Signal Integrity Seminar

Oscilloscope Measurements

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Contents

- Oscilloscopes and their parameters
- Probes, probe loading minimization

- HW accelerated eye and clock recovery
- Jitter measurements
- Equalization and Embedding/De-embedding
- Crosstalk measurement and characterization

Oscilloscopes and their parameters

Real-time vs. Equivalent-sampling

Parameters vs. performance

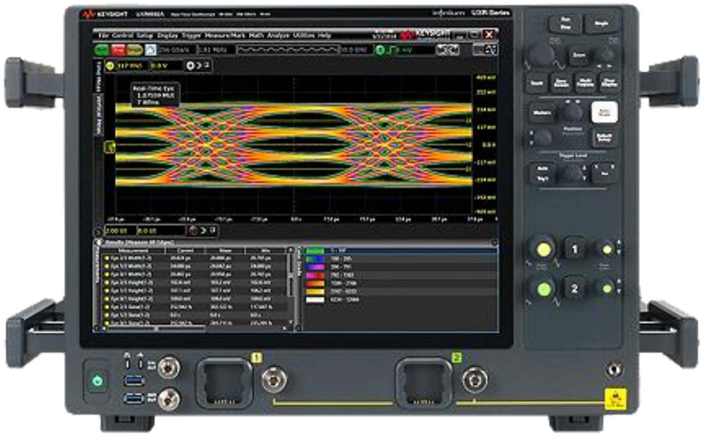
Oscilloscopes

- Capture behavior of an electrical signal in time
- **DSO** = Digital Storage Oscilloscope
  - Samples & displays analog signal

DUT → Probe → Analog Front-end → A/D → Digital storage → Display

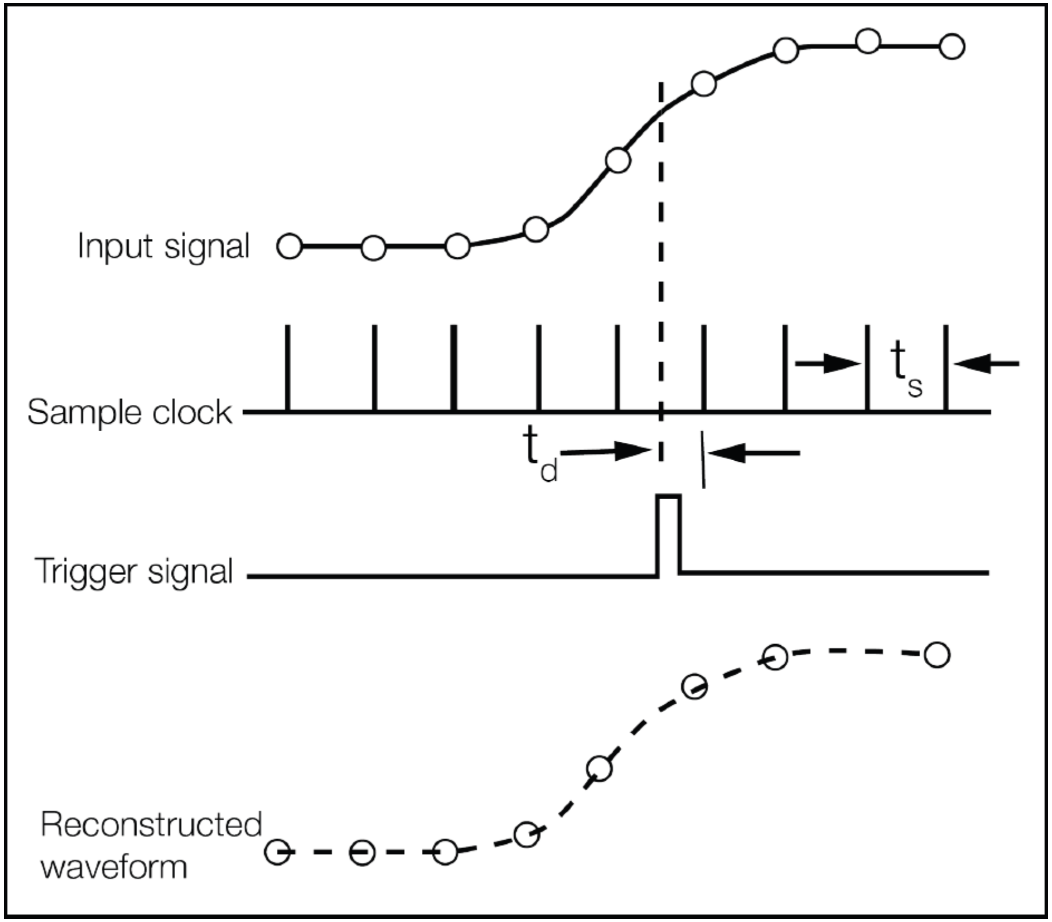
Oscilloscope types

- Real-time Scope
  - Single-shot capture with high sample rate (up to 256 GSa/s)
  - Behaves similarly to „Fast ADC“
  - Suitable for most signals



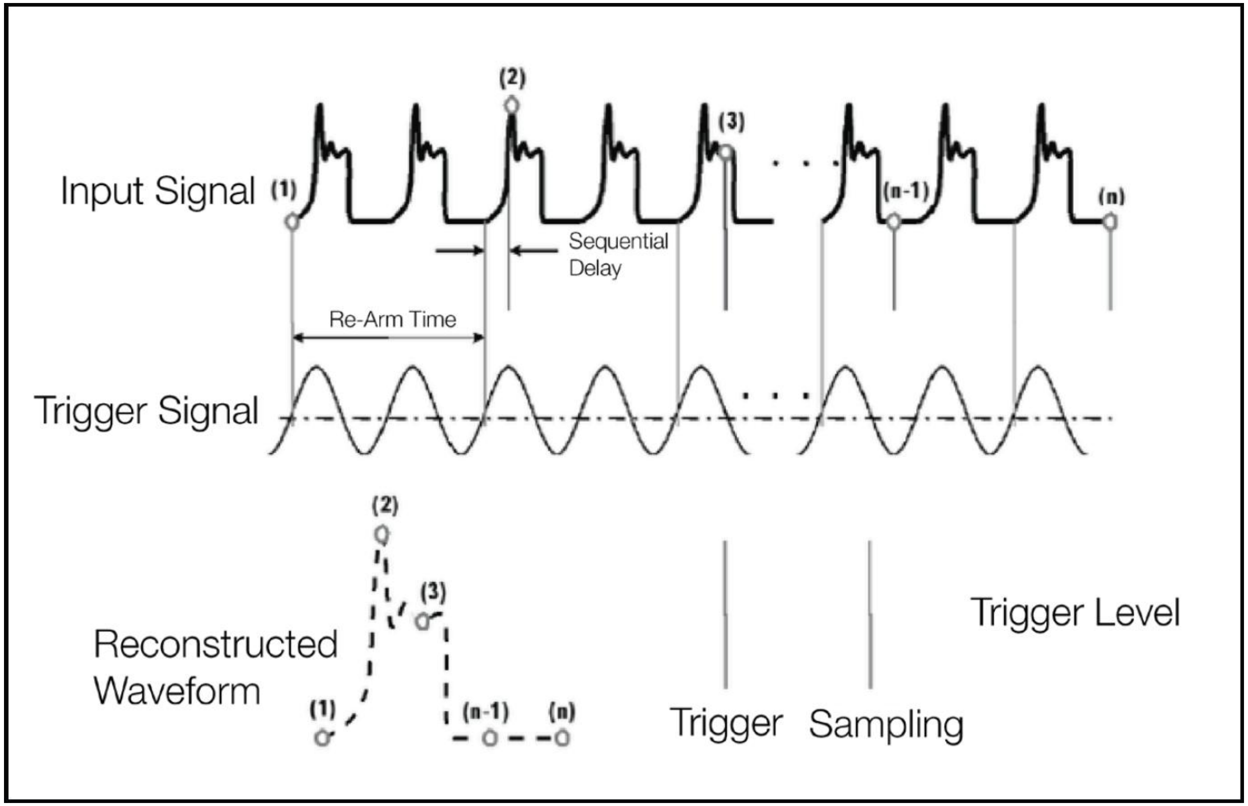
- Equivalent-time sampling scope
  - Low sample rate (typ. <100 MSa/s)
  - Each sample taken from different signal period, then signal is reconstructed
  - Only for periodic signals

Real-time oscilloscopes



Sampling rate >> Signal frequency

Equivalent-time sampling oscilloscopes



Sampling rate << Signal frequency

Real-Time vs. Equivalent-sampling advantages

Real-time Oscilloscope	Equivalent-sampling Oscilloscope
• Captures one-time transients	• Higher resolution ADC (16bit vs. 10bit)
• No explicit trigger needed	• Wider bandwidth
• Does not require a repetitive waveform	• Lower noise floor
• Cycle to cycle jitter direct measurement	• Lower intrinsic jitter
• Large record lengths	• Can include front end optical modules
• Up to 110 GHz	• Only solution for frequencies above 110 GHz
• Great for troubleshooting	• Can achieve solutions at a reduced cost (~90k$ vs. 1M$ at 100 GHz)

Oscilloscope parameters

- ADC Number of bits
- **ENOB**:
  - Effective Number Of Bits
  - (ADC ENOB
    vs. System ENOB)

Oscilloscope	ADC-bits	ENOB at 1GHz
Keysight MXR	10 bits	8,0 bits
Manufacturer 1	12 bits	8,4 bits
Manufacturer 2	12 bits	8,45 bits

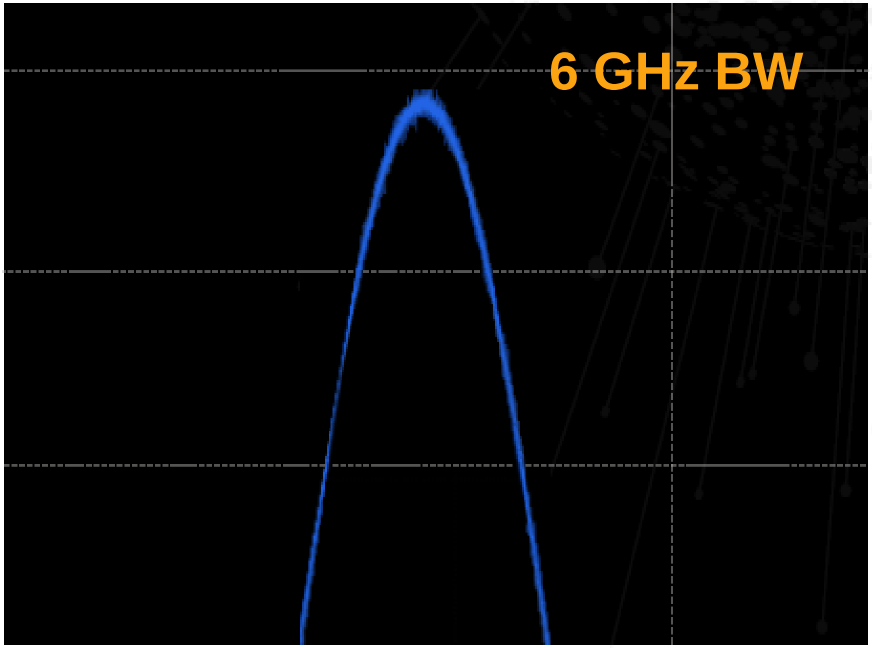
- **Bandwidth** – should be sufficient but not too wide
- **Frequency characteristic** – should be flat
- **Sampling frequency**

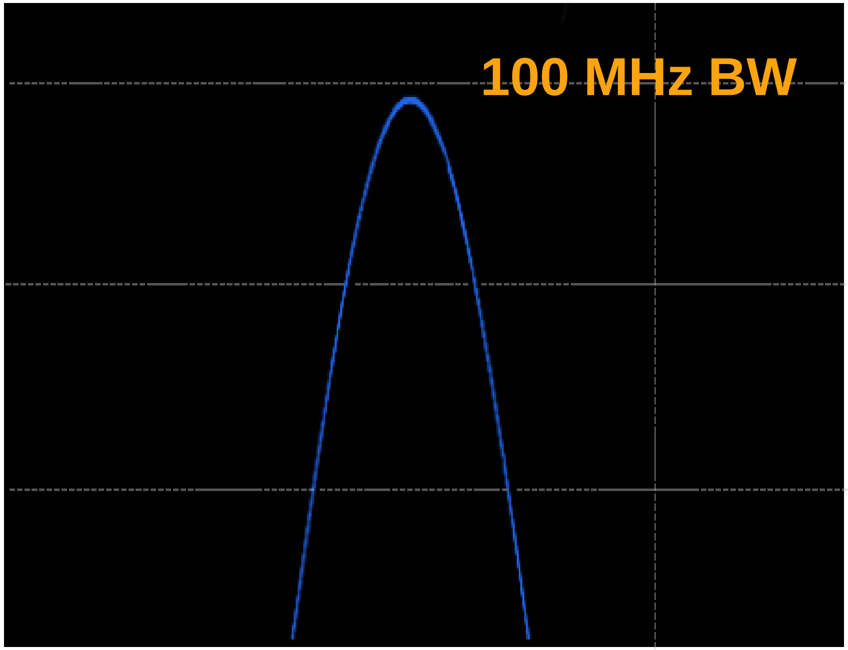
- **Noise floor** – varies with DC offsets

Bandwidth choice

Optimal choice depends on the measured signal.

Example: noise at 20 MHz sinewave





Noise power: $P_N = kTB$ is proportional to bandwidth B

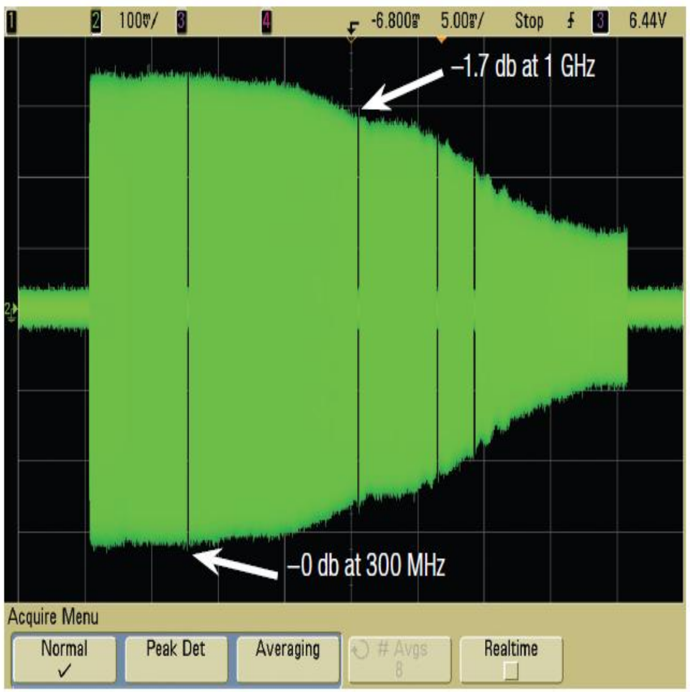
Keysight scopes are able to reduce bandwidth by both HW and SW filters!

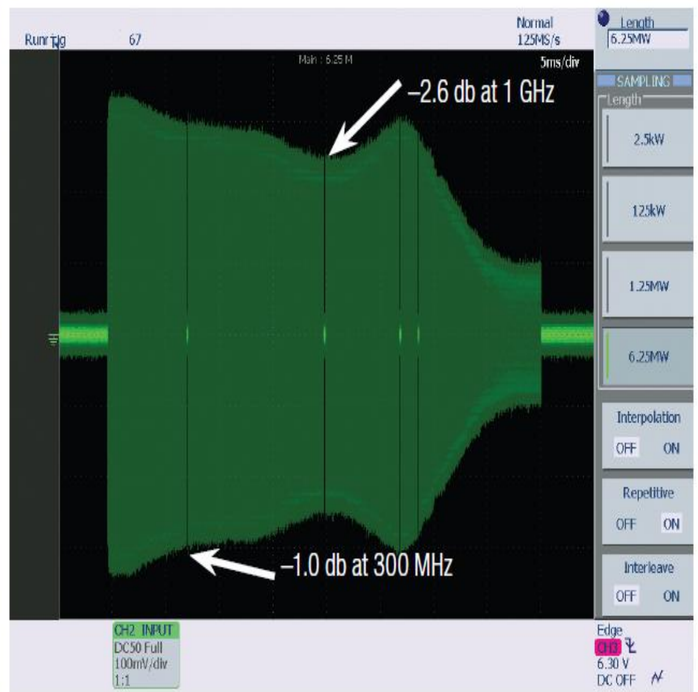
Frequency response flatness

20 MHz to 2 GHz frequency chirp

Both oscilloscopes with 1 GHz bandwidth

Keysight





Other manfacturer

Protocols and frequencies

Protocol	Symbol rate	Scope Bandwidth	Application
Ethernet 1000BASE-T	125 MBd (4 páry)	>= 1 GHz	LAN
Ethernet 1000BASE-T1	750 MBd (1 pár)	>= 2.5GHz	Automotive, IoT
USB 2.0	480 Mbd (Mbit/s)	>=2 GHz	
USB 3.2	5 Gbit/s (10 Gbit/s Gen2)	>=13 GHz (16 GHz Gen2)	
USB 4	20 Gbit/s	>=33 GHz	
DDR4-3200	3200 GT/s	>= 13 GHz	
DDR5-7200	7200 GT/s	>= 16 GHz	
CAN (FD)	1 Mbit/s (15 Mbit/s)	>= 50 MHz (100 MHz)	Automotive
I2C	5 Mbit/s	>= 70 MHz	Embedded

Oscilloscope Probes

Connection to circuit

Probe loading

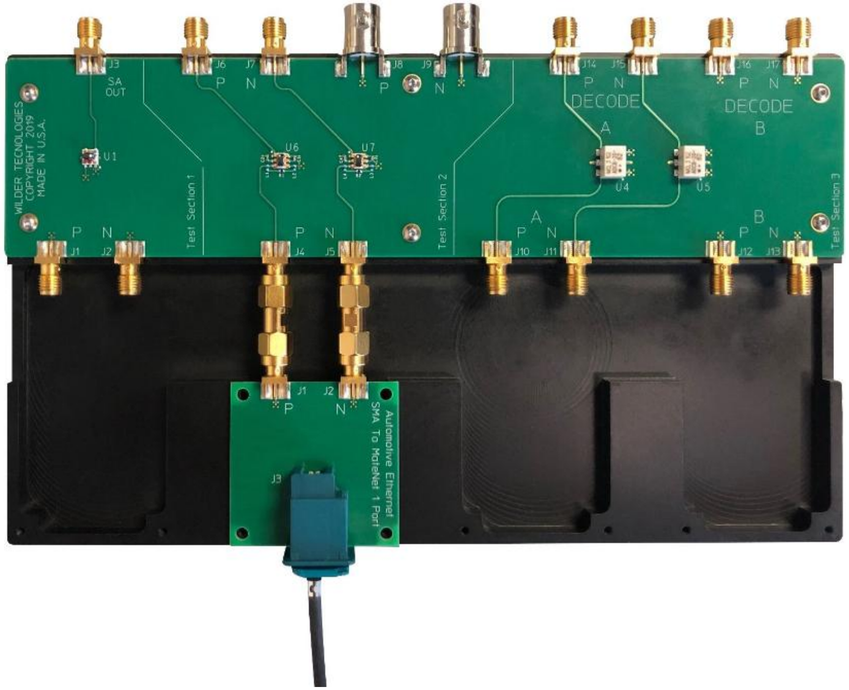
Review of probes

Connection to the circuit: the options

1. Connectors:
   - Coaxial cables/connectors – size depends on frequency
   - 1mm (up to 110 GHz), Precision BNC (up to 18-20 GHz)
2. Fixtures:
   - Interface for a particular device or connector
3. Probes

Fixture examples

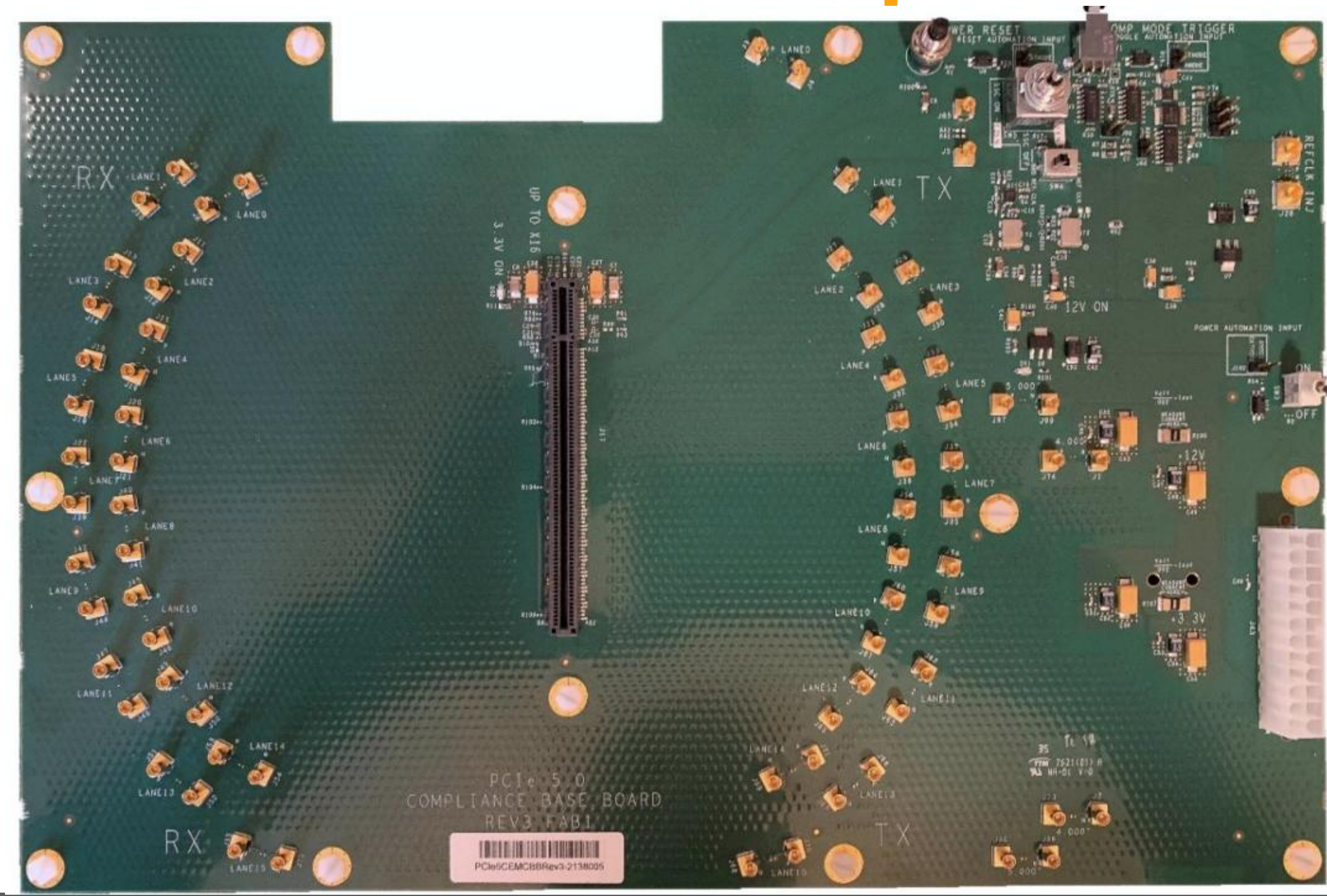
AE6941A Automotive Ethernet Test Fixture



U7242A USB 3.0 Test Fixture

N5395C Ethernet 10/100/1G Tx Test Fixture

Fixture examples



Ideal probe

- Reaches any point of DUT
- Presents perfect signal replica
- Infinite range, resolution and without noise
- Does not affect the probed circuit

- Ideal probe does not exist!

Scope vs. System bandwidth

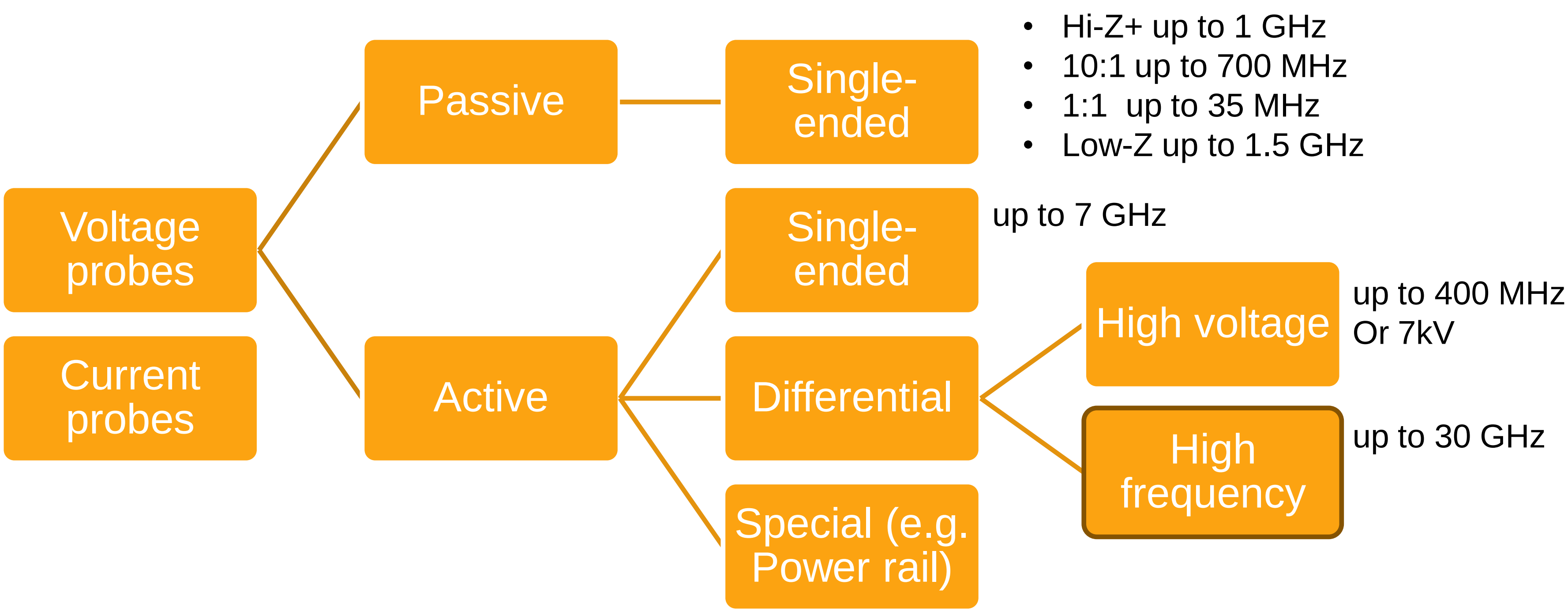
- Oscilloscope + probe are a system, both limit the performance

$$BW_{system} = \frac{1}{\sqrt{\frac{1}{(BW_{scope})^2} + \frac{1}{(BW_{probe})^2}}}$$

- $\sqrt{2}$-factor BW reduction, when $BW_{scope} = BW_{probe}$
- Examples:
  - 300 MHz probe, 500MHz scope → 257 MHz system
  - 1GHz probe, 1GHz scope → 707 MHz system

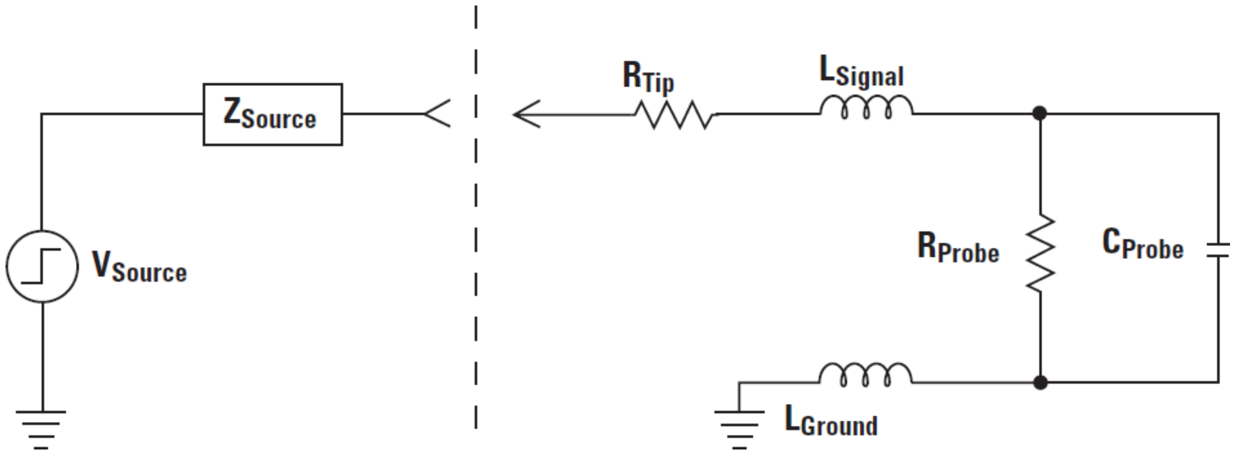
- Rule of thumb:
  Rise time (10-90%) [µs] × 3db Bandwidth (MHz) = 0.35
  - 1 GHz BW ↔ 0,35 ns maximal rise time

Probe types


Voltage probes
Current probes
Passive
Active
Single-ended
• Hi-Z+ up to 1 GHz
• 10:1 up to 700 MHz
• 1:1 up to 35 MHz
• Low-Z up to 1.5 GHz
Single-ended
up to 7 GHz
Differential
Special (e.g. Power rail)
High voltage
up to 400 MHz
Or 7kV
High frequency
up to 30 GHz

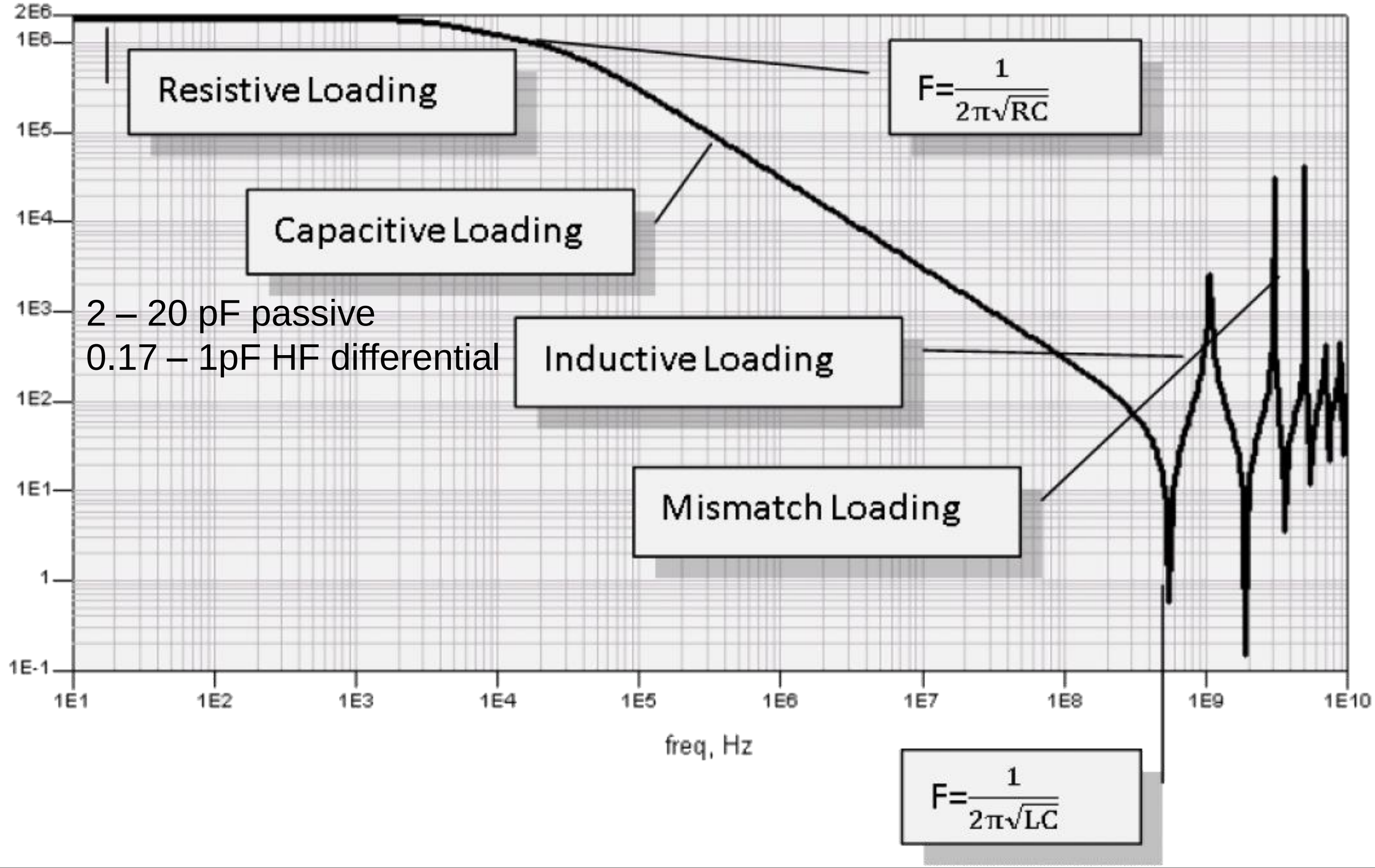
Real probe

- Distorts the signal – Depends on probe frequency response
- Loads probed circuit = Probe Loading
- Requires leads to signals and possibly ground (single-ended)



Probe Loading

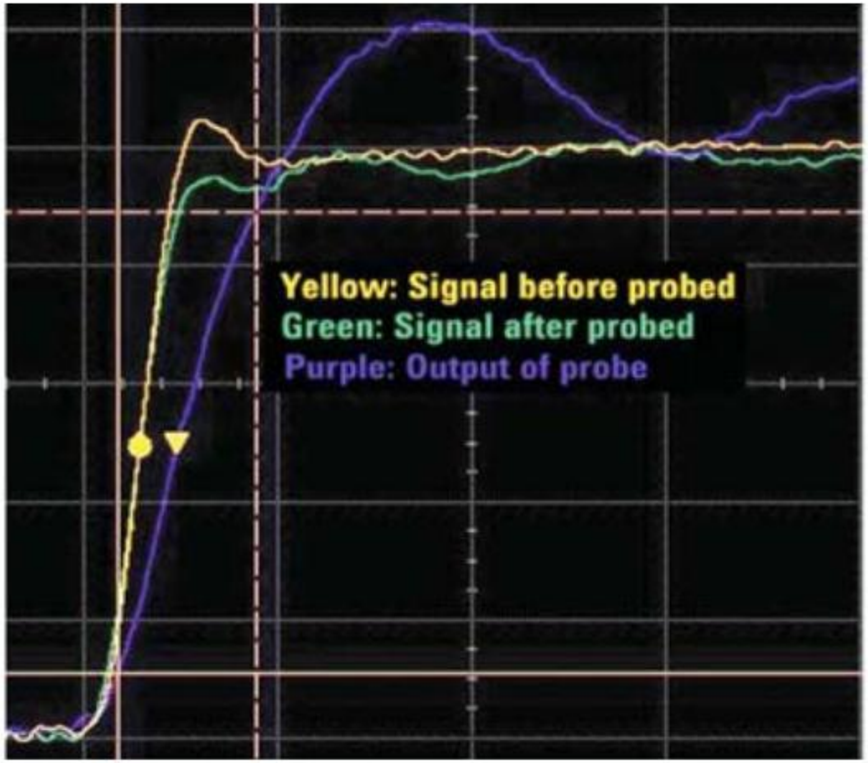
≥10MΩ passive
50 – 100kΩ HF differential



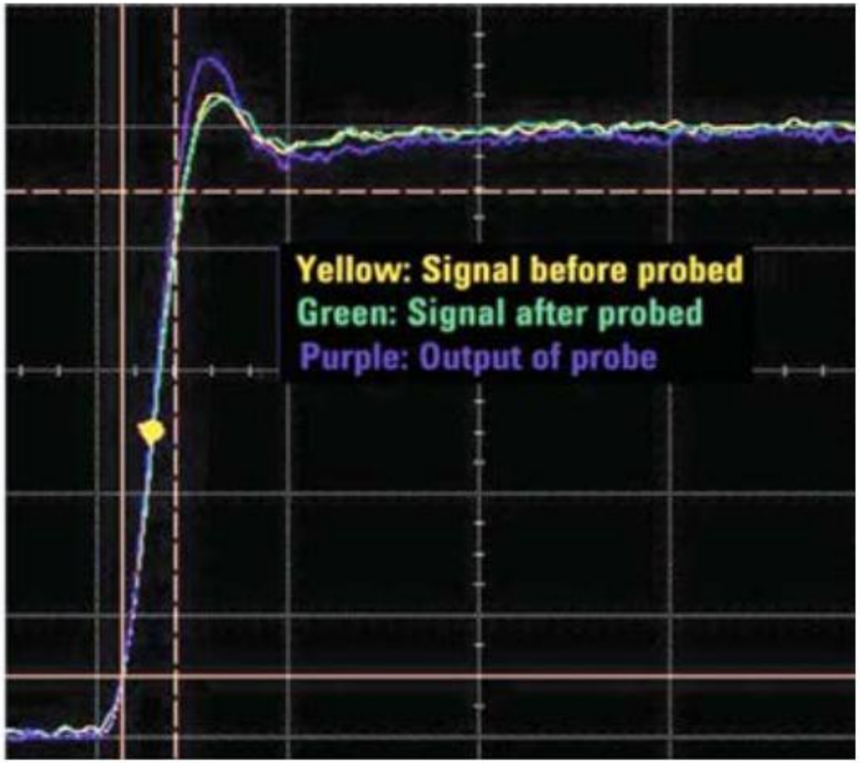
2 – 20 pF passive
0.17 – 1pF HF differential

Probe Loading

N2873A 500-MHz passive probe
15-cm alligator ground lead:



N2796A 2-GHz active probe
1.8-cm ground lead:

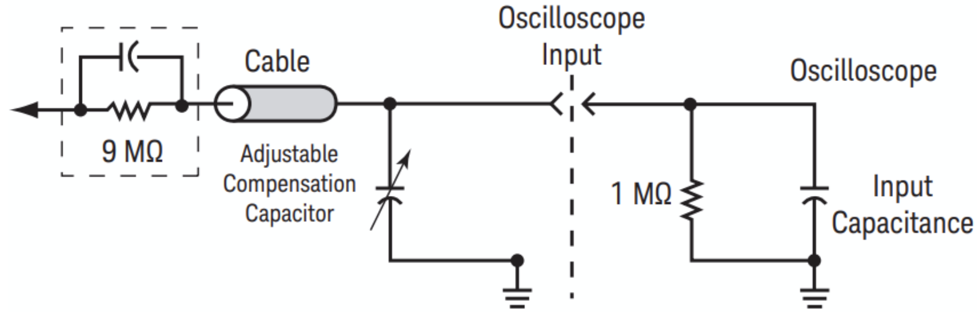


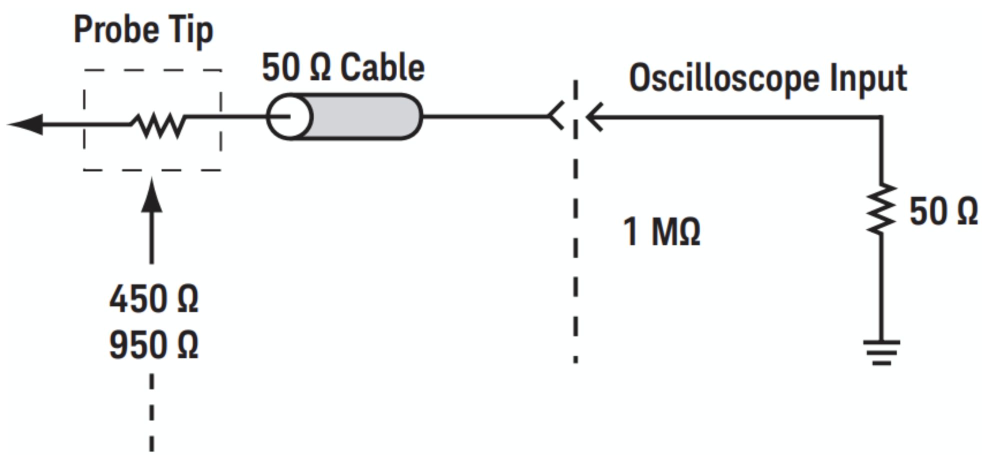
Passive Probes

Passive Probes

- Rugged
- Inexpensive
- Wide dynamic range

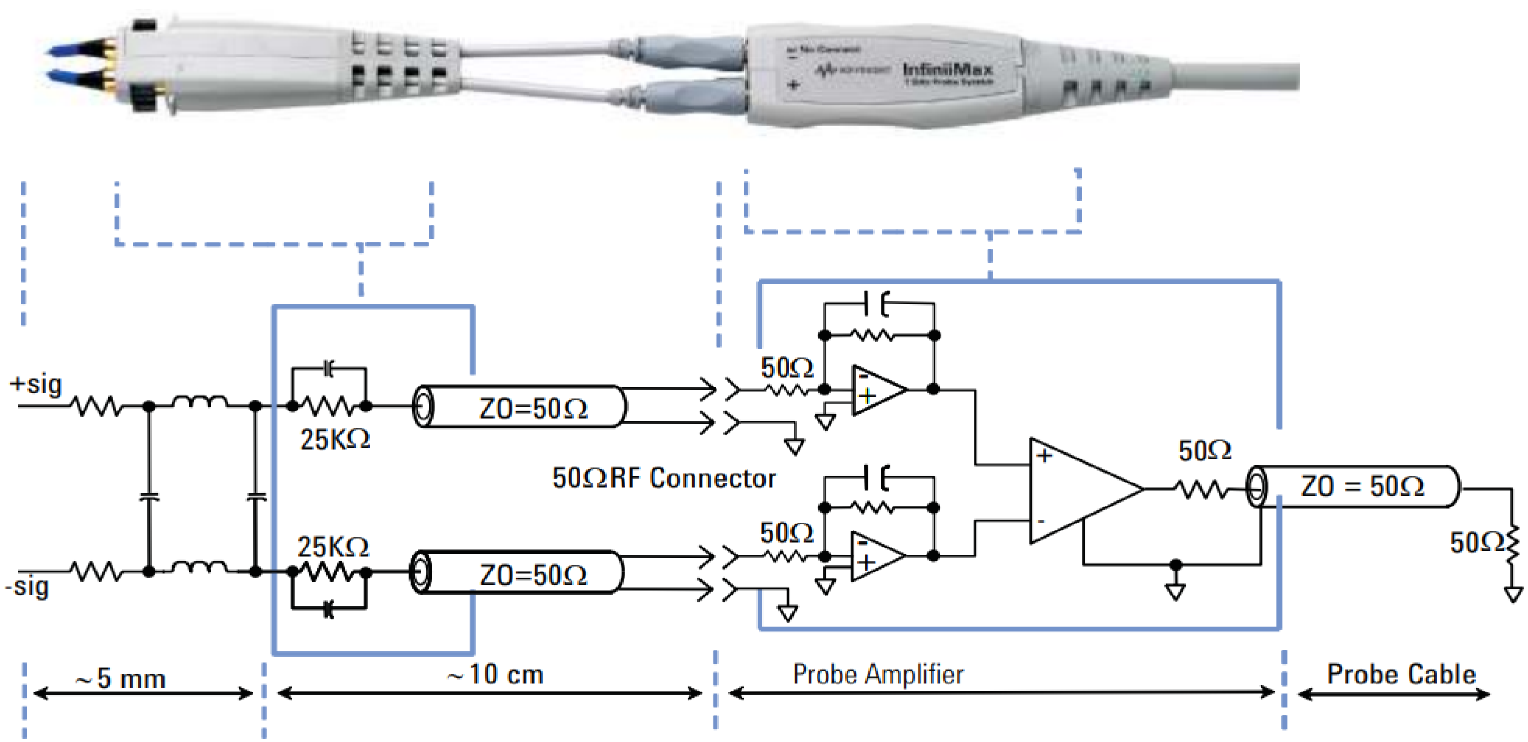
- High impedance
  - High capacitance loading
  - Up to 1 GHz
- Low impedance
  - Require 50Ω scope input
  - Low C/high R loading
  - Up to 1,5 GHz





Active probes

- Less parasitics
- More expensive
- Both differential and single-ended



InfiniiMax vs. InfiniiMode Active probes

InfiniiMax

- Up to 30 GHz bandwidth
- A-B, A, B, (A+B)/2 modes
- Modular system
- Solder-in, browser, socketed tips
- Lowest probe loading
- S-parameter corrections
- Damping resistor tips

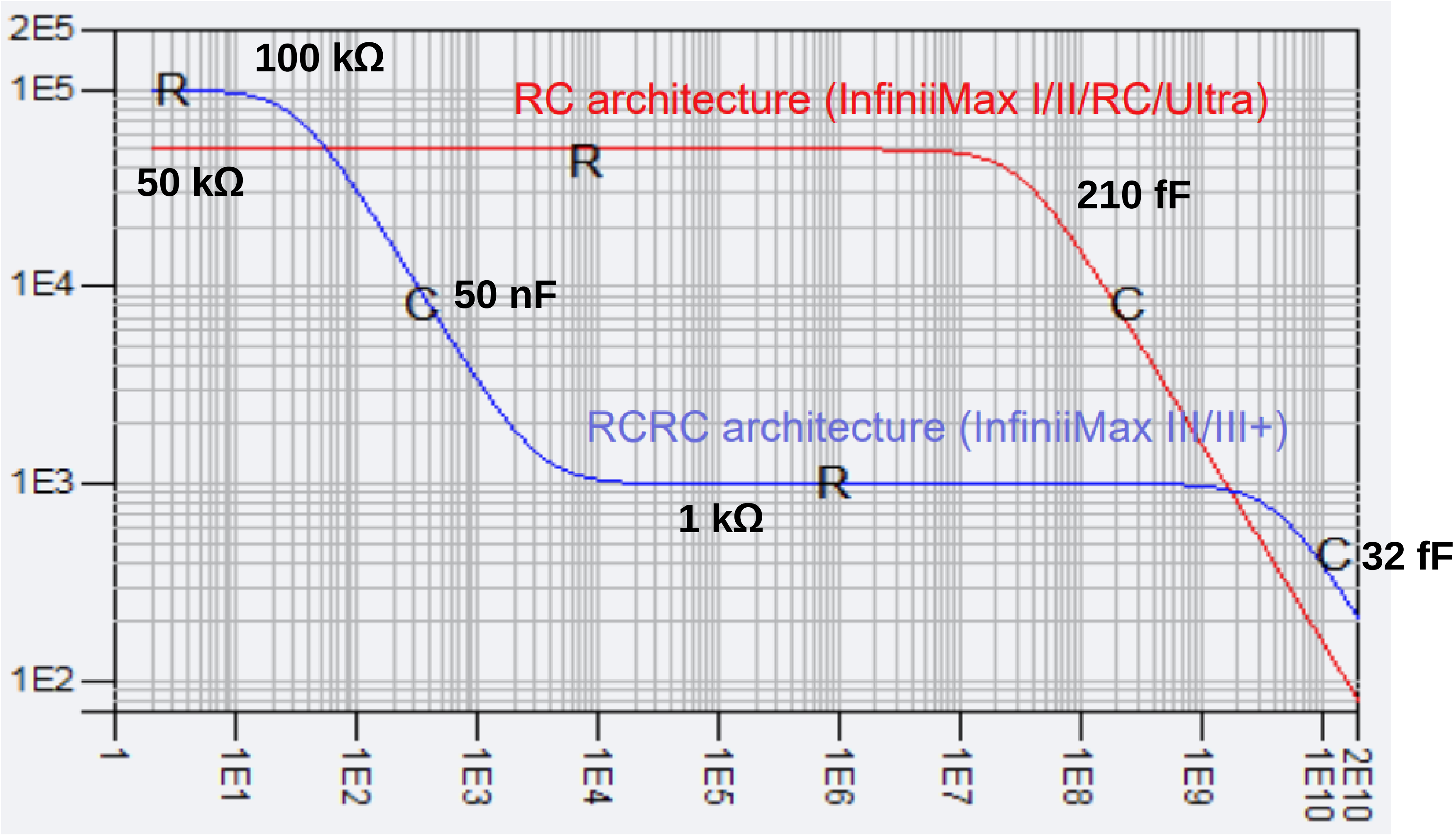
InfiniiMode

- 1,5 – 6 GHz bandwidth
- A-B, A, B, (A+B)/2 modes
- Solder-in, browser, socketed tips
- Dual attenuation ratio (2:1,10:1)
- Cost effective

InfiniiMax probe family

	InfiniiMax I 1130B-34B	InfiniiMax II 1168B/69B	InfiniiMax III N2801A-03A	InfiniiMax III+ N2830A-32A N7000A-03A	InfiniiMax RC MX0023A	InfiniiMax Ultra MX0020-25A
Probe interface	AutoProbe I	AutoProbe I	AutoProbe II	AutoProbe I or II	AutoProbe II	AutoProbe II
1.5 GHz	1130B					
3.5 GHz	1131B					
4 GHz				N2830A (IM)		
5 GHz	1132B					
7 GHz	1134B					
8 GHz				N2831A (IM) N7000A (IM)		
10 GHz		1168B				MX0020A (IM)
13 GHz		1169B		N2832A (IM) N7001A (IM)		MX0021A (IM)
16 GHz				N7002A (IM)		MX0022A (IM)
20 GHz			N2801A	N7003A (IM)		MX0024A (IM)
25 GHz			N2802A		MX0023A	MX0025A (IM)
30 GHz			N2803A			

RCRC vs. RC impedance profile



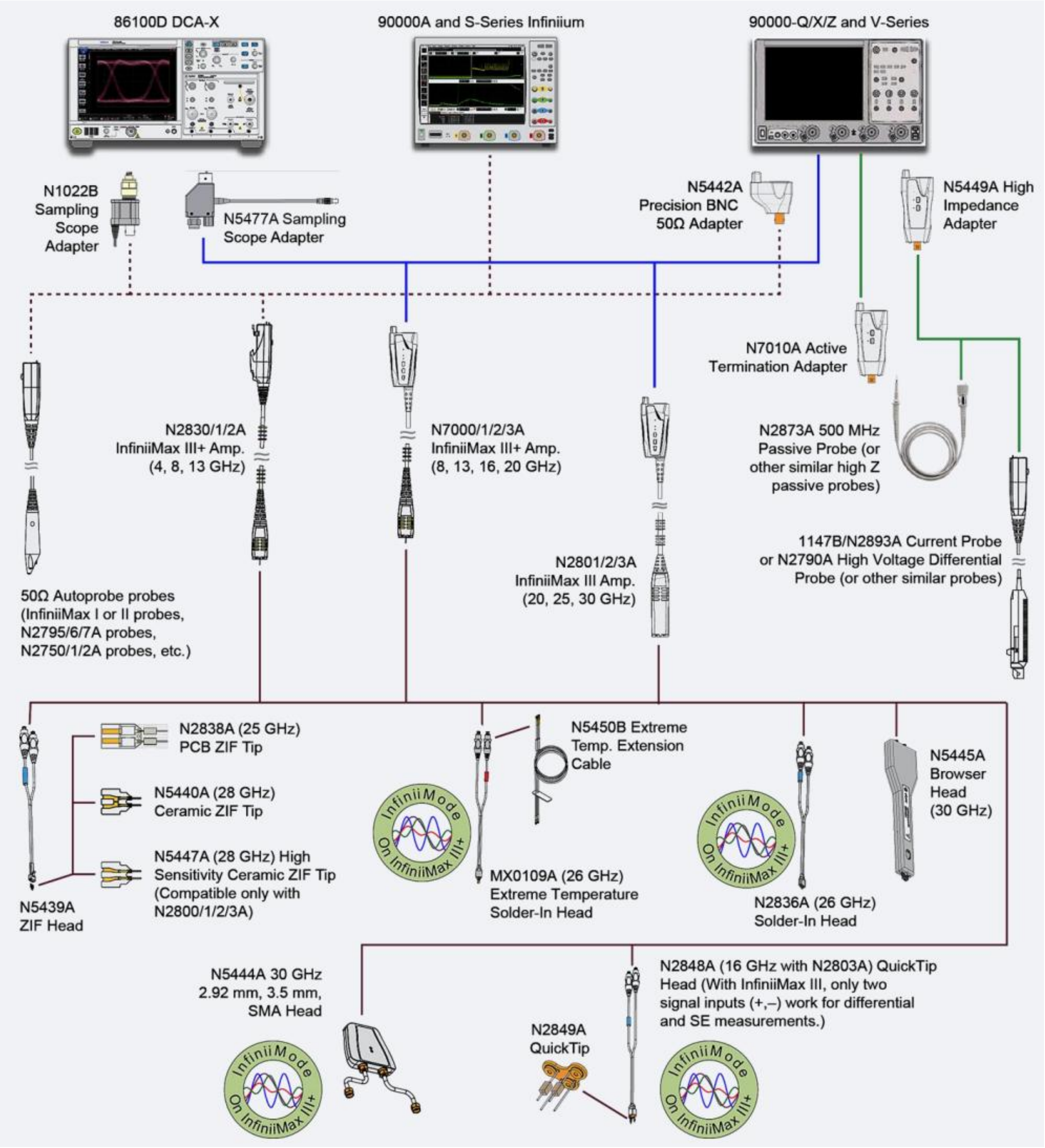
InfiniiMax III/III+ Probing system

Oscilloscope

Adapter

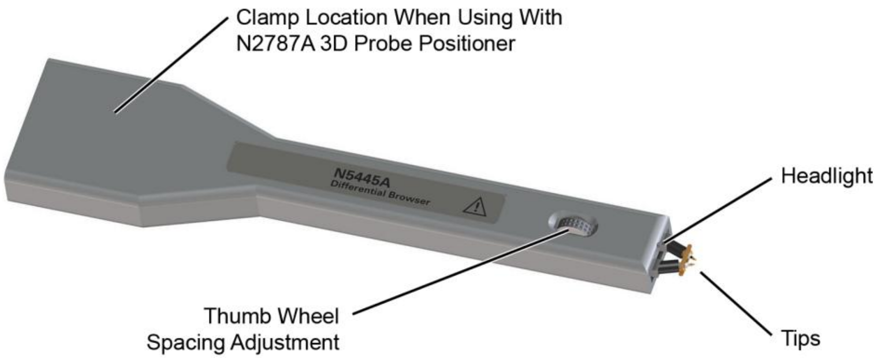
Probe amplifier

Probe head



Browser probe heads

- General-purpose troubleshooting
- Hand-held measurement
- Up to 30 GHz BW



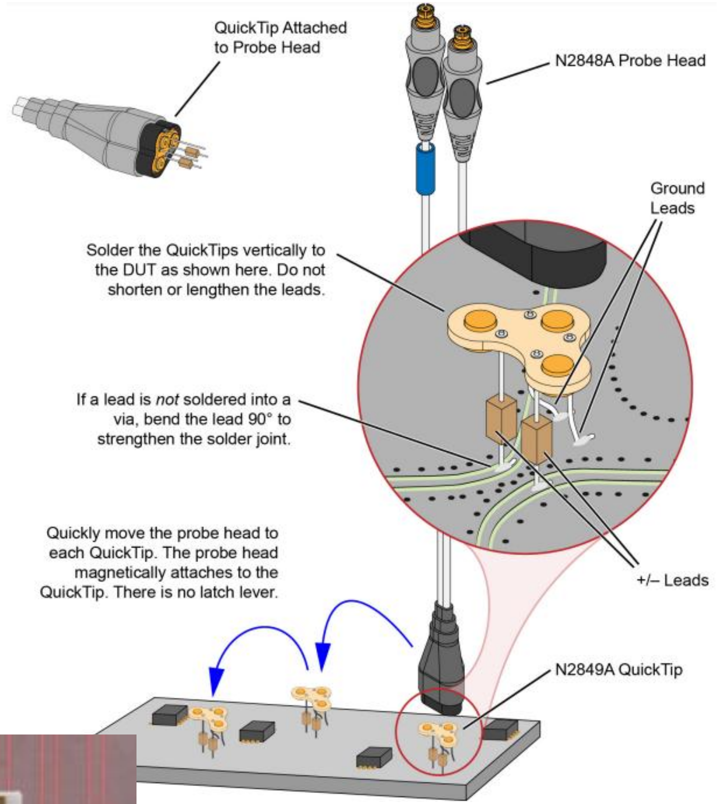
SMA differential probe

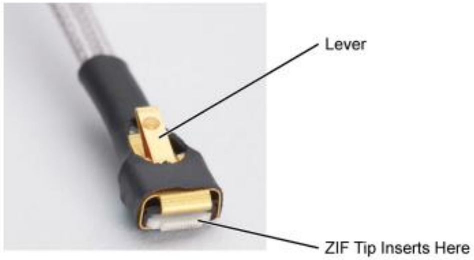
- Saves channels
- Minimal skew
- Semi-rigid cables
- Possible DC offset (±4V)
- Up to 30 GHz

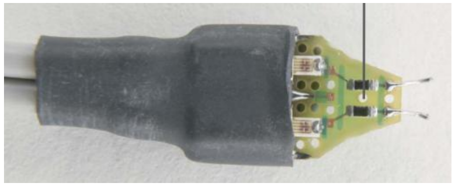
MX0105A

Solder-in probes

- Best conection fidelity
  - low parasitics
- Reliable joint
- Good repeatibilty
- Various options:
  - Quick tip (16 GHz)
  - ZIF Zero insertion force (28 GHz)
  - Solder-in head (26 GHz)

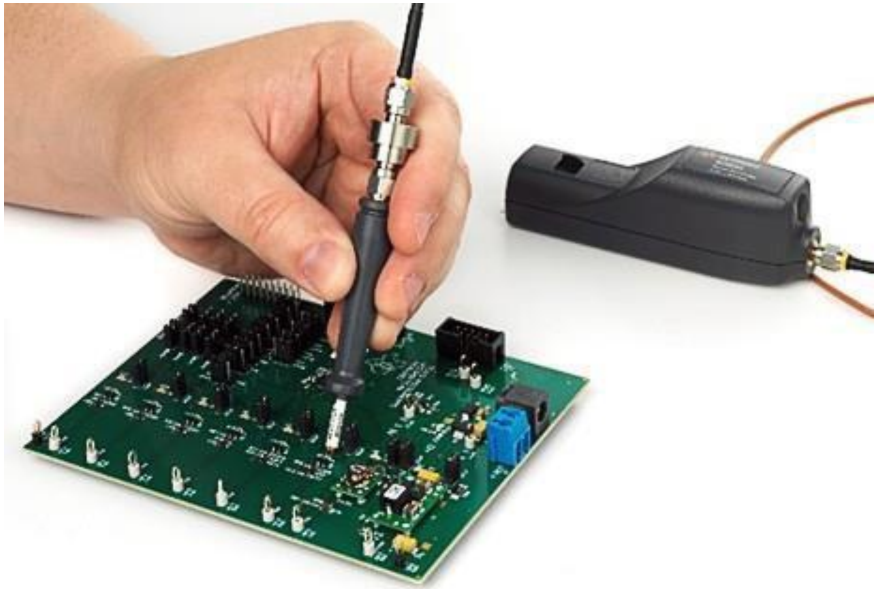






Power rail probe

- High DC offset possible (up to 24 V)
- High DC impedance - 50 kΩ
- 2 or 6 GHz bandwidth
- Suitable for measuring noise, ripple, or crosstalk on DC power rails



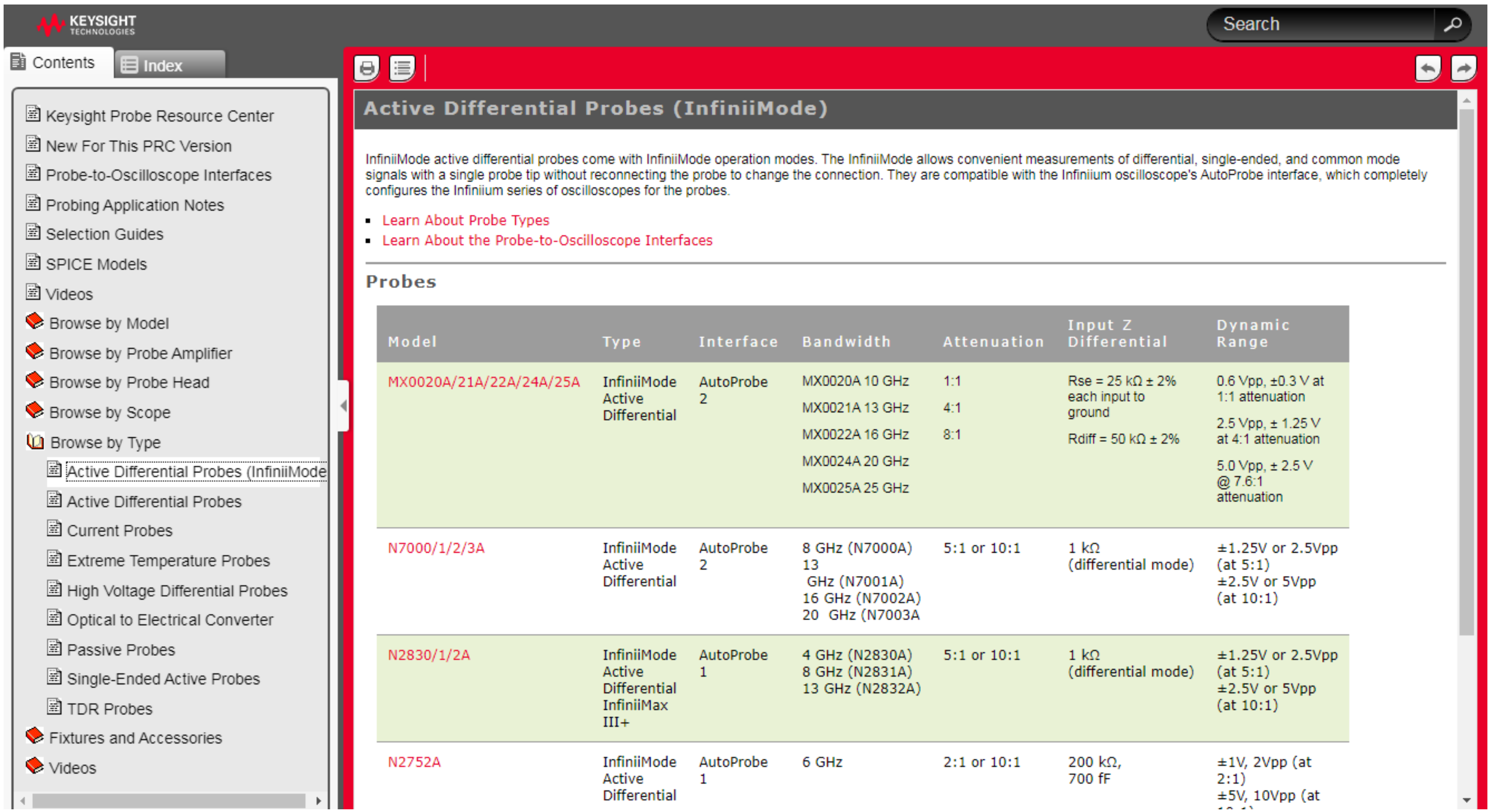
Keysight Probe Resource Center

- Datasheets, user guides for probes, heads, fixtures and accessories
  - Browsable by Scope/Probehead/Amplifier
- Application notes
- Selection guides
- Spice models
- Kept up-to-date

prc.keysight.com

Keysight Probe Resource Center

Online: https://prc.keysight.com/



KEYSIGHT TECHNOLOGIES

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Active Differential Probes (InfiniiMode)

InfiniiMode active differential probes come with InfiniiMode operation modes. The InfiniiMode allows convenient measurements of differential, single-ended, and common mode signals with a single probe tip without reconnecting the probe to change the connection. They are compatible with the Infiniium oscilloscope's AutoProbe interface, which completely configures the Infiniium series of oscilloscopes for the probes.

- Learn About Probe Types
- Learn About the Probe-to-Oscilloscope Interfaces

Probes

Model	Type	Interface	Bandwidth	Attenuation	Input Z Differential	Dynamic Range
MX0020A/21A/22A/24A/25A	InfiniiMode Active Differential	AutoProbe 2	MX0020A 10 GHz MX0021A 13 GHz MX0022A 16 GHz MX0024A 20 GHz MX0025A 25 GHz	1:1 4:1 8:1	Rse = 25 kΩ ± 2% each input to ground Rdiff = 50 kΩ ± 2%	0.6 Vpp, ±0.3 V at 1:1 attenuation 2.5 Vpp, ± 1.25 V at 4:1 attenuation 5.0 Vpp, ± 2.5 V @ 7.6:1 attenuation
N7000/1/2/3A	InfiniiMode Active Differential	AutoProbe 2	8 GHz (N7000A) 13 GHz (N7001A) 16 GHz (N7002A) 20 GHz (N7003A	5:1 or 10:1	1 kΩ (differential mode)	±1.25V or 2.5Vpp (at 5:1) ±2.5V or 5Vpp (at 10:1)
N2830/1/2A	InfiniiMode Active Differential InfiniiMax III+	AutoProbe 1	4 GHz (N2830A) 8 GHz (N2831A) 13 GHz (N2832A)	5:1 or 10:1	1 kΩ (differential mode)	±1.25V or 2.5Vpp (at 5:1) ±2.5V or 5Vpp (at 10:1)
N2752A	InfiniiMode Active Differential	AutoProbe 1	6 GHz	2:1 or 10:1	200 kΩ, 700 fF	±1V, 2Vpp (at 2:1) ±5V, 10Vpp (at

Summary

- Real-time scopes are usually more flexible than equivalent sampling scopes
- Scope should be chosen with respect to the signals to be captured
- Connection to the circuit (probing) affects (loads) the circuit and modifies signal
- Keysight provide variety of probing systems and fixtures that cover frequency range up to 30 GHz
- Oscilloscope and probe are a system, the overall parameters are affected by both

Eye-diagram measurements

Clock recovery

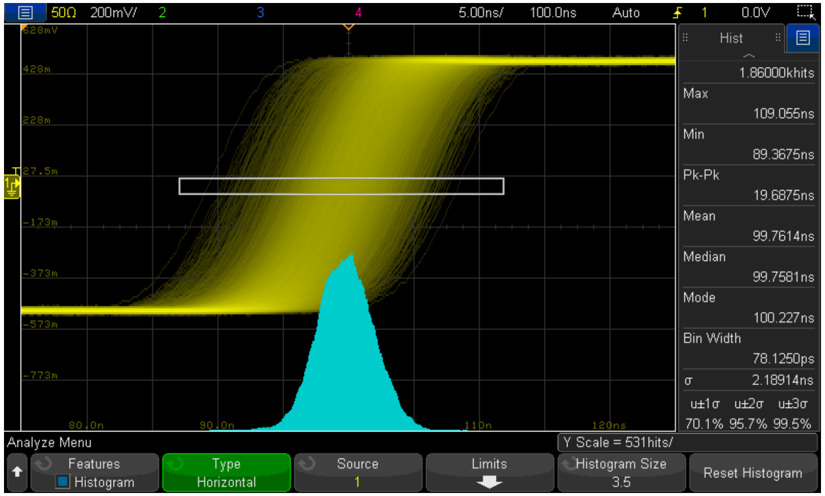
HW-acceleration

Jitter analysis

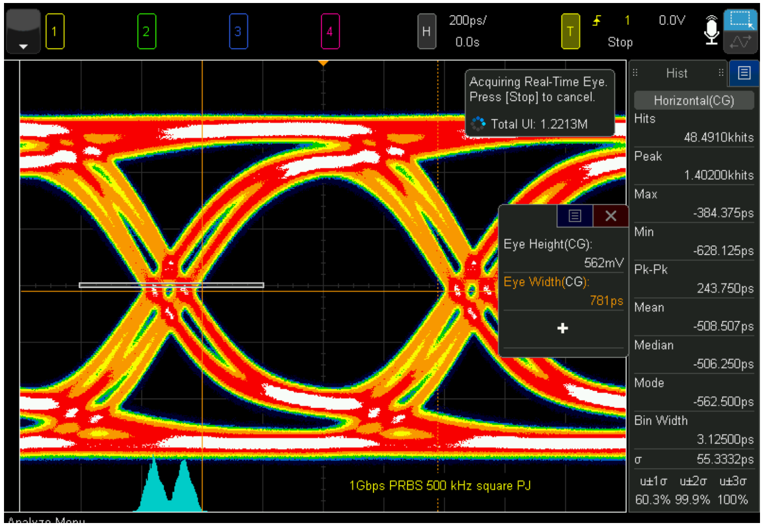
Crosstalk analysis

InfiniiVision = “Debug scopes“

- InfiniiVision 3000G
  - 100MHz – 1GHz
  - Histogram analysis



- InfiniiVision 6000X
  - 1GHz – 6GHz
  - Histogram analysis
  - Jitter, TIE plot
  - Eye diagram



Infiniium = “Analysis scopes”

- **EXR, MXR and UXR platform: 500 MHz – 110GHz**
- **Basic applications:**
  - Segmented memory, History mode
  - Clock recovery
  - Eye-diagram (HW accelerated for UXR,MXR)
  - Fault hunter
- **Available applications**
  - Vertical, timing, and phase noise analysis - EZJIT – D9110JITA
  - De-embedding – D9110DMBA
  - Equalization and crosstalk – D9110ASIA
  - Power rail and PMIC integrity – D9110POWA

  - Protocol decoding, Compliance SW, etc.

Clock recovery

Clock signal is required for almost all measurements, e.g. eye diagram, jitter and crosstalk analysis, etc. More information in the previous part of presentation.

Constant frequency

Phase-locked loop
- 1st order PLL
- 2nd order PLL
- 3rd order PLL

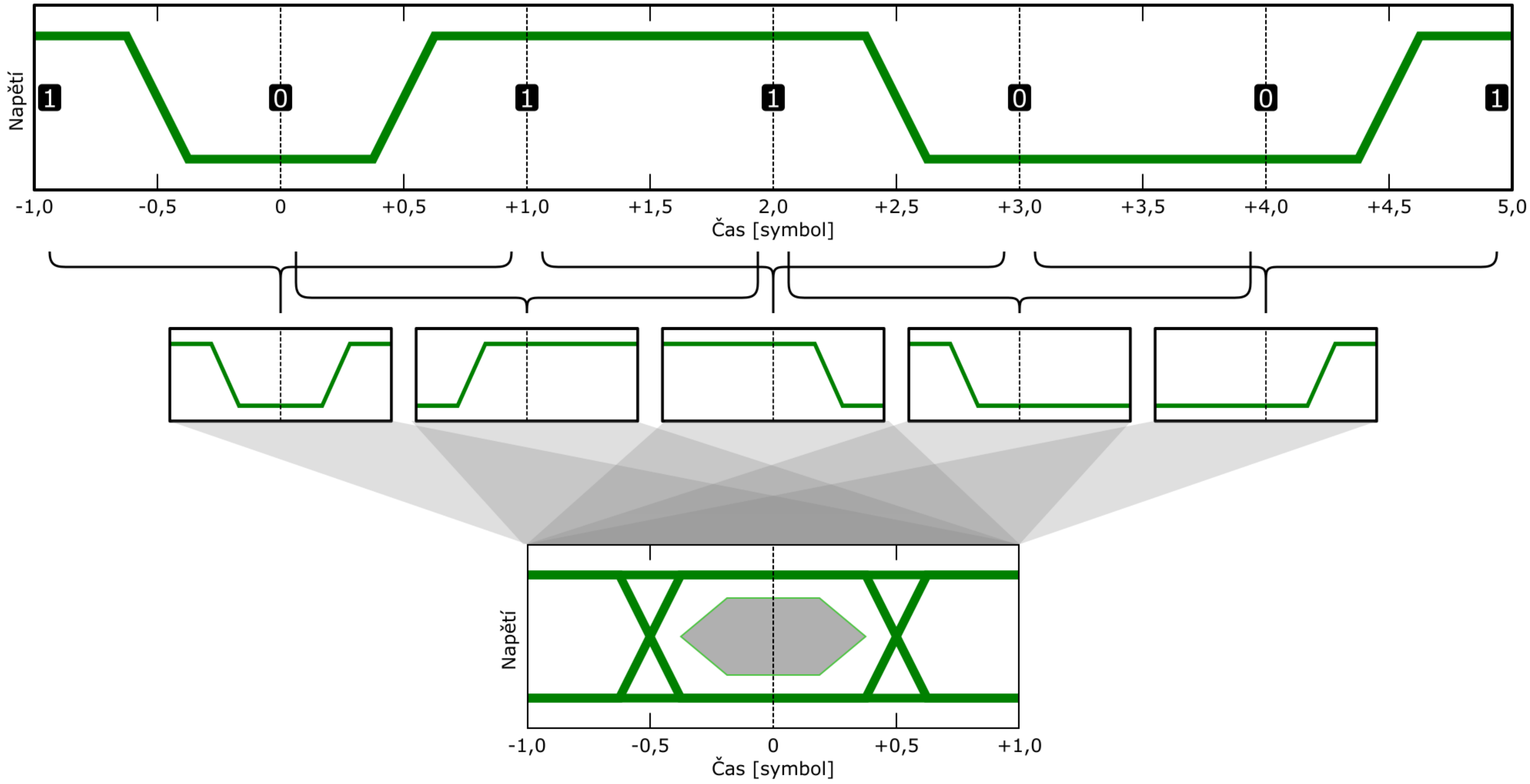
Equalized PLL
- Equalized 1st order PLL
- Equalized 2nd order PLL
- Equalized 3rd order PLL

Protocol decode
- PCIe 5 CXL
- PCIe 6 CXL.
- MIPI M-PHY
- FLEX ray
- USB PD BMC
- USB 3 LFPS

Clock recovered from data

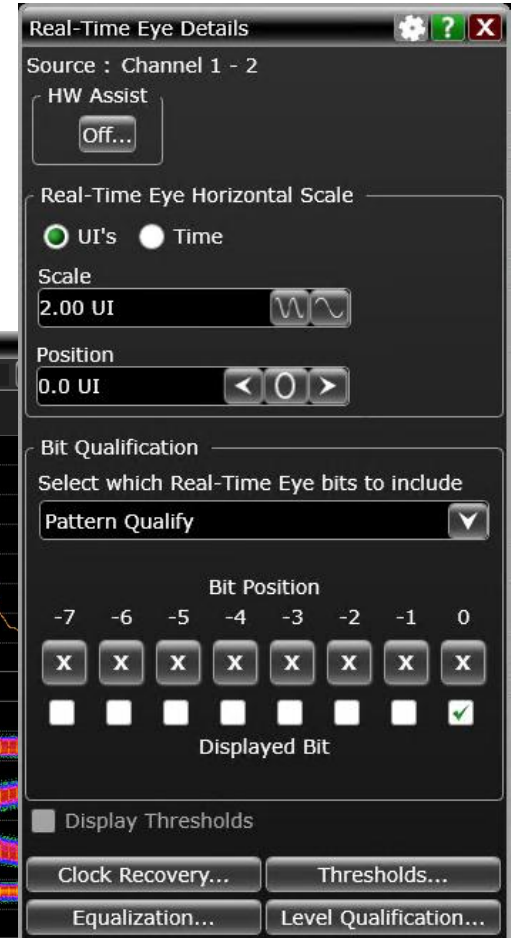
Explicit Signal
- Explicit clock
- Explicit 1st order PLL
- Explicit 2nd order PLL
- Explicit 3rd order PLL

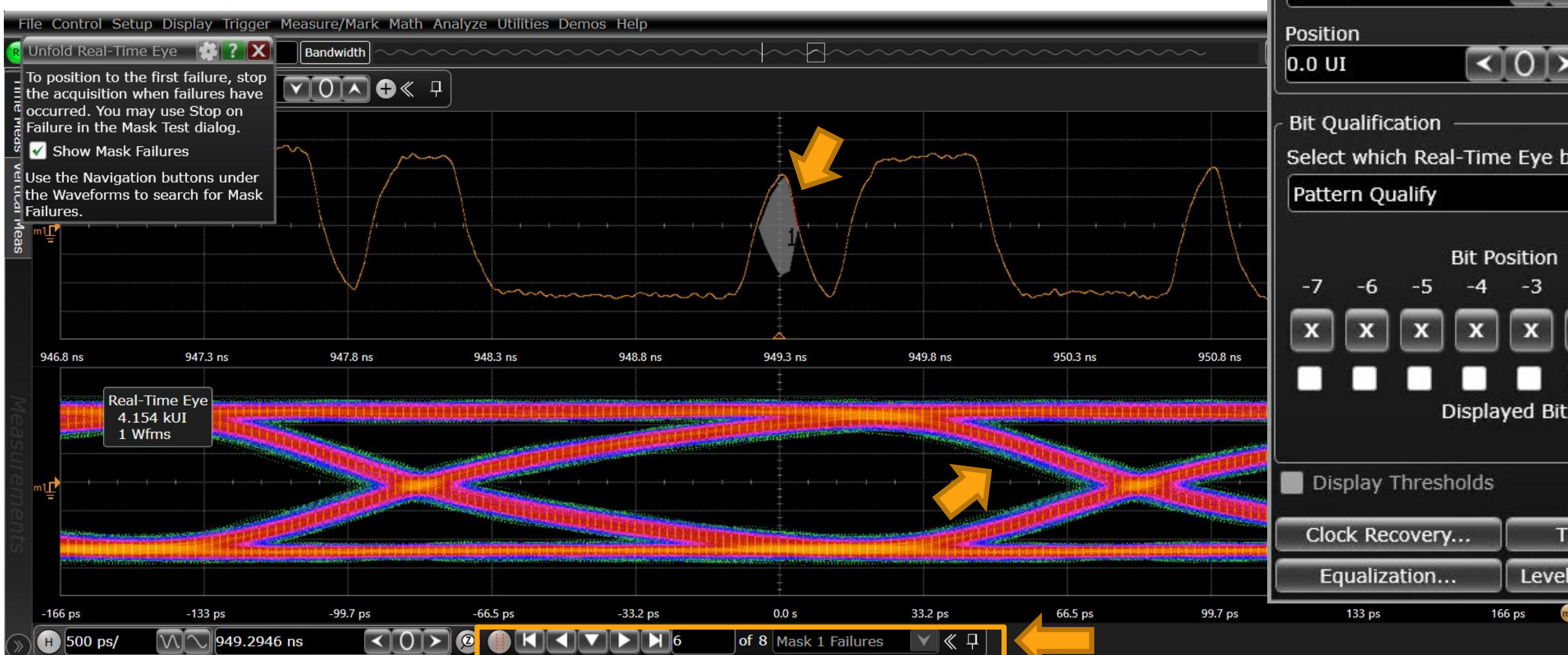
Eye-diagram formation



Real-time eye diagram

- Deep acquisition folded to create Eye-diagram
  - Can be unfolded to find failure – mask-based
- HW acceleration possible for MXR and UXR
  - ASIC-based – 200k waveforms/second, 750k UI/second
- Bit qualification filters incl. 8-bit pattern 0/X/1





HW acceleration

Not available for all settings – setup guide provided

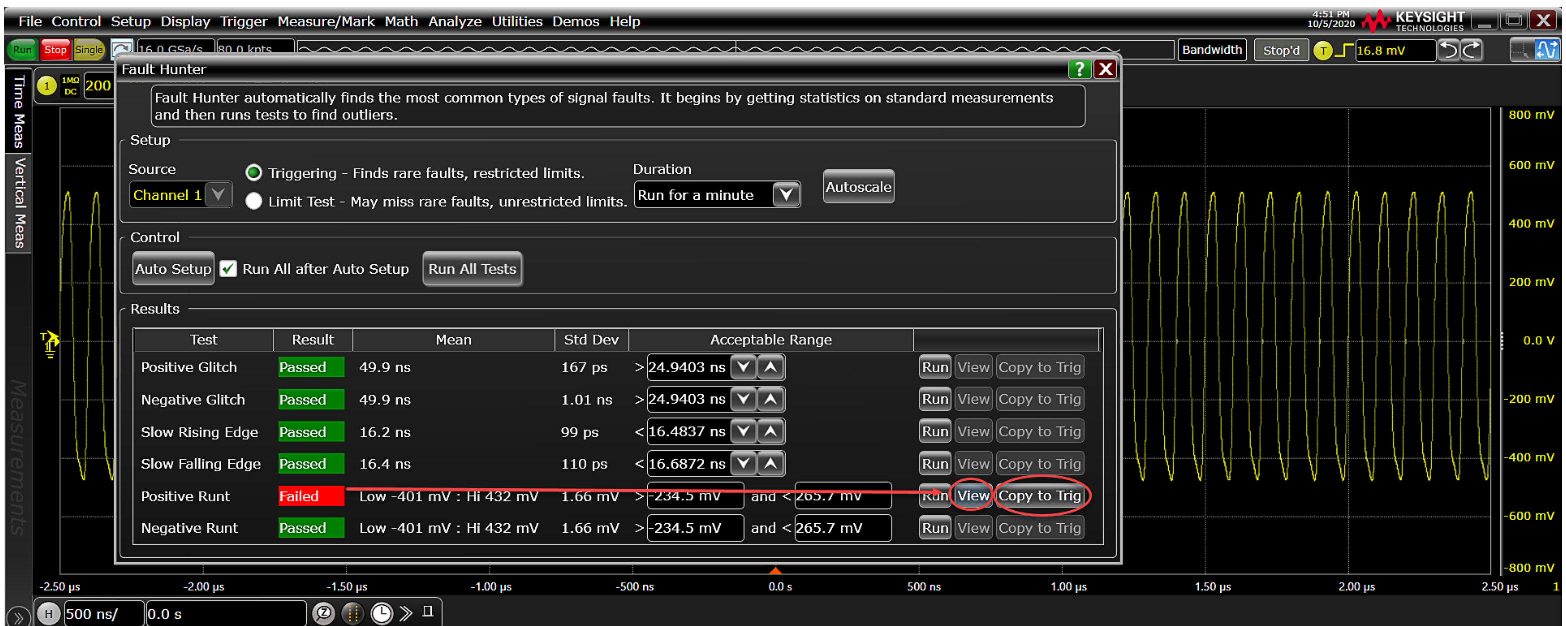
Hardware Acceleration

Real-Time Eye | Equalization

Waveform	Reason	Suggested Fix	Dialog	Auto Setup
Channel 1	Clock Recovery method (Constant Frequency) is not supported in hardware.	Use one of the PLL methods, such as Second Order PLL.	Clock Recovery Setup...	Auto
Channel 1	Measurement Threshold (10%,50%,90% of top, base) is not supported in hardware.	Use Hysteresis Thresholds.	Measurement Thresholds...	Auto
Channel 1	Fast Plot Mode is required when Real-Time Eye is on to use hardware acceleration.	Turn on Fast Plot, although this is often forced off by another reason.	Acquisition Setup...	
Channel 2	Clock Recovery method (Constant Frequency) is not supported in hardware.	Use one of the PLL methods, such as Second Order PLL.	Clock Recovery Setup...	Auto
Channel 2	Measurement Threshold (10%,50%,90% of top, base) is not supported in hardware.	Use Hysteresis Thresholds.	Measurement Thresholds...	Auto
Channel 2	Clock recovery runs faster in software when not displaying the Real-Time Eye.			

Infinium FaultHunter

- Learns good signal from first 30s and looks for rare faults for up to 48 hours
- Glitch, slow edges, runt (small amplitude)



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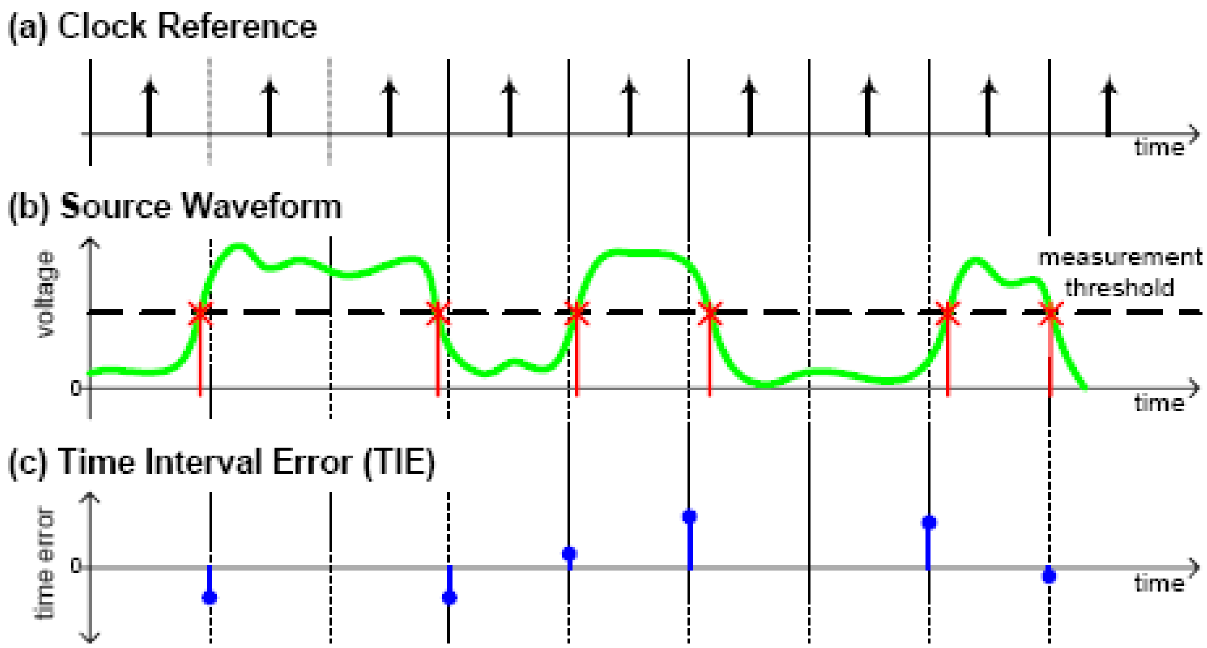
Optional applications

Jitter analysis

Crosstalk analysis

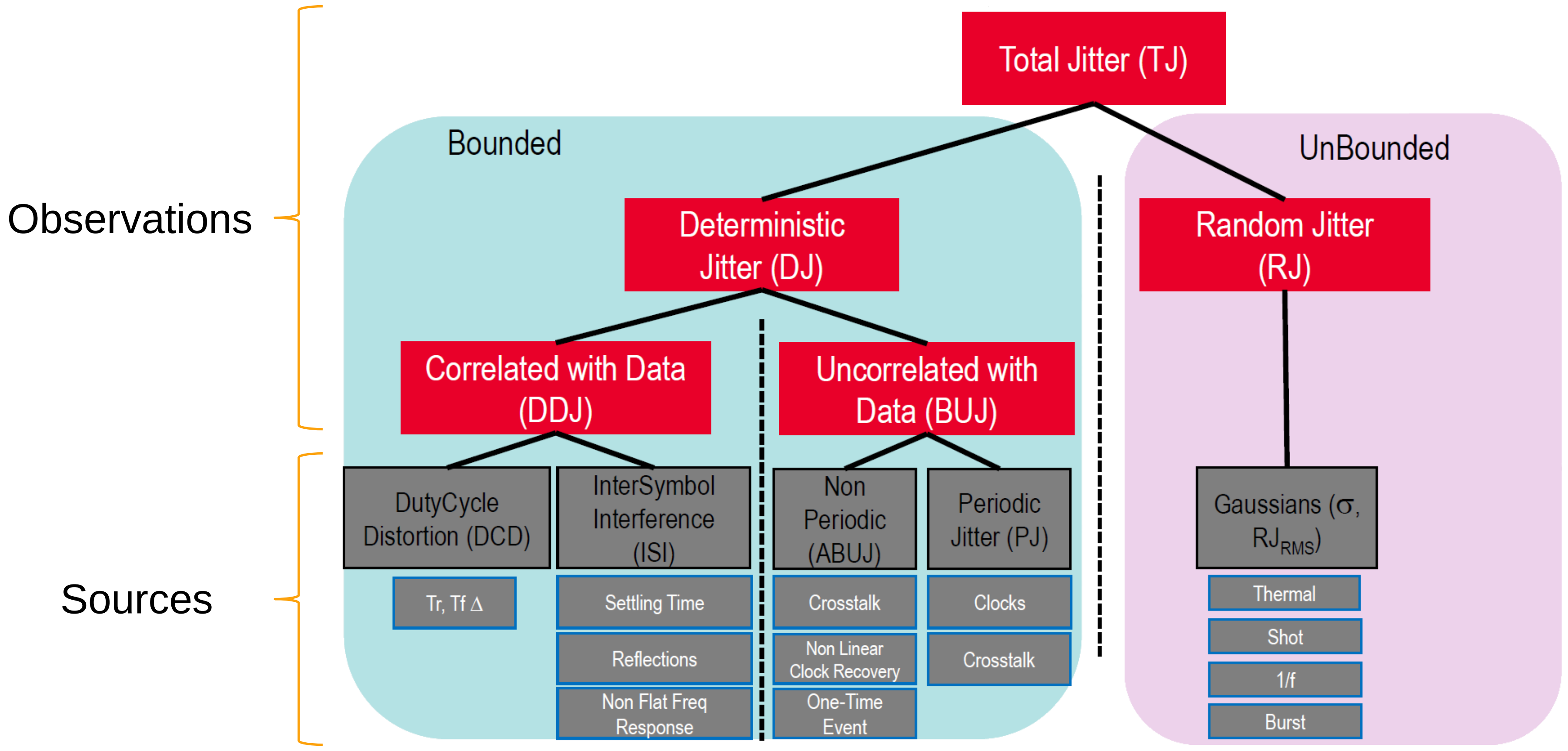
Jitter analysis – TIE error

- Time interval error is monitored for each transition



- Sources of TIE are shown on the next slide

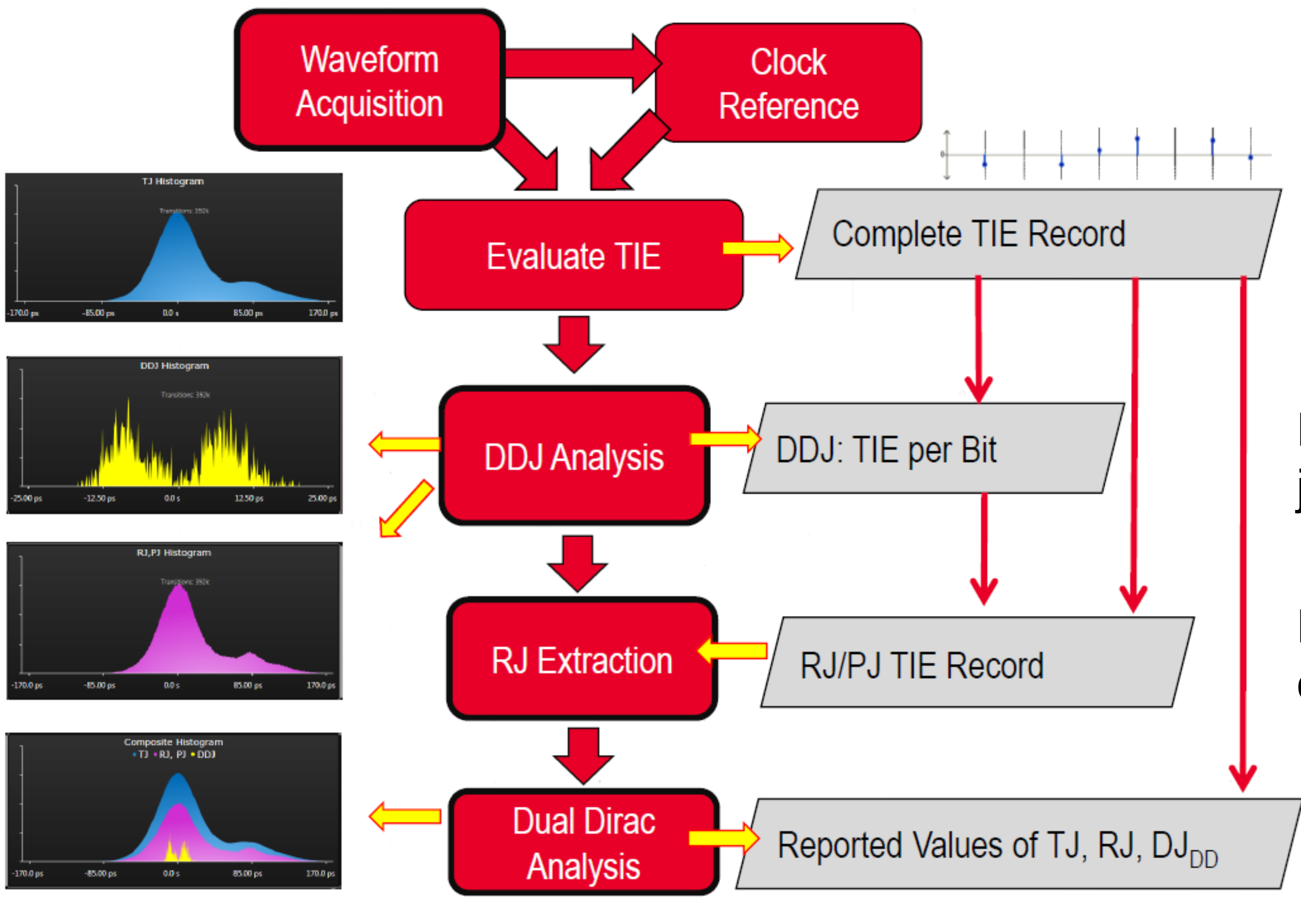
Jitter Classification & Identification



Jitter Classification & Identification

	acronym	bounded/ unbounded	correlated/ uncorrelated	periodic/ aperiodic	Example cause
Random Jitter	RJ	Unbounded	Uncorrelated	Aperiodic	Thermal noise
Deterministic Jitter	DJ	Bounded	Either	Either	Inter-Symbol Interference
Periodic Jitter	PJ	Bounded	Either	Periodic	Power supply feed-through
Sinusoidal Jitter	SJ	Bounded	Uncorrelated	Periodic	Electromagnetic interference
Data-Dependent Jitter	DDJ	Bounded	Correlated	Aperiodic	Impedance mismatch
Duty-Cycle Distortion	DCD	Bounded	Correlated	Periodic	Clock asymmetry
Inter-Symbol Interference	ISI	Bounded	Correlated	Aperiodic	Non-uniform frequency response of a transmission line
Bounded Uncorrelated Jitter	BUJ	Bounded	Uncorrelated	Aperiodic	Crosstalk

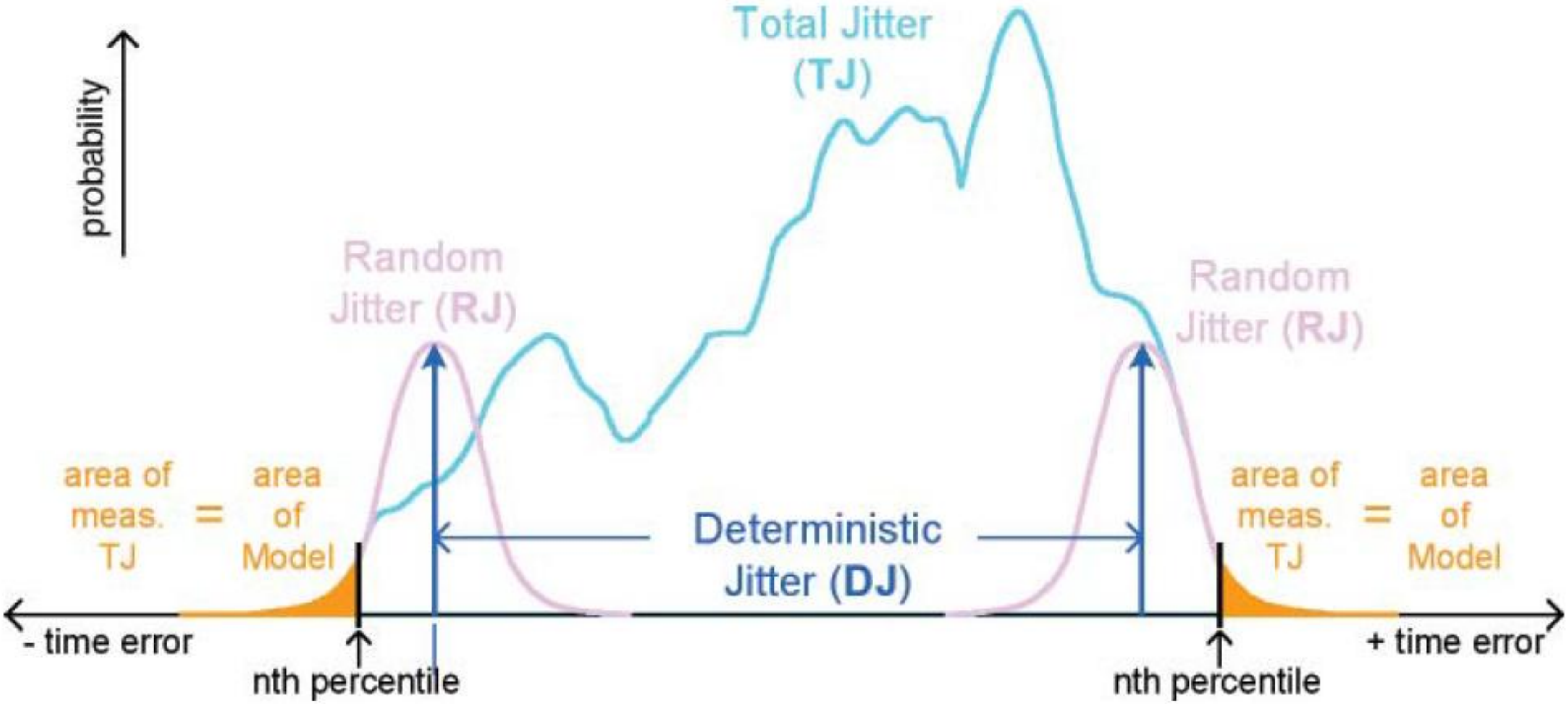
Jitter analysis workflow



Data-dependent jitter extracted

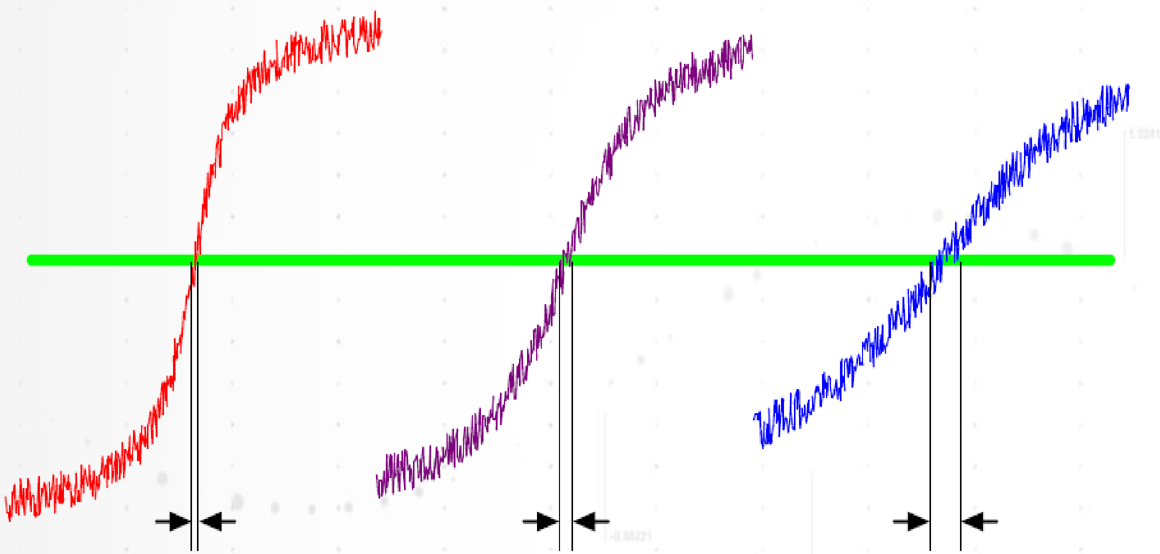
Random jitter extracted

dual-Dirac model



Intrinsic Oscilloscope Jitter

- Vertical noise affects the jitter, the amount depends on slew rate
- Sample clock jitter affects the measurement as well
- Can be compensated by the EZJIT application
- Values: MXR ~118 – 181 fs_{RMS}, UXR 15-50 fs_{RMS}



TIE:

$$\sqrt{\left(\frac{Noise}{SlewRate}\right)^2 + SampleClockJitter^2} \quad \text{sec rms}$$

Periodic Jitter:

$$\sqrt{2} \cdot \sqrt{\left(\frac{Noise}{SlewRate}\right)^2 + SampleClockJitter^2} \quad \text{sec rms}$$

Cycle-Cycle:

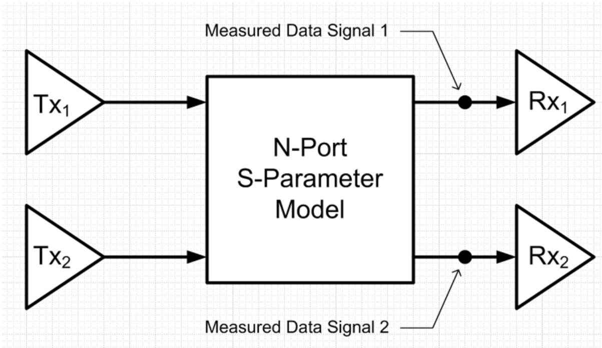
$$\sqrt{3} \cdot \sqrt{\left(\frac{Noise}{SlewRate}\right)^2 + SampleClockJitter^2} \quad \text{sec rms}$$

D90x0ASIA
Advanced Signal Integrity Software

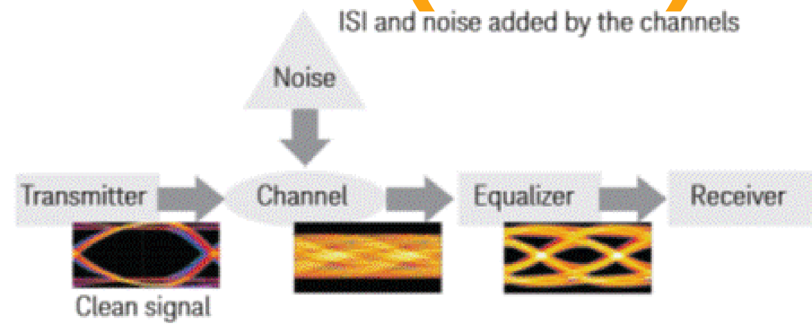
- Equalization:
  - FFE, DFE and CTLE modelling

- InfiniiSim:
  - Embedding and De-embedding
  - Insert channel effects
  - Software replacing of channel elements
  - Basic features available also in D9110DMBA

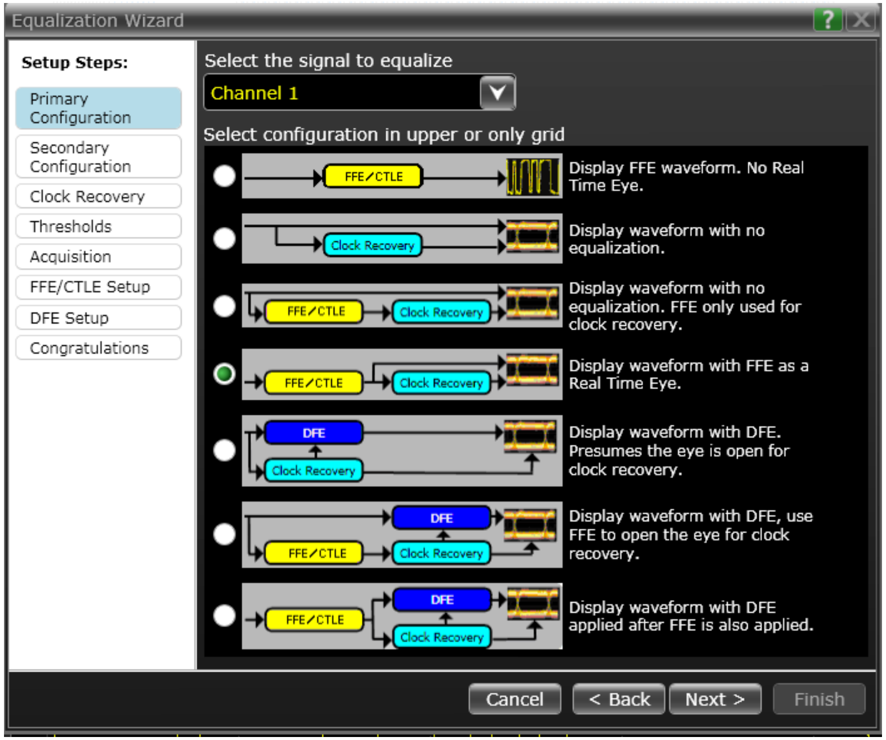
- Crosstalk:
  - In-depth analysis and quantification
  - Identify crosstalk agressors including power supply
  - Remove crosstalk effects
  - Waveform without crostalk can be used for EZJIT



Serial Data Equalization (SDE)

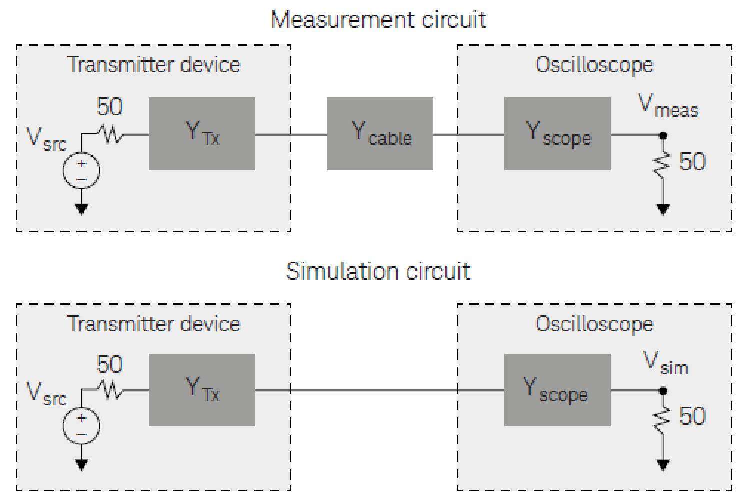


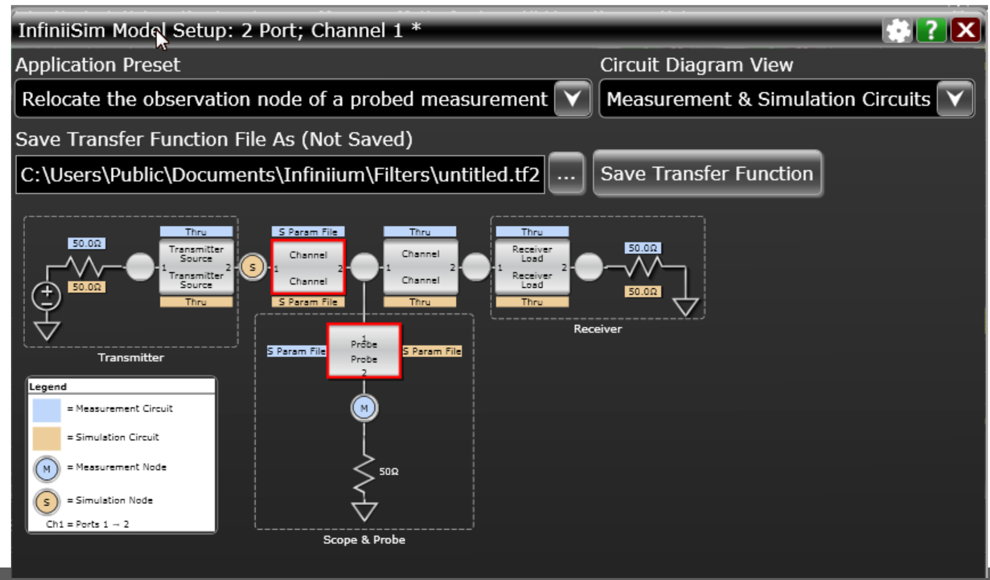
- Reduces ISI (inter-symbol interference)
- Compensates for losses on higher frequecies
- Opens the eye – comparison available
- Tap optimization for higher/wider eye
- Options:
  - FFE – Feed-forward eq.
  - CTLE – Continuous-time linear eq. (USB3 compatible)
  - DFE – decision feedback eq. (adaptive)
- Works on any data pattern



InfiniiSim – Embeding/DeEmbeding

- Compares transfer functions of measurement and simulation circuit
- Shows signal from a point that cannot be probed
- Removes scope input reflection or probe-loading
- Can simulate addition or replacement of a channel element
- Custom setups with up to 27 elements



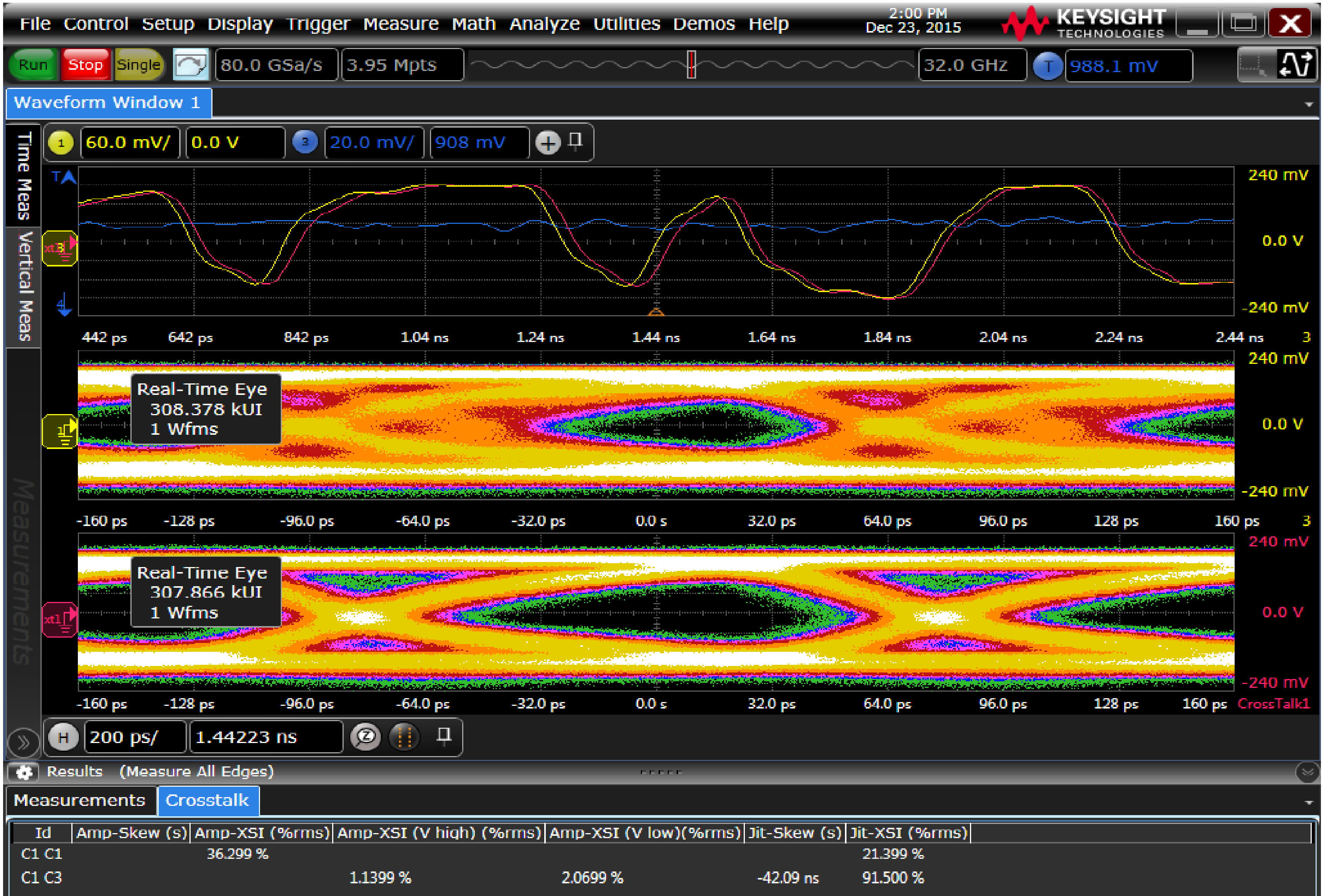


Power supply crosstalk analysis

Data agressor → PSU victim
e.g. Ground bounce, Vcc bounce

PSU agressor → Data victim

PS aggressor → data victim



PS aggressor → data victim

PS aggressor → data victim

Transmission Line Crostalk analysis

- Identification of victim-agressor pairs
- NEXT and FEXT identification
- Inter-symbol interference estimation
- Allows crosstalk removal

Results (Measure All Edges)

Bookmarks Crosstalk

Vic:Aggr	Volt, Skew (s)	Volt, Error (rms)	Volt, Error (p-p)	V high, Error (rms)	V high, Error (p-p)	V low, Error (rms)	V low, Error (p-p)	Time, Skew (s)	Time, Error (rms)	Time, Error (p-p)
c1:c1		38%	74%						32%	17%
c1:c2	-25.00 ps	9%	14%							
c1:c4				6%	11%	2%	2%	-10.00 ns	15%	11%

FEXT removal example

Summary

- InfiniiVision and Infiinium oscilloscope families
- Clock recovery is crucial for advanced measurements
- HW accelerated eye diagram improves the chance of capturing rare faults
- Basic eye diagram analysis available in all Infiniium scopes
- Advanced software options available:
  - Jitter analysis
  - Crosstalk analysis
  - Equalization (FFE, CTLE, DFE)
  - InfiniiSim Embedding/De-embedding

Thank you for your attention!