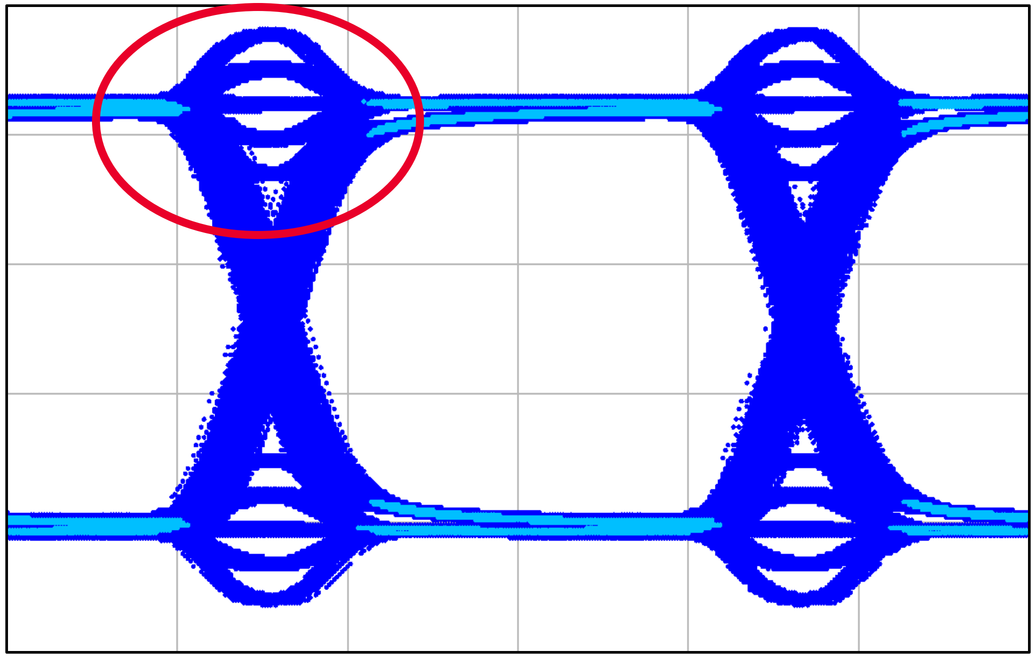
Crosstalk voltage signature in RxData7's waveforms



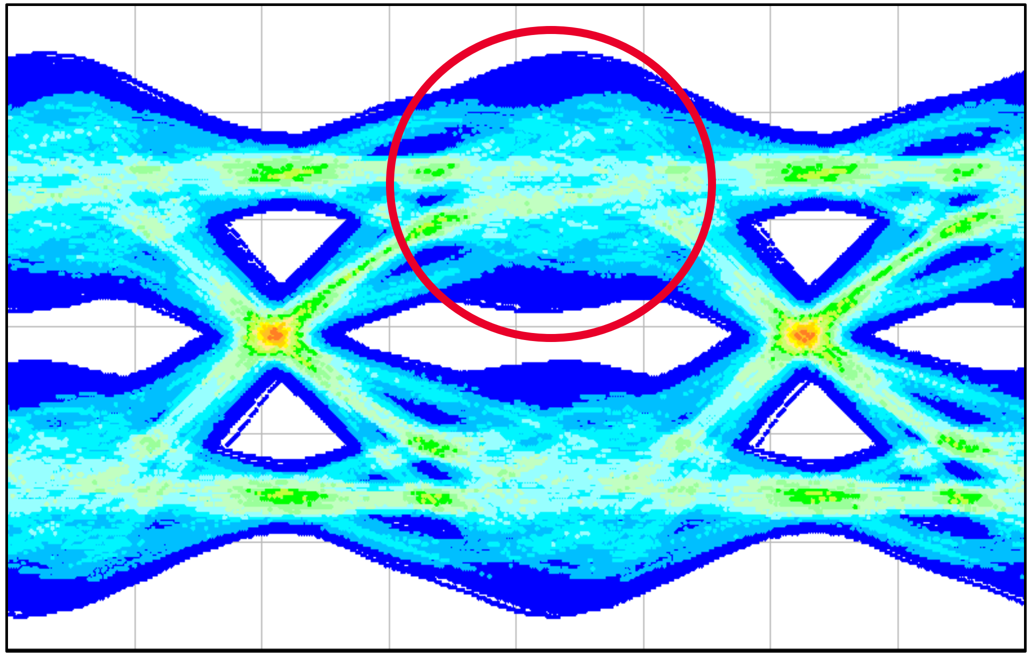
Far-end crosstalk shows up as peaks in the transitions

Far-end Crosstalk Signature Looks Different

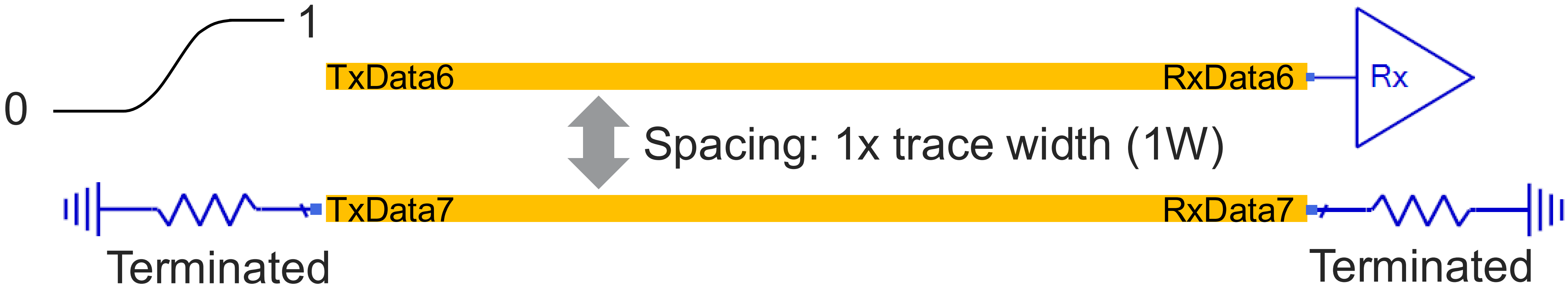
Received eye example



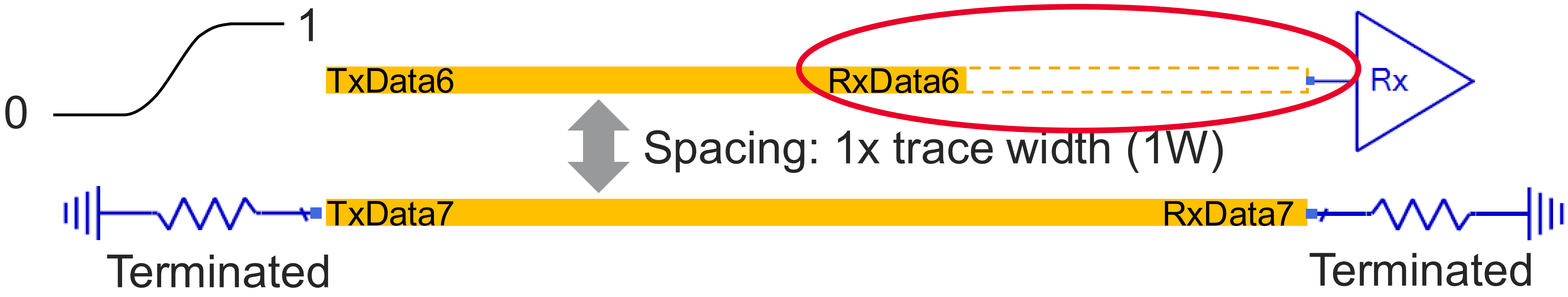
Received eye at RxData7
without equalization

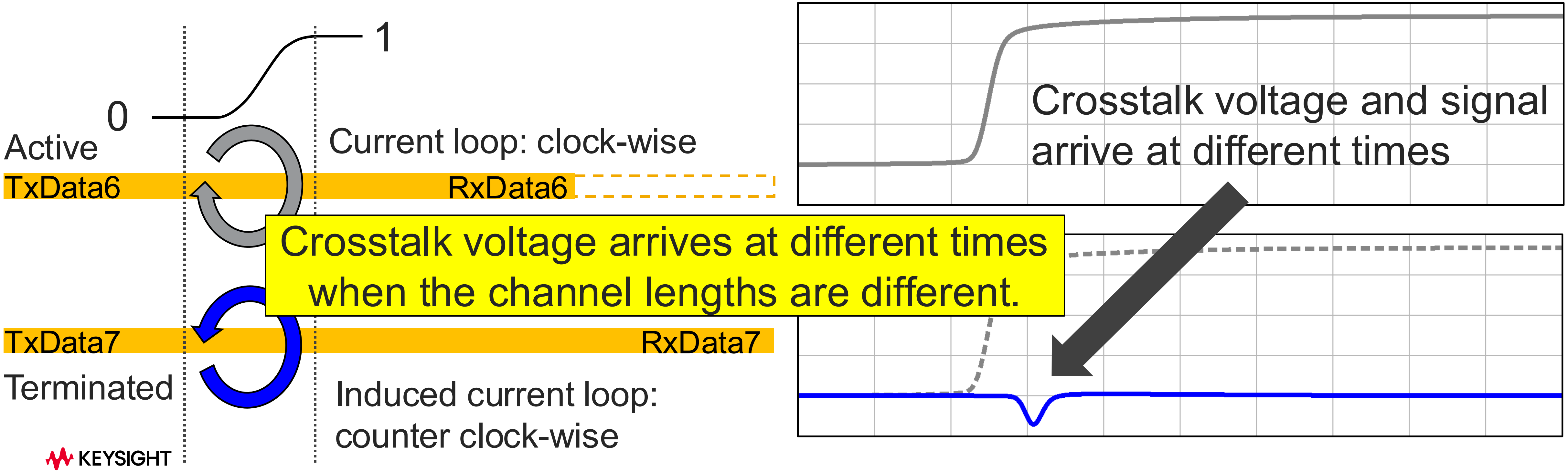


Previous Channels Have the Same Lengths



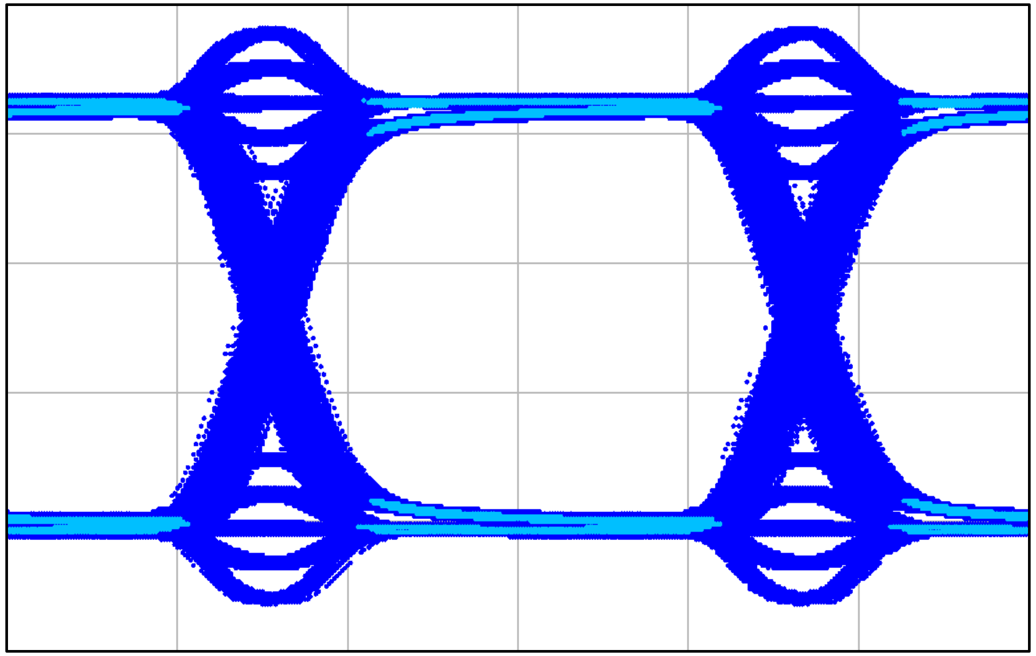
Change the Channel Length to Offset the Timing of Crosstalk



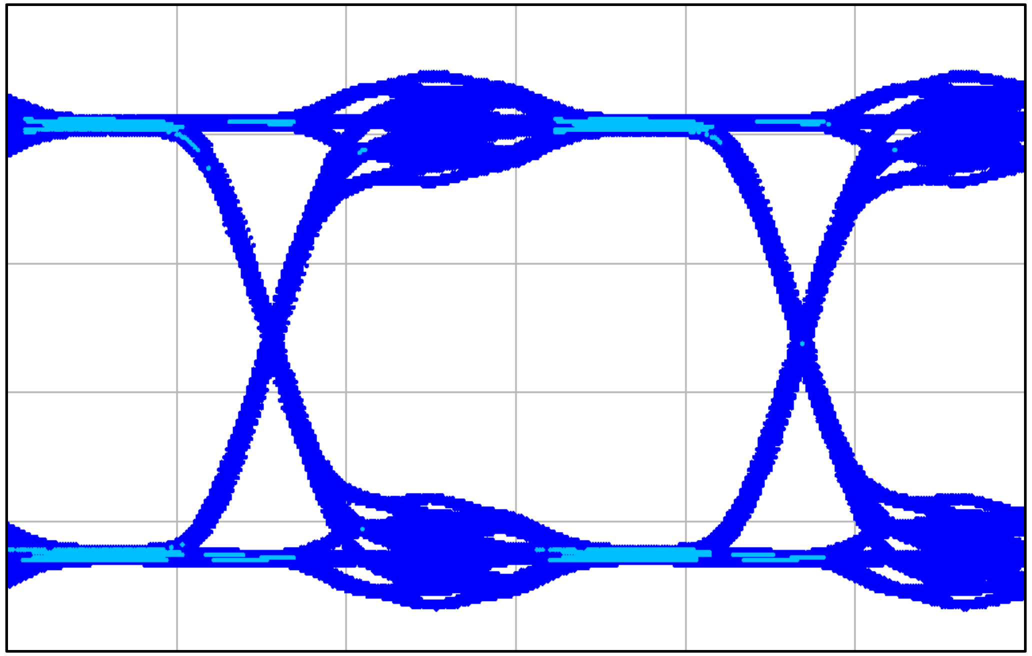


Xtalk and Length Variation Cause Vertical Eye Collapse

Received eye example
With **same channel lengths**



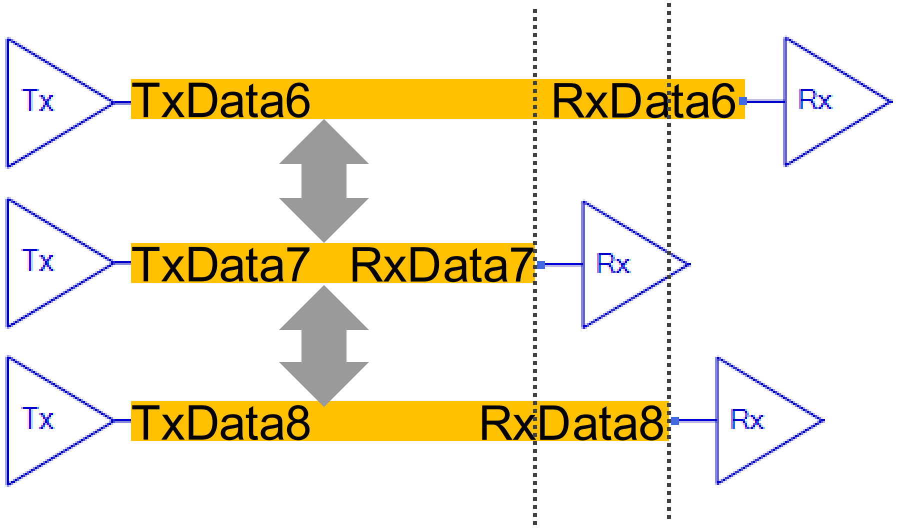
Received eye example
With **different channel lengths**

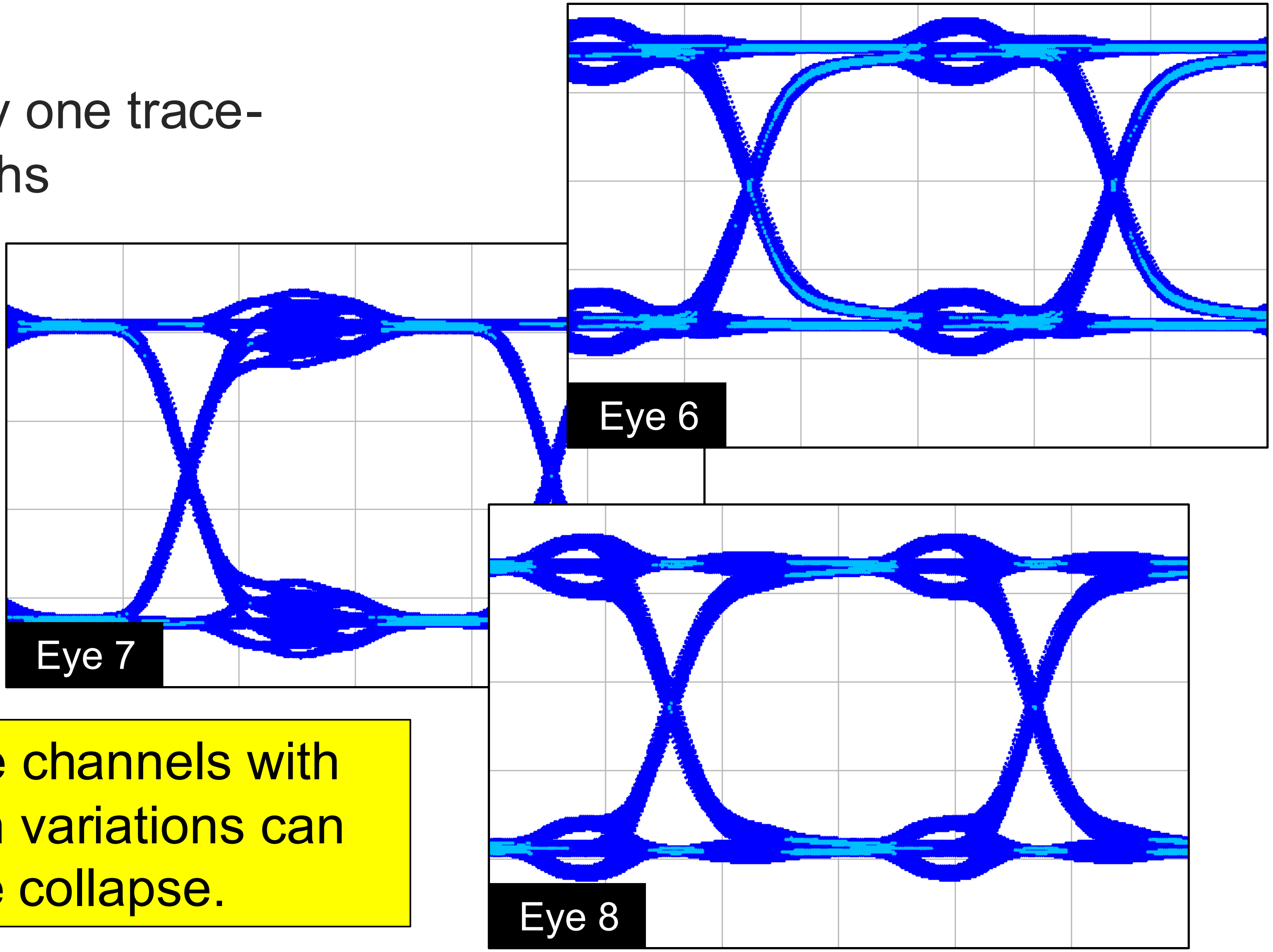


Crosstalk with channel length variations can cause vertical eye collapse!

Xtalk and Length Variation Cause Vertical Eye Collapse

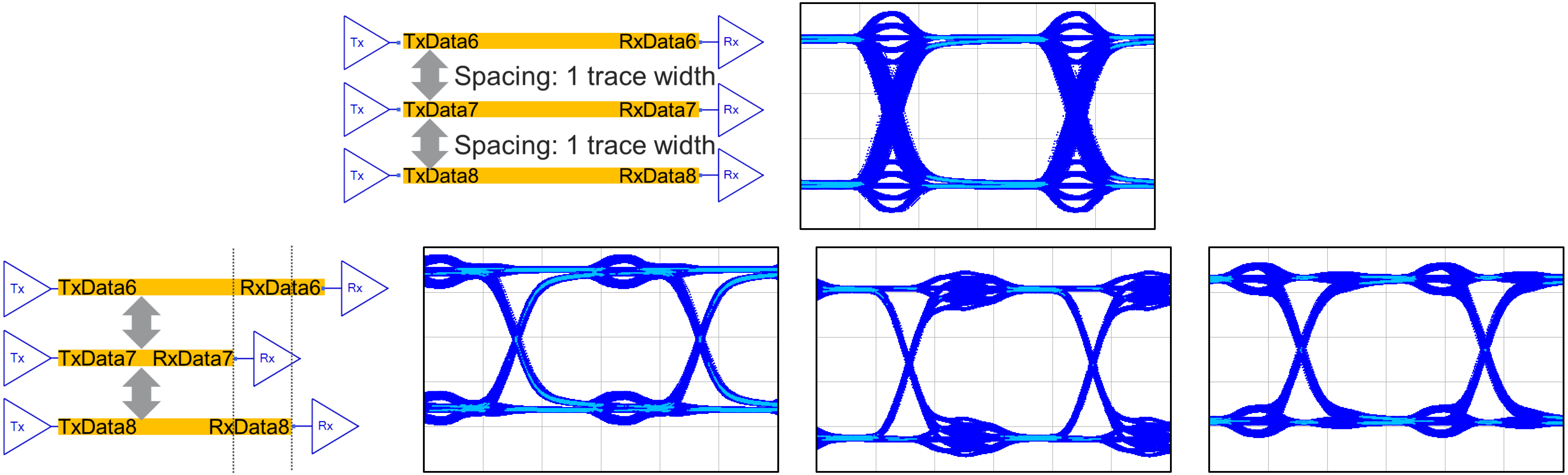
3 nearby channels separated by one trace-width and with all different lengths





Crosstalk from multiple channels with multiple channel length variations can cause vertical eye collapse.

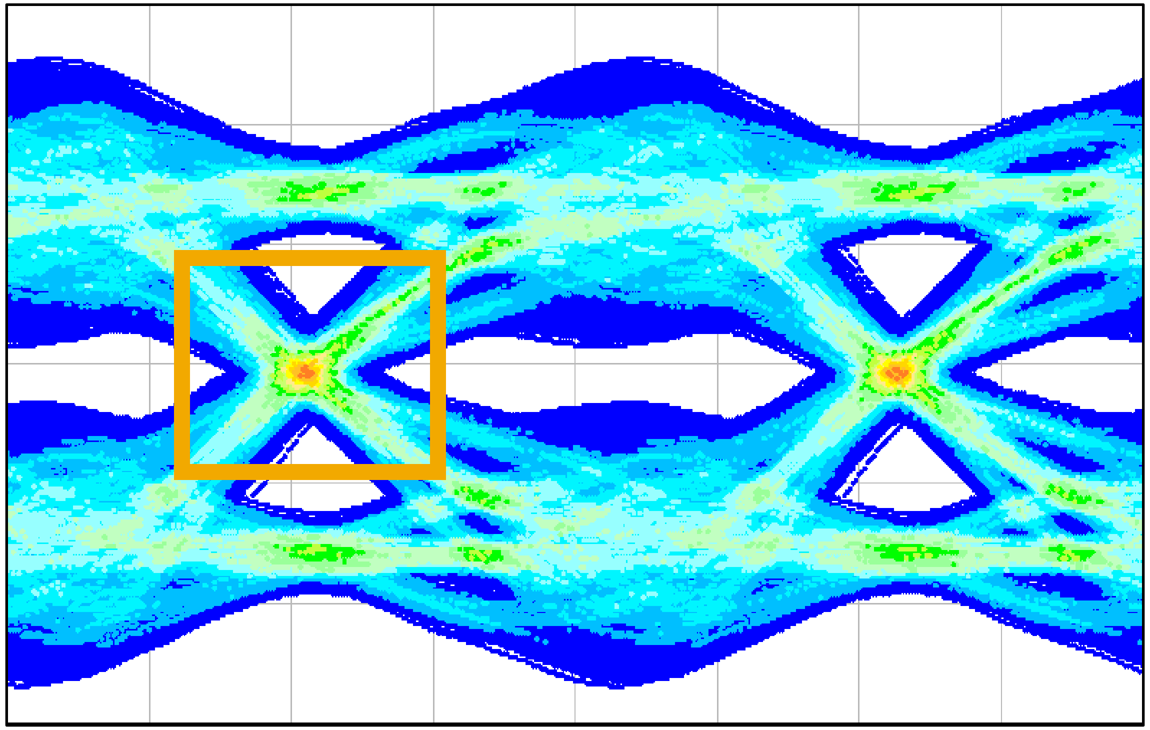
Fix Vertical Eye Closure by Increasing Channel Spacing



Signs in the Eye	Root cause	Fixes
• Peaks in eye transitions • Lumped peaks in the eyes	Crosstalk from adjacent channels	• Move channels farther apart • Maintain the same channel length

Eye Shows Reflection, Crosstalk, and Considerable Loss

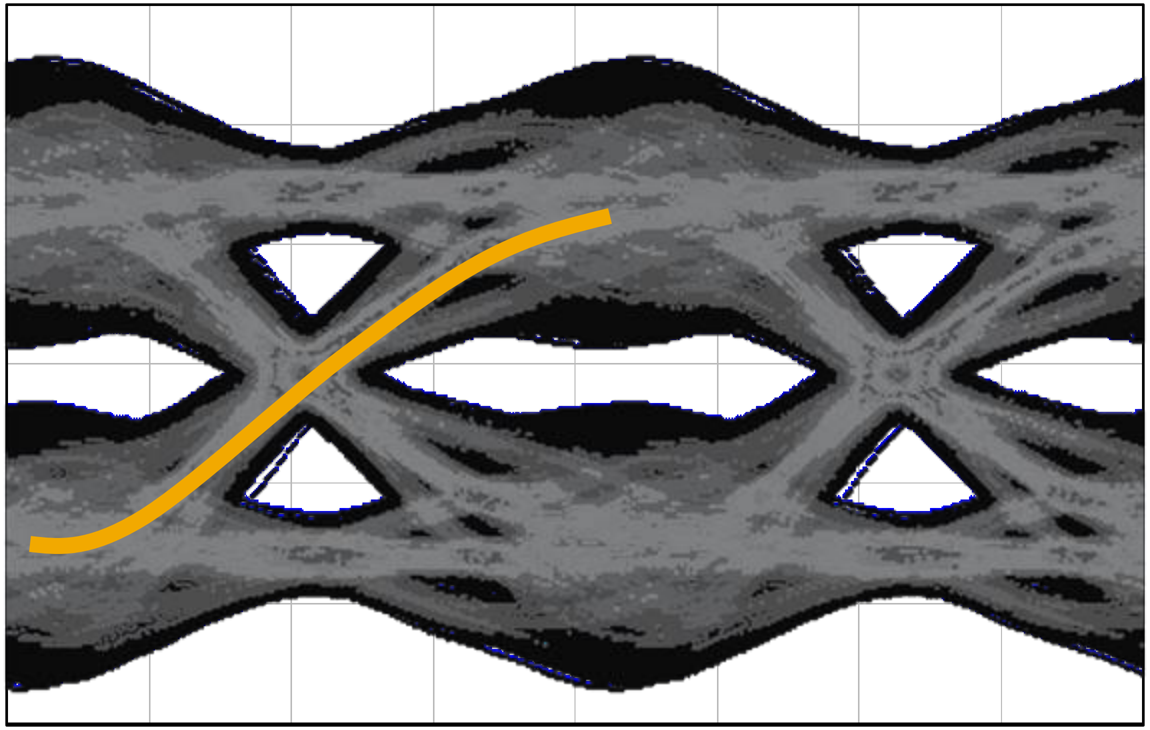
Received eye at RxData7 without equalization



3. Signs of frequency-dependent loss

Rise Time Degradation Indicates Loss in the Channel

Received eye at RxData7 without equalization

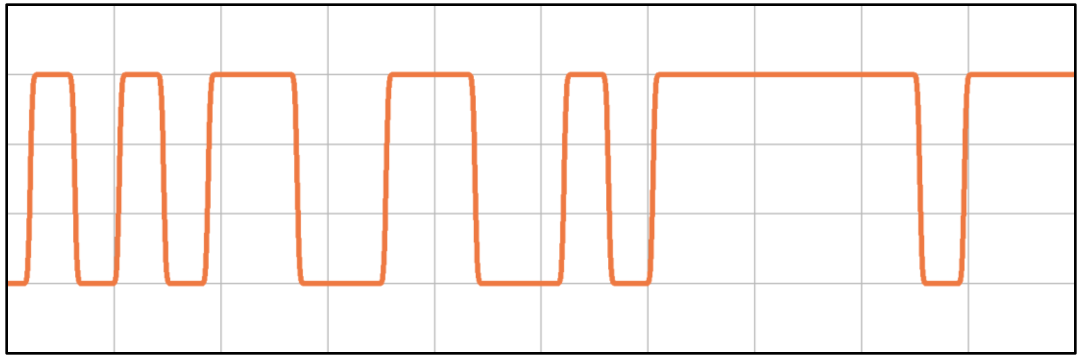


3. Signs of frequency-dependent loss

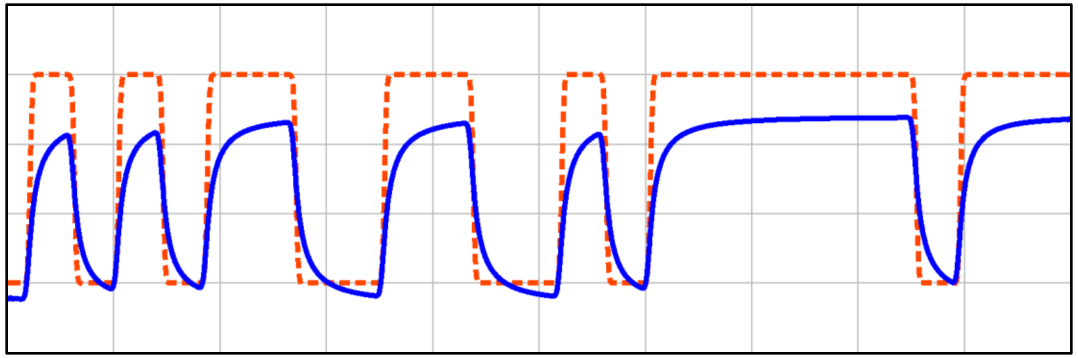
Frequency-dependent loss causes rise time degradation which reduces both timing margin and voltage margin.

Interconnects Attenuate High-frequency Components More

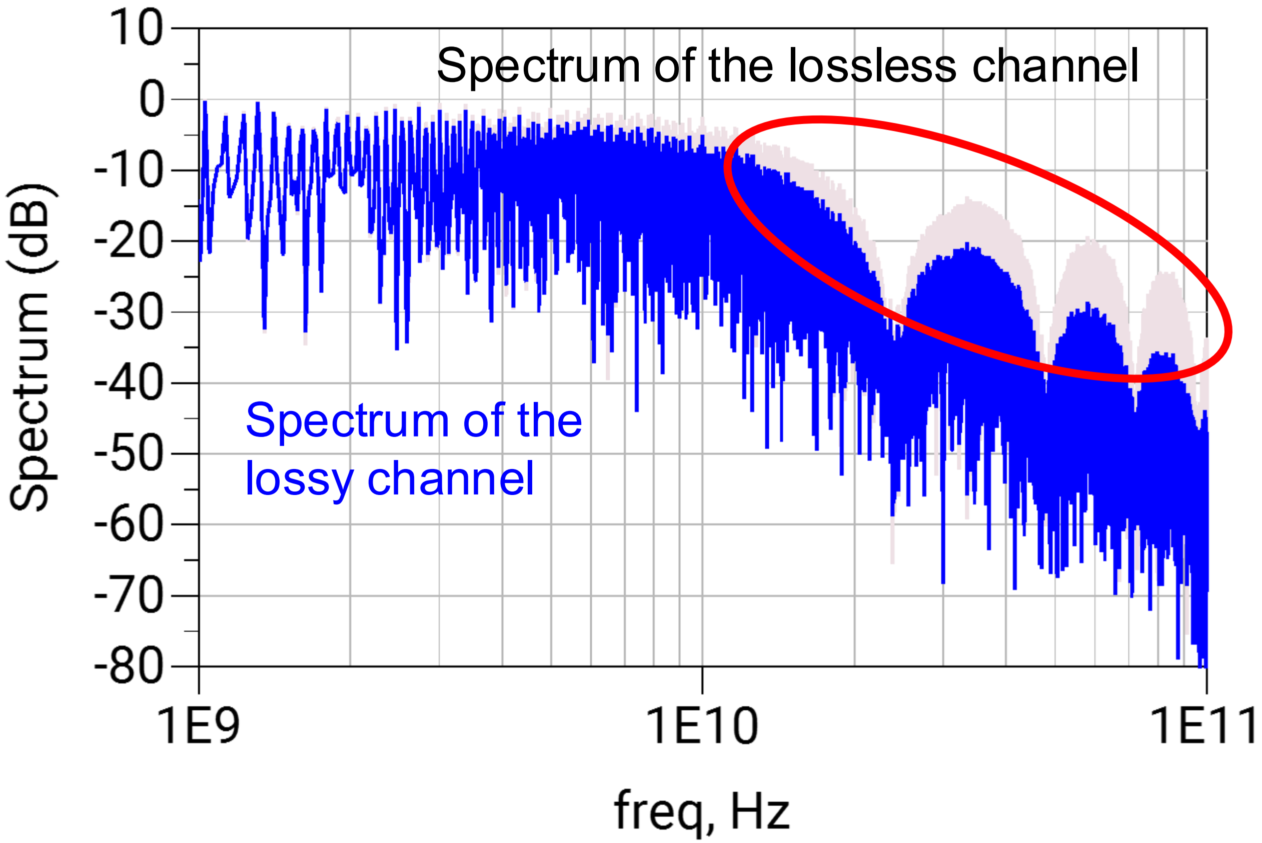
Received waveform after a lossless channel



Received waveform after a lossy channel



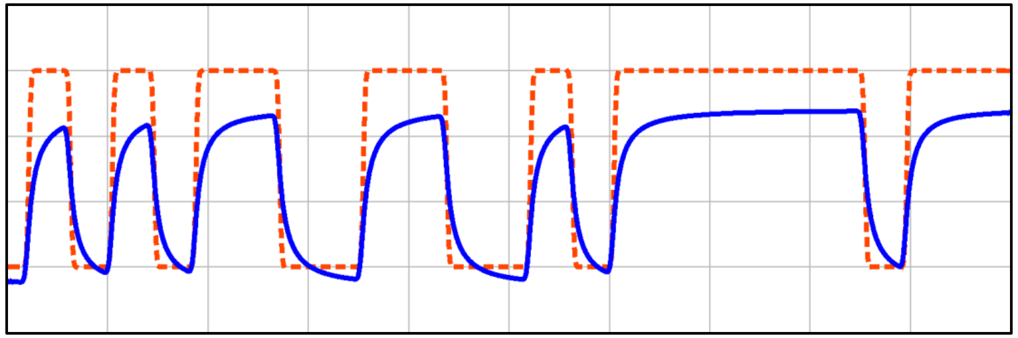
The lossy channel acts as a low-pass filter.

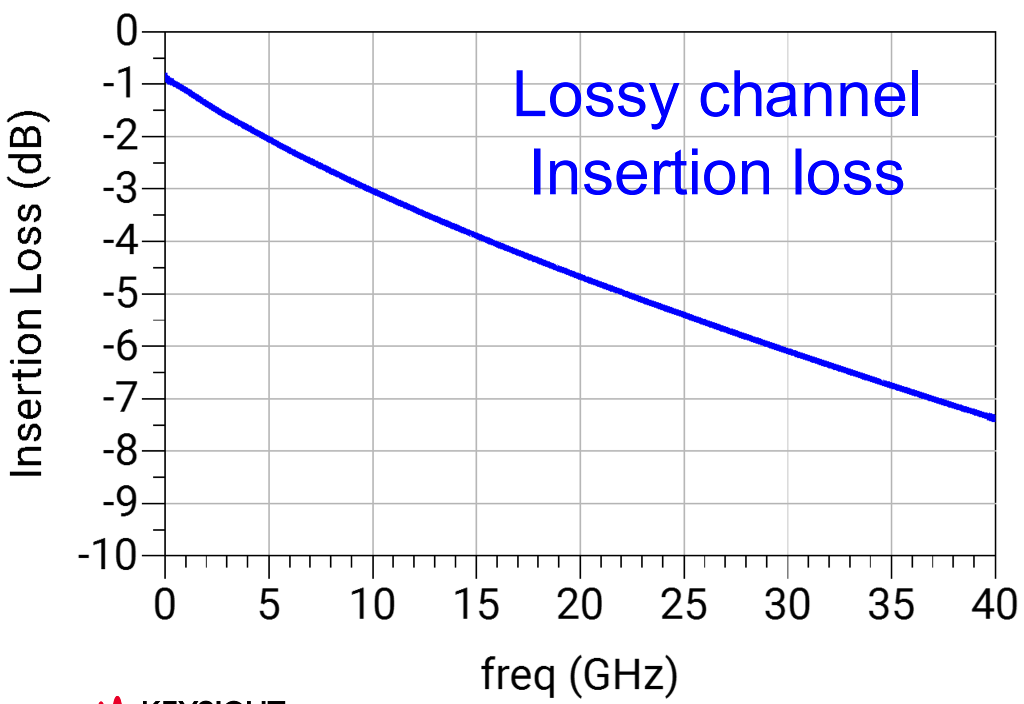


This low-pass filter degrades the fast rise time.

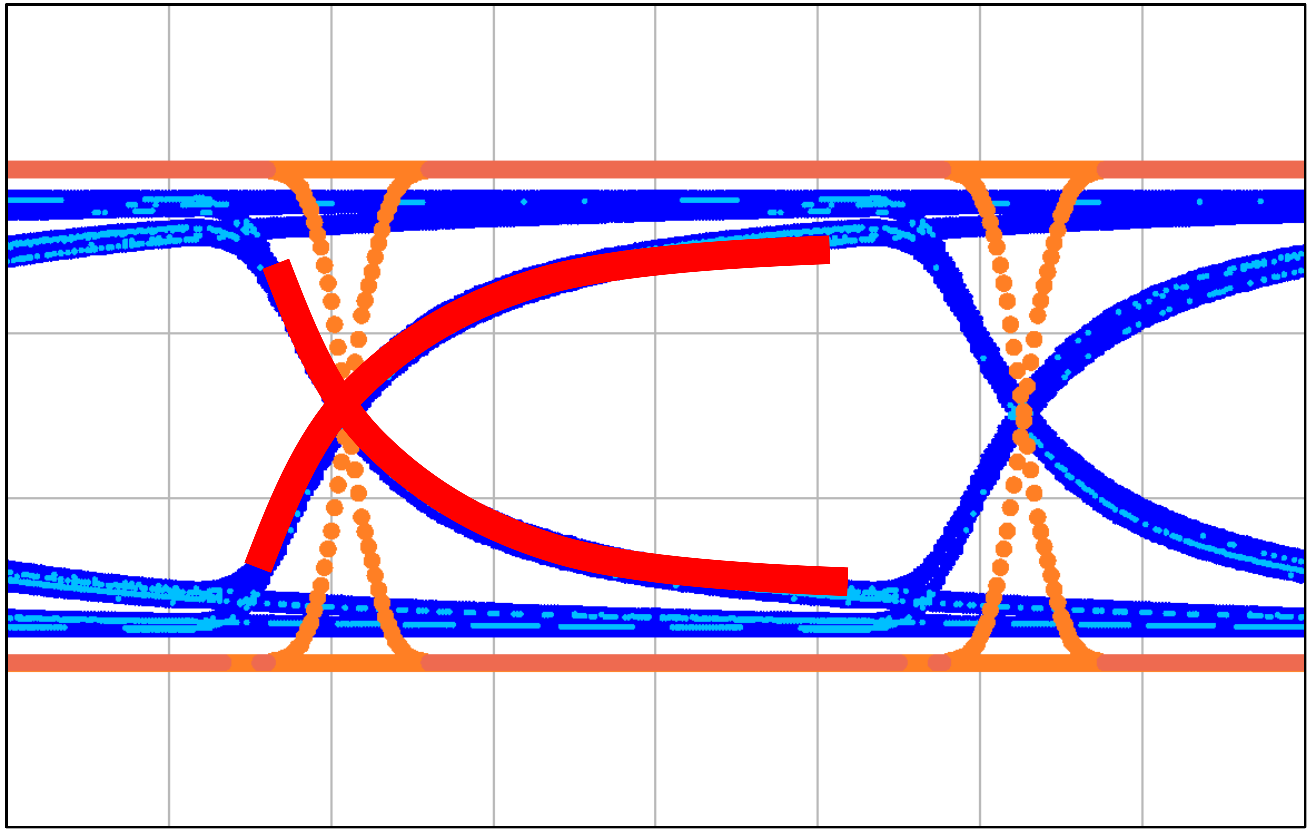
Interconnects Attenuate High-frequency Components More

Received waveform after a lossy channel



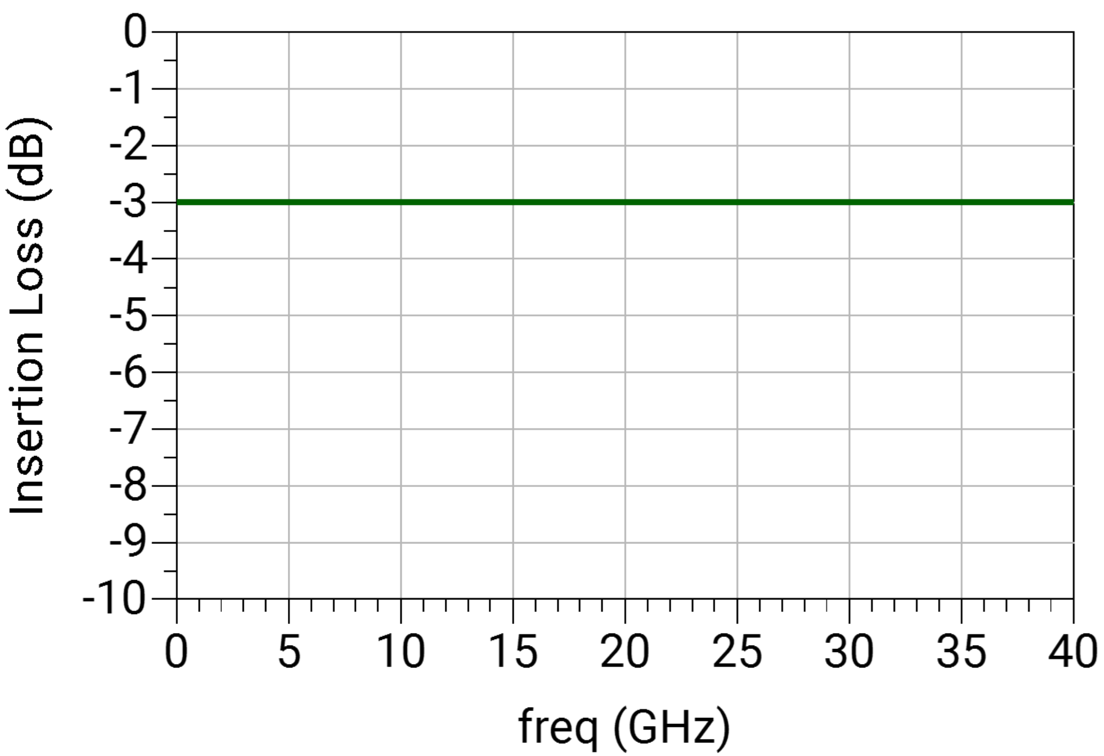


Frequency-dependent loss reduces eye height and width

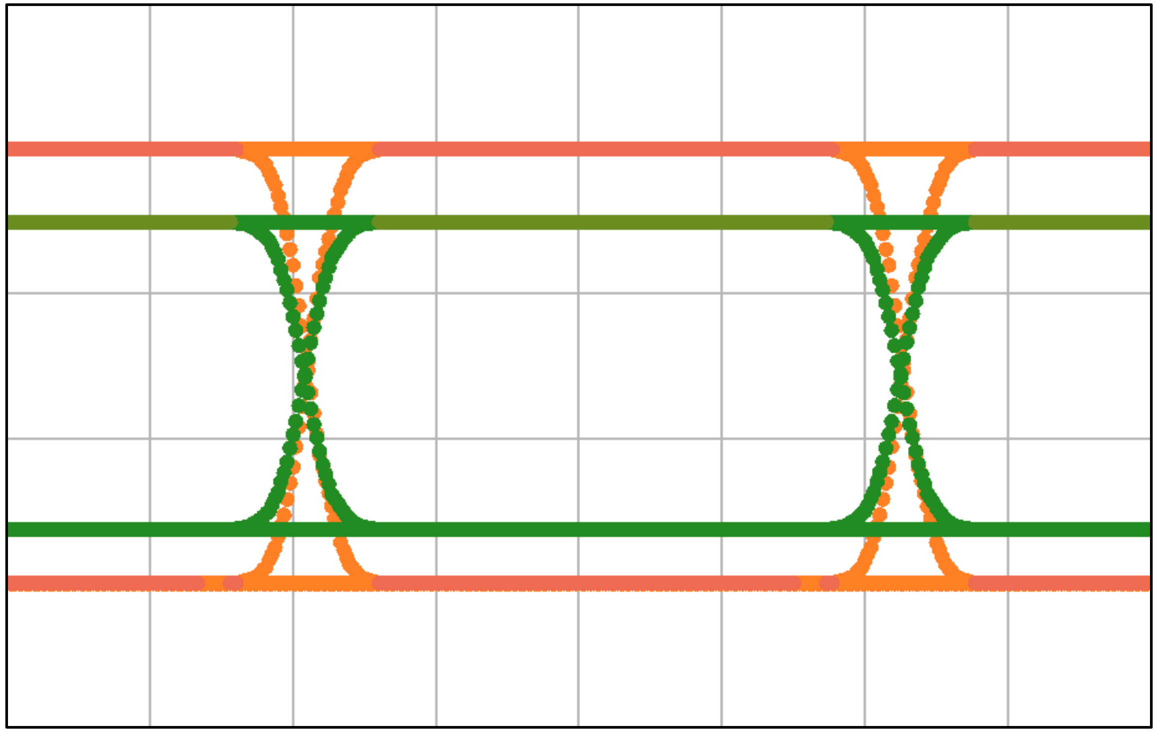


Constant Loss Over Frequency Only Reduces Eye Amplitude

Lossy channel with constant Insertion loss

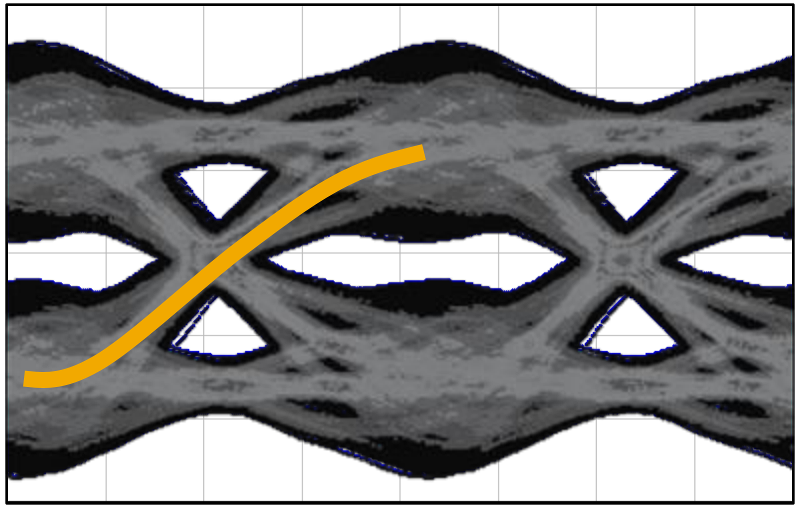


Frequency-independent loss does not degrade rise time

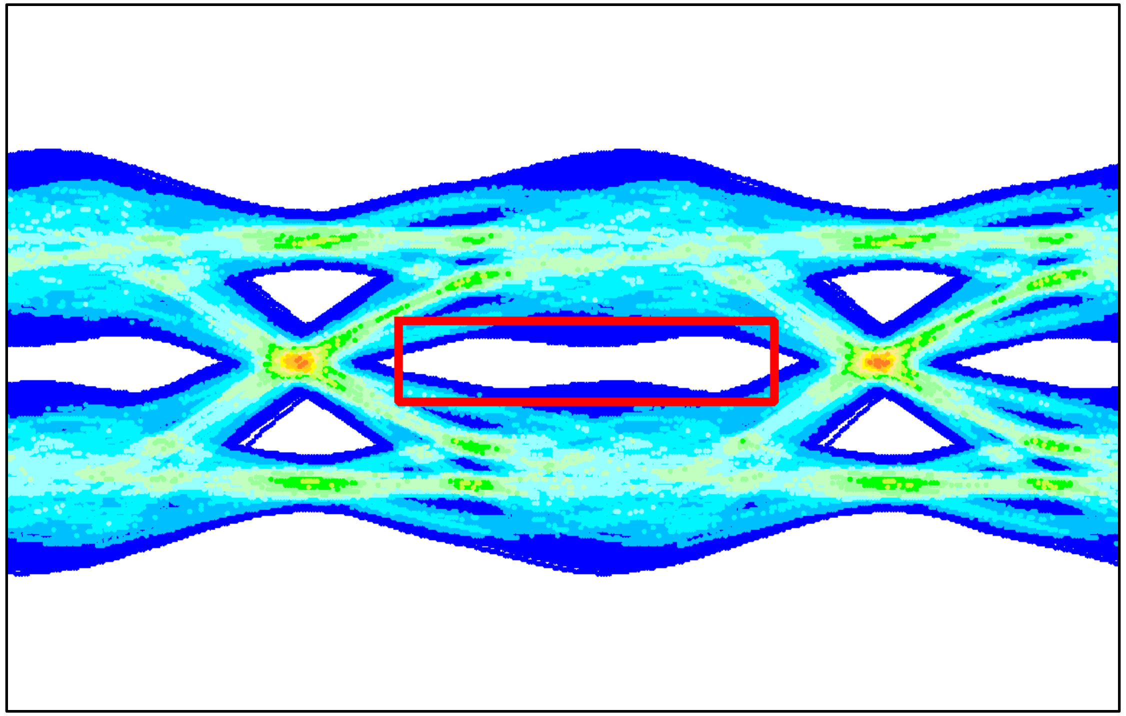


Reduces Loss by Reducing Channel Length

Received eye at RxData7 without equalization



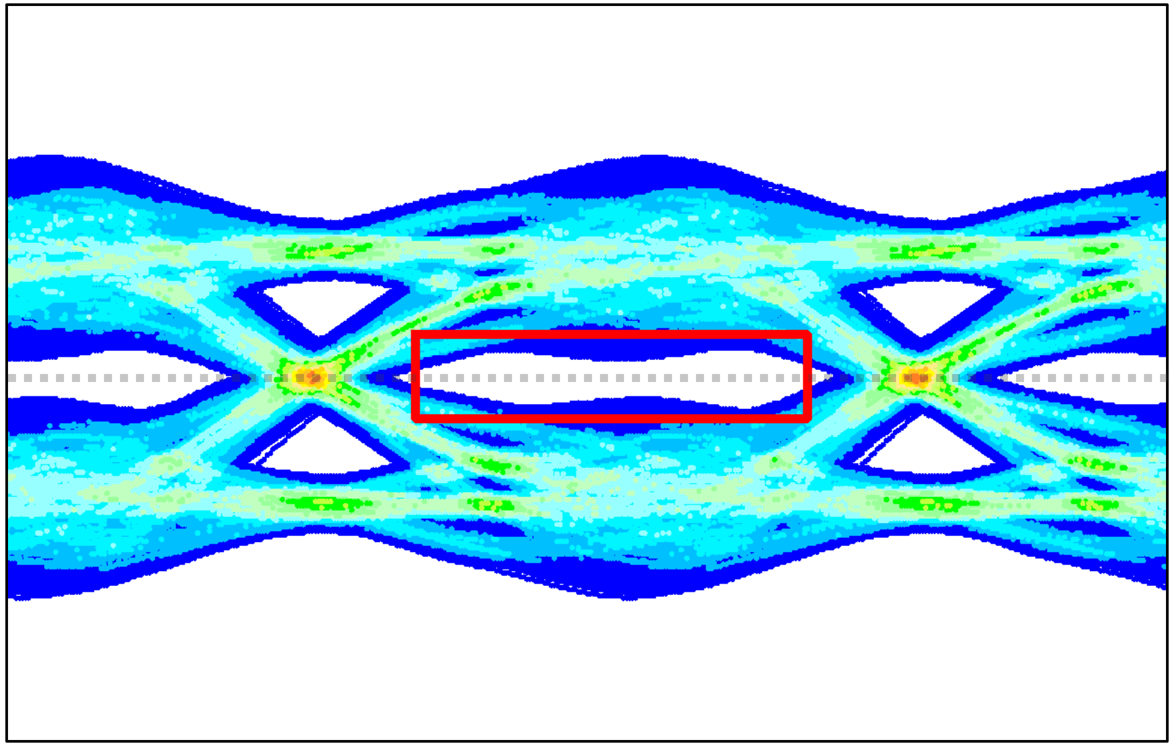
Use an eye mask as a reference as the channel length reduces



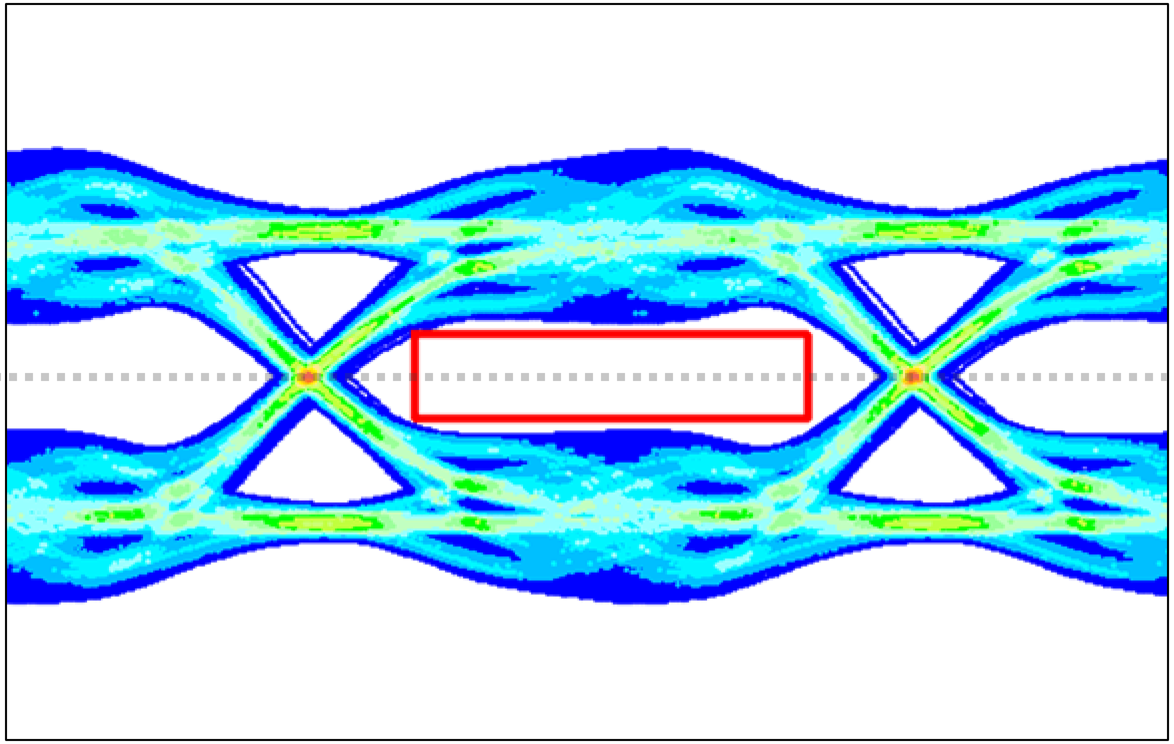
Expect a larger eye-opening as channel length decreases.

Eye Opens Up as Channel Length Decreases

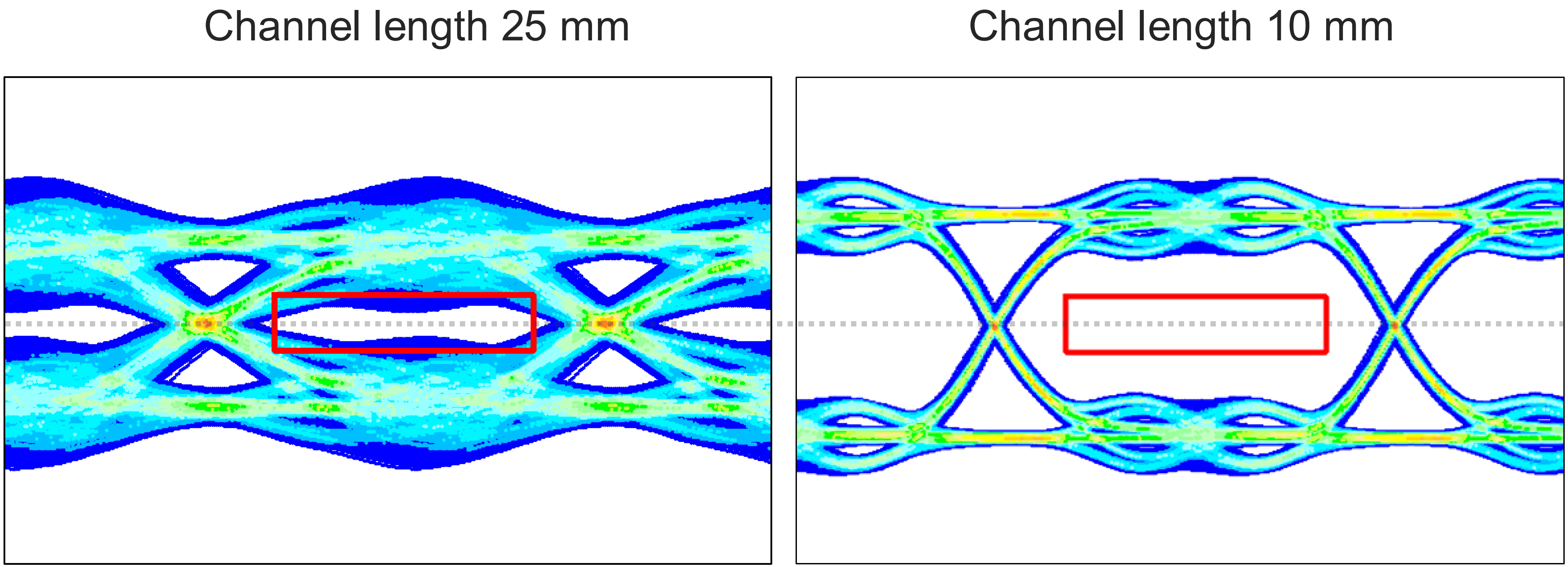
Channel length 25 mm



Channel length 18 mm

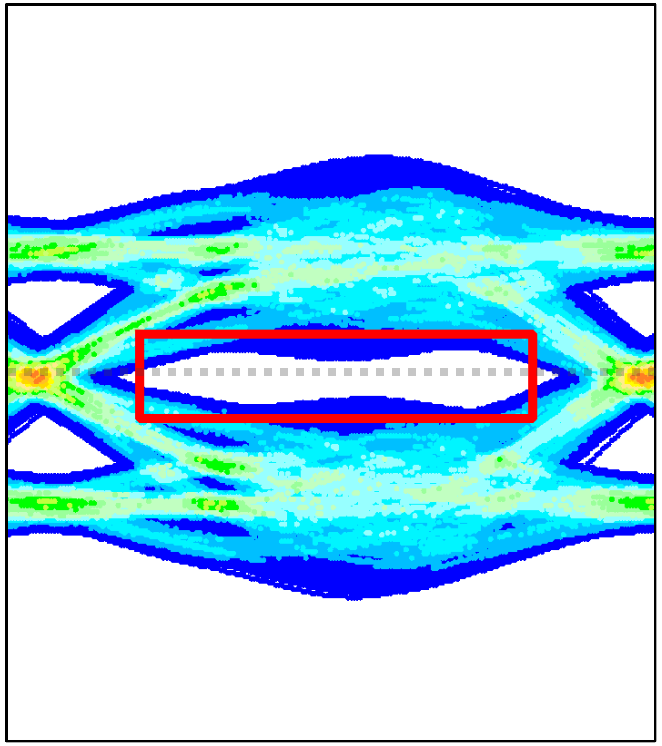


Eye Opens Up as Channel Length Decreases

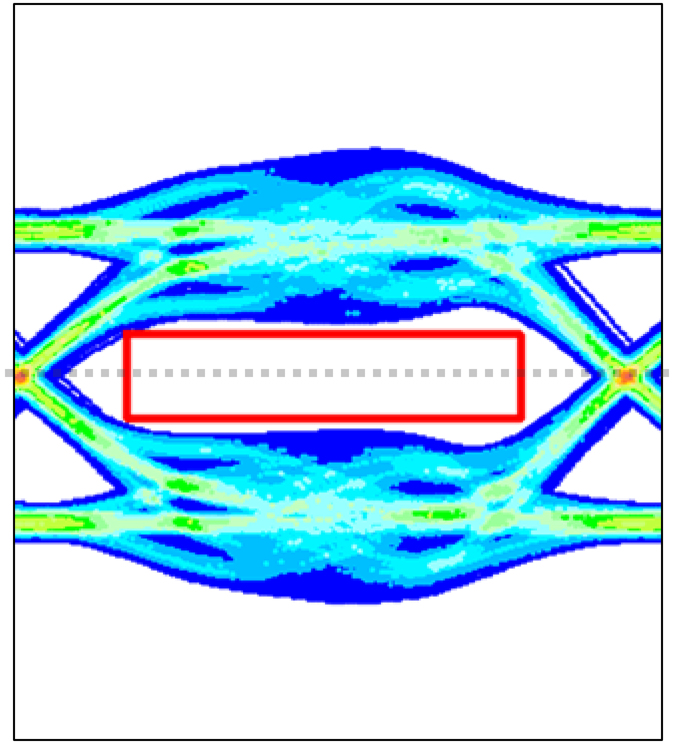


Eye Opens Up as Channel Length Decreases

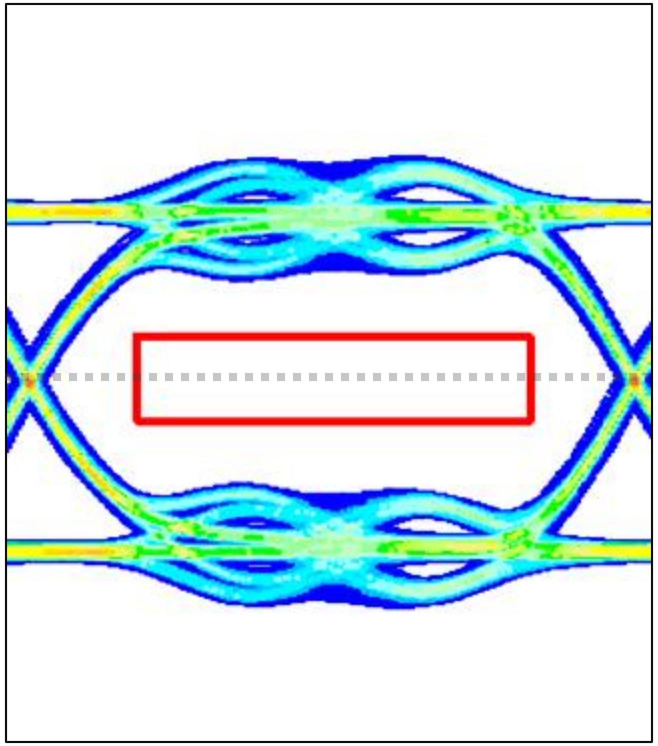
Channel length 25 mm



Channel length 18 mm



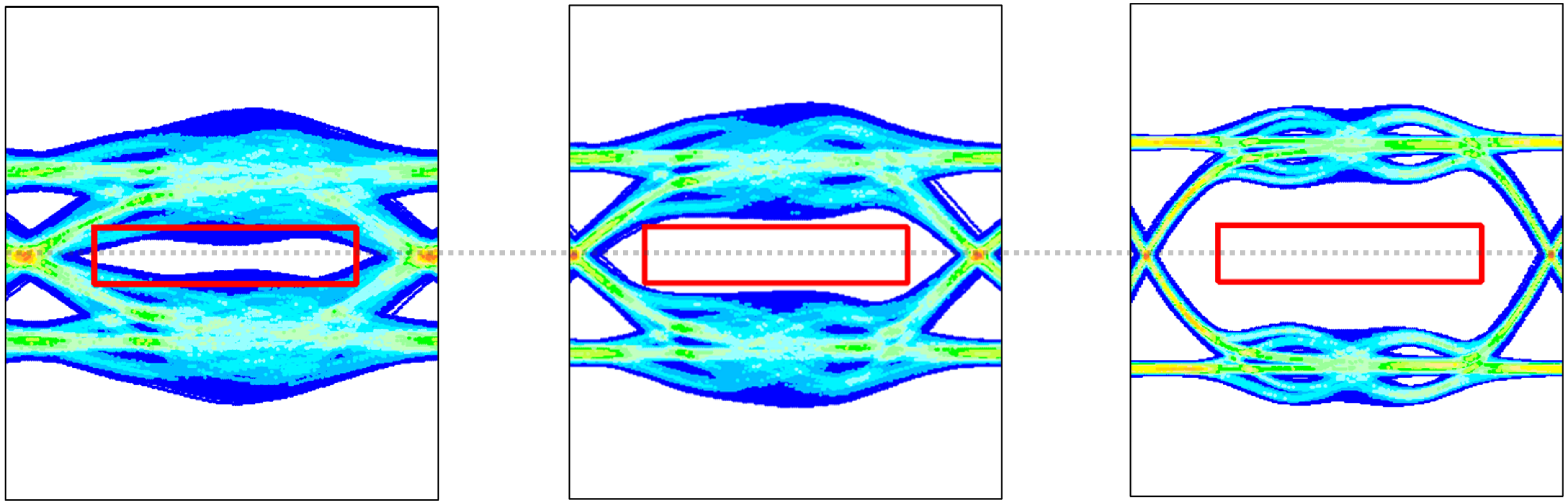
Channel length 10 mm



As expected, one achieves a larger eye-opening as channel length decreases.

KEYSIGHT

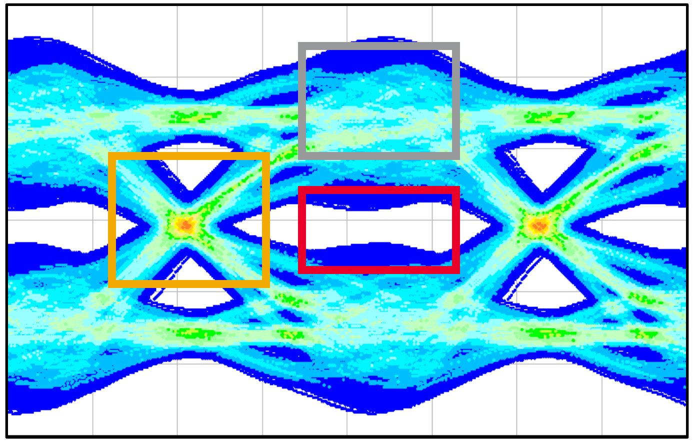
Fix Rise Time Degradation by Decreasing Channel Length



Channel length 25 mm | Channel length 18 mm | Channel length 10 mm

Signs in the Eye	Root cause	Fixes
• The transition edge slope is slow/gradual	Frequency-dependent loss from the channel	• Reduce channel length to reduce loss

Improve Your Signal Integrity by Removing the Root Cause

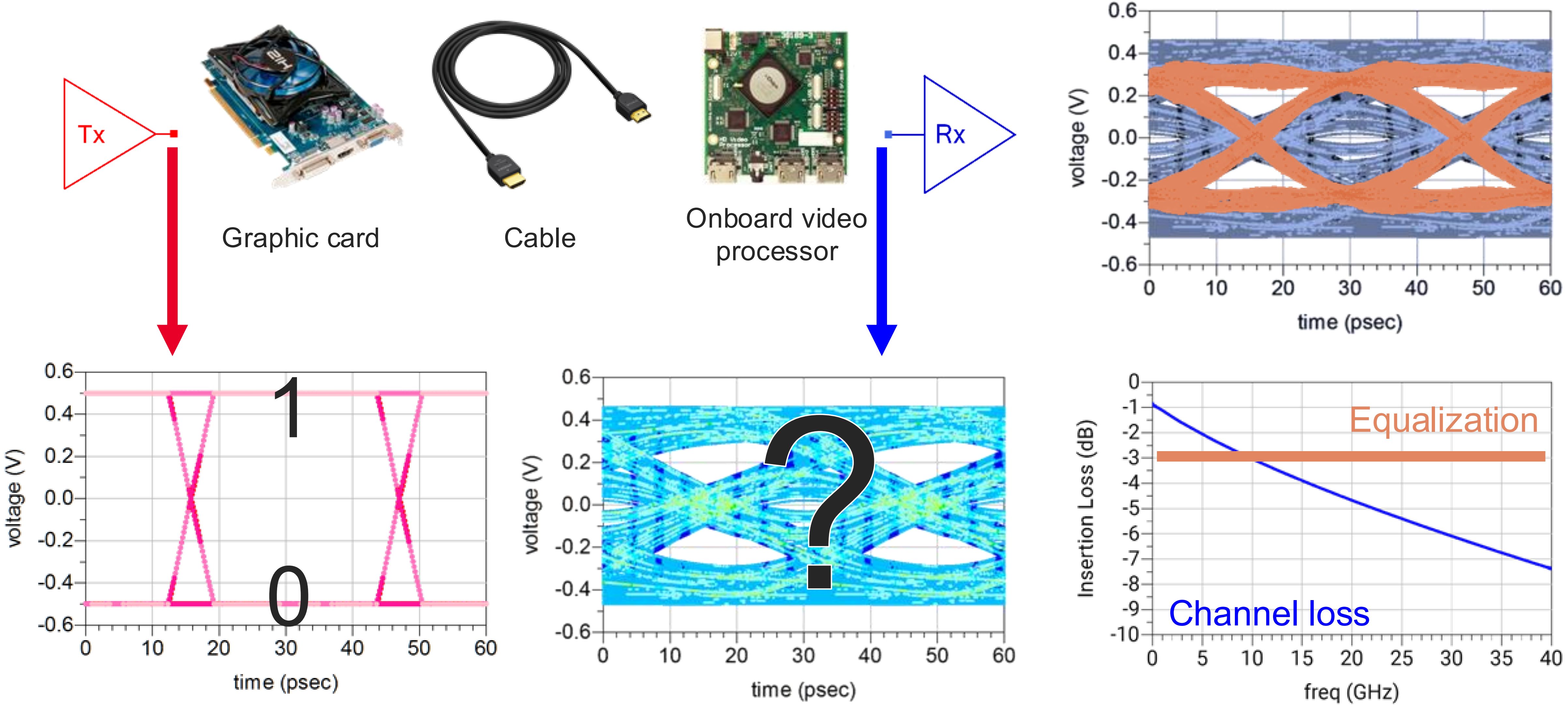


1. Signs of reflection
2. Signs of crosstalk
3. Signs of frequency-dependent loss

Signs in the Eye	Root cause	Fixes
• Deformed eye shape • Reduced eye amplitude	Impedance discontinuities	• Locate impedance discontinuity and match it with channel impedance
• Peaks in eye transitions • Lumped peaks in the eyes	Crosstalk from adjacent channels	• Move channels farther apart • Maintain the same channel length
• The transition edge slope is slow/gradual	Frequency-dependent loss from the channel	• Reduce channel length to reduce loss

What to Do When Life Gives You a ~~Lemon~~ Closed Eye

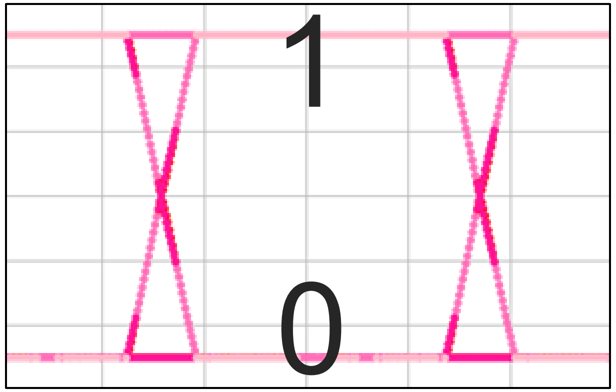
Apply EQ at Rx When the Channel is Built and Fixed

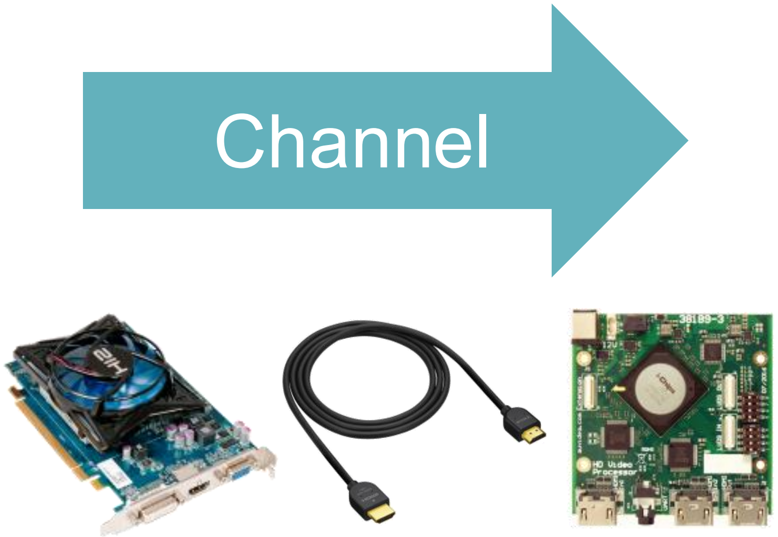


Apply equalization at the receiver to recover data

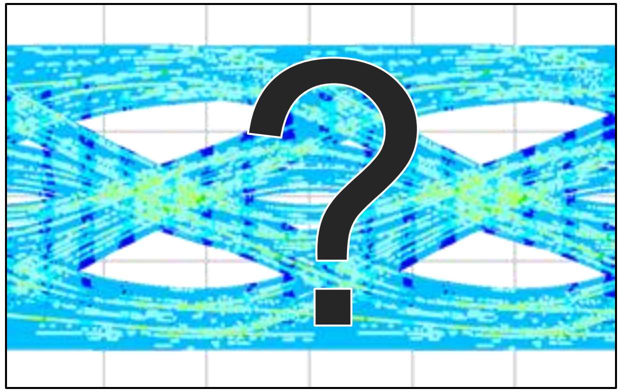
Frequency-dependent Loss Causes Inter-symbol Interference

Tx PRBS → Tx Eye

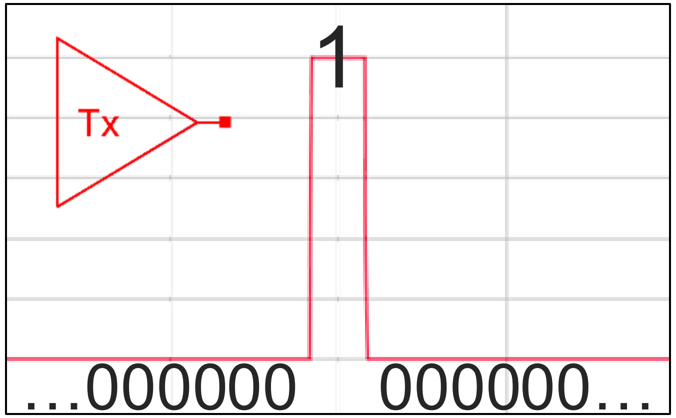




Rx PRBS → Rx Eye

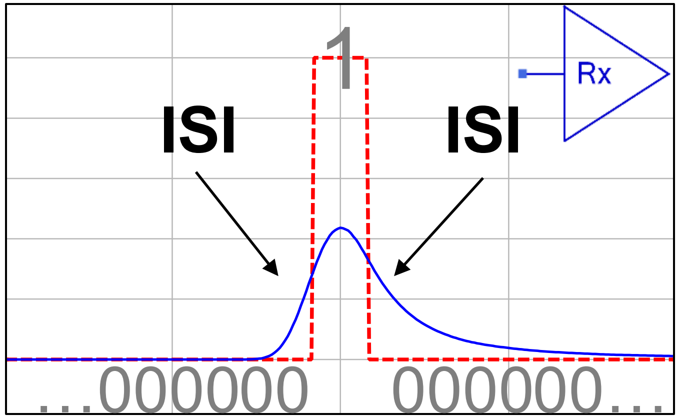


Single Pulse

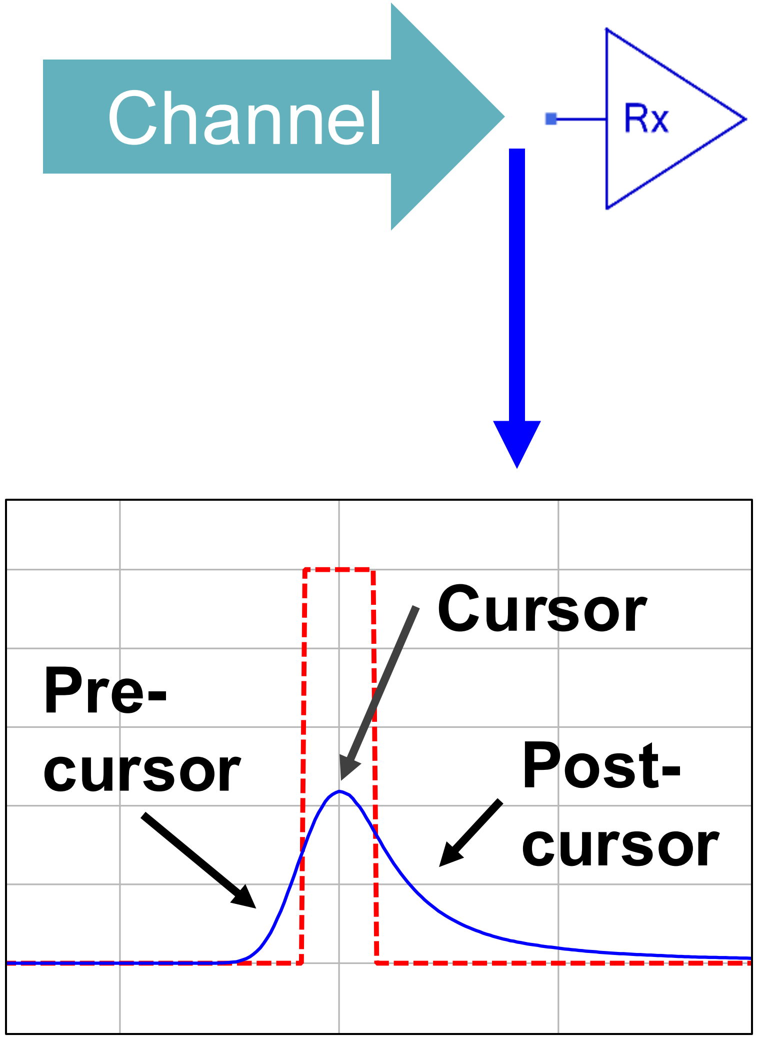


The low-pass nature of the channel introduced inter-symbol interference (ISI) in the bits transferred.

Single Pulse Response

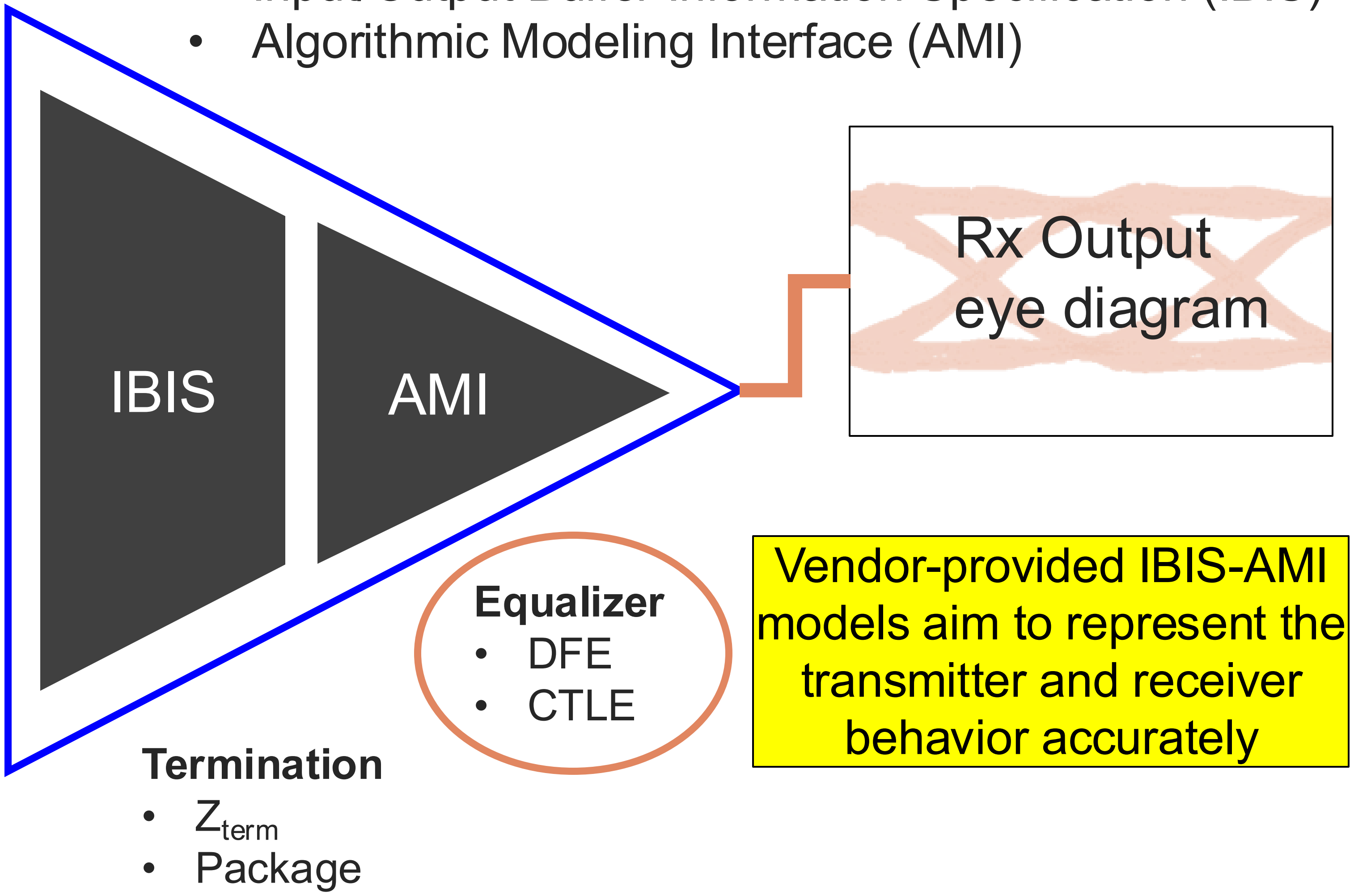


Use Receiver Model to Configure the Equalization



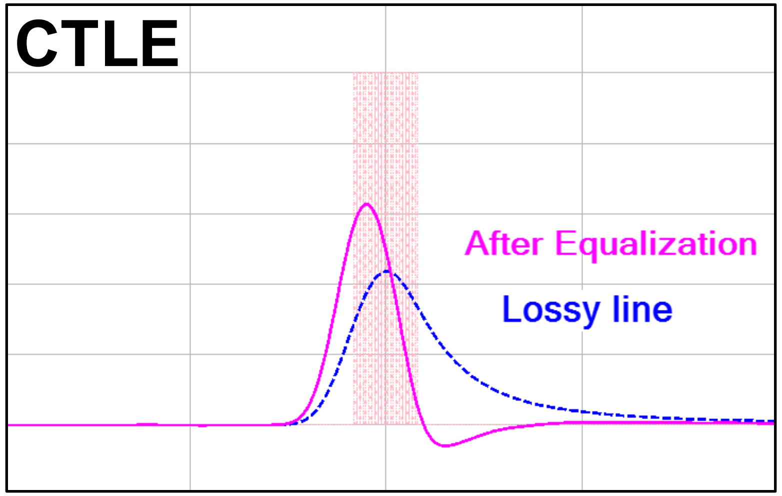
Receiver model

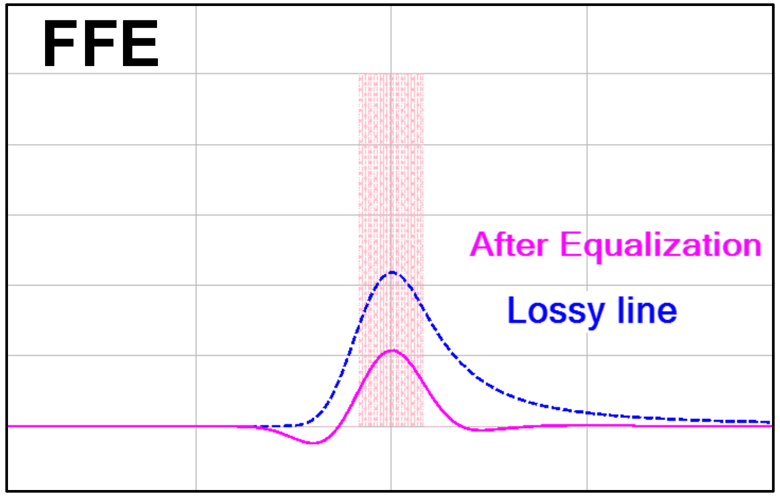
- Input/Output Buffer Information Specification (IBIS)
- Algorithmic Modeling Interface (AMI)

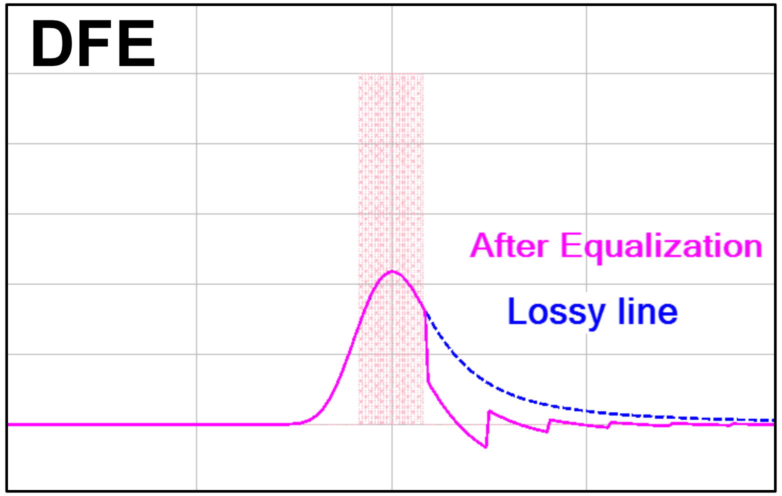


Vendor-provided IBIS-AMI models aim to represent the transmitter and receiver behavior accurately

Three Equalization Techniques and Their Properties



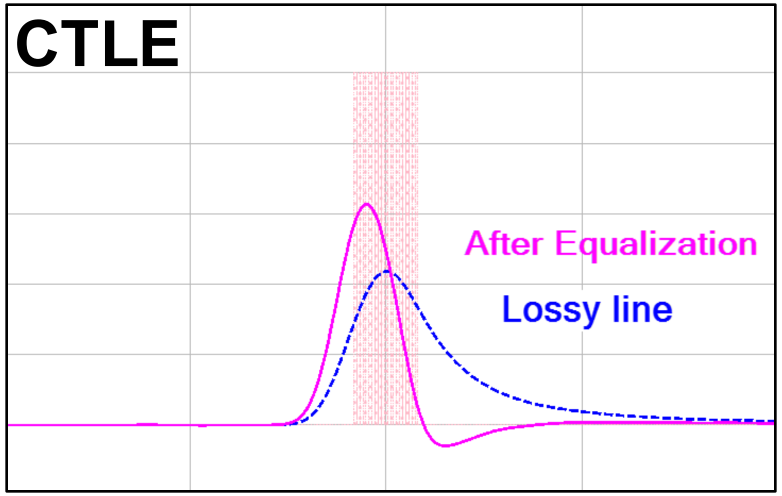


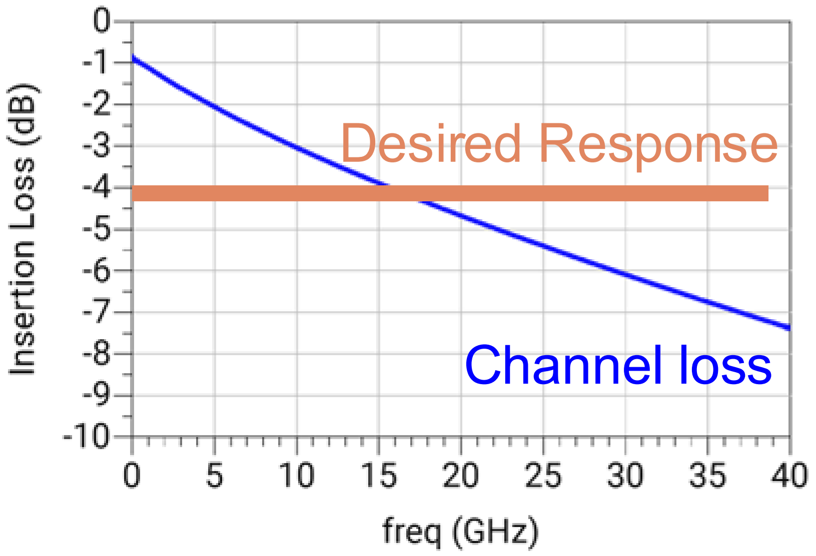


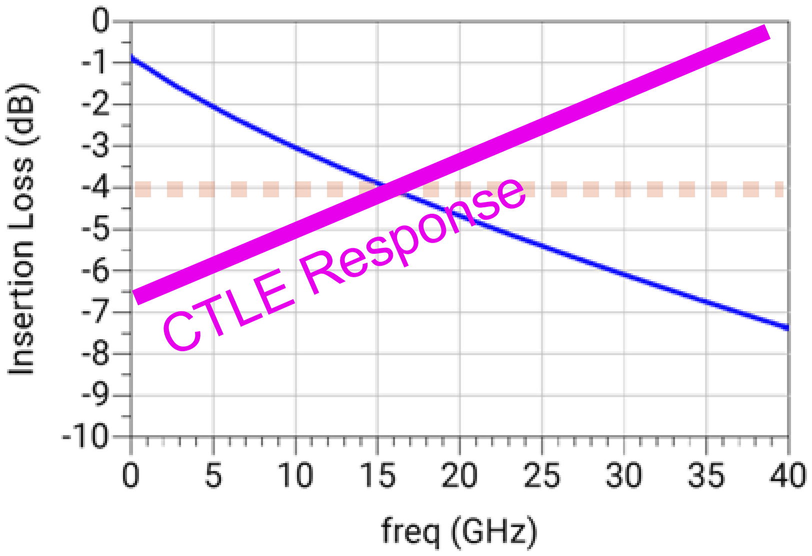
Continuous Time Linear Equalization	Feed Forward Equalization	Decision Feedback Equalization
Linear	Linear	**Non-Linear**
Analog/Digital	Digital	Digital
Only post cursor	**Pre and post cursor**	Only post cursor
Tx* or Rx	Tx* or Rx	**Rx**

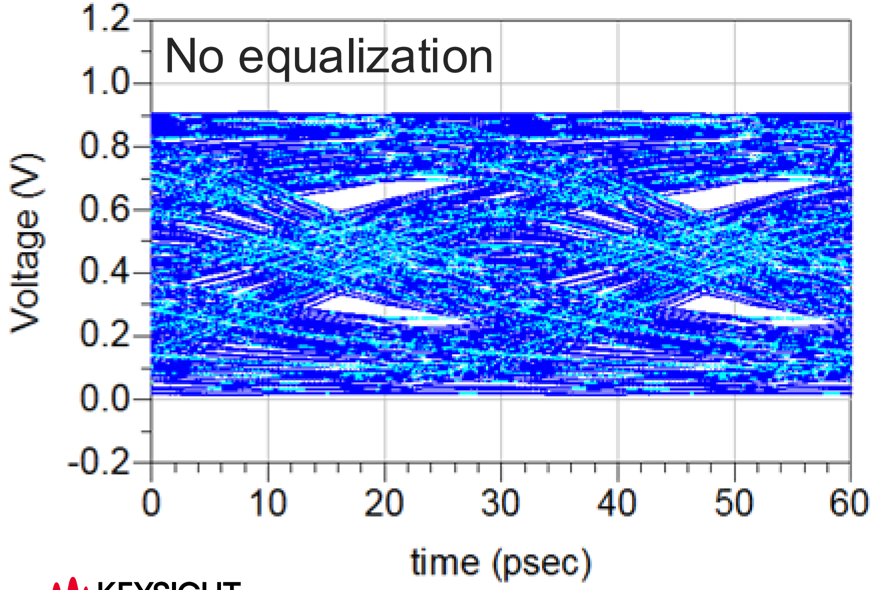
*Need a back channel

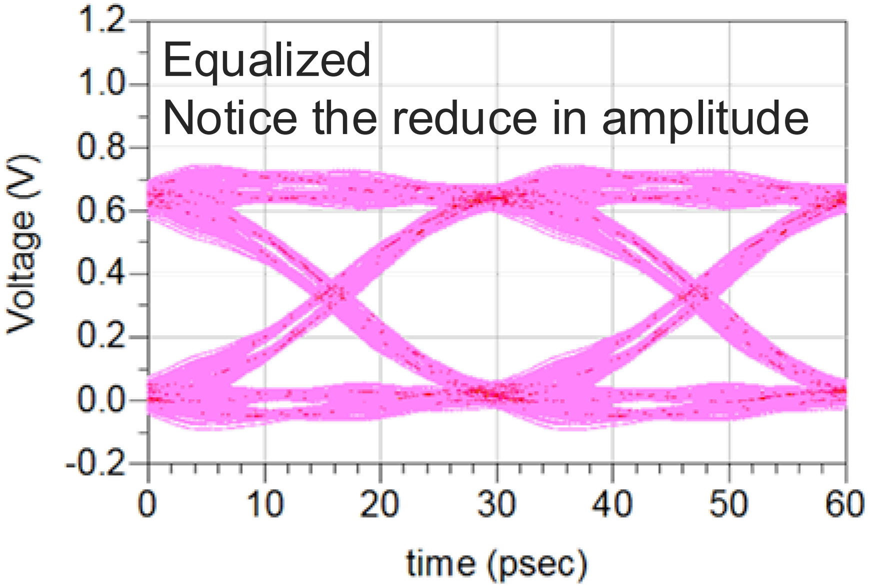
Continuous Time Linear Eq. (CTLE) As a High-pass Filter





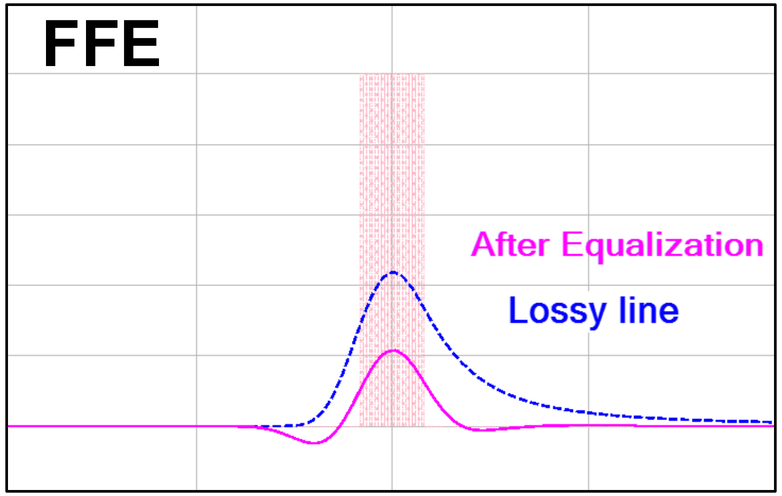


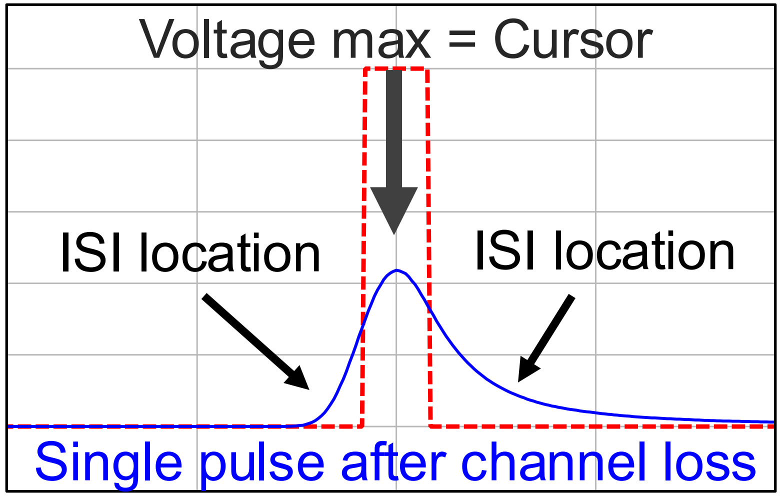


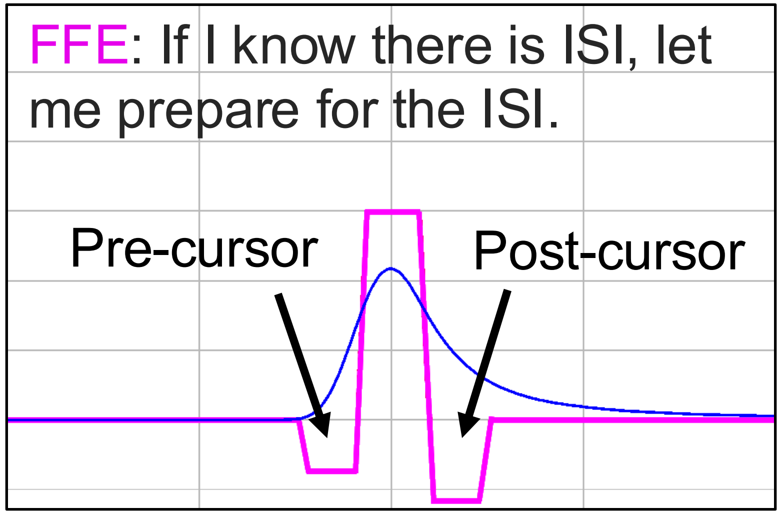


The goal of CTLE is to create a **high-pass** filter that complements the low-pass nature of the channel.

FFE Pre-distorted the Pulse to Counteract the ISI

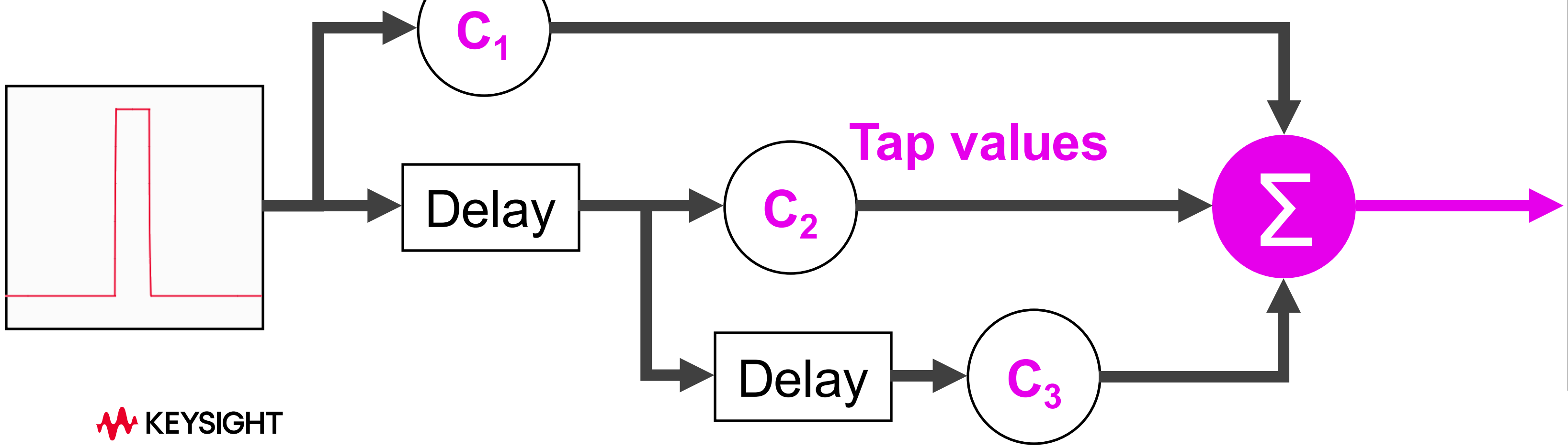


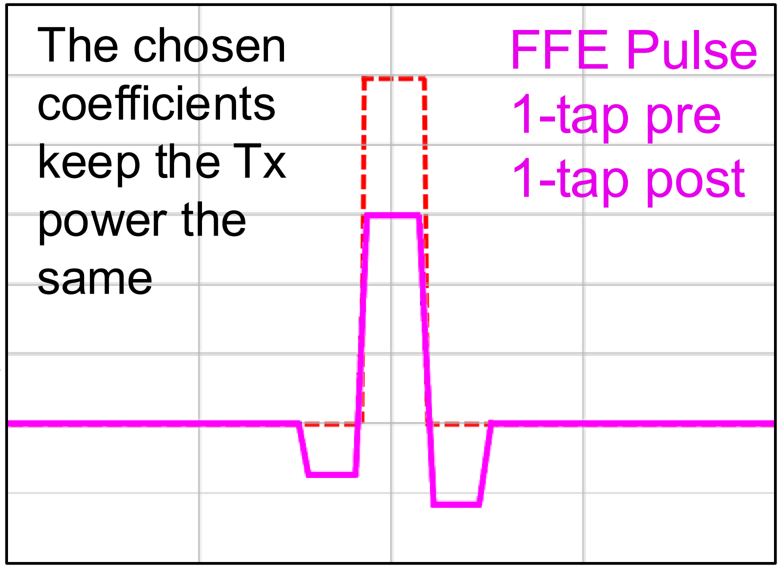




Feed-forward equalizer algorithm to create the pre-distorted pulse

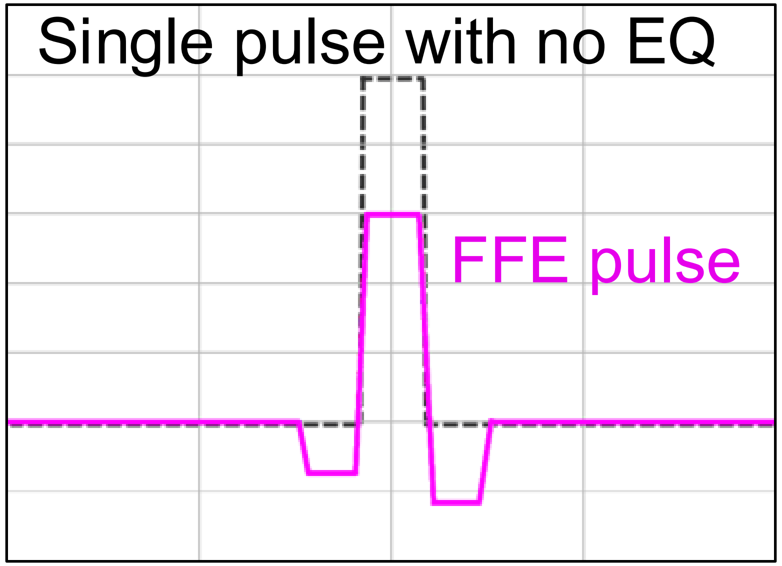
In the time domain, FFE pre-distorted the pulse to compensate for the ISI.



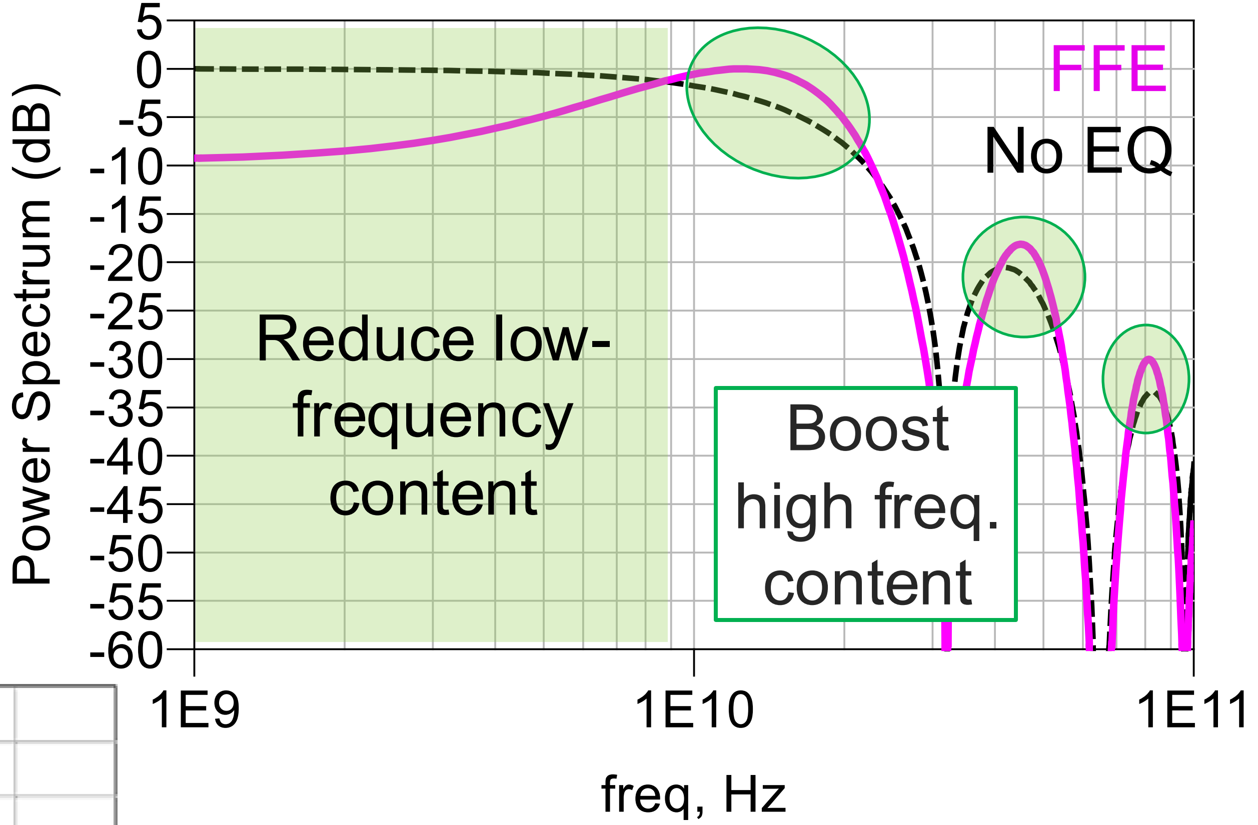


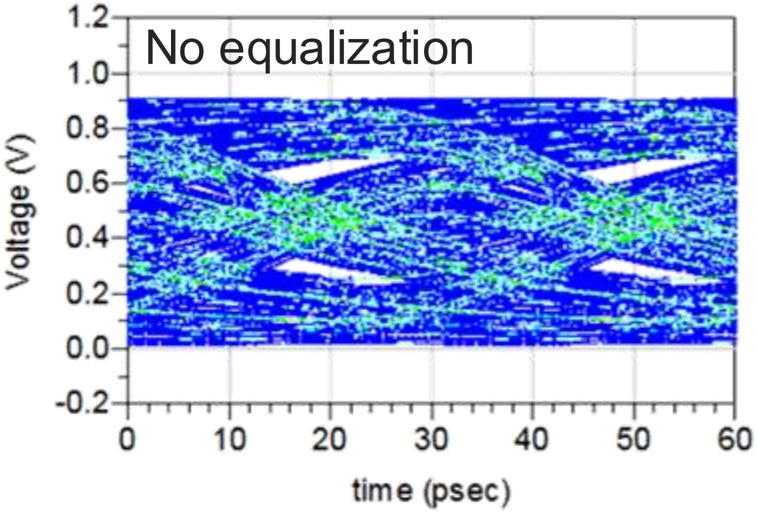
KEYSIGHT

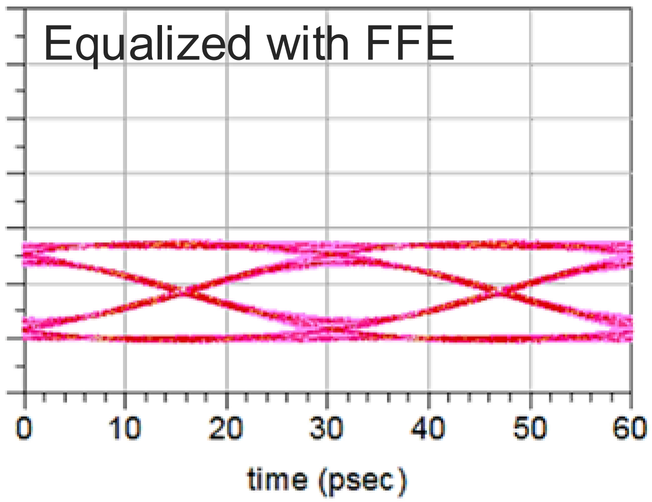
FFE Lowers the Low-Freq. Content and Add High Freq.



Fourier Transform



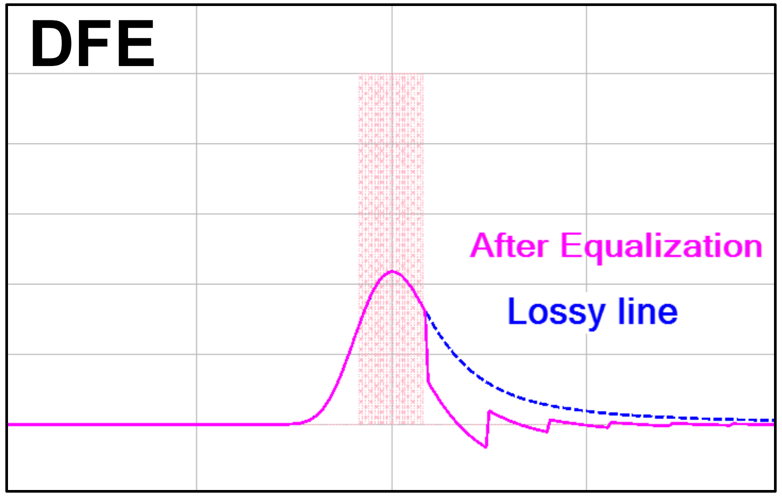




FFE pre-distorted the pulse to **reduce low frequency** content and **add more high frequency content** that complements the low-pass nature of the channel.

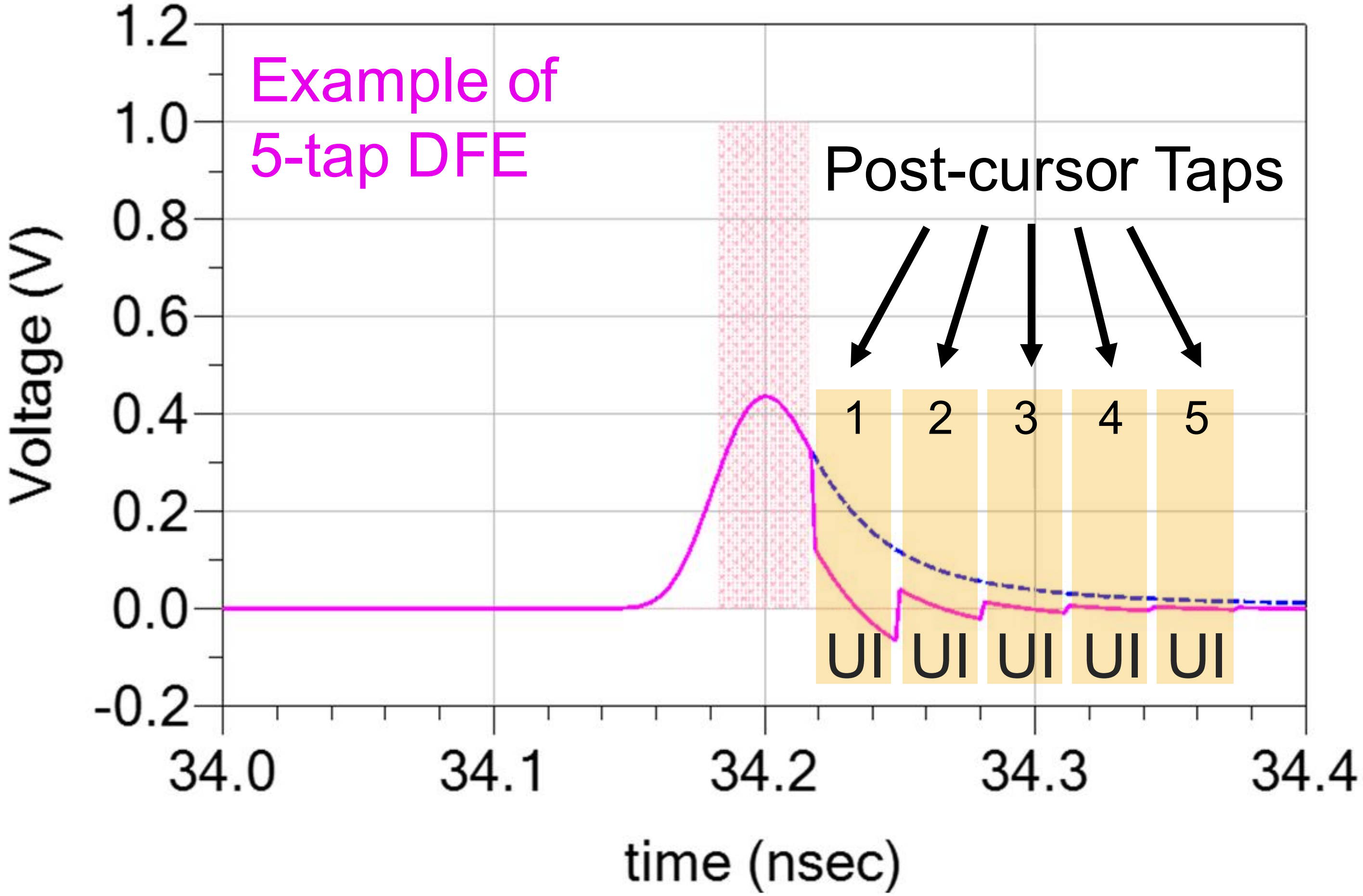
KEYSIGHT

DFE Uses Feedback Algorithm to Reduce Post-cursor ISI

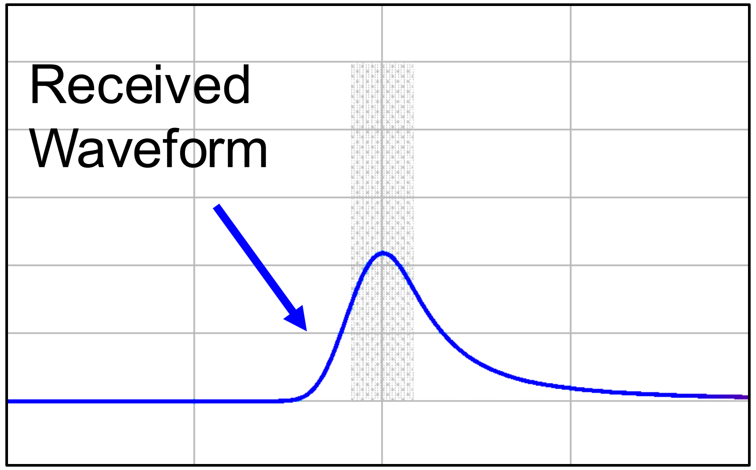


DFE adjusts the voltage level of the pulse. After locating the maximum value (cursor), the algorithm applies tap values to adjust the voltage level at selected post-cursors.

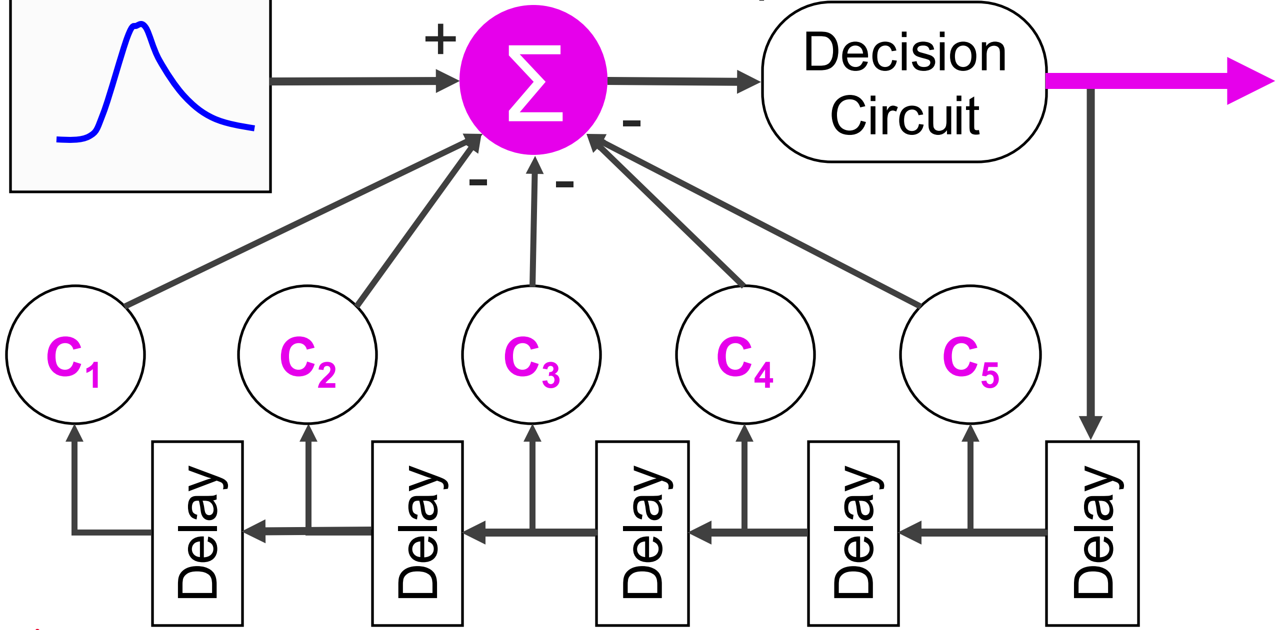
DFE: If I am seeing a "1", emphasize the next "0", vice versa.

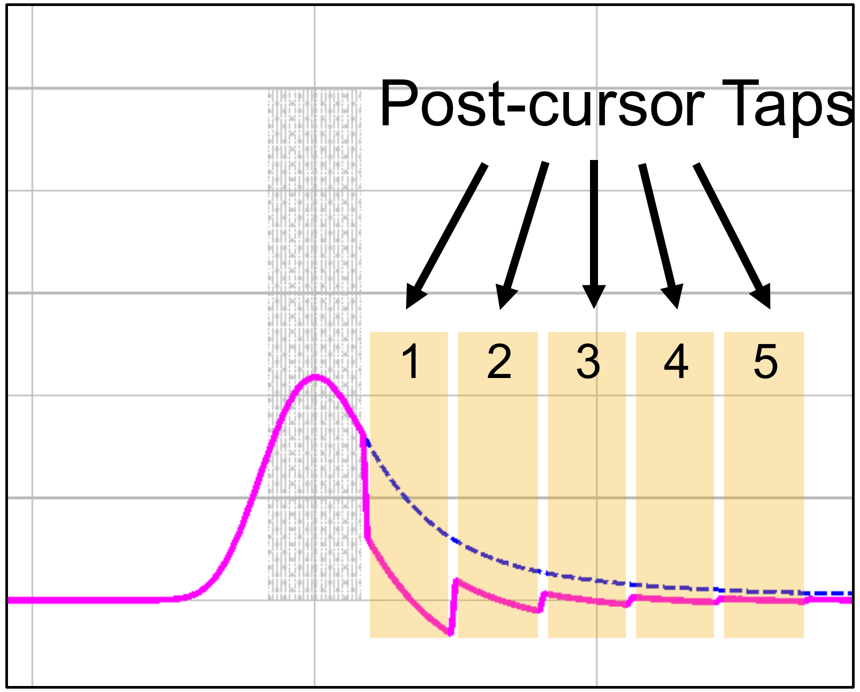


DFE Uses Feedback Algorithm to Reduce Post-cursor ISI



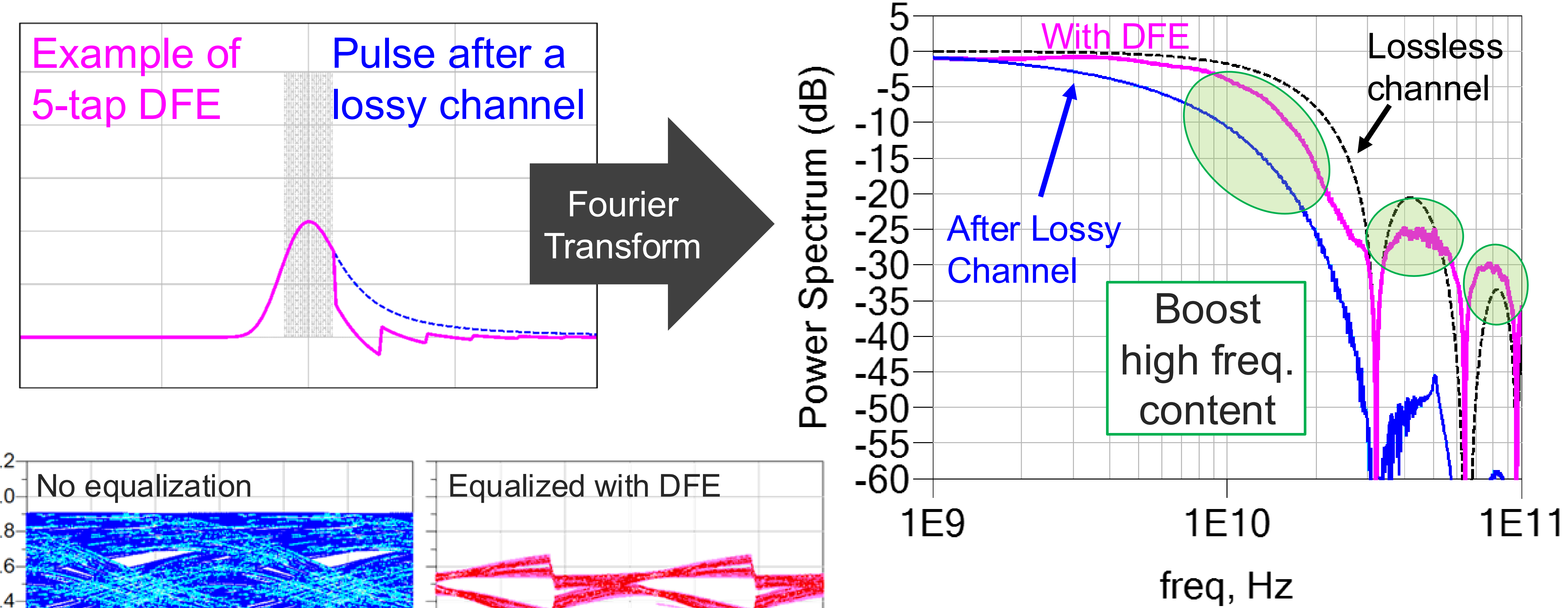
The decision process is non-linear.

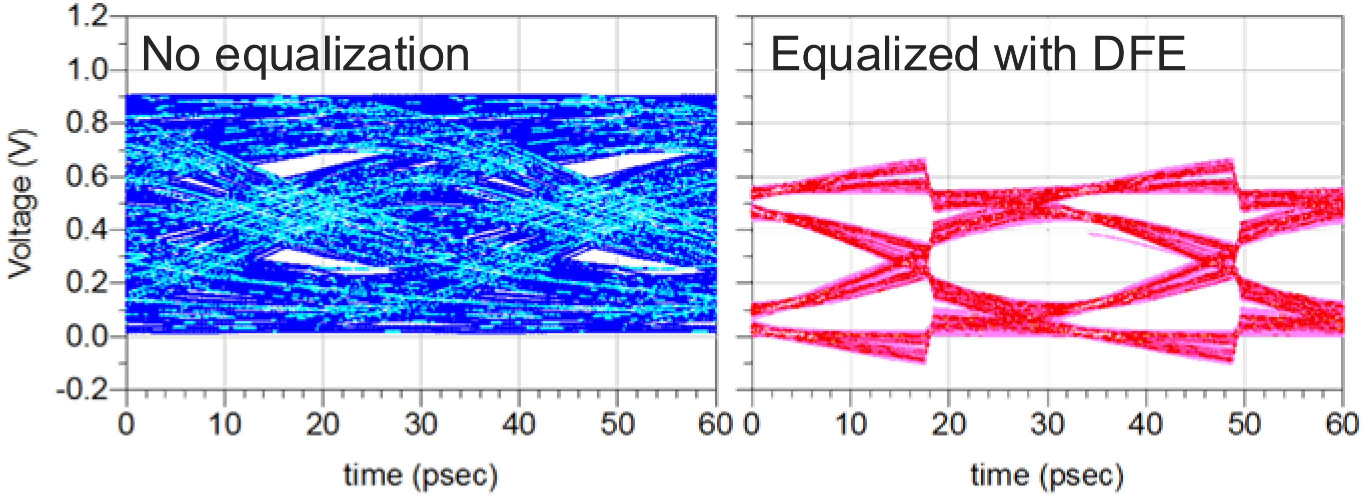




The decision circuit produces a symbol decision. The ISI is then directly subtracted by the feedback .

DFE Opens the Eye and Has a Signature When Applied

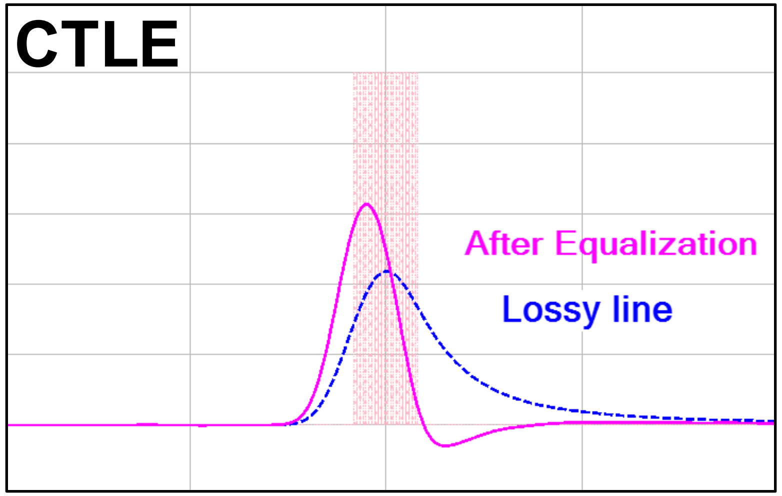


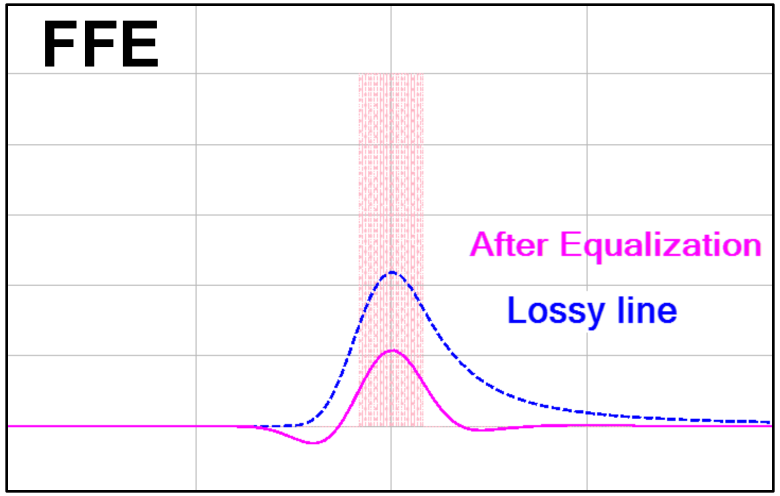


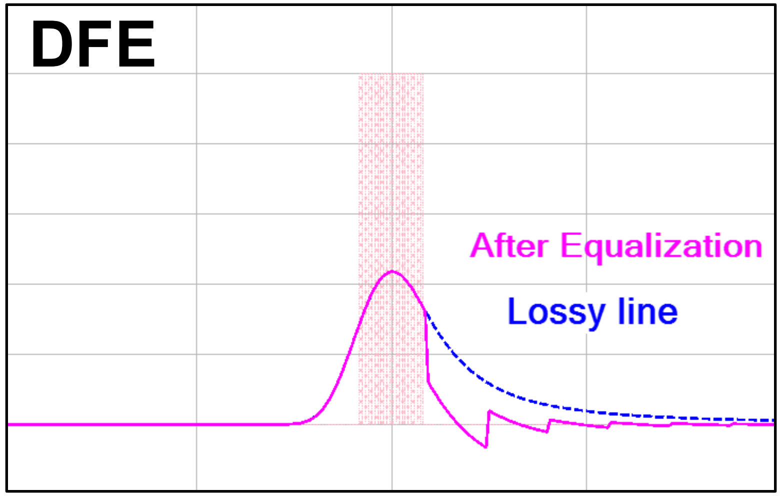
DFE adds more **high frequency content** that complements the low-pass nature of the channel.

KEYSIGHT

Equalization Is an Important Part of Channel SI Analysis

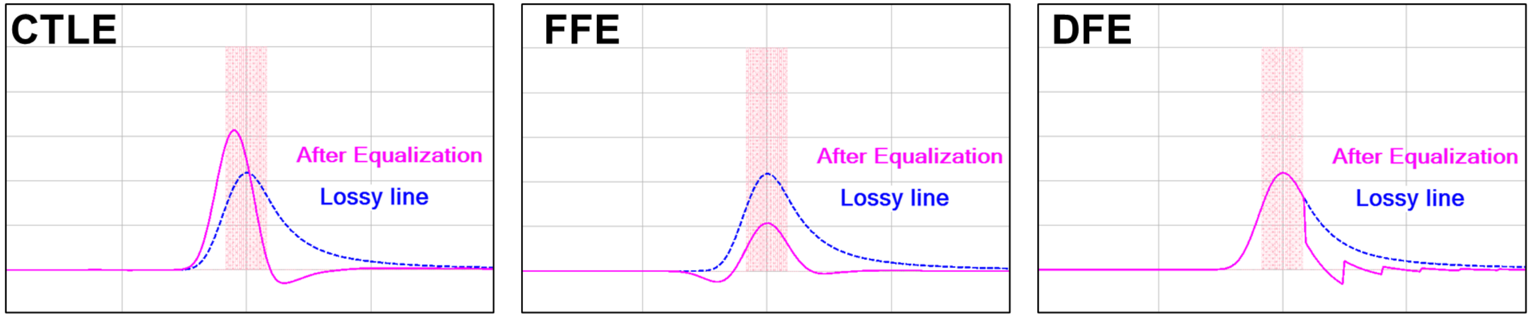






- EQ equalizes the frequency-dependent spectrum.
- Equalization at Tx can affect the system crosstalk level.
- ADS is the tool to simulate equalization and how it impacts the system

When in Doubt, Start the Equalization Configuration at the Rx



Start here!

Tx

Tx Equalization

- Power limitation
- Adaptation to channel
- System crosstalk level

+ Noise
+ Crosstalk voltage

Rx Equalization

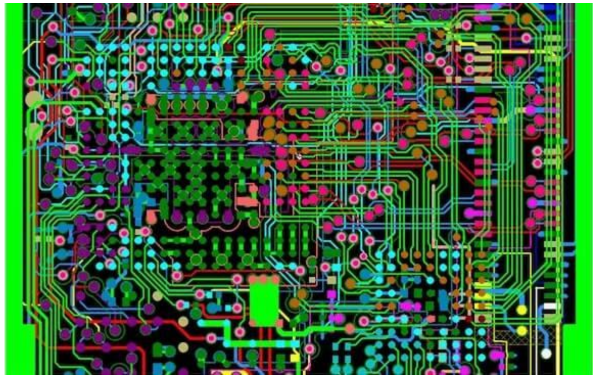
- Noise amplification
- Implementation complexity
- Signal to noise ratio

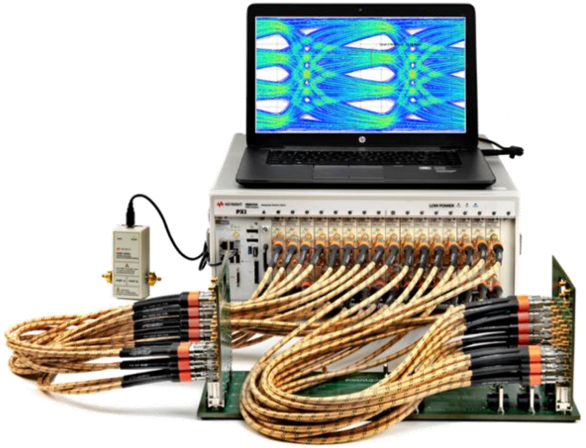
Rx

Since we have additional noise at Rx, we need to consider the signal-to-noise ratio. In general, it's preferable to start adjusting EQ at the Rx so we don't increase the system crosstalk voltage.

Why Electronic Design Automation

Traditional Design Process Is Too Costly When Design Fails





Create designs based on vendor guidance → Fabricate prototype → Measure and verify performance

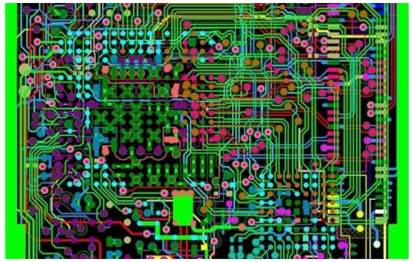
For a smartphone PCB, a re-spin can cost from $50,000 to $100,000 and many weeks of engineering time.
The traditional approach is inefficient, expensive, and likely to miss the time-to-market.

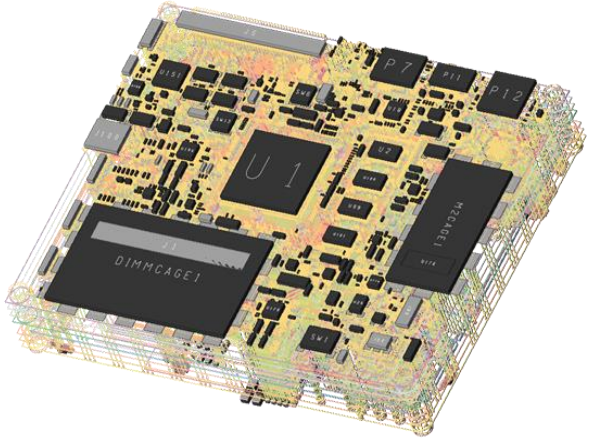
When a design fails

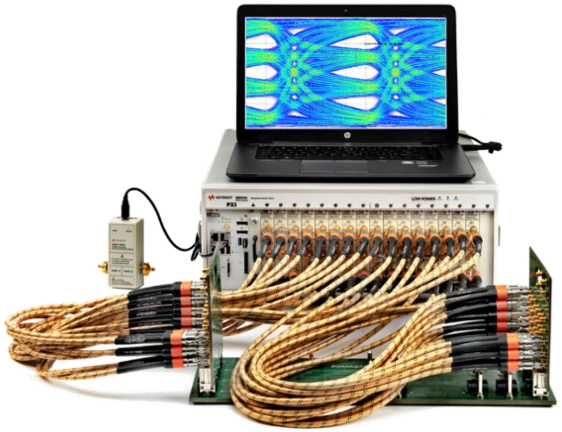
Modify Design

Weeks of time and money

Cost-Efficient Process with Electronic Design Automation







Create Virtual Design Prototype → Simulate and Validate Prototype → Fabricate Prototype → Measure and Verify Performance

When a design fails

Modify Design

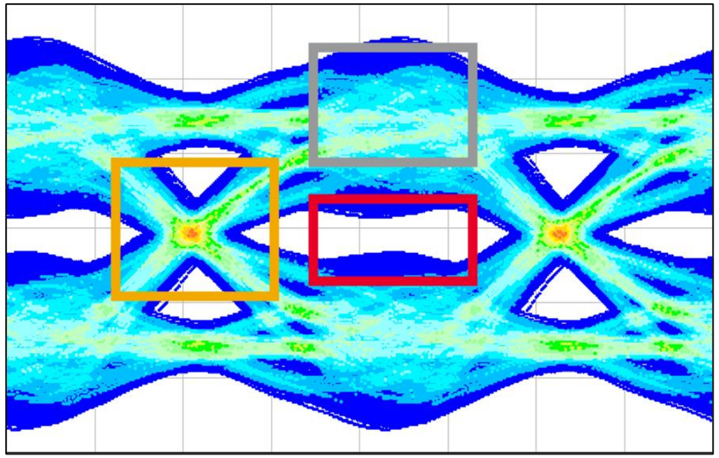
~~Weeks~~ Hours of time

By adding EDA to the design cycle, one can detect performance issues early on, save a lot of time and money, and, most importantly, get the product to market before anyone else.

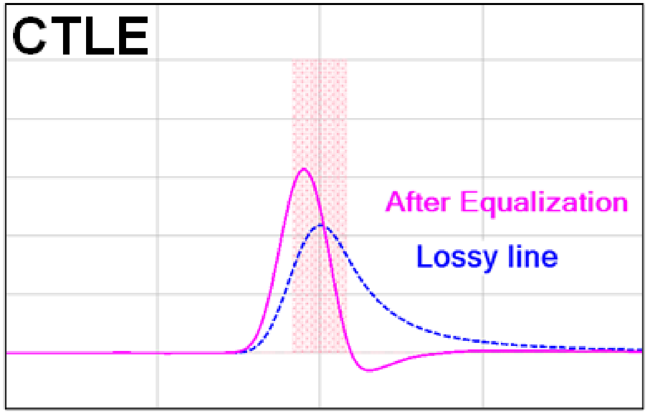
Keysight ADS Demo Video

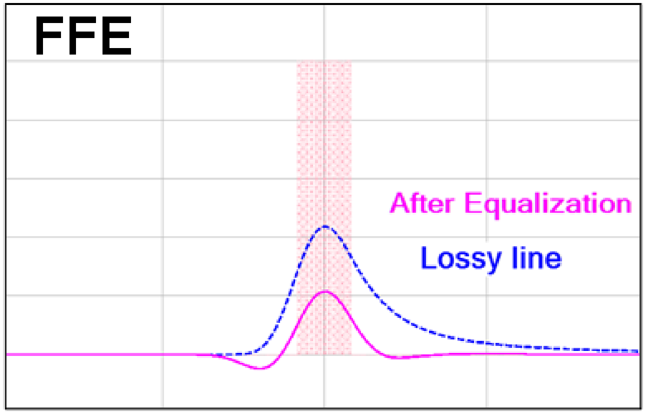
Summary

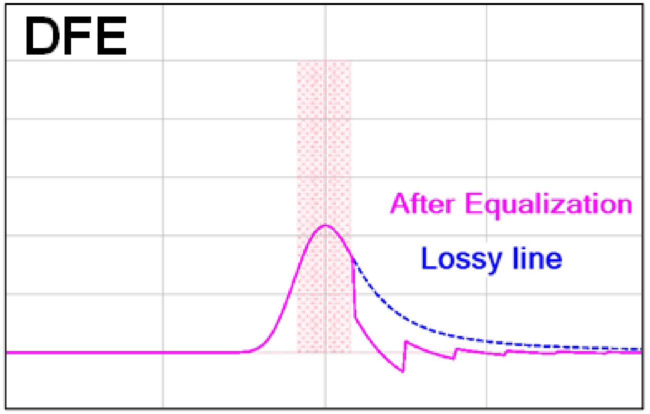
Find the Root Cause to Solve all Signal Integrity Problems



1. Signs of reflection
2. Signs of crosstalk
3. Signs of frequency-dependent loss







Rule Number 9: Anticipate Before You Measure or Simulate

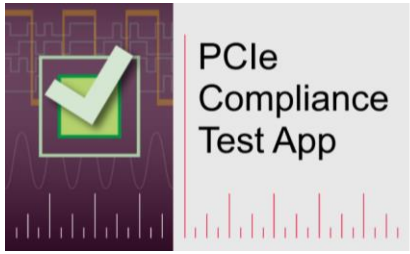
Why You Should Design Digital Systems with Keysight

Standard-focused and Compliance

Improve productivity, ensure interoperability

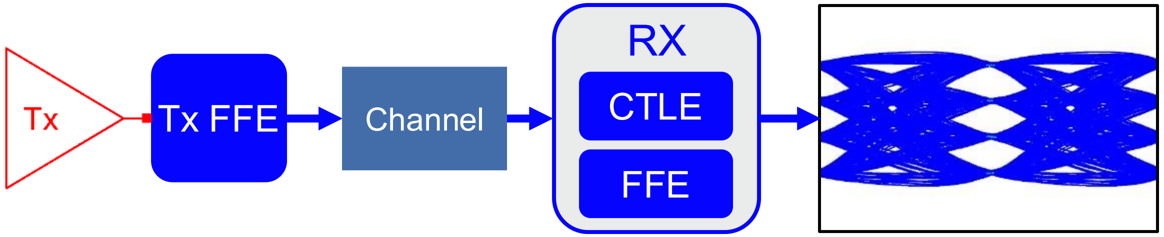
DDR

UCIe™
Universal Chiplet
Interconnect Express



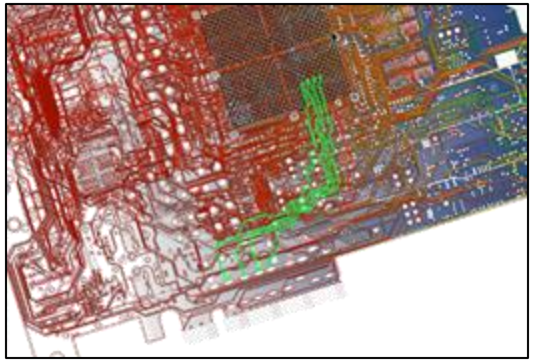
End-to-end Physical Analysis

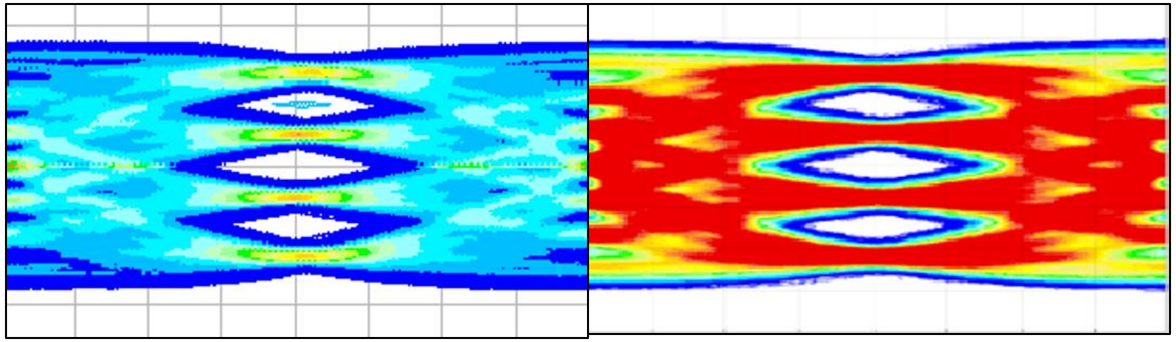
Identify system level issues, optimize performance



Simulation and Measurement Solutions

Enable practical design validation, secure first-pass design success





Simulate your digital system with ADS2025 Update 2

Thank you