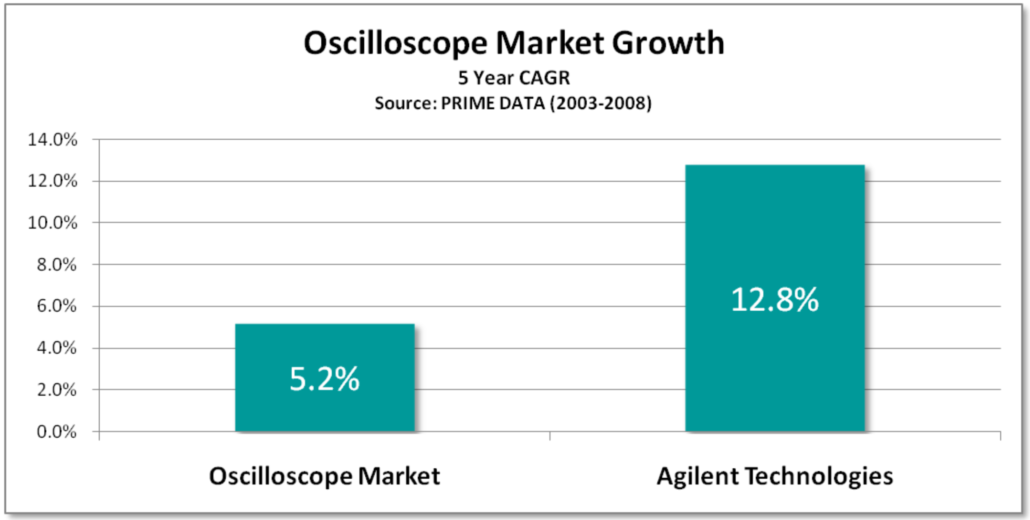
Understanding how real time oscilloscopes achieve > 16 GHz bandwidth

Agilent Technologies

Agilent Oscilloscope Portfolio



Fastest growing oscilloscope manufacturer

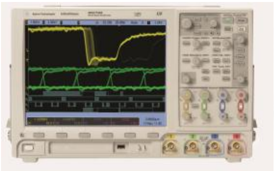
U1600A/B Series

U2700 Series

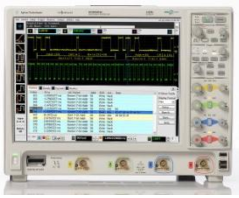
1000 Series

5000 Series

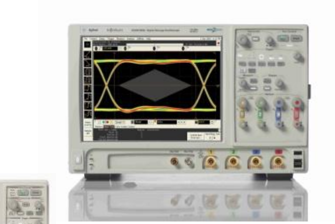
6000 Series



7000B Series



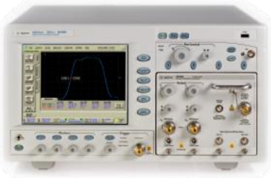
9000 Series



90000 Series

NEW April 27

90000 X-Series



DCA-J Sampling

90000A 8 Channel Form Factor

- Highest bandwidth and signal to noise ratio at 8 and 12 GHz
- 8 channels and only 7 rack U high
- 40 GSa/s across all eight channels
- Up to 25mS of captured data (1 G memory)
- PCIe download speeds of 80 Mb/s, including Fibre connector
- Full Diskless Operation, Run Without Hard Drive

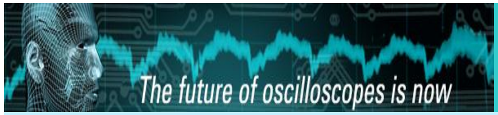
Introducing the Infiniium 90000 X-Series Oscilloscopes

Engineered for 32 GHz true analog bandwidth that delivers:

The industry’s highest real-time measurement accuracy

The industry’s first 30 GHz oscilloscope probing system

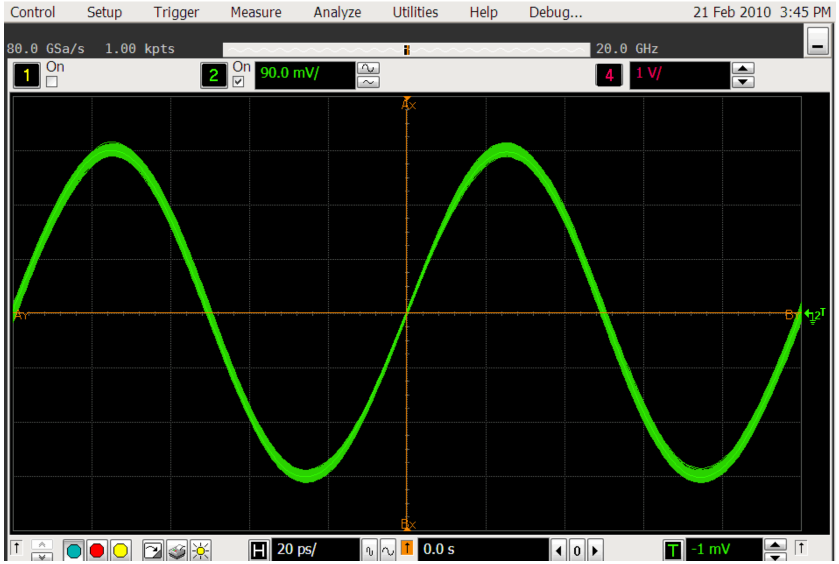
The industry’s most comprehensive measurement software

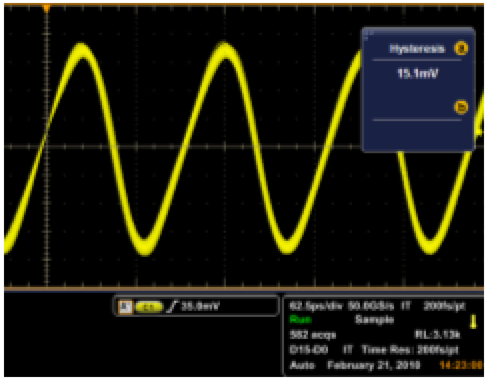
 The future of oscilloscopes is now	**DSA-X 91604A**	**DSA-X 92004A**	**DSA-X 92504A**	**DSA-X 92804A**	**DSA-X 93204A**
Analog Bandwidth	16 GHz	20 GHz	25 GHz	28 GHz	32 GHz
Max Sample Rate	80 GSa/s				
Max Memory	2 Gpt				
Probe Bandwidth	Up to 30 GHz				

Bandwidth upgradable scopes and probes

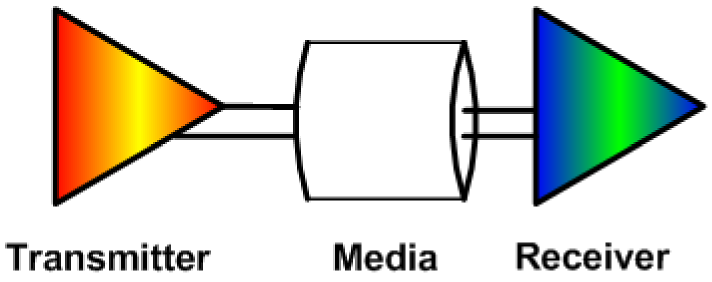
Schedule

1. Brief de-embedding presentation
2. Scope Architecture
3. Hardware Performance
4. Frequency Interleaving
5. DSP Boosting
6. Measurement Comparisons
7. Conclusion

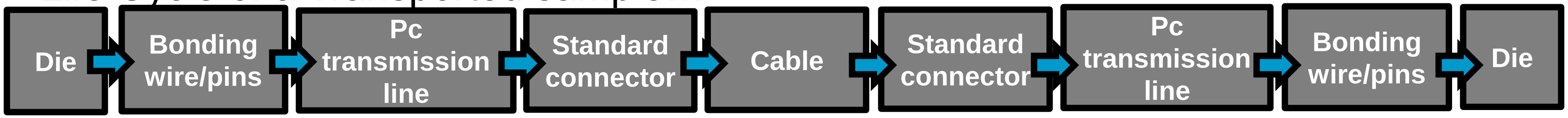




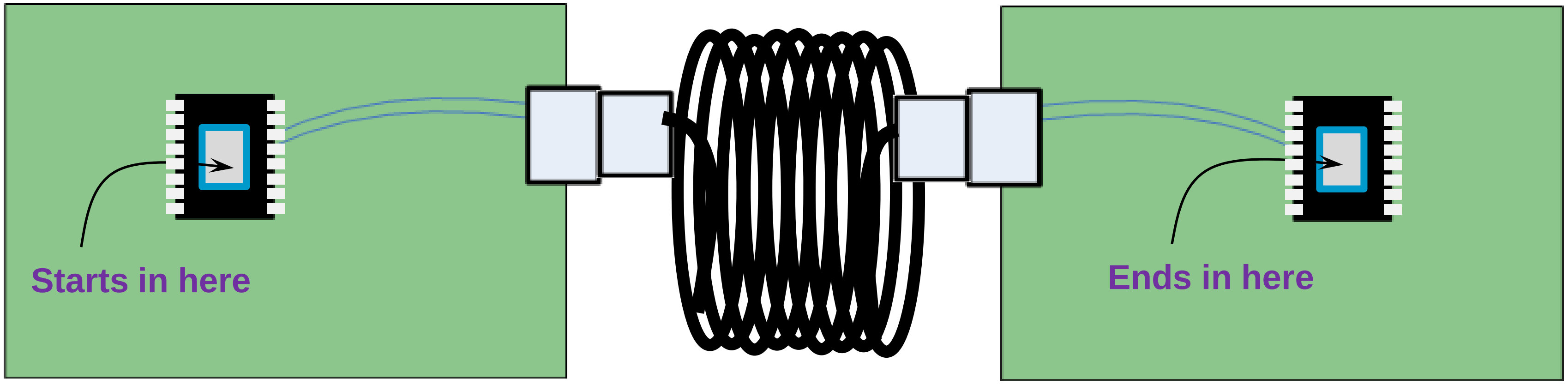
A common system: Link



Life Cycle of a Transported sample…



Die → Bonding wire/pins → Pc transmission line → Standard connector → Cable → Standard connector → Pc transmission line → Bonding wire/pins → Die

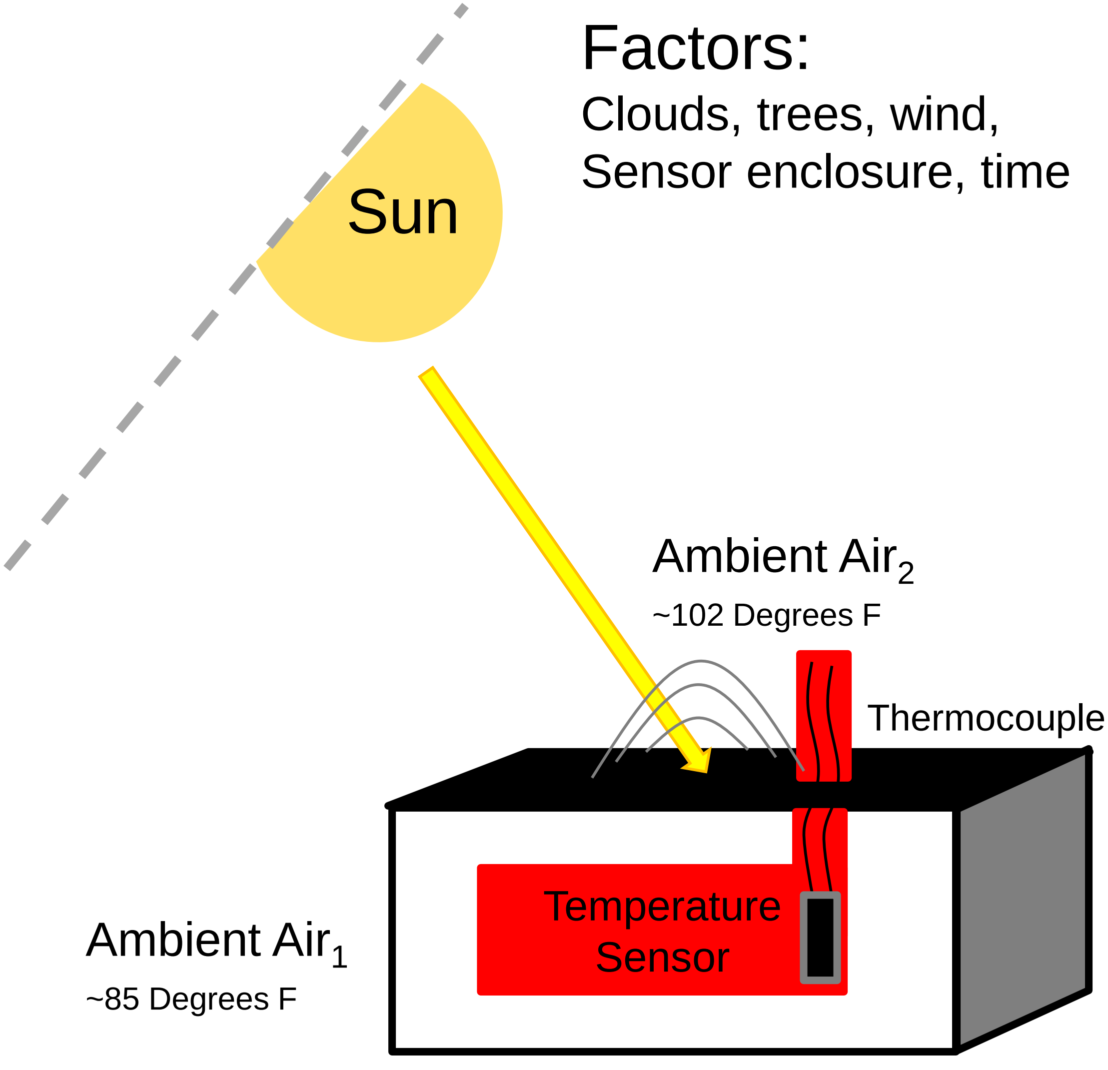


Familiar Sight?

Bank Temperature sign

Factors:

Clouds, trees, wind,
Sensor enclosure, time



Sun

Ambient Air$_2$

~102 Degrees F

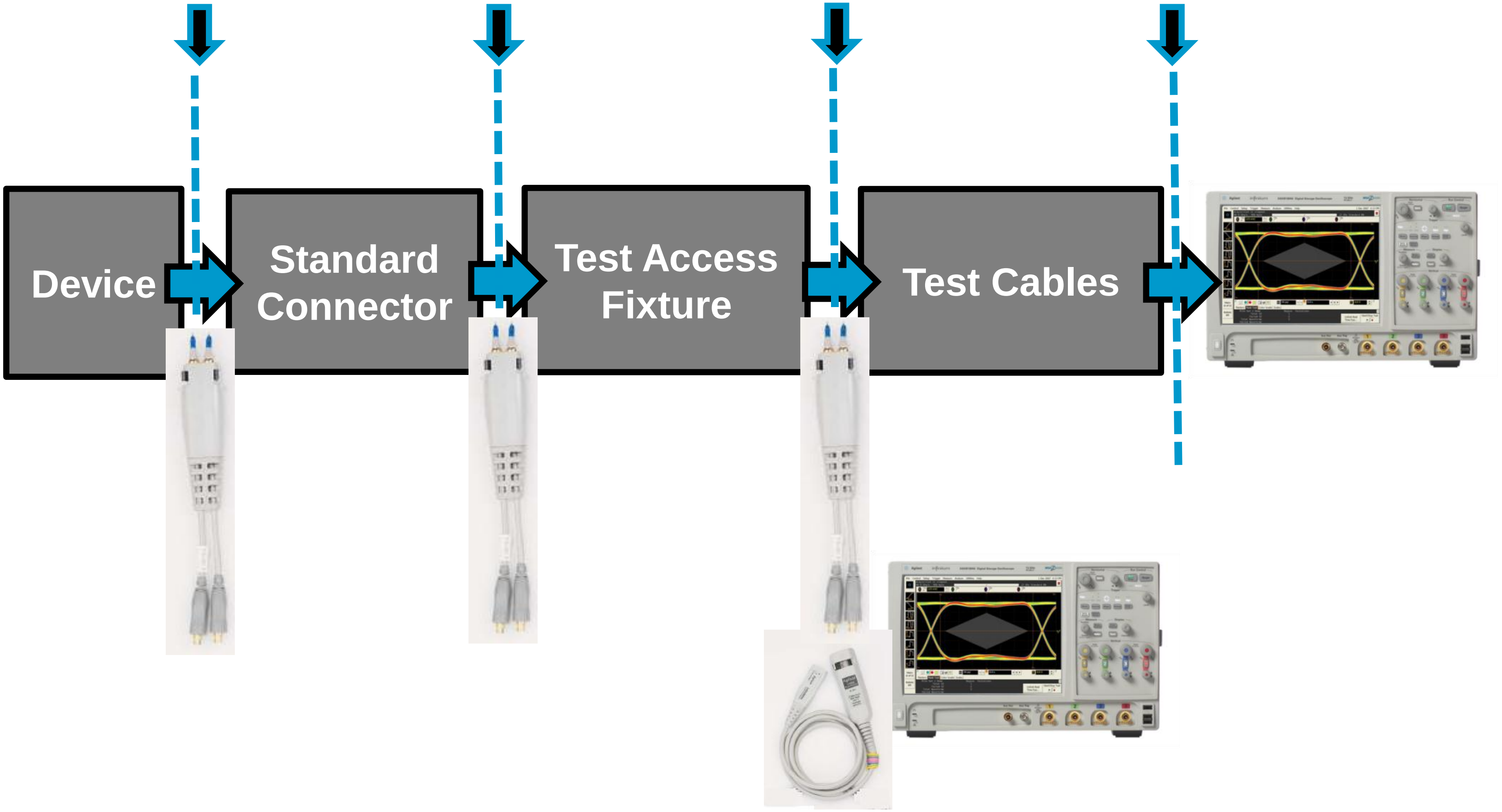
Thermocouple

Temperature Sensor

Ambient Air$_1$

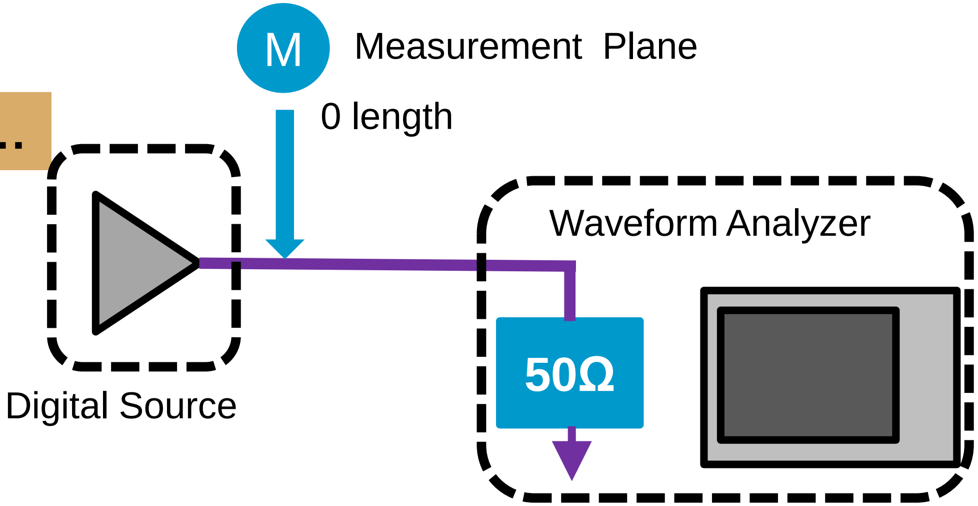
~85 Degrees F

Measurement Plane



Measuring Waveforms on a System

What you want to Do…



M Measurement Plane

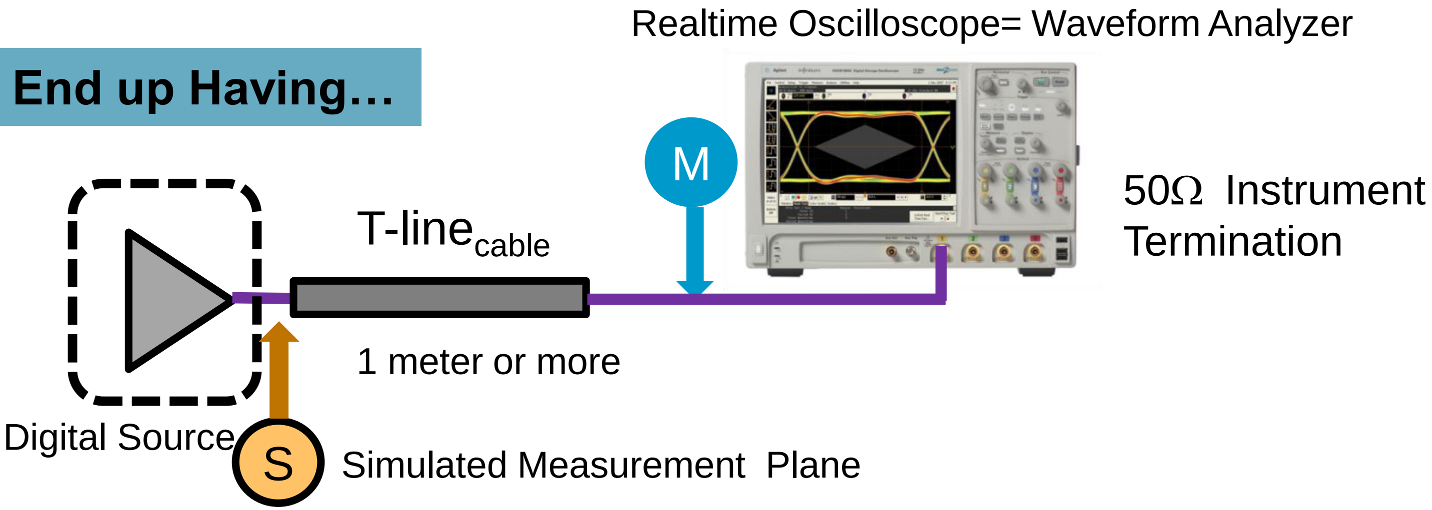
0 length

Waveform Analyzer

50Ω

Digital Source

What you End up Having…



Realtime Oscilloscope= Waveform Analyzer

M

50Ω Instrument Termination

T-line$_{\text{cable}}$

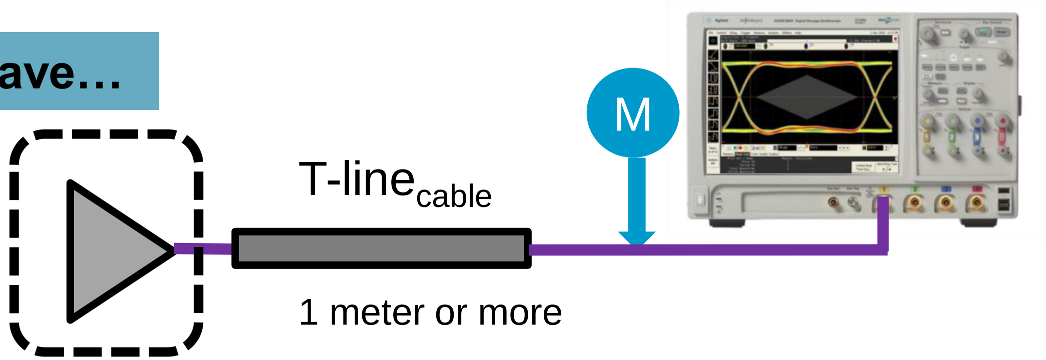
1 meter or more

Digital Source

S Simulated Measurement Plane

Simulating an Additional Channel Element

What you Have…



Realtime Oscilloscope= Waveform Analyzer

M

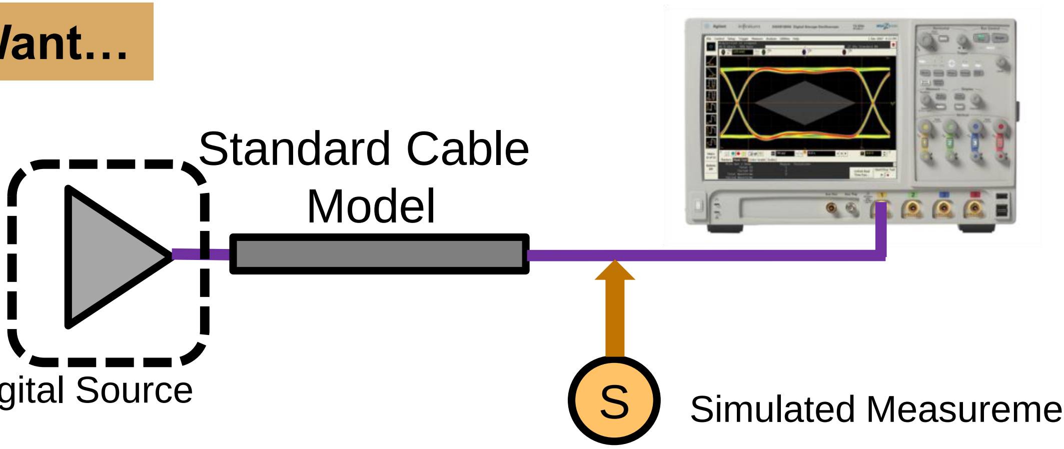
50Ω Instrument Termination

T-line$_{\text{cable}}$

1 meter or more

Digital Source

What you Want…



Realtime Oscilloscope= Waveform Analyzer

Standard Cable Model

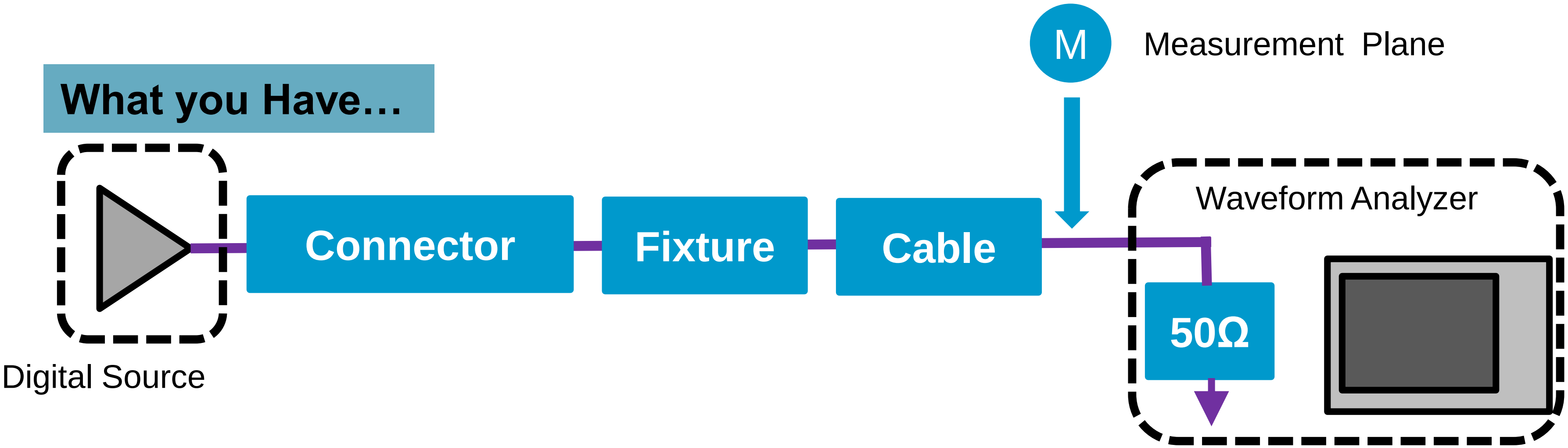
50Ω Instrument Termination

Digital Source

S

Simulated Measurement Plane

Virtual Probing (or Measurement Plane Relocation)



M Measurement Plane

What you Have…

Digital Source

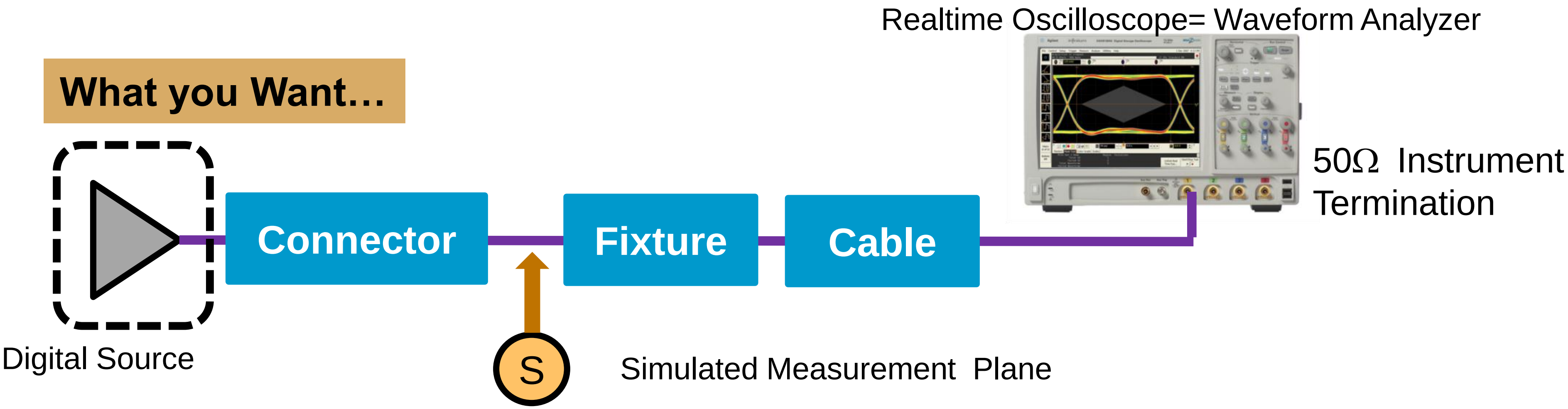
Connector

Fixture

Cable

Waveform Analyzer

50Ω



Realtime Oscilloscope= Waveform Analyzer

What you Want…

Digital Source

Connector

Fixture

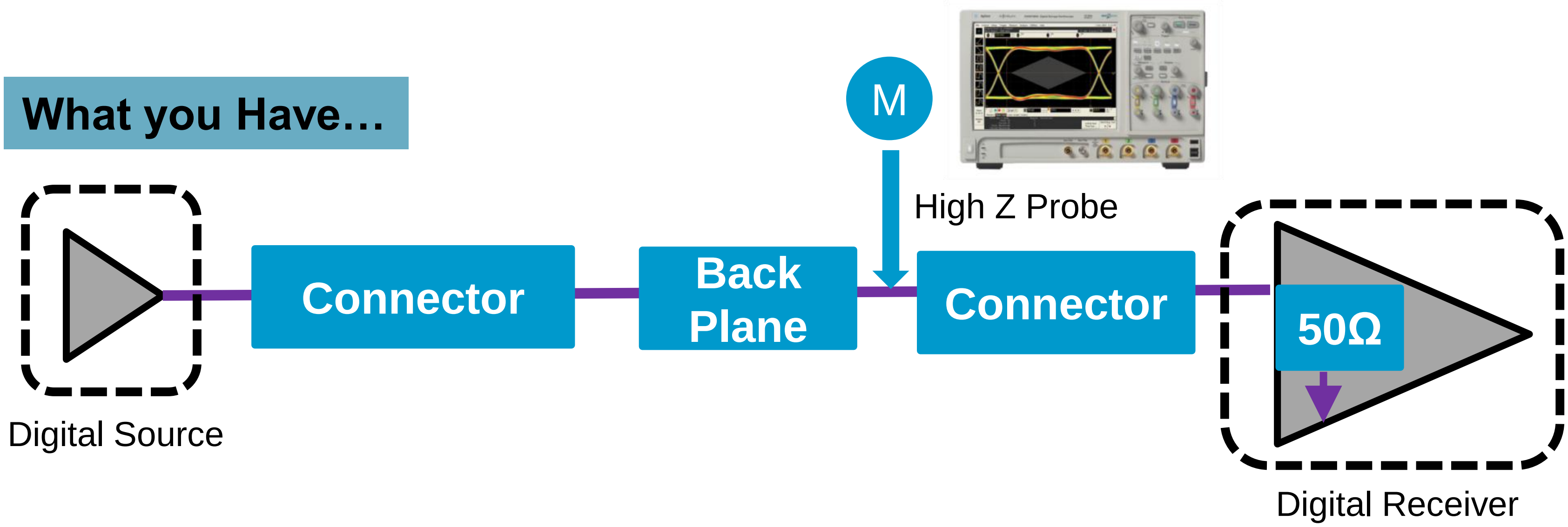
Cable

50Ω Instrument
Termination

S Simulated Measurement Plane

Virtual Probing (or Measurement Plane Relocation)

What you Have…



M

High Z Probe

Digital Source

Connector

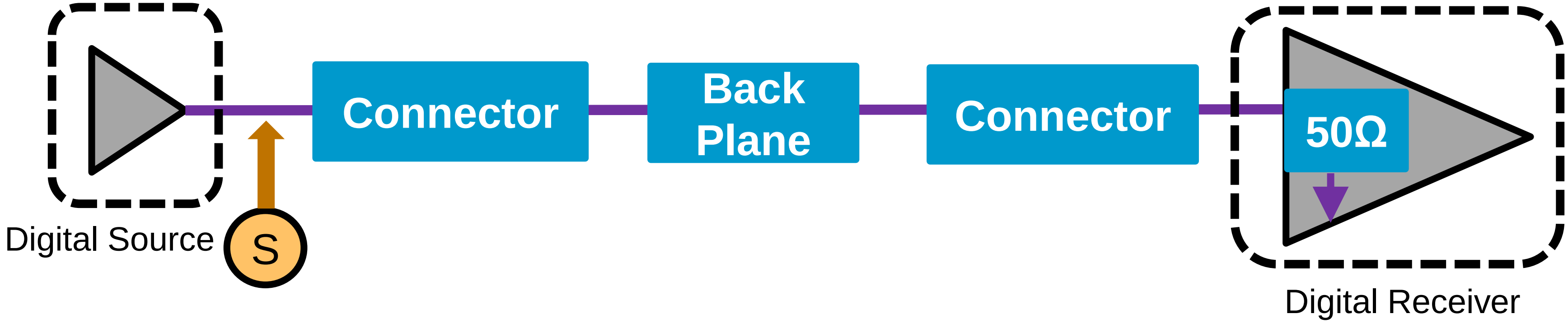
Back Plane

Connector

50Ω

Digital Receiver

What you Want…



Digital Source

S

Connector

Back Plane

Connector

50Ω

Digital Receiver

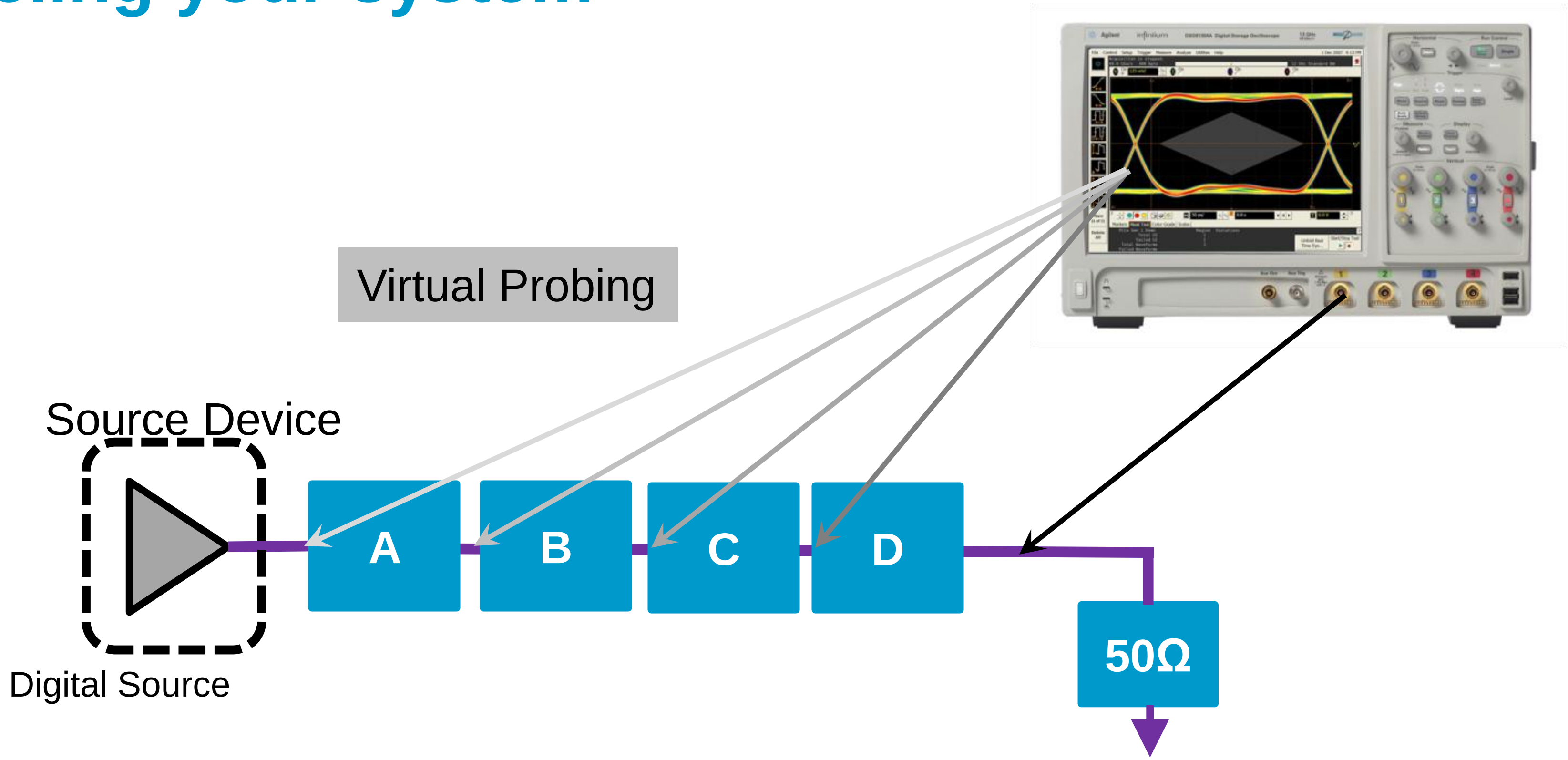
‘Simulated’ Measurements?

Is it *Unreasonable* to consider that these scenarios can yield a new class of measurements where a waveform acquisition can be *TRANSFORMED* to a VIEW at another location either real or virtual??

NO!! It is NOT Unreasonable!

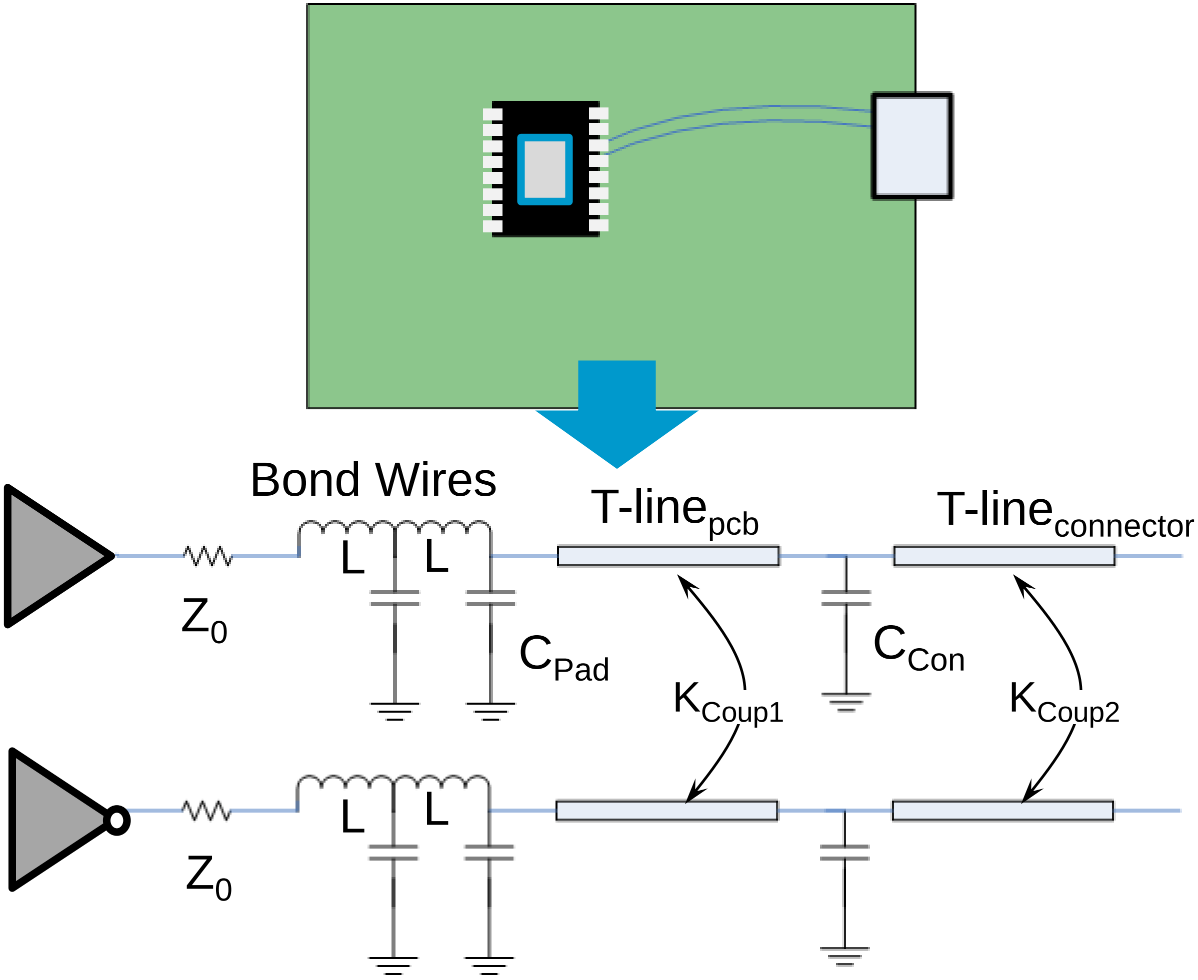
If we can describe the system accurately then it is ‘just math’!

Modeling your system

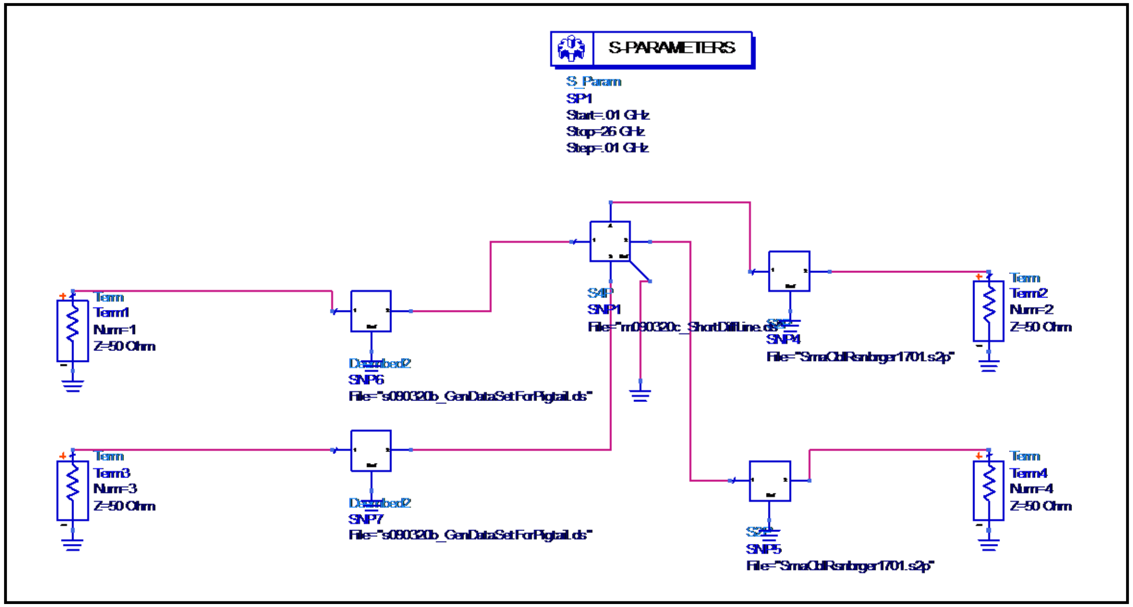


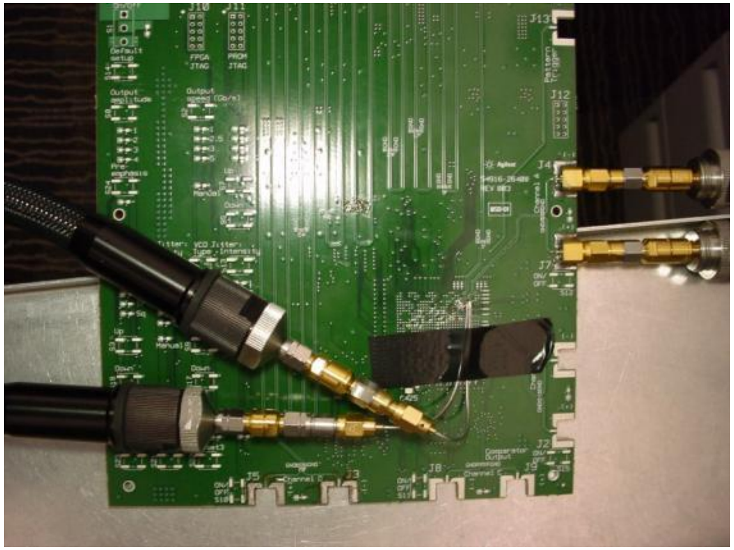
Circuit Elements: capacitors, inductors, resistors
Parameters: Z, Y, S-Parameters
Time Domain: Impulse Response
Frequency Domain: Transfer Functions

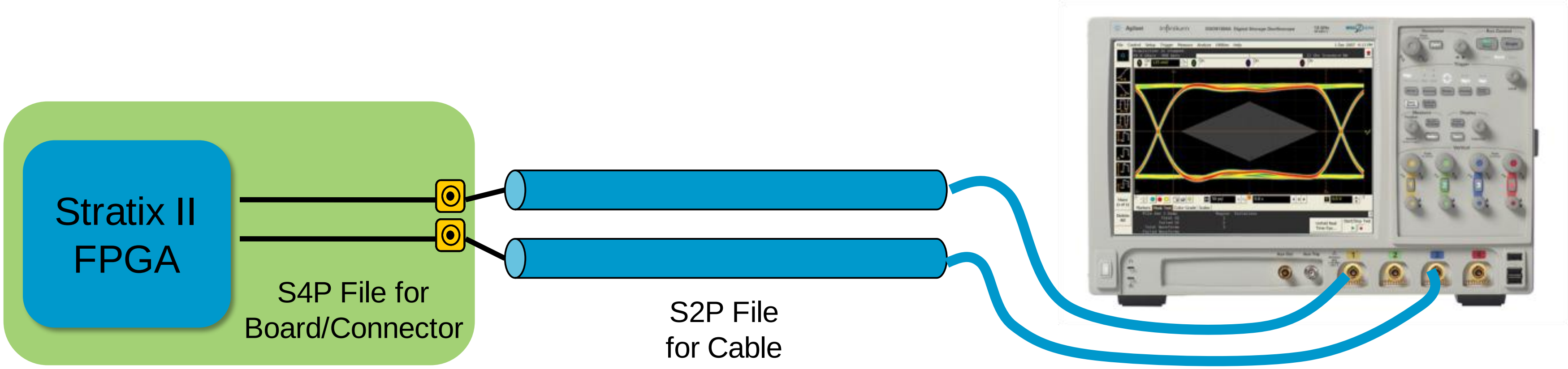
How a Source might be modeled:



Creating models in ADS (Agilent Design System)







Stratix II FPGA

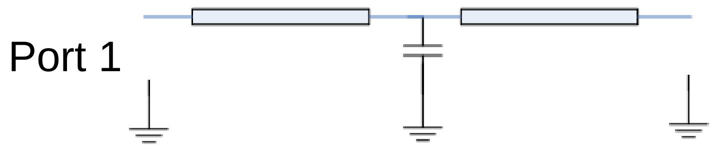
S4P File for Board/Connector

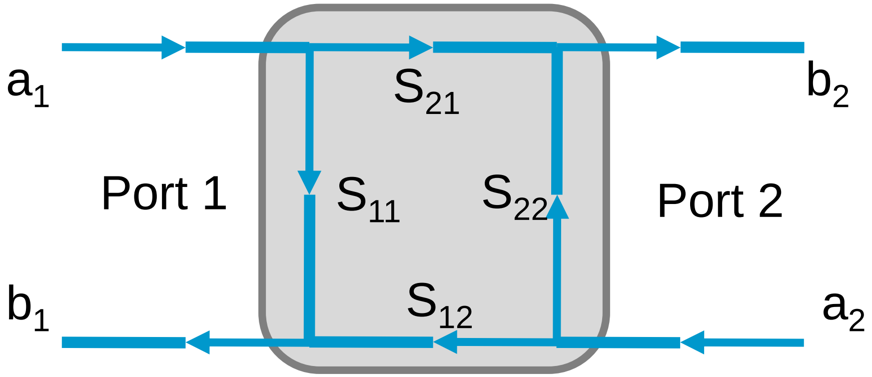
S2P File for Cable

S-Parameters: Definition

$$S_{jk} = \frac{b_j}{a_k}$$

- A Matrix of S-Parameters is used to describe multi-port devices
- a1,a2 represent the waves <u>entering</u> ports 1,2 respectively
- b1,b2 represent the waves <u>exiting</u> ports 1,2 respectively
- The voltage observed on port 1 is described by the vector addition of the voltage waves described by a1,b1
- Frequency based (Sinusoids)



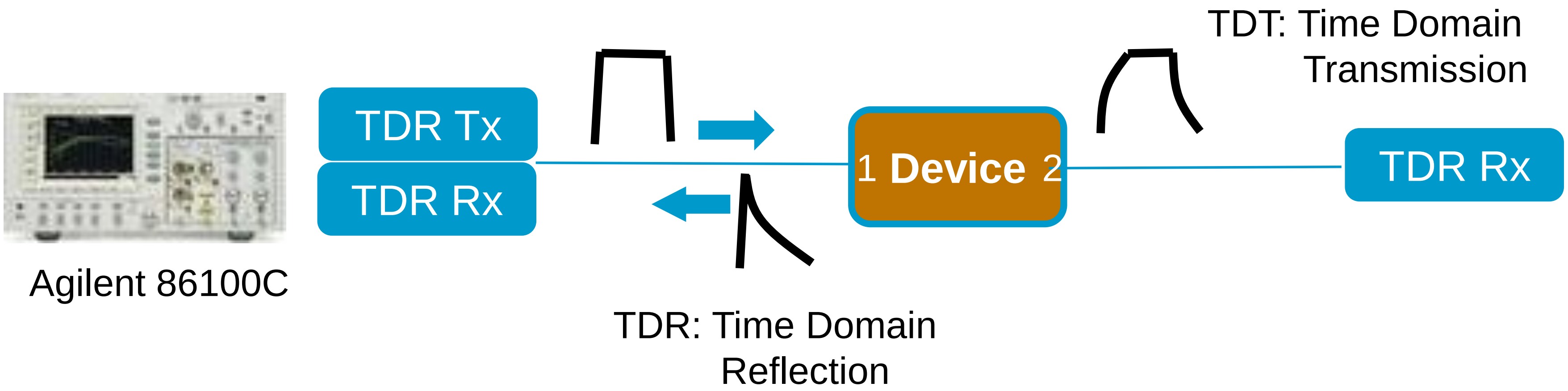


$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

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

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

S-Parameters: Time Domain View



TDR Tx

TDR Rx

1 **Device** 2

TDR Rx

Agilent 86100C

TDR: Time Domain Reflection

TDT: Time Domain Transmission

Digital Communication Analyzer

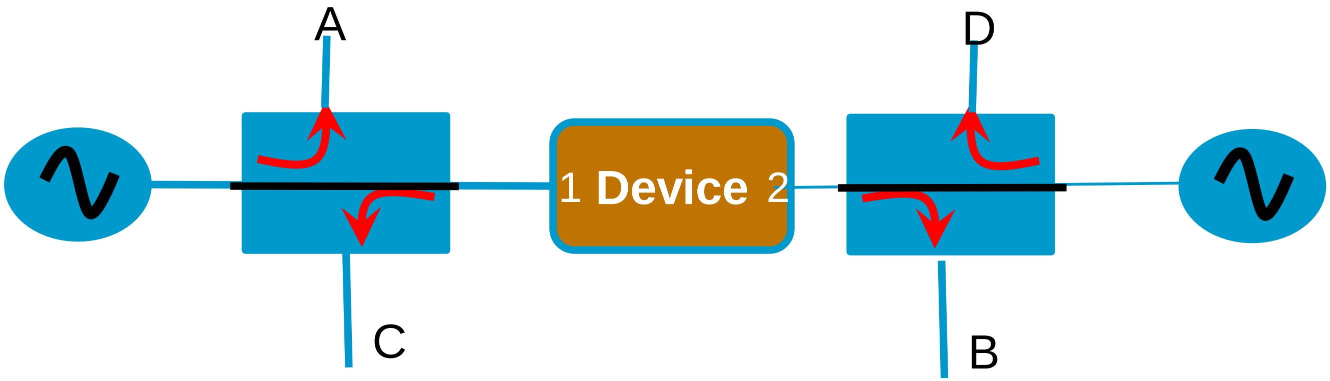
Evaluate Wave Reflected at Port 1 vs Wave incident at Port 1… S_{11}

Evaluate Wave Transmitted through to Port 2 vs Wave incident at Port 1… S_{21}

Flip Device around and repeat for S_{22} and S_{12}.

S-Parameters: Frequency Domain View

Agilent E5071C



Vector Network Analyzer

Sinusoidal Stimulus

Directional Devices Pick off voltage waves A, B, C, D

- S_{21} = B/A vector
- S_{11} = C/A vector
- S_{12} = C/D vector
- S_{22} = B/D vector

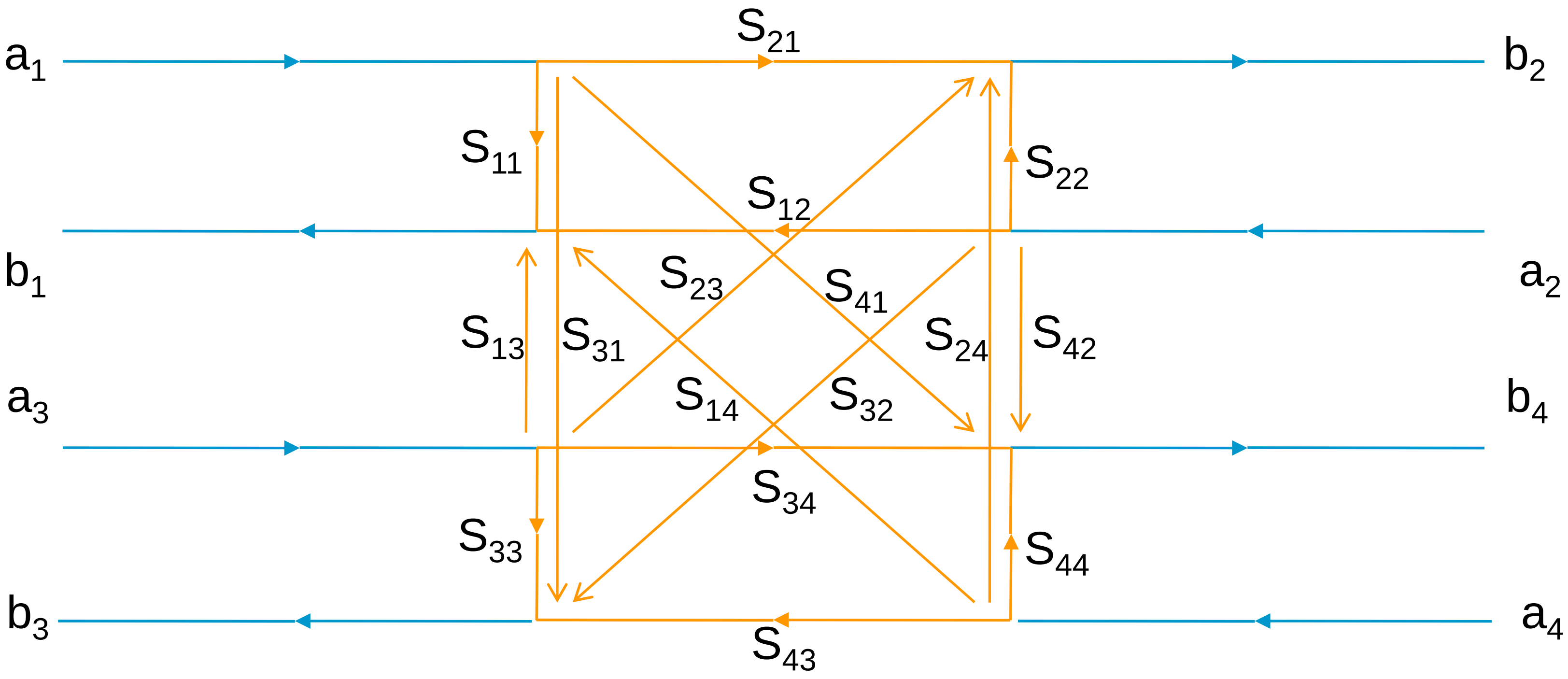
S-Parameters: 2 to 4 Port

2 Port

4 Port

1 Differential Lane

S-Parameters: 4-Port

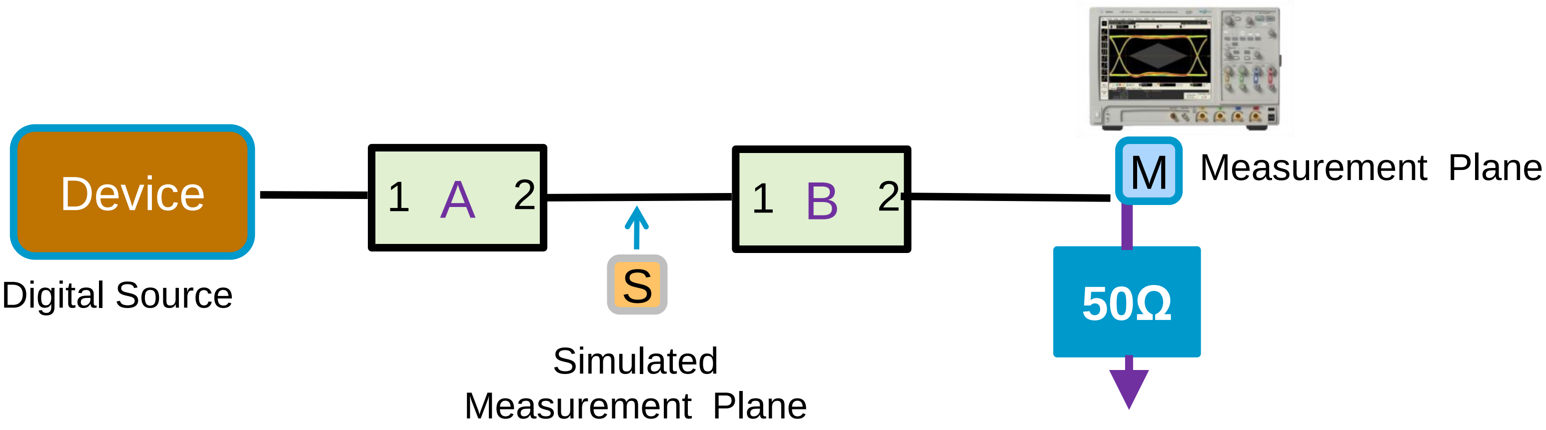


$$\begin{pmatrix} b1 \\ b2 \\ b3 \\ b4 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{pmatrix} \begin{pmatrix} a1 \\ a2 \\ a3 \\ a4 \end{pmatrix}$$

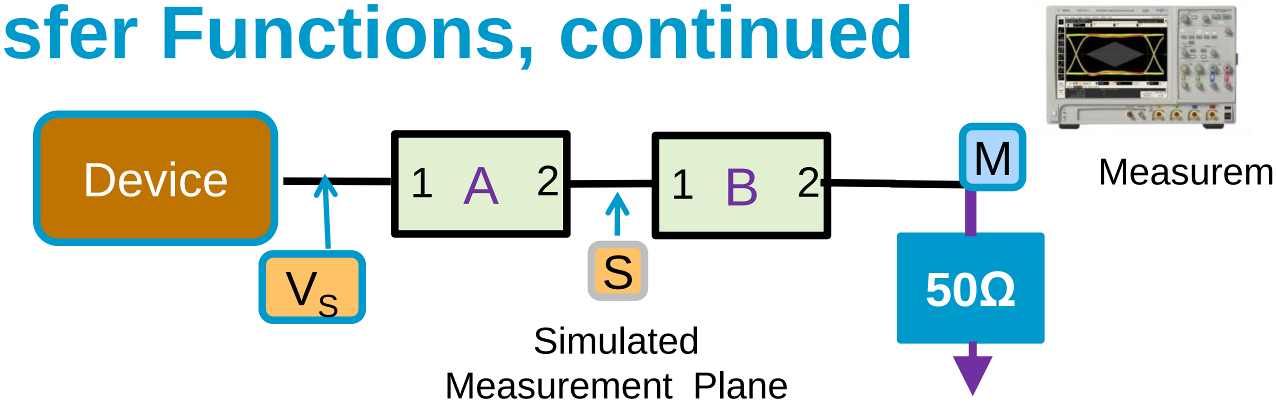
Transfer Functions

If you want to see signal at S but can only measure at M, what do you do?

- A Transfer Function describes the ratio of a voltage wave <u>entering/exiting</u> one port to a voltage wave <u>exiting/entering</u> another port.
- An S-Parameter or combination of S-Parameters can be used as a Transfer Function.
- Transfer Functions are commonly described in the frequency domain H(s), where s=jw



Transfer Functions, continued



Device

V_S

1 A 2

1 B 2

S

M

50Ω

Measurement Plane

Simulated
Measurement Plane

$$\boxed{M} * H(s) = \boxed{S}$$

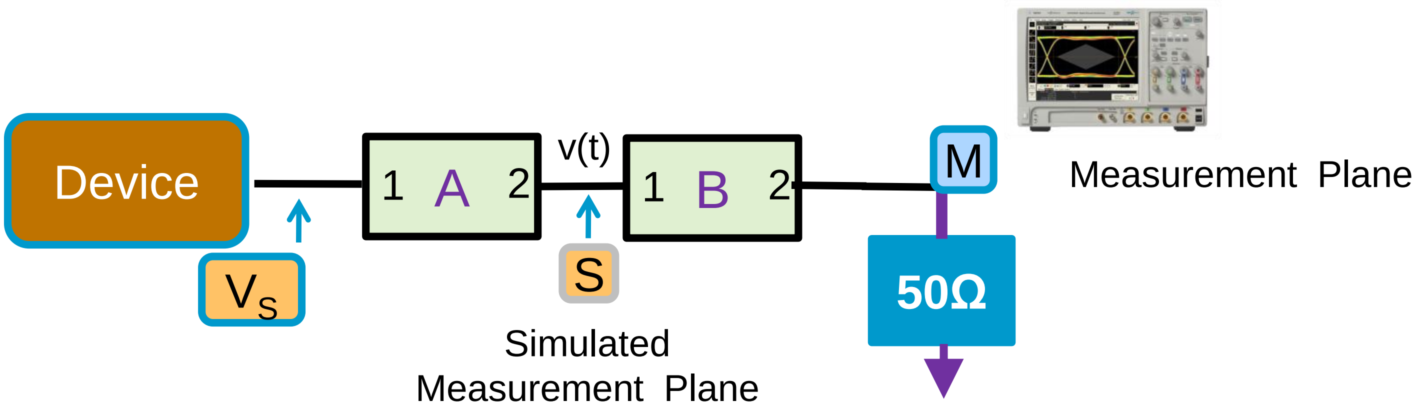
$$M(k) * H(n-k) = S(n)$$

Acquisition Data

Simulated Measurement

Discrete Time Representation
of Transfer Function

Transfer Functions, continued



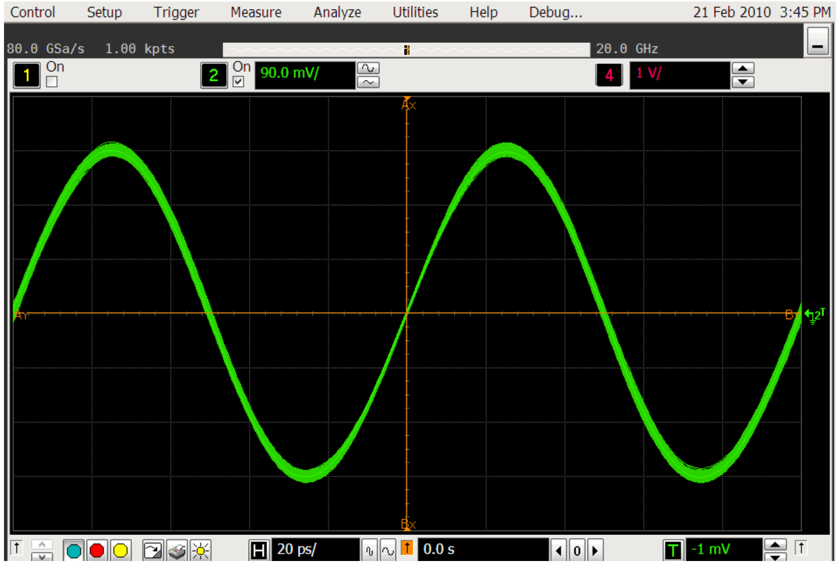
An Ambiguity is what Relationship from M to S truly is:

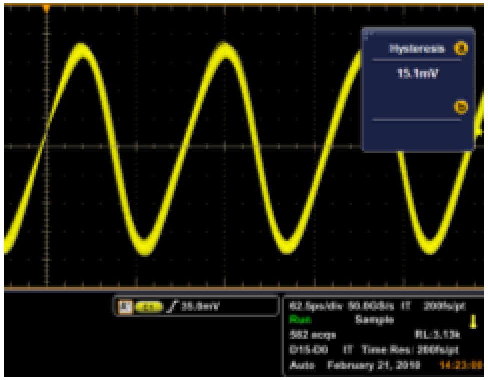
It could be:

1. $S = S_{21B}^{-1} \times M$ (Simple Gain Compensation)
2. S = The node voltage, v(t), in the circuit (Reference Plane Relocation)
3. S = The node voltage, v(t), with Element B removed and 50Ω to ground connected (Channel Element Removal or De-Embedding)

Schedule

1. Brief de-embedding presentation
2. Scope Architecture
3. Hardware Performance
4. Frequency Interleaving
5. DSP Boosting
6. Measurement Comparisons
7. Conclusion





Scope Architecture

This presentation will focus on the pre-amplifier and the importance of understanding its bandwidth

Attenuator

Pre-Amplifier

Sampler

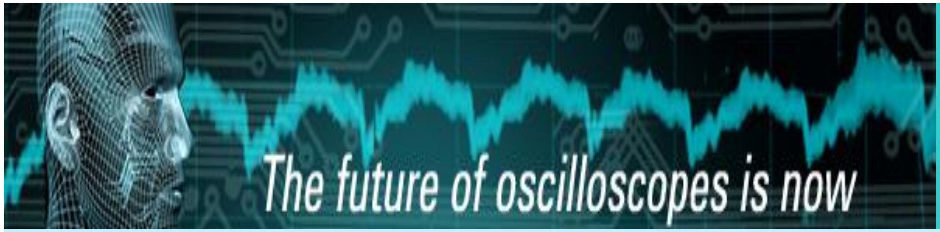
ADC

Memory Controller

Memory

Trigger Chip

Typical Scope Configuration

	**Maximum Preamplifier Bandwidth**		**Oscilloscope Bandwidth Spec**
DSP Boosting	16 GHz	→	20 GHz
Frequency Interleave	16 GHz	→	30 GHz
True Analog Bandwidth	32 GHz		32 GHz

The oscilloscope pre-amplifier

1. Presents a DC coupled 50 ohm termination impedance at the scopes inputs to its full bandwidth
2. Provides a mean to offset the dynamic range of the input signal
3. Corrects the response of the oscilloscope
4. Provides anti-aliasing at maximum sample rate
5. Can drive both sampler IC and the trigger IC
6. Isolates the sampler IC from the trigger outputs

Agilent's proprietary multi-chip modules

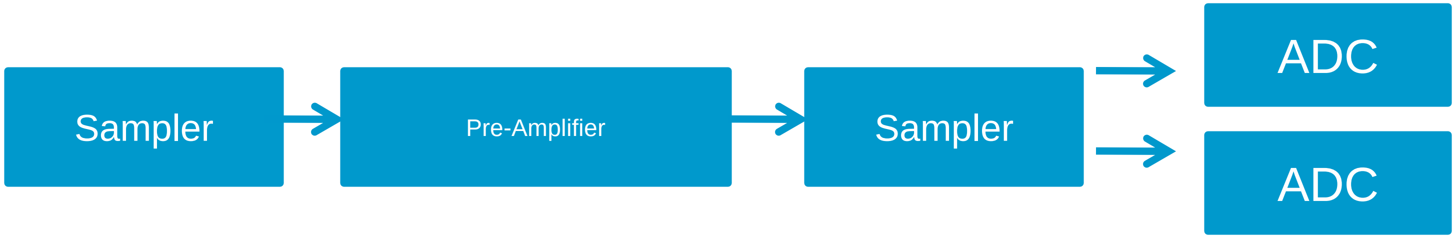
Preamplifier output bandwidth determines the bandwidth of the oscilloscope

Unless:

You DSP boost

You use frequency interleaving

Hardware Performance (pre-amplifier BW)


Sampler

Pre-Amplifier

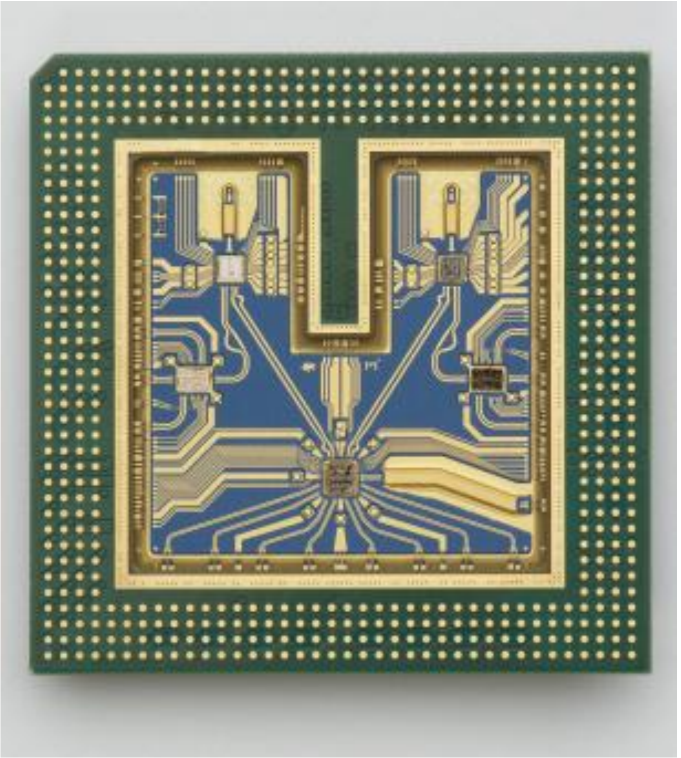
Sampler

ADC

ADC

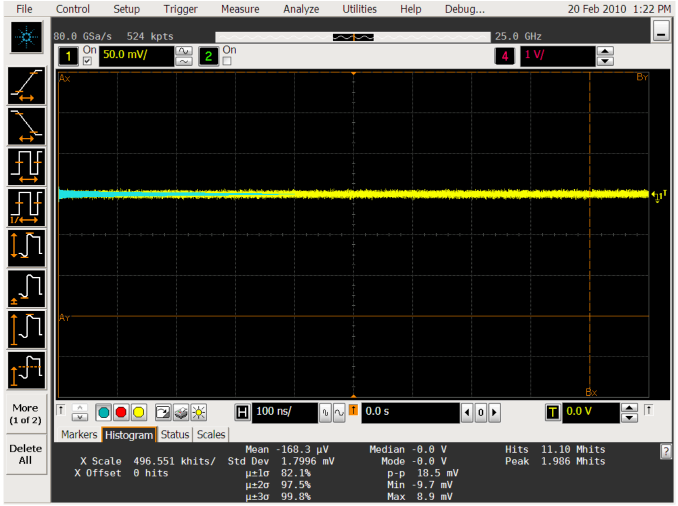
Requires significant investment to achieve raw hardware performance to bandwidths > 16 GHz

Semiconductor Process	Cutoff Frequency (GHz)
Agilent Indium Phosphide HBT	200
IBM 8HP	207
Infineon B7HF200	200
IBM 7HP	110
ST BiCMOS9MW	230
IHP SG25H1	190

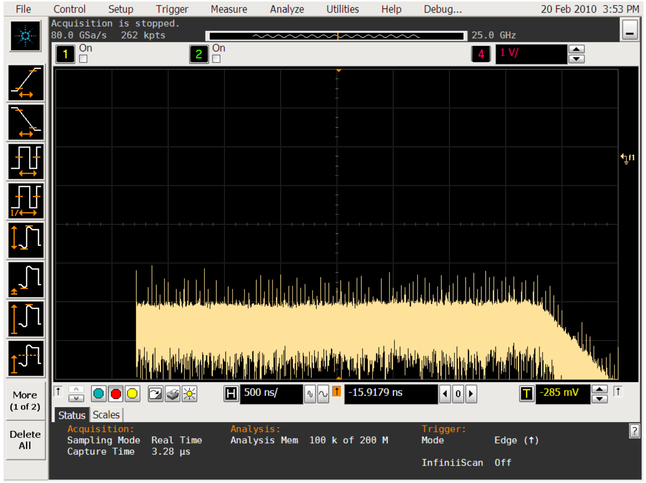


Key Points of Hardware Performance

- ☐ Requires investment in state of the art chip processes
- ☐ Typically will have linear noise density to full bandwidth
- ☐ No noise penalty due to DSP
- ☐ Flat frequency response
- ☐ Design is still a key part of the oscilloscope performance

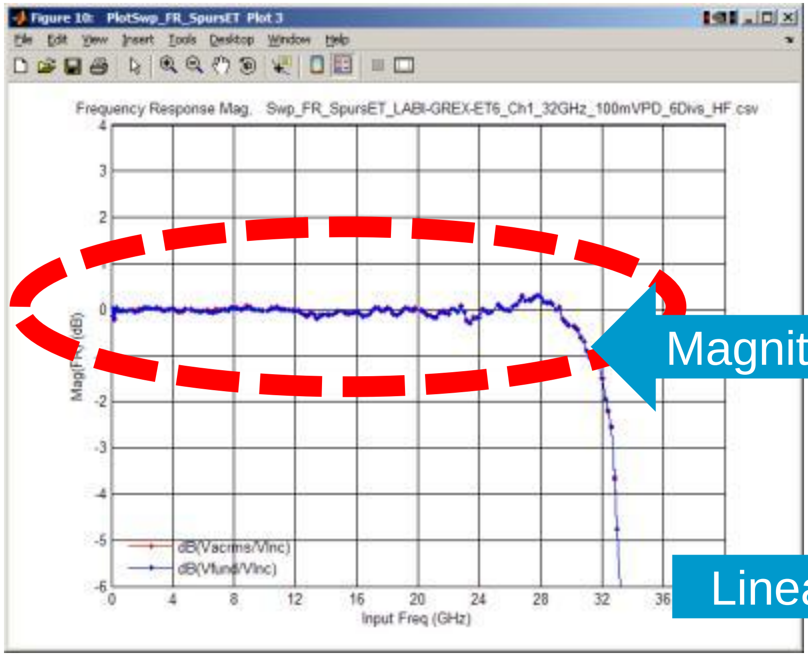


```
                 Mean -168.3 µV     Median -0.0 V       Hits  11.10 Mhits
X Scale  496.551 khits/ Std Dev  1.7996 mV    Mode -0.0 V       Peak  1.986 Mhits
X Offset  0 hits          µ±1σ  82.1%          p-p  18.5 mV
                          µ±2σ  97.5%          Min -9.7 mV
                          µ±3σ  99.8%          Max  8.9 mV
```



```
Acquisition:                      Analysis:                      Trigger:
Sampling Mode   Real Time         Analysis Mem  100 k of 200 M   Mode         Edge (↑)
Capture Time    3.28 µs
                                                                 InfiniiScan  Off
```

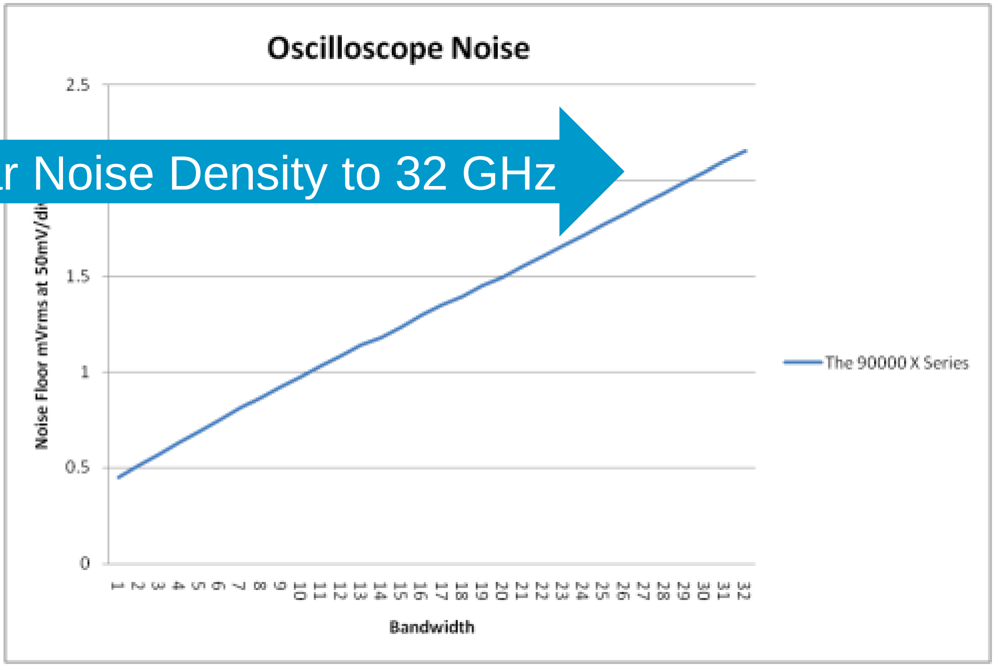
Data from 90000 X-Series (Hardware Perf.)



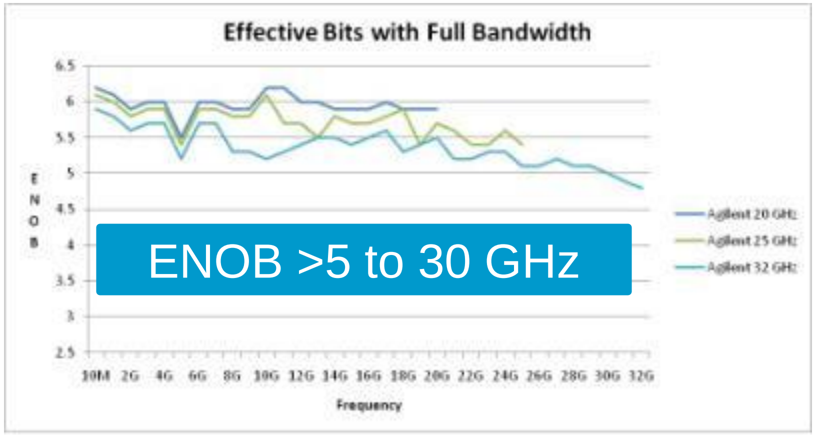
Magnitude Flatness +/-0.25dB

90000 X-Series features:

- 32 GHz pre-amplifier enabled by its InP front end
- performance advantages of true analog bandwidth (low noise, jitter, flat response)

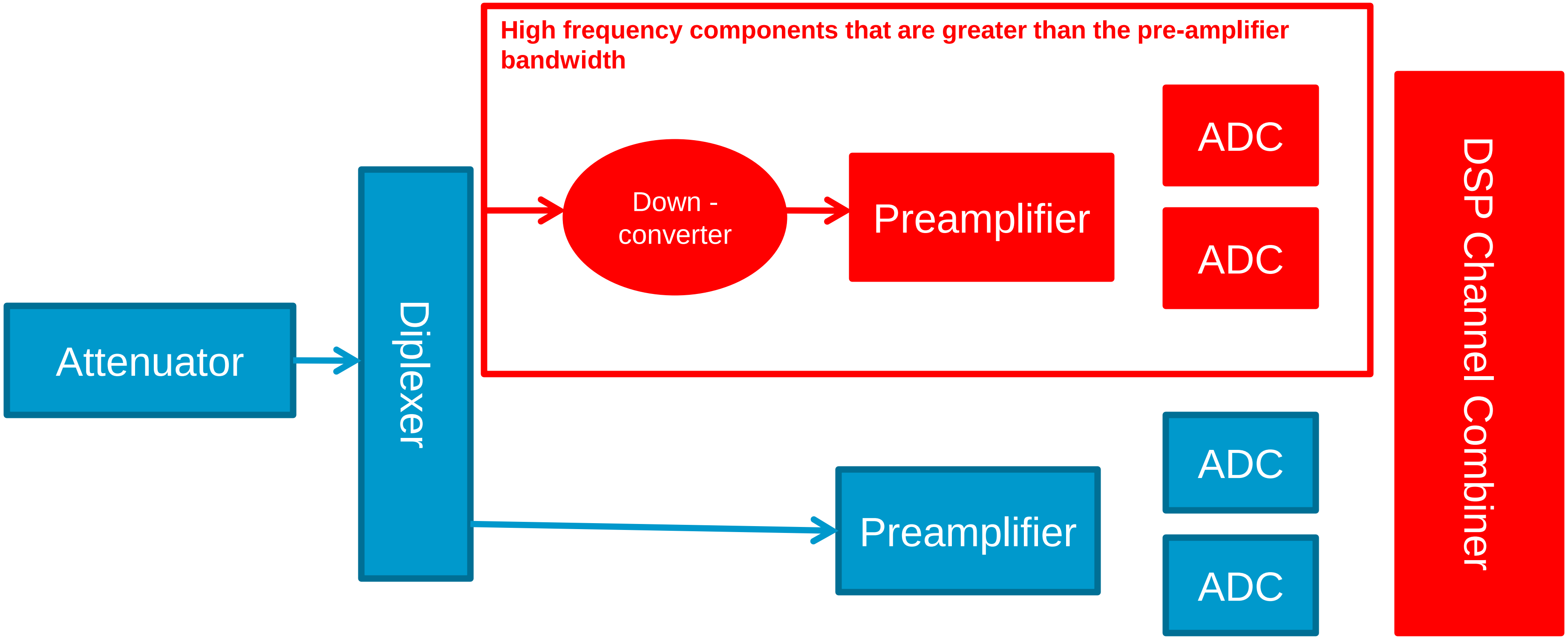


Linear Noise Density to 32 GHz



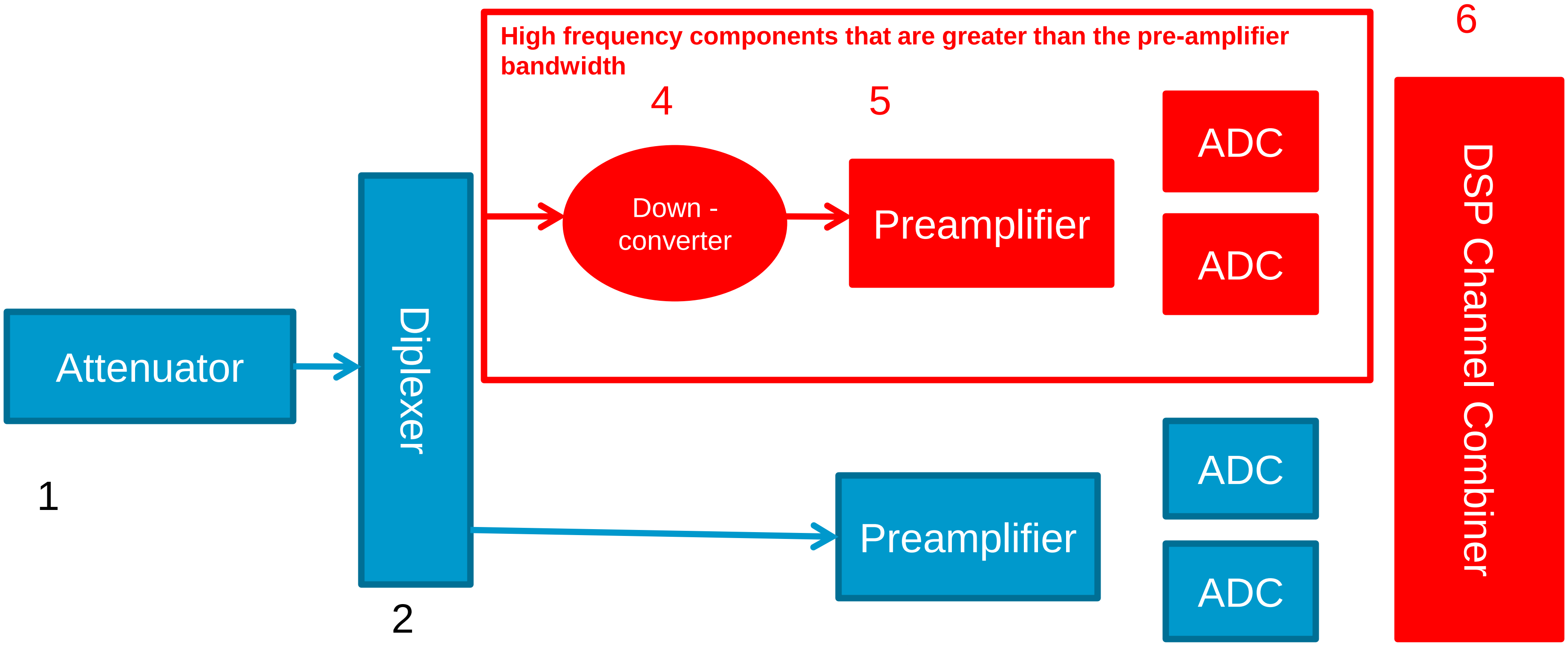
ENOB >5 to 30 GHz

What is Frequency Interleaving



Frequency Interleaving is an RF Technique that allows for faster time to market to achieve higher bandwidth

How does frequency interleaving work?



High frequency components that are greater than the pre-amplifier bandwidth

6

4

5

ADC

Down - converter

Preamplifier

ADC

DSP Channel Combiner

Attenuator

Diplexer

ADC

1

Preamplifier

ADC

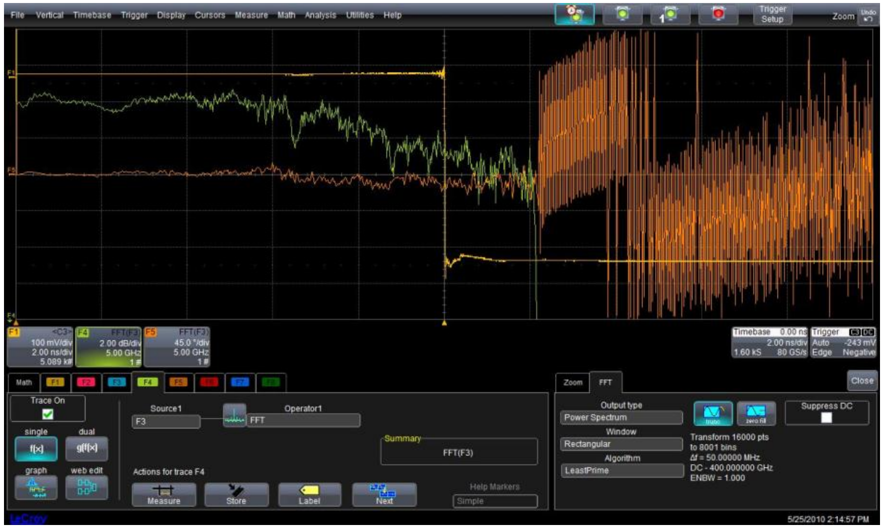
2

3

1. Signal enters an attenuator
2. Signal then enters a diplexer
3. Low frequency content goes through pre-amplifer
4. High frequency content is immediately down-converted
5. Down-converted HF content, goes through lower BW rated pre-amplifier
6. Signal is all put back together

Key Points of Frequency Interleaving

- ☐ Requires significant DSP processing
- ☐ Enabled by high powered PC
- ☐ Achieved through significant advances in RF design
- ☐ Down-conversion is a key part of the acquisition
- ☐ Signal is actually interleaved twice
- ☐ Allows for faster bandwidths with less investment than hardware performance



F1 <C3> 100 mV/div 2.00 ns/div 5.089 k#

F4 FFT(F3) 2.00 dB/div 5.00 GHz 1 #

F5 FFT(F3) 45.0 °/div 5.00 GHz 1 #

Timebase 0.00 ns 2.00 ns/div 1.60 kS 80 GS/s

Trigger C3 DC Auto -243 mV Edge Negative

Trace On ☑

Source1: F3

Operator1: FFT

Summary: FFT(F3)

Actions for trace F4

Help Markers: Simple

Output type: Power Spectrum

Window: Rectangular

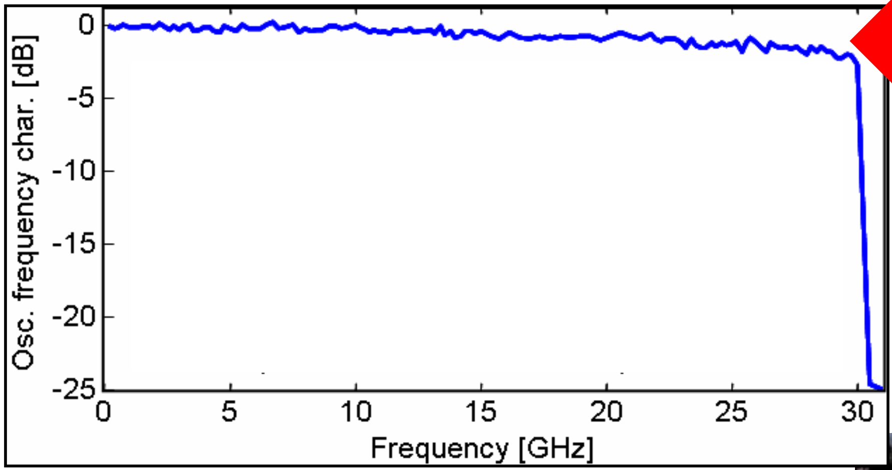
Algorithm: LeastPrime

Suppress DC ☐

Transform 16000 pts
to 8001 bins
Δf = 50.00000 MHz
DC - 400.000000 GHz
ENBW = 1.000

5/25/2010 2:14:57 PM

Data from frequency interleaved oscilloscope



> 3dB magnitude loss

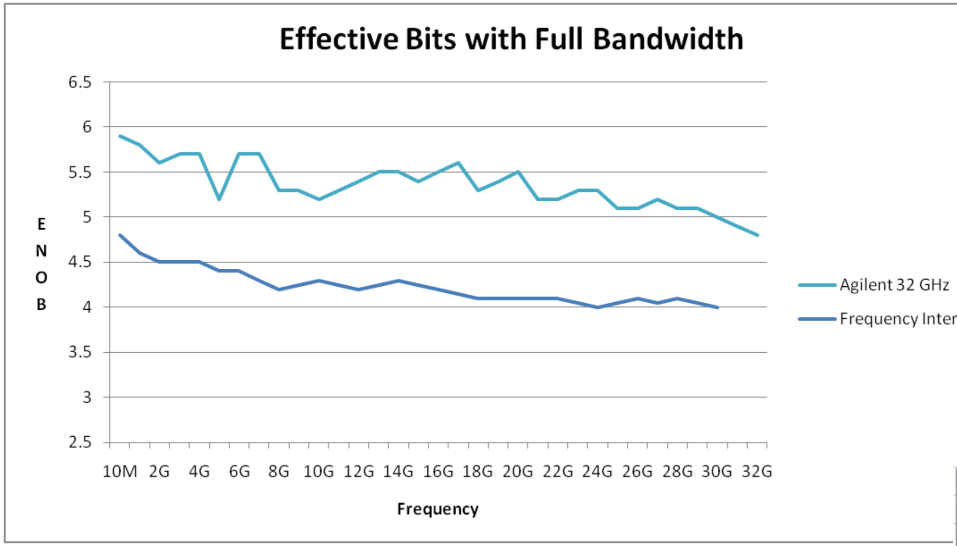
Frequency interleaved scopes feature:

- preamplifier bandwidth rated to ½ the bandwidth of the oscilloscope
- first oscilloscope to reach >20 GHz

dVer	P1:pkpk(C3)	P2:ampl(C3)	P3:max(C3)	P4:min(C3)	P5:sdev(C3)	P6:mean(C3)	P7:base(C3)	P8:top(C3)	P9
lue	50.8 mV	50.8 mV	26.1 mV	-24.7 mV	6.22 mV	-542 µV	-24.7 mV	26.1 mV	
tus	✓	⊼	✓	✓	✓	✓	⊼	⊼	

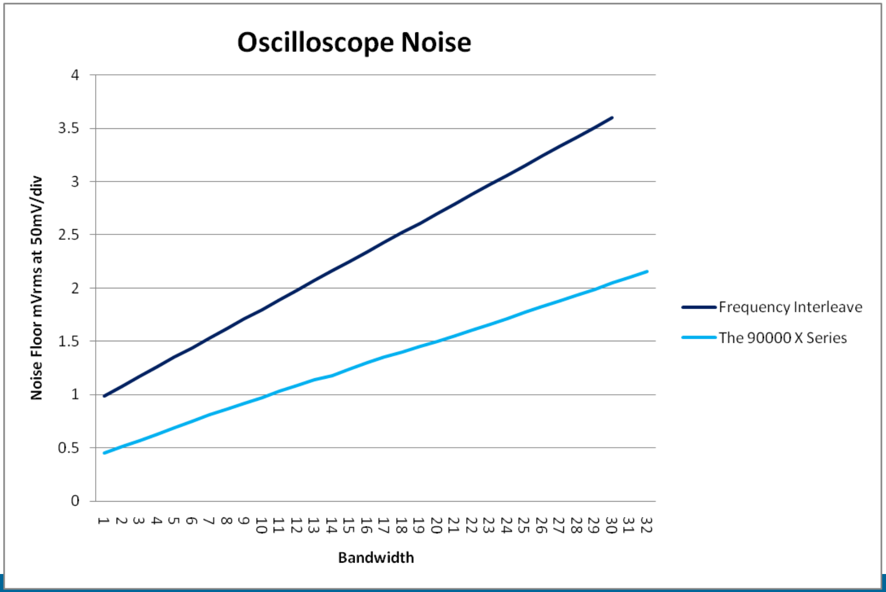
Noise density has 8dB gain at the “mixer point”

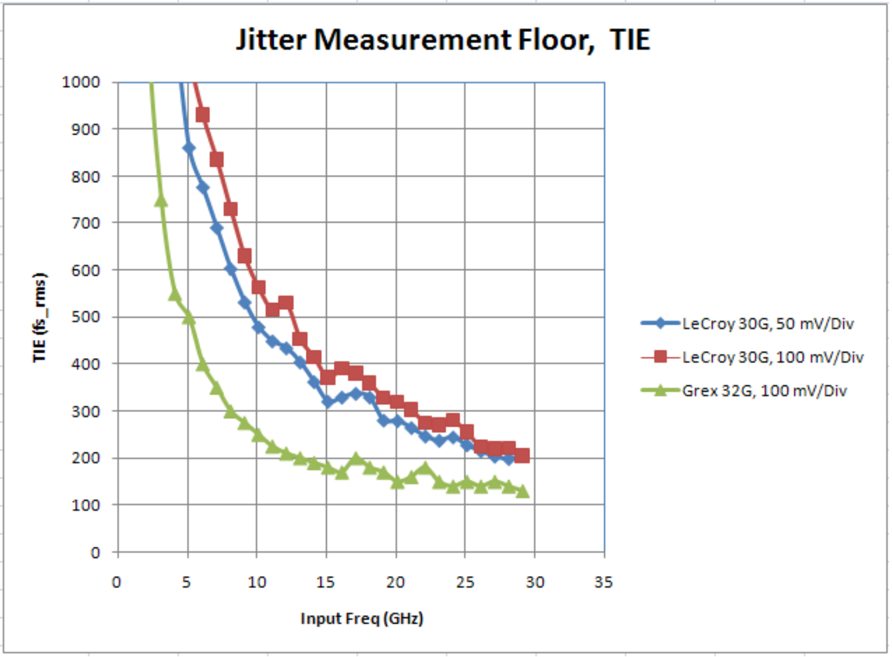
Hardware performance vs. frequency interleaving



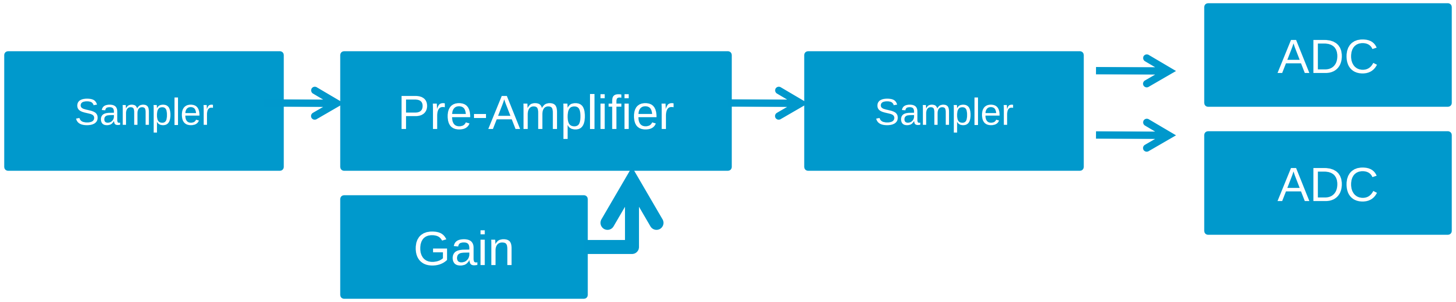
Hardware performance has:

- ☐ 25% higher ENOB
- ☐ ½ the noise floor
- ☐ ½ the noise density
- ☐ 2-5x lower jitter meas. Floor
- ☐ 5x flatter frequency response





DSP boosting (extending the bandwidth)



Sampler

Pre-Amplifier

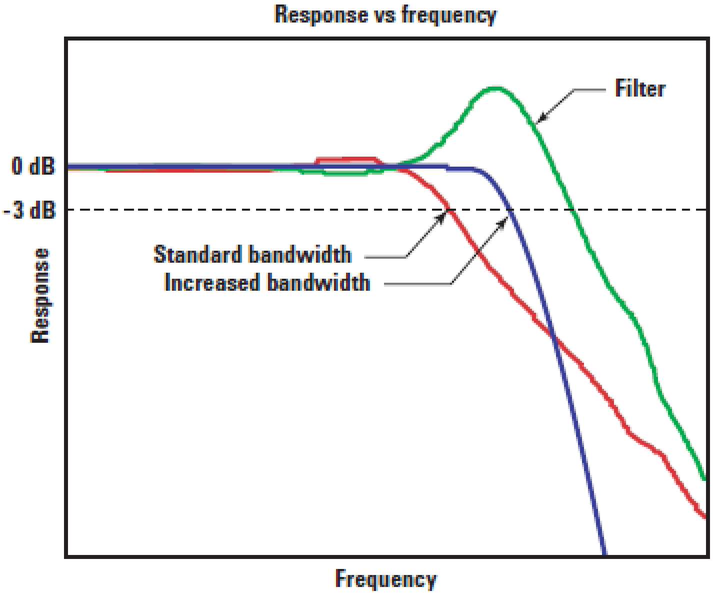
Gain

Sampler

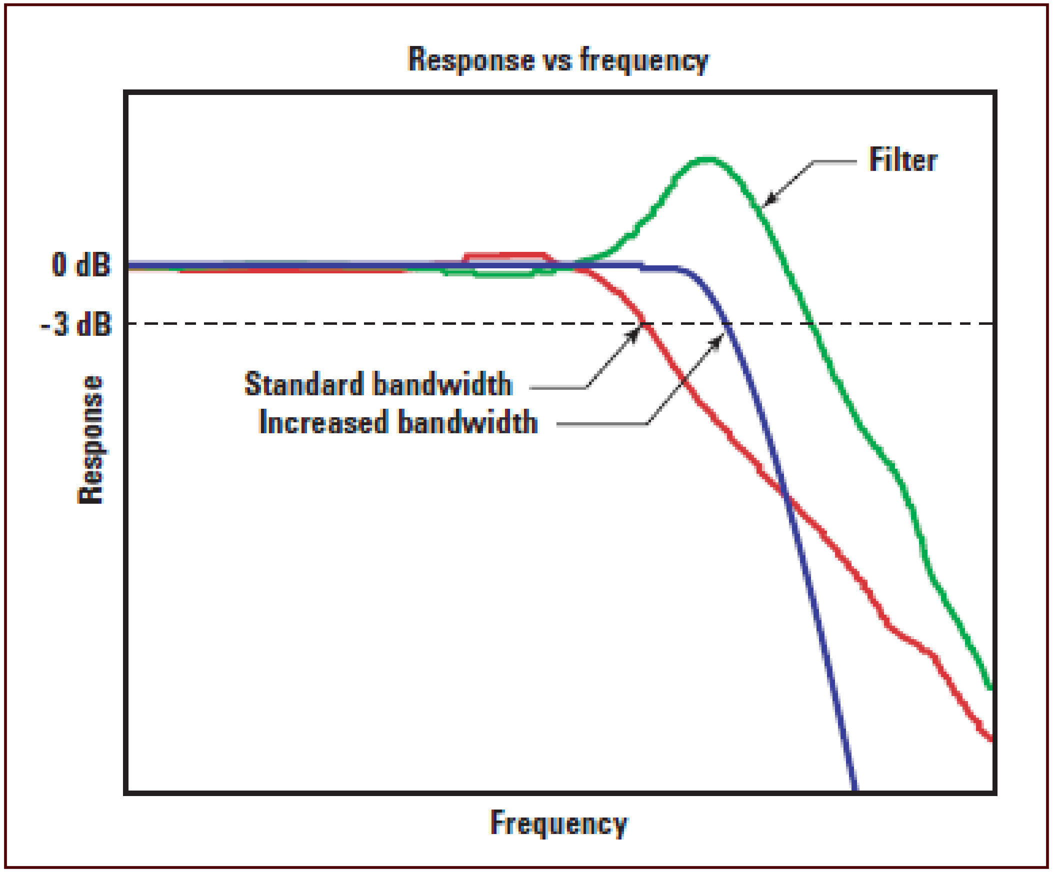
ADC

ADC

- ✓ Does not extend the bandwidth as much as frequency interleaving.
- ✓ Does not require additional hardware to extend the bandwidth
- ✓ Frequency extension achieved with filters



How DSP boosting works



1. Pre-amplifier bandwidth (red trace) does not achieve full bandwidth
2. Filter is applied that “boosts” the high frequency components of the oscilloscope (green trace)
3. Additional bandwidth is achieved, up to 25% bandwidth increase (blue trace)
4. Bit tradeoff of the signal is the noise increase and ENOB erosion of the 2nd harmonic

Filter and software work together to achiever higher bandwidth

Key points of DSP boosting

- ☐ Requires bandwidth boosting of high frequency components through DSP processing
- ☐ Achieves up to 25% additional bandwidth without the addition of extra hardware
- ☐ Trades off measurement accuracy for extra bandwidth as the noise density is significantly increased where boosting filter is applied

Curs1 Y Pos -3.4dB

Curs2 Y Pos -19.4dB

Cursor 1: Math 4

Cursor 2: Math 4

M4 10.0dB 2.5GHz

V1 -3.4dB

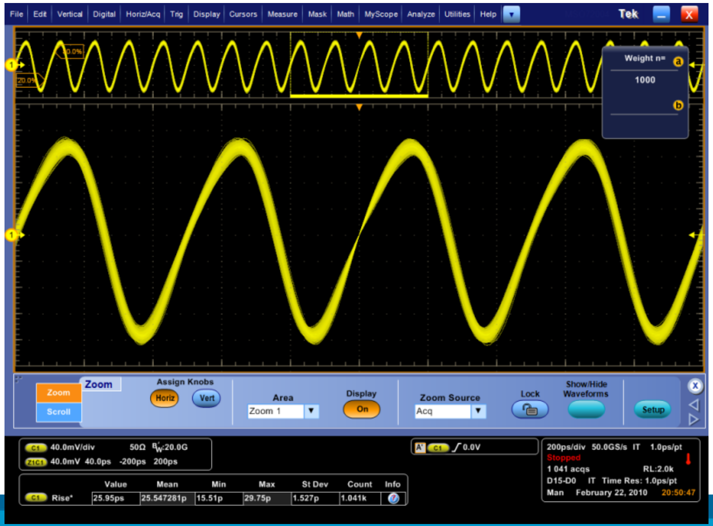
V2 -19.4dB

ΔV -16.0dB

A' C1 0.0V

200ns/div 50.0GS/s IT 1.0ps/pt
Run Sample
51 acqs RL:2.0M
D15-D0 IT Time Res: 1.0ps/pt
Man February 22, 2010 22:03:51

	Value	Mean	Min	Max	St Dev	Count	Info
C1 Rise*	24.99ps	25.225145p	21.98p	27.4p	1.309p	50.0	



Area: Zoom 1

Zoom Source: Acq

C1 40.0mV/div 50Ω BW:20.0G

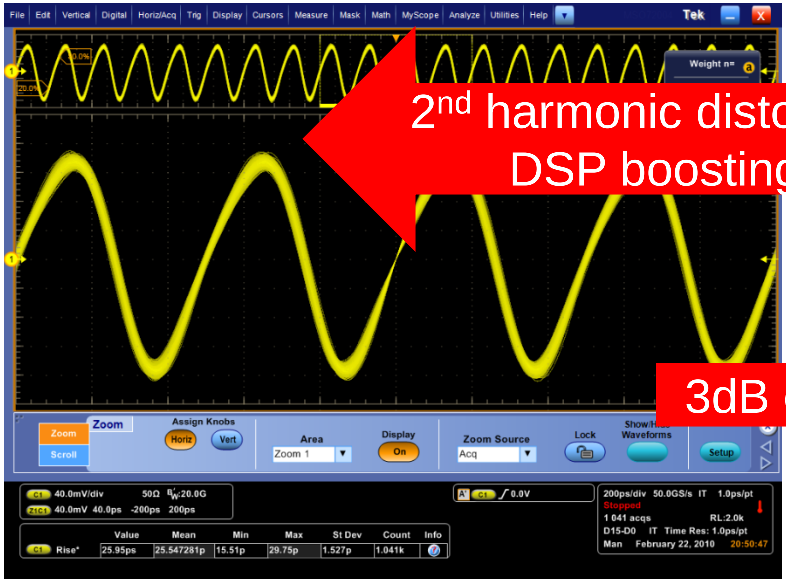
Z1C1 40.0mV 40.0ps -200ps 200ps

A' C1 0.0V

200ps/div 50.0GS/s IT 1.0ps/pt
Stopped
1 041 acqs RL:2.0k
D15-D0 IT Time Res: 1.0ps/pt
Man February 22, 2010 20:50:47

	Value	Mean	Min	Max	St Dev	Count	Info
C1 Rise*	25.95ps	25.547281p	15.51p	29.75p	1.527p	1.041k	

Data from DSP boosted oscilloscope



```
C1    40.0mV/div        50Ω  BW:20.0G
Z1C1  40.0mV  40.0ps  -200ps  200ps
```

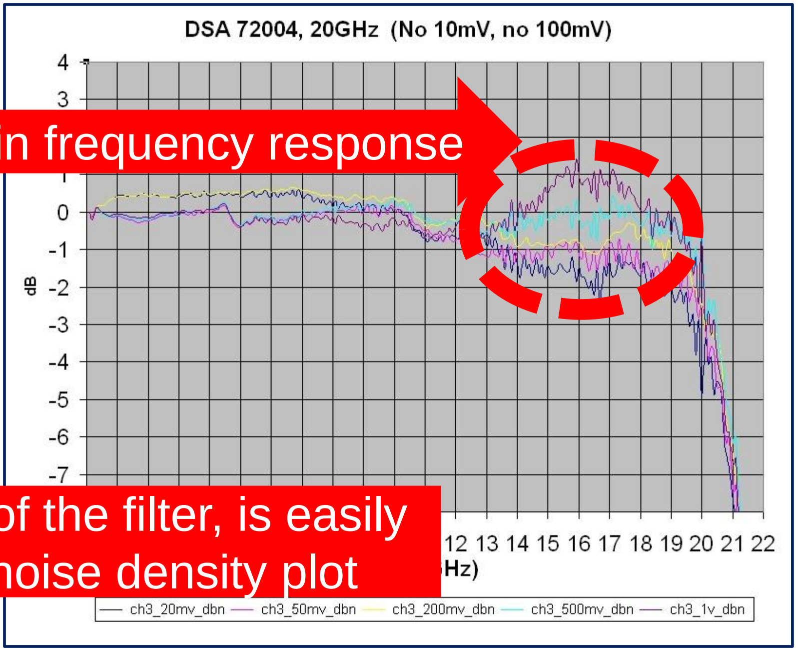
	Value	Mean	Min	Max	St Dev	Count	Info
C1 Rise*	25.95ps	25.547281p	15.51p	29.75p	1.527p	1.041k	

```
A' C1 ∫ 0.0V
```

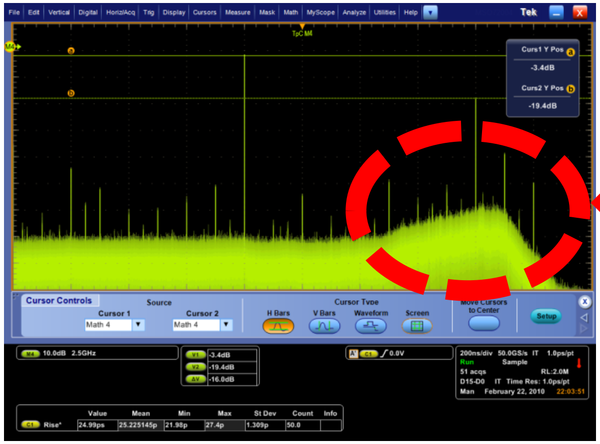
```
200ps/div  50.0GS/s  IT   1.0ps/pt
Stopped
1 041 acqs                  RL:2.0k
D15-D0    IT  Time Res: 1.0ps/pt
Man    February 22, 2010   20:50:47
```

2

2nd harmonic distortion caused by DSP boosting at 10 Ghz



3dB of variation in frequency response



```
Curs1 Y Pos  -3.4dB
Curs2 Y Pos  -19.4dB
```

Source
Cursor 1: Math 4
Cursor 2: Math 4

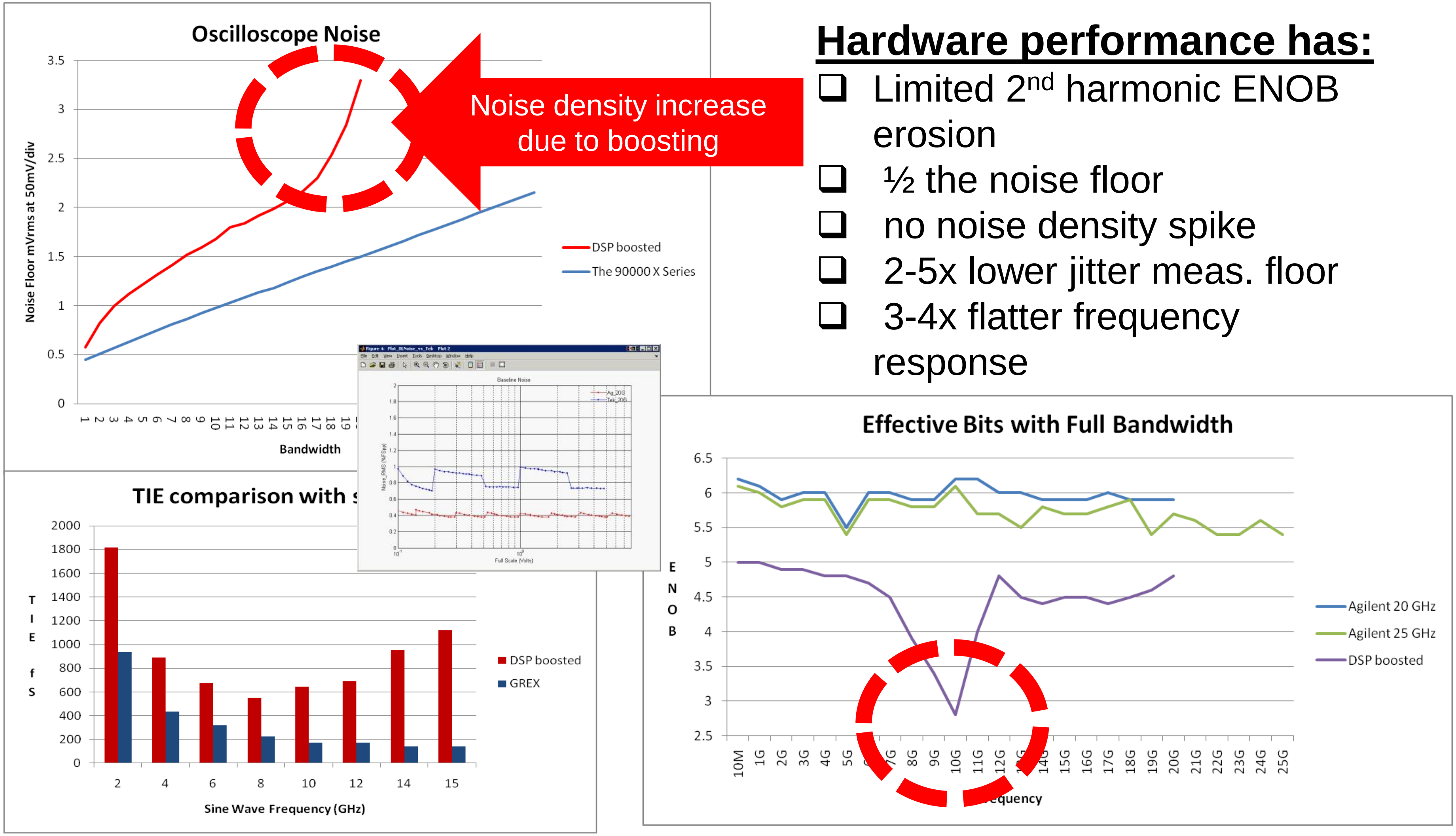
```
M4  10.0dB  2.5GHz
V1  -3.4dB
V2  -19.4dB
ΔV  -16.0dB
A' C1 ∫ 0.0V
```

```
200ns/div  50.0GS/s  IT   1.0ps/pt
Run          Sample
51 acqs                     RL:2.0M
D15-D0    IT  Time Res: 1.0ps/pt
Man    February 22, 2010   22:03:51
```

	Value	Mean	Min	Max	St Dev	Count	Info
C1 Rise*	24.99ps	25.225145p	21.98p	27.4p	1.309p	50.0	

Notice the gain of the filter, is easily shown in the noise density plot

Hardware performance vs. DSP boosting



Noise density increase due to boosting

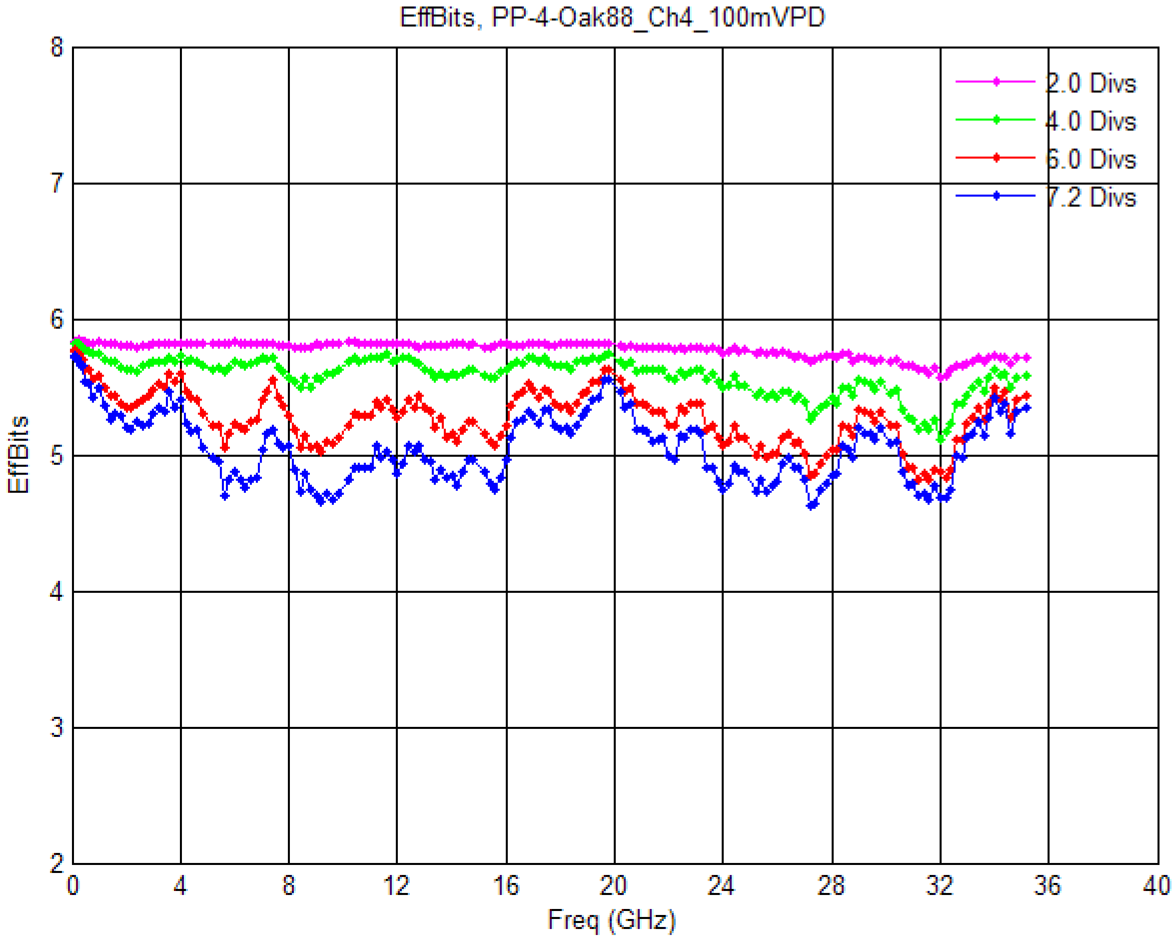
Hardware performance has:

- ❑ Limited 2nd harmonic ENOB erosion
- ❑ ½ the noise floor
- ❑ no noise density spike
- ❑ 2-5x lower jitter meas. floor
- ❑ 3-4x flatter frequency response

DPO7000, DSA/DPO70000, and DSA/DPO70000B Series Digital Phosphor Oscilloscopes Specifications and Performance Verification Technical Reference”

Conclusion

- ☐ Agilent’s 90000 X-Series oscilloscope is the only oscilloscope with >16 GHz pre-amplifier bandwidth and as a result has the lowest noise floor, highest effective bits, and flattest frequency response
- ☐ Frequency interleaving achieves the highest frequency gain, with the least pre-amplifier bandwidth, but trade-off is signal is down-converted and interleaved twice
- ☐ DSP boosting achieves higher bandwidth with little additional hardware, but tradeoff is increased noise


EffBits, PP-4-Oak88_Ch4_100mVPD
EffBits
Freq (GHz)
8
7
6
5
4
3
2
0
4
8
12
16
20
24
28
32
36
40
2.0 Divs
4.0 Divs
6.0 Divs
7.2 Divs