Signal Integrity Trouble-Shooting and Measurement Techniques

DAY 2 – Signal Measurements and Setups

Fabian Kung (Multimedia University)

Agenda for Today

- Electrical signals and signal representation.
- Morning Break
- Measurement domains and instrumentation.
- Live measurement exercise 1.
- Lunch Break
- Electrical probes and probing.
- Measurement examples.
- Afternoon Break
- Live measurement exercise 2.

1. Review of Electrical Signals and Signal Representation

Periodic, Non-Periodic and Random Signals

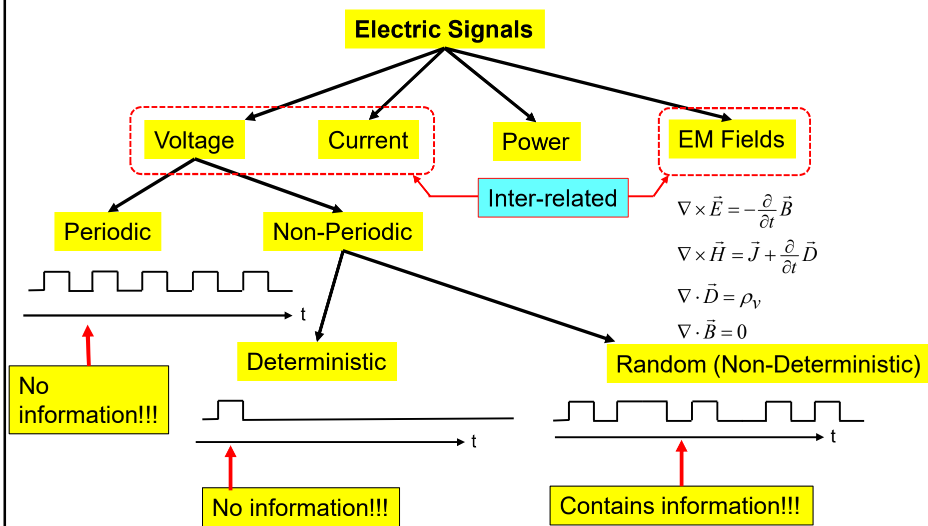
- **Signal** – A useful quantity or parameter that *changes with time*.
- Our focus will be **electrical signals**.
- Type of electrical signals:
  - Voltage signal.
  - Current signal.
  - Power signal.
  - Field or vector type signals such as time-varying electromagnetic (EM) fields.

Our focus, $P(t) = v(t)i(t)$

Voltage ↔ Electric Field (**E**)
Current ↔ Magnetic Field (**B**)

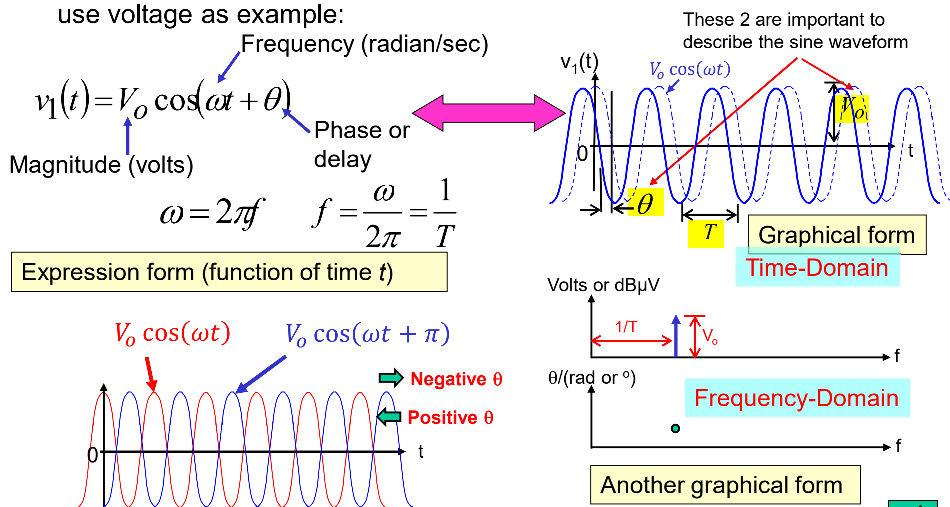
- Each of the signal type above in turn can be classified into **Periodic** and **Non-periodic** signals.
- Non-periodic signals (their period is infinite) include a class of signals called **random signals** which are of interest to telecommunication.

Electrical Signals



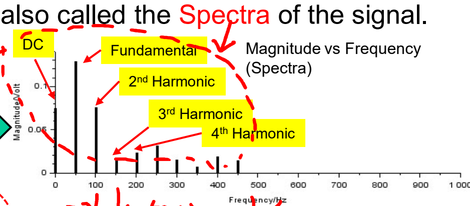
Signal Representations – Periodic Sinusoids

- Let us consider the most **fundamental signal**, the periodic sinusoid, we use voltage as example:

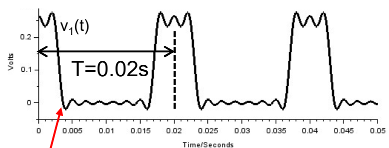


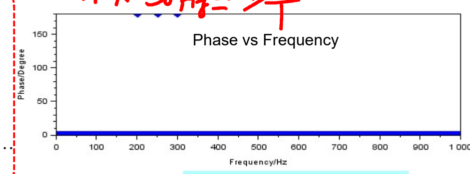
Signal Representations – General Periodic Signals

- From Fourier Series principle every periodic signals can be considered as being constructed from sinusoids with frequencies in harmonic relationship.
- An example of digital pulses with T = 0.02s (f = 50 Hz), up to 9th harmonics.
- The magnitude vs frequency plot is also called the Spectra of the signal.



$\leftarrow 50\,Hz = 1/T$





$$v_1(t)=V_{DC}+V_{o1}\cos(\omega t+\theta_1)+V_{o2}\cos(2\omega t+\theta_2)+V_{o3}\cos(3\omega t+\theta_3)+\cdots$$

DC | Fundamental | 2nd Harmonic | 3rd Harmonic

Time-Domain

Frequency-Domain

Signal Representations – Non-Periodic Signals

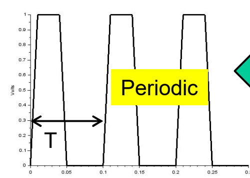
- The concept of Fourier Series can be extended to non-periodic signals, where it becomes the Fourier Transform. Essentially non-periodic signals can be viewed as periodic signal with period → infinity, thus the spectra becomes continuous.

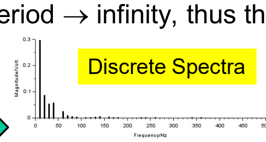
$$v(t)=\sum_{n=-\infty}^{\infty} c_n e^{jn\frac{2\pi}{T}t}$$

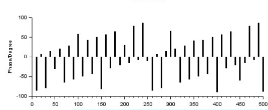
ω

$$c_n=\frac{1}{T}\int_{-\infty}^{\infty} v(t)e^{-jn\frac{2\pi}{T}t}dt$$

Fourier Series of Periodic Signal







Time-Domain

Frequency-Domain

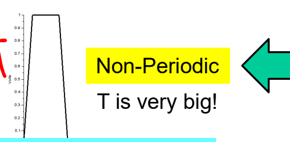
Inverse FT

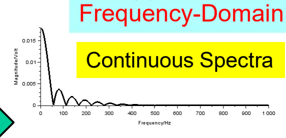
$$v(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty} V(\omega)e^{j\omega t}d\omega$$

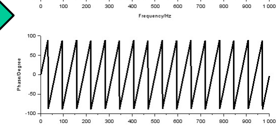
Forward FT

$$V(\omega)=\int_{-\infty}^{\infty} v(t)e^{-j\omega t}dt$$

Fourier Transform



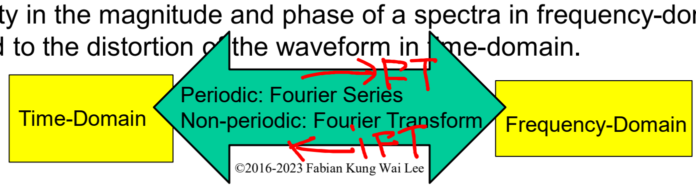




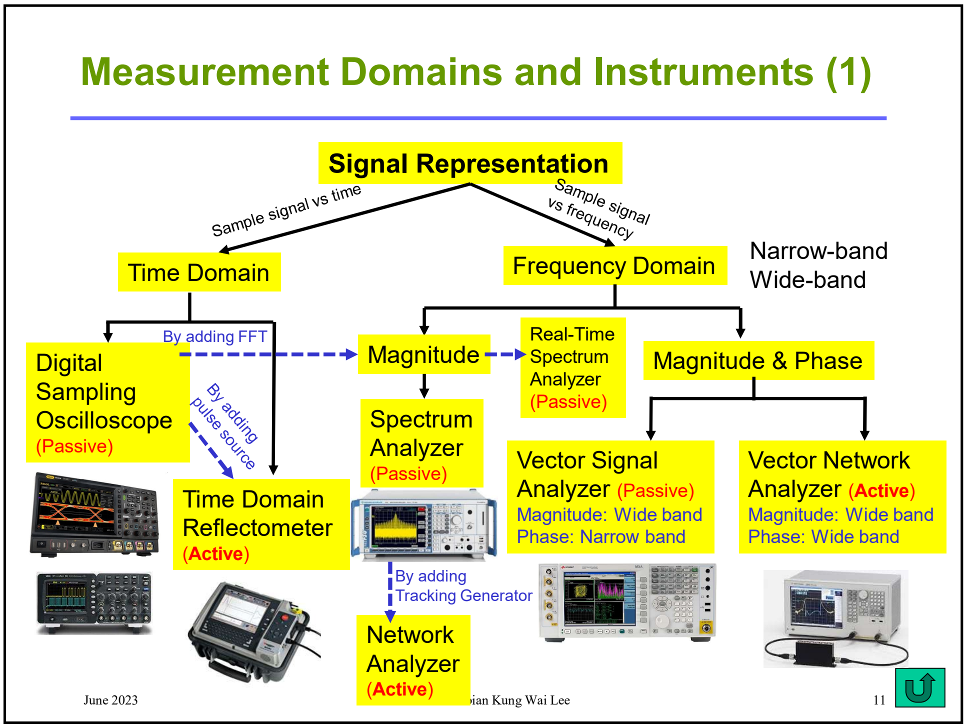
A digital version of this operation Using sample values of v(t) is known as fast Fourier Transform (FFT)

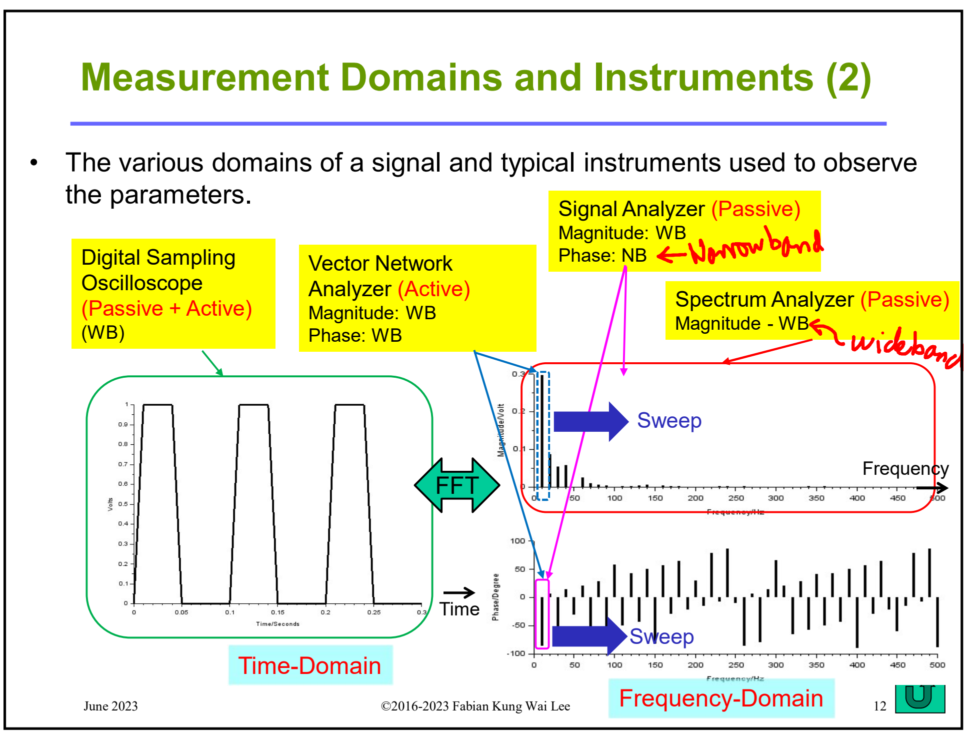
Summary for Section 1

- Depending on the pattern of the signal in time, we can classify a signal as periodic, non-periodic and random.
- Signals can be presented in time, frequency or mixed (both time and frequency) domains.
- Signal representation in time-domain is called the **waveforms**, in frequency-domain it is the **spectra**.
- For periodic signals the spectra is **discrete.**
- If the periodic signals is not sinusoid then it can be broken up into infinite number of sinusoids with perfectly align frequency, magnitude and phase (Fourier Series).
- For non-periodic signals the spectra is **continuous** (Fourier Transform).
- Integrity in the magnitude and phase of a spectra in frequency-domain is related to the distortion of the waveform in time-domain.



2. Measurement Domains and Instrumentation


Measurement Domains and Instruments (1)
Signal Representation
Sample signal vs time
Sample signal vs frequency
Time Domain
Frequency Domain
Narrow-band
Wide-band
By adding FFT
Digital Sampling Oscilloscope (Passive)
By adding pulse source
Magnitude
Real-Time Spectrum Analyzer (Passive)
Magnitude & Phase
Spectrum Analyzer (Passive)
Time Domain Reflectometer (Active)
Vector Signal Analyzer (Passive)
Magnitude: Wide band
Phase: Narrow band
Vector Network Analyzer (Active)
Magnitude: Wide band
Phase: Wide band
By adding Tracking Generator
Network Analyzer (Active)
June 2023
11


Measurement Domains and Instruments (2)
• The various domains of a signal and typical instruments used to observe the parameters.
Signal Analyzer (Passive)
Magnitude: WB
Phase: NB ← Narrowband
Digital Sampling Oscilloscope
(Passive + Active)
(WB)
Vector Network Analyzer (Active)
Magnitude: WB
Phase: WB
Spectrum Analyzer (Passive)
Magnitude - WB ← wideband
Sweep
Frequency
FFT
Time
Sweep
Time-Domain
Frequency-Domain
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12

Passive and Active Measurements (1)

- Measurement without stimulus (Passive measurement).

Device under test (DUT) → Electrical Energy → Measurement Instrument

Power → Device under test (DUT)

Digital Scope

S. Analyzer

- Example, digital sampling oscilloscope (DSO), spectrum analyzer, vector signal analyzer.
- Checking signal quality (integrity), system functions, general debugging etc.

Passive and Active Measurements (2)

- Measurement with stimulus (Active measurement).

Part 2

Stimulus → Electrical Energy → Port 1 → Device under test (DUT) → Measurement Instrument

Transmission Measurement

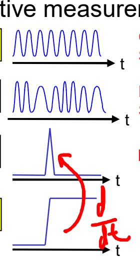
Power

Stimulus → Electrical Energy → Device under test (DUT) → Measurement Instrument

Port 1

Reflection Measurement

Typical stimulus signals for Active measurement:



1 Continuous Sine Wave

2 Modulated Sine Wave

3 Impulse Input

4 Step Input

$\frac{d}{dt}$

The Resultant Output

1 Steady-state FD response.

2 Modulated FD response.

3 Impulse TD response.

4 Step TD response.

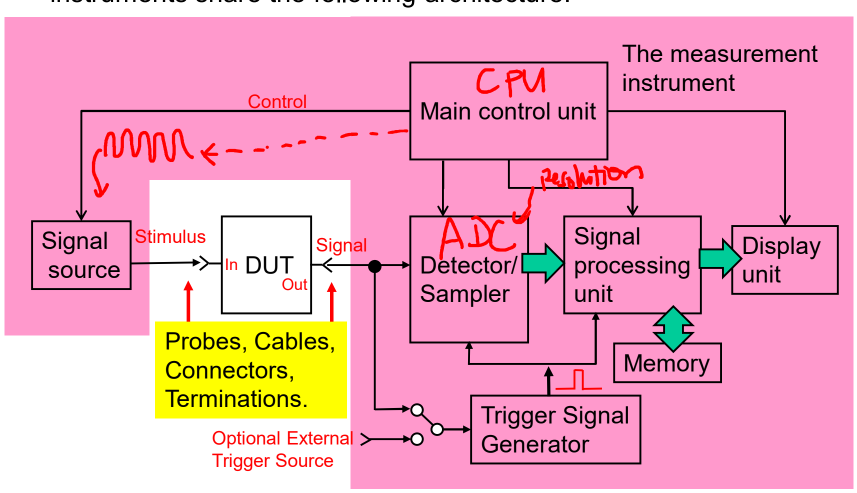
Related by: Fourier Transform (FFT)

Passive and Active Measurements (3)

- Transmission Measurement – Network analyser, vector network analyser.
- Used for checking the quality of the signal path (loss/attenuation, distortion), components or systems with inputs/outputs (e.g. filters, amplifiers, splitters, combiners).
- Reflection Measurement – Time-domain reflectometer, vector network analyser.
- Used for checking the 'matching' between components and signal path, antenna etc. A good matching between the component and signal source will have very small reflected signal power.

General Block Diagram of Modern Measurement Instrument

- Whether time, frequency or hybrid domains, most modern measurement instruments share the following architecture:

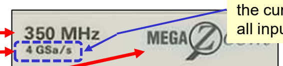


TD Measurement Instruments (1)

- **Digital Sampling Oscilloscope (DSO)** – Uses an ADC to digitize the electrical signal on its inputs (usually called the channels), store the digitized signal in memory and subsequently show on a display.

Main DSO criteria:
- Input bandwidth.
- ADC sampling rate.
- ADC resolution (8, 10 or 12 bits).
- Sampling mode – **equivalent** or **real** time.
- Memory depth.
- Probe type (passive, active, matched)
- Input impedance
- Pure analog input or mixed signal type.
- Instrument background noise (affects SNR of captured signal).

Be careful, this could be the cumulative rate for all input channels.



Optional digital input port

TD Measurement Instruments (2)

- ADC sampling rate determines the instrument bandwidth, e.g. the highest sinusoidal signal component the instrument can distinguish without aliasing (remember Nyquist Sampling Theorem).
- Most entry to mid-range DSOs use 8-bits ADC resolution, higher-end models typically have 10 to 14 bits ADC resolution. ADC resolution affects the instrument accuracy and background noise.
- Basic DSO functions can be enhanced by including a signal source to perform measurements with stimulus, for example **time-domain reflectometry** (TDR) and **transmission** (TDT) measurements.
- DSO with enhanced memory storage can also be used to perform tests such as **Eye-Diagram** and **Bit-Error Rate** (BER) measurements of digital signals.

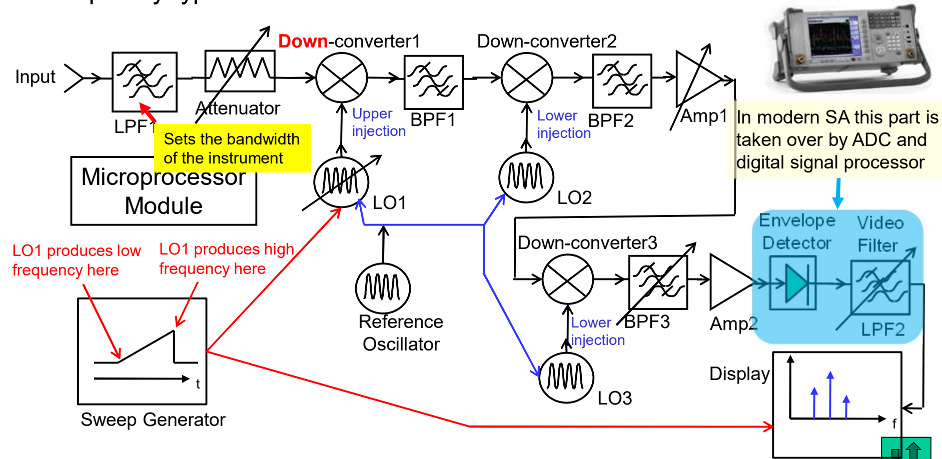
Typically required at least 10 bits ADC resolution

Note: Also show example of equivalent-time ultra wideband DSO

PC based DSO

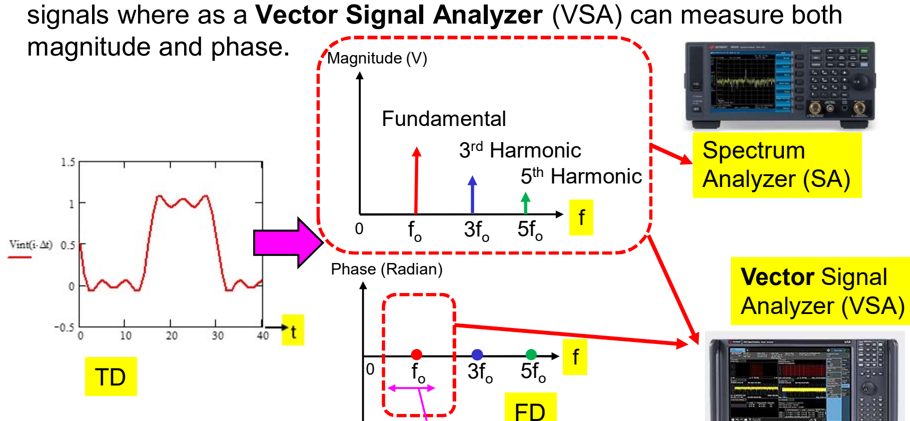
FD Measurement Instruments (1)

- **Spectrum Analyser (SA)** – For observing the spectra of signals. Two basic approaches, **sweep-frequency** and **real-time**. Classical sweep-frequency type SA architecture is shown below.



FD Measurement Instruments (2)

- Recall that a signals can be broken down into sinusoidal components.
- The SA only measures the magnitude of the sinusoid components of signals where as a **Vector Signal Analyzer** (VSA) can measure both magnitude and phase.



Note: when used in VSA mode, today (e.g. 2016-2023) commercial instruments can measure up to 750 MHz bandwidth

FD Measurement Instruments (3)

- **Spectrum Analyzer (SA)** – For observing the spectra of signals.
- **Vector Signal Analyzer (VSA)** – Possesses basic functions of the SA. In addition it can measure the phase of sinusoidal components (usually for the fundamental component only). This is useful for analysing modulated signals (it can demodulate the signals).
- **Vector Network Analyzer (VNA)** – Similar to the sweep frequency SA, the VNA has built-in sinusoidal signal source and can measure the relative magnitude and phase of signals between its ports. Useful for characterizing the frequency response of system or components.

Note, hybrid instruments:
• Modern FD instruments can combine SA and VSA into one machine or
• SA and VNA functions into one Machine or
• SA, VNA and VSA into one machine.

FD Measurement Instruments (4)

Two ports

Keysight FieldFox Handheld Microwave Analyzer combines SA and VNA into one instrument, 5 kHz to 44 GHz

Note: This slide is to illustrate the myriad form of FD instruments, It is not an endorsement of the product or comparison Between manufacturers

Anritsu MS2038C Handheld VNA (5 kHz to 20 GHz) and SA (9 kHz to 20 GHz)

Tektronix RSA360B PC based VSA (9 kHz to 6.2 GHz)

R&S FSVA Spectrum & Signal Analyzer (2 Hz to 44 GHz)

Rigol RSA5065-TG (100 kHz to 6.5 GHz)

Tracking Generator output

Keysight N9000B CXA basic Signal Analyzer, 9 kHz to 26.5 GHz

Pico VNA108 PC based VNA (300 kHz to 8.5 GHz)

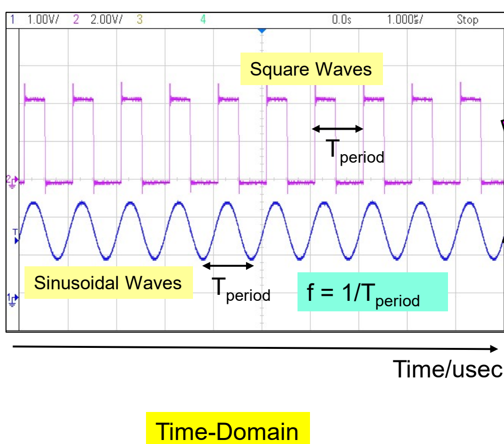
FD Measurement Instruments (5)

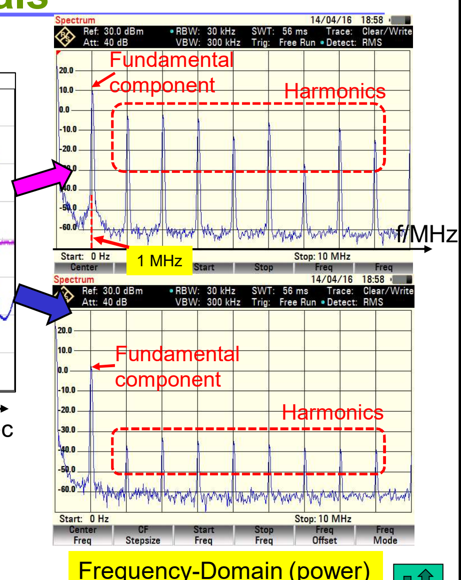
- FD instrument basic criteria:
  - Input bandwidth.
  - Analysis bandwidth.
  - Input power dynamic range.
  - Detector ADC resolution (can go as high as 24-bits).
  - Display average noise level (DANL).
  - Phase noise.
  - Amplitude accuracy.
  - Phase accuracy.
  - Sweeping speed.

N = number of bits
2^N

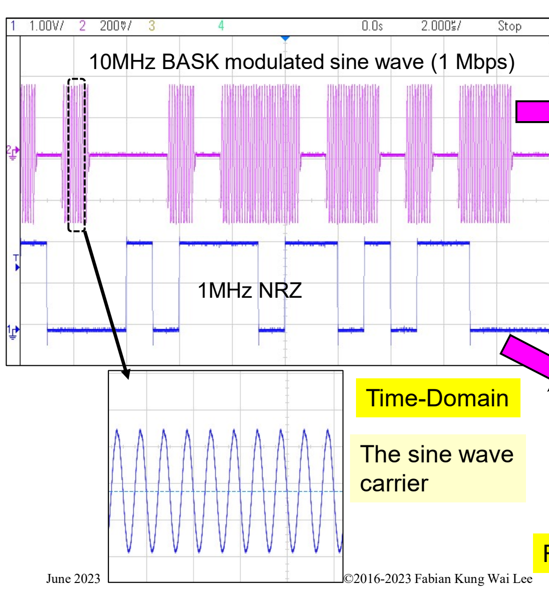
Example 2.1 - Measured Periodic Signals

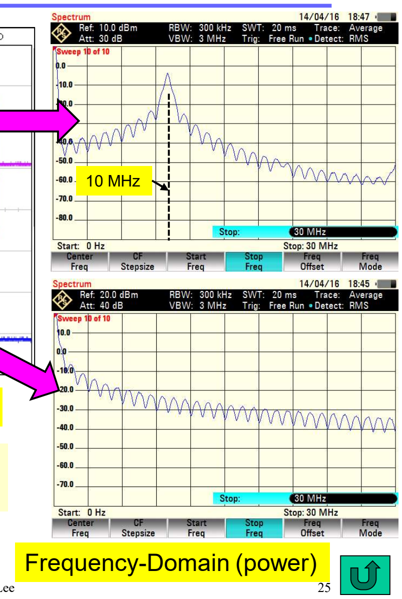
1 MHz square and sine voltage signals:





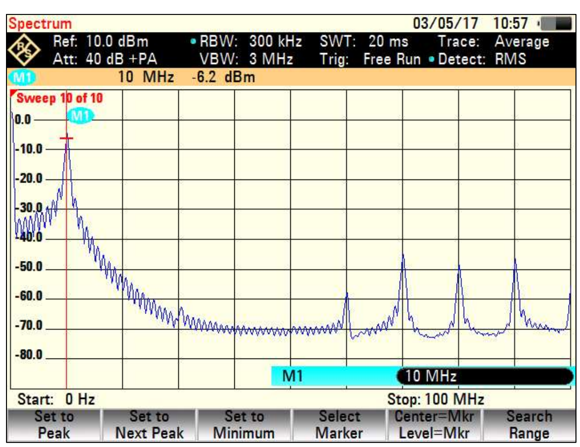
Example 2.2 - Measured Non-Periodic and Random Signals





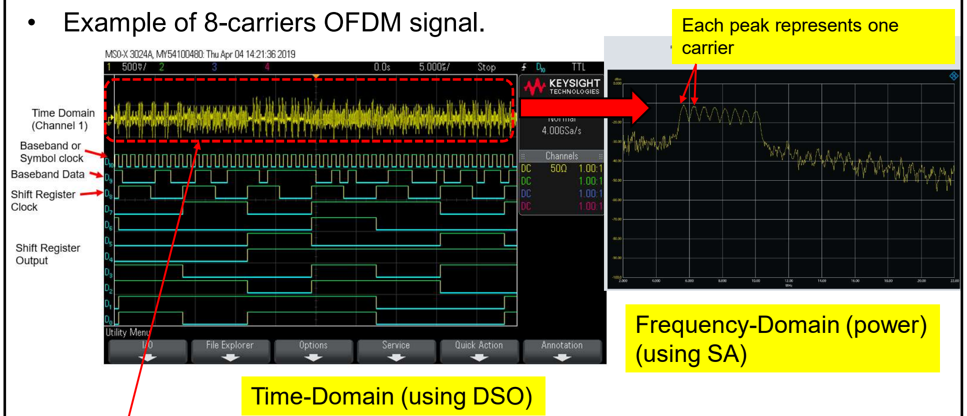
Example 2.2 Cont…

- The spectra of the 10 MHz BASK signal on extended span, 100 kHz to 100 MHz.



Example 2.3 – Measured Non-Periodic, Random and Multi-Carriers Signals

- Example of 8-carriers OFDM signal.



This signal consists of **8 modulated sine waves** combined together

Summary of Section 2

- Presently measurement instrument can be grouped into time-domain, frequency-domain and mixed (hybrid) domain.
- Modern instruments uses digital sampling, with FFT and digital filtering to perform signal analysis.
- In each of this group, the instrument is capable of standard passive type measurement. With addition of a signal source some instruments can also perform active type measurement.

3. Electrical Probes and Probing

Oscilloscope Probe Types

- The probe is the device that siphons a small amount of the electrical charge from the device under test to the input impedance of the oscilloscope, this charge will cause a voltage across the input impedance and sampled by the scope's ADC.

signal
GND

Probe → Voltage Probe, Current Probe

Invert
Non-invert
GND

Current Probe → Active

Voltage Probe → Single-Ended Probe, Differential Probe

Single-Ended Probe → Passive, Active

Passive:
- 1:1 (1MΩ)
- 10:1 10MΩ

- Wideband 10:1 and 20:1 RF matched Probes (50Ω)

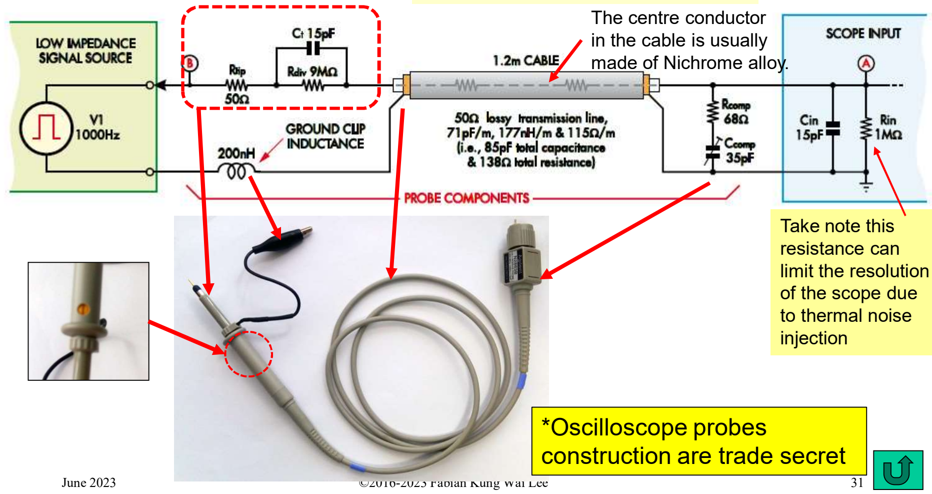
Active

Differential Probe → Passive, Active

Single-Ended Passive Oscilloscope Probe Construction

- A best guess of the equivalent electrical model of a 10:1 passive oscilloscope probe.*

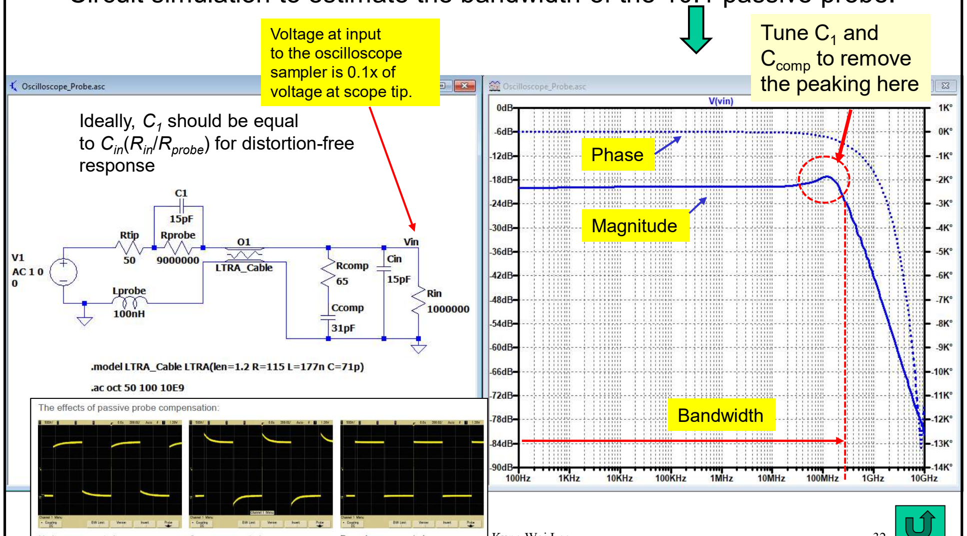
Image source: 'Silicon Chips", Oct 2009.
D. Ford, "Secret world of oscilloscope probes"



*Oscilloscope probes construction are trade secret

Single-Ended Passive Oscilloscope Probe Bandwidth

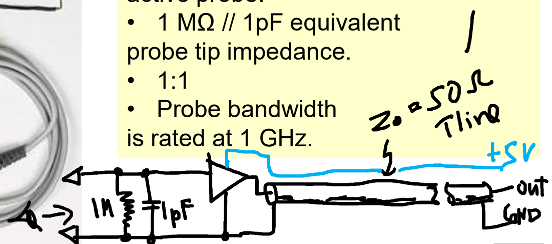
- Circuit simulation to estimate the bandwidth of the 10:1 passive probe.



Single-Ended Active Oscilloscope Probe

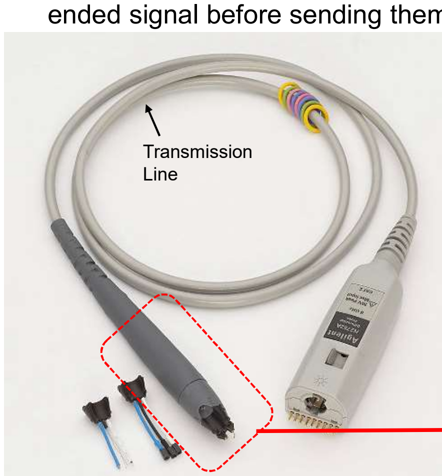
- The active probe contains a wide bandwidth impedance-matched (to 50Ω) low-noise amplifier at the probe tip, usually FET based amplifier (FET has lowest noise figure among active devices).
- The amplifier provides amplification of the voltage signal with good SNR, and isolation between the DUT and the probe cable/oscilloscope input impedance.

An example of Keysights N2795A active probe:
- 1 MΩ // 1pF equivalent probe tip impedance.
- 1:1
- Probe bandwidth is rated at 1 GHz.

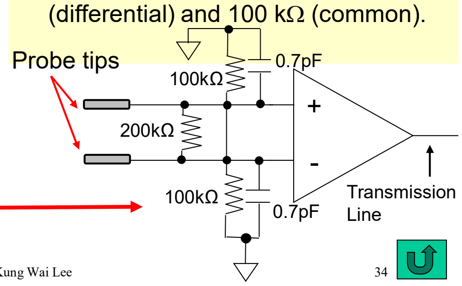


Differential Active Oscilloscope Probe

- Most differential probes are active probe, the tip usually contains a differential amplifier which converts the differential voltage into signal ended signal before sending them to the oscilloscope input sampler.

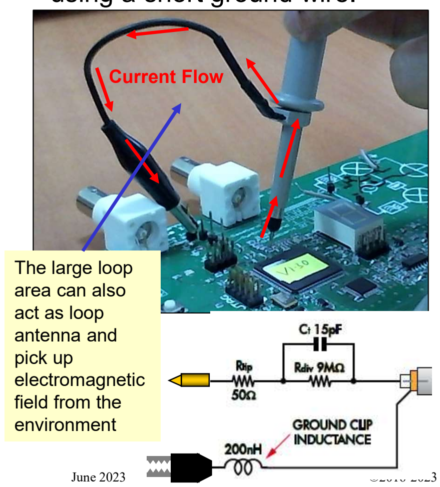


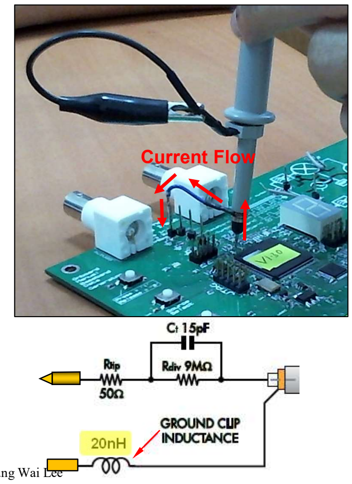
An example of Keysights N2750A active differential probe:
- 2:1 and 10:1
- Probe bandwidth is rated at 1.5 GHz.
- Probe impedance = 200 kΩ (differential) and 100 kΩ (common).



Oscilloscope Probe - Effect of Ground Clip Wire Length on Probe Bandwidth (1)

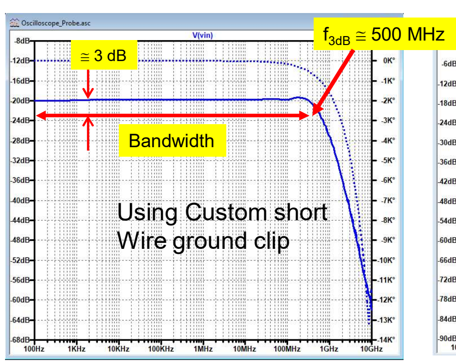
- The ground clip inductance depends on the loop area formed by the probe and ground clip wire. This area can be reduced (hence the inductance) by using a short ground wire.



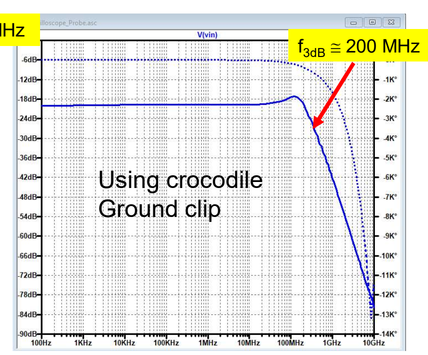


Oscilloscope Probe - Effect of Ground Clip Wire Length on Probe Bandwidth (2)

- The ground clip inductance has a huge impact on the oscilloscope probe actual bandwidth and response.



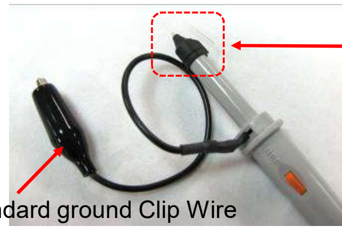
With L_{probe} = 10 nH



With L_{probe} = 100 nH

Oscilloscope Probe - Reducing Ground Clip Stray Inductance

- Most high bandwidth oscilloscope probes provide a few options of ground clip wire, and you can also DIY if necessary.

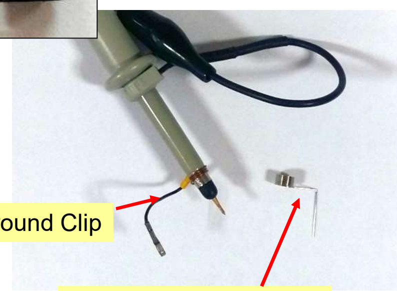


Standard ground Clip Wire

Commercial 'Coil-Type' short ground clip wire

Another commercial foil Type ground

Low-inductive ground connection for N287xA probes keeps the probe loading low to achieve high signal integrity measurements



DIY Ground Clip

Commercial spring type ground clip wire

Wideband Passive Oscilloscope Probe

- An example of 50Ω passive probe from Tektronix. Typically low noise and very high bandwidth.

50 Ω Divider (Zo) Low Capacitance

P6150 Data Sheet

P6150

Features & Benefits

Low Impedance Zo TDR Passive Probes

- Low Capacitive Loading to Extremely High Frequencies
- Interchangeable Attenuator Tip Assemblies: 1X, 10X (P6150)

Applications

- High-speed Device Characterization in Microwave Communication, Signal Processing and Logic Applications
- Propagation Delays for ECL, GaAs and Other Logic Circuitry and Devices
- Circuit Board Impedance Testing (TDR)
- High-speed Sampling Systems

10:1 ADC input 50Ω

Characteristics

Nominal Length – 1 m.
Attenuation – 10X: ±2%, 1X: ±2%.
Bandwidth – 9 GHz, ≥3 GHz
Rise Time – <38.8 ps, ≤170 ps.
Loading Input R/C – 500 Ω/<0.15 pF, 50 Ω/N/A.
Max V_{in} – 12.5 V_{RMS}*1.
Propagation Delay – 4.40 ns ±0.1 ns, 4.40 ns ±0.1 ns.
*1 Limited by scope input or 30 V_{RMS}, whichever is less.

Recommended Instruments

TDS8000, CSA8000, TDS820, 11801C, CSA803C, TDS7404, CSA7 and TDS6604 with TCA-SMA adapter.

Ordering Information

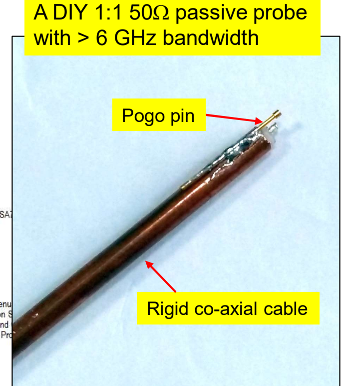
P6150
10X, 9 GHz, 1.0 m, Low Impedance Probe.

Includes: One 1X Attenuator Head (206-0398-00); Two 10X Attenu (206-0399-03); 1.0 m Cable Assembly (174-1341-00); Instruction S (070-7173-01); and 1 Accessory Kit consisting of: 20 each Ground Adjustable Ground Lead, 10 each Electrical Contact and 2 each Pro Board Ground Connectors (020-1708-00).

Additional Accessories

	Order
Electrical Contact	
GND, CLIP, PH, BRZ	131-4474-00
GND, LEAD, 0.025 WIRE NICKEL	131-4473-00
0.025 NICKEL ALLOY 52 WIRE	131-4468-00
SMA Male to BNC Female	015-0554-00

A DIY 1:1 50Ω passive probe with > 6 GHz bandwidth

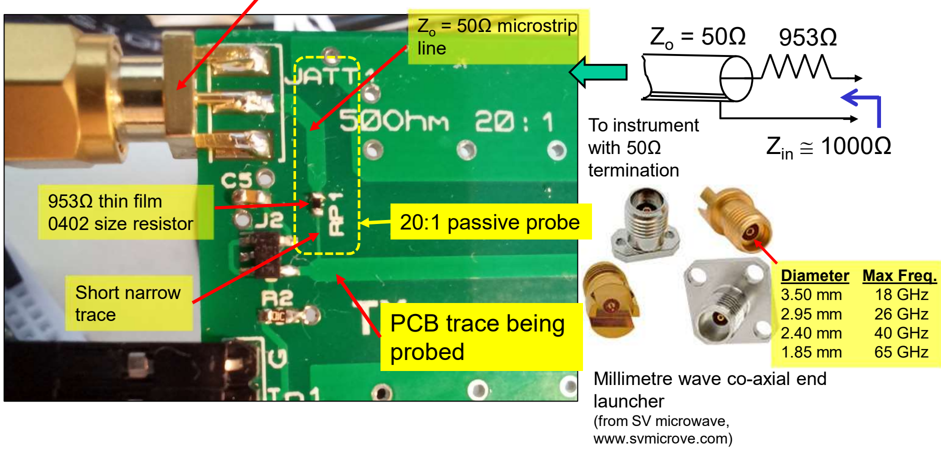


Pogo pin

Rigid co-axial cable

On-Board Wideband Passive 20:1 Oscilloscope Probe

- Built-in co-axial end launcher.
- Effective up to microwave and millimetre wave frequencies.

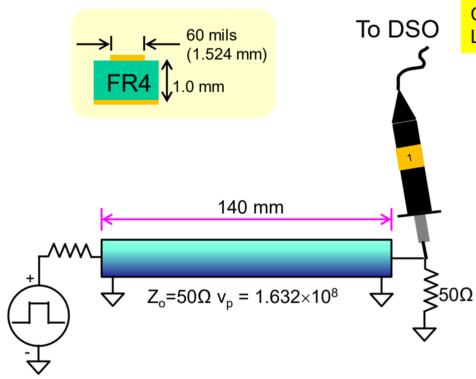


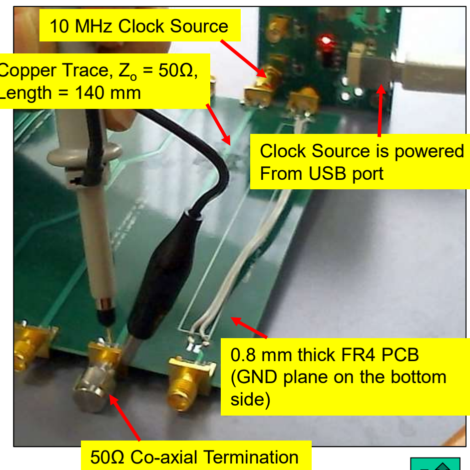
Summary of Section 3

Probe Type	Characteristics	When to Use
Passive 10:1 Probe	• DC input impedance is 10MΩ. • Voltage signal is attenuated by 10X, low SNR. • Small loading effect (if used within stipulated bandwidth)	• For low-to-mid range frequency probing, DC to 500 MHz. • Set scope Z_{in} to 1MΩ.
Active 1:1 Probe	• DC input impedance is 1MΩ. • Voltage signal is not attenuated, high SNR. • Small loading effect.	• For low-to-high range frequency probing, DC to 3000 MHz. • Set scope Z_{in} to 50Ω.
Wideband Passive 10:1 (20:1) Probe	• DC input impedance is 450Ω. • Voltage signal is attenuated by 10X, low SNR. • Medium loading effect.	• For low-to-very high range frequency probing, DC to 9 GHz. • Set scope Z_{in} to 50Ω.
On-board wideband passive 10:1 (20:1) probe	• DC input impedance is 450Ω. • Voltage signal is attenuated by 10X, low SNR. • Medium loading effect.	• For low to milimeter-wave frequency, DC to >20 GHz. • Set scope Z_{in} to 50Ω.

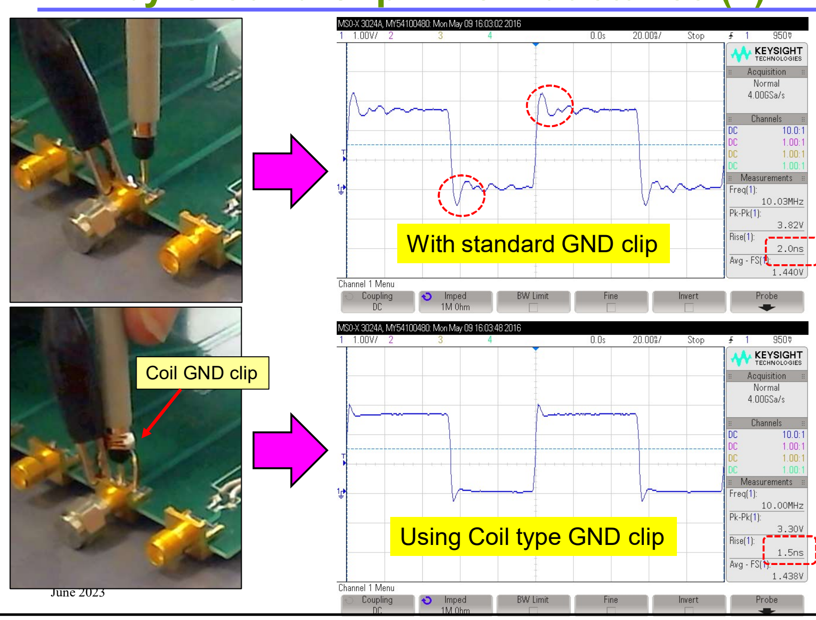
Example 3.1 – Measured Distortion Caused by Ground Clip Wire Inductance (1)

- Here we have a simple circuit consisting of a 'microstrip' transmission line, termination and clock source.



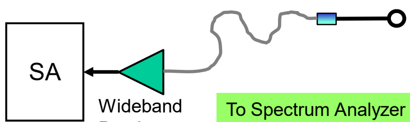


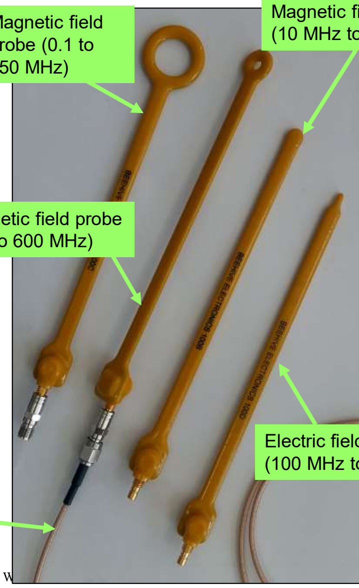
Example 3.1 – Measured Distortion Caused by Ground Clip Wire Inductance (2)



Probe for Spectrum Analyser (SA) - Near-Field Probes (Non-Contact Probes)

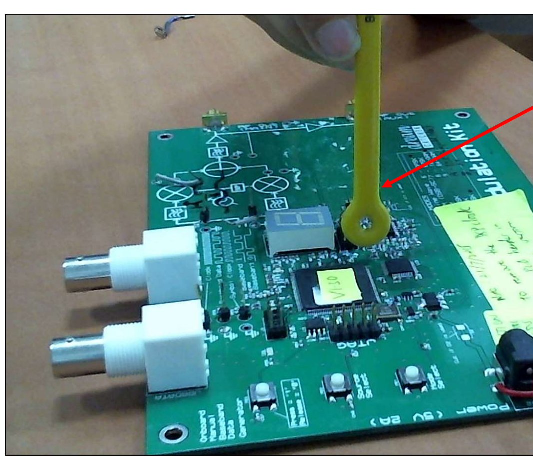
- The near-field probes are designed to 'pick' up static or quasi-static electric and magnetic fields near the surface of the PCB (with circuits powered up of course!).
- Usually used together with SA and pre-amplifier.
- **E** field probe is useful for capturing emissions from conductors with high voltage fluctuation (high impedance traces). Whereas **H** field probe is for capturing emission from large current fluctuation (low impedance traces).



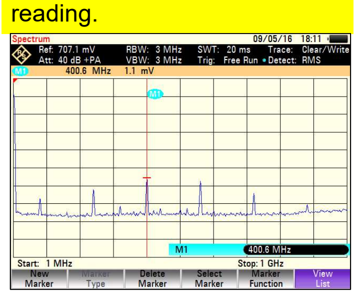


Example 3.2 – Measured Magnetic Field Emitted by PCB

A good tutorial - https://www.youtube.com/watch?v=ctynv2kIT6Q



1. Always hold the probe more than 5 mm above the PCB surface to avoid the probe loading the PCB circuits.
2. Need to adjust the probe orientation to find the largest reading.



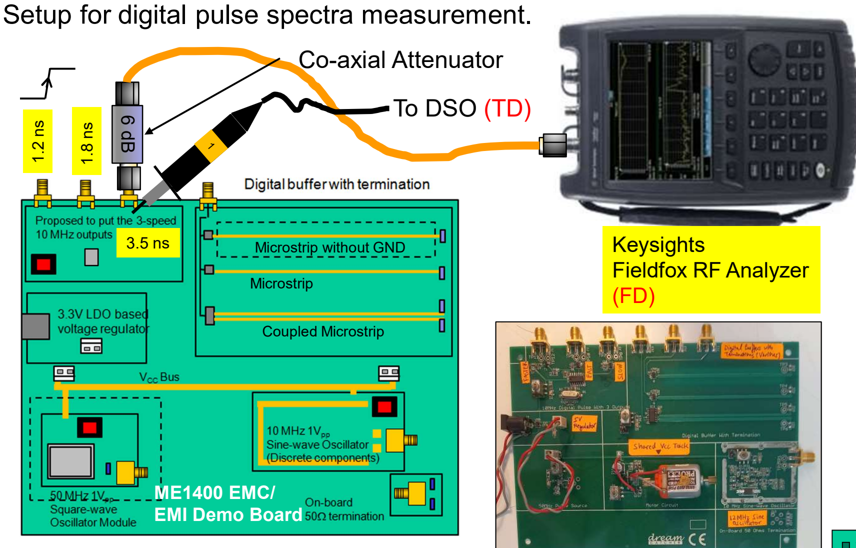
4. Measurements Examples

TFD

Time and Frequency Domain

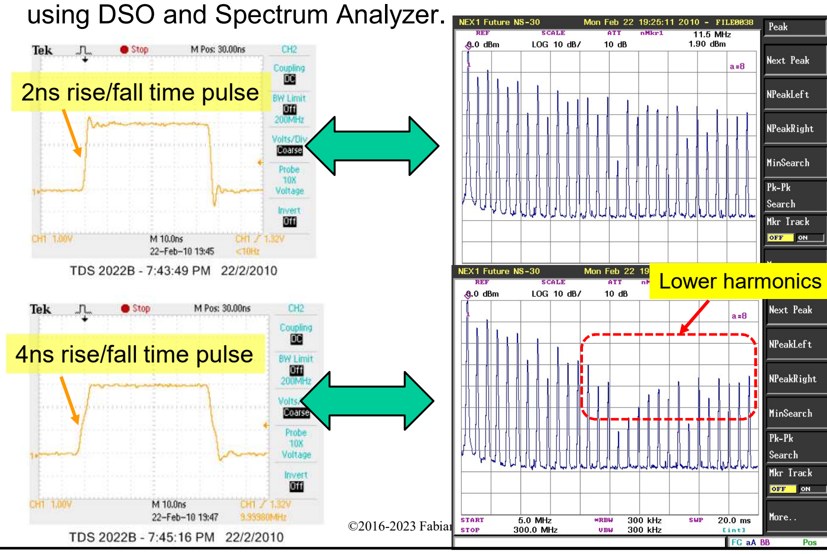
Observing the Spectra of Digital Clock Signal (1)

- Setup for digital pulse spectra measurement.



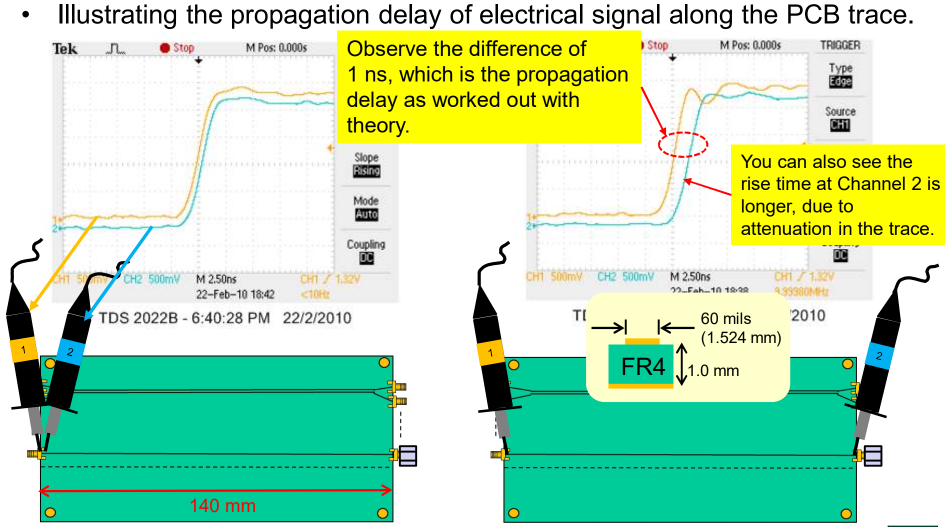
TFD **Observing the Spectra of Digital Clock Signal (2)**

- Comparison of pulse with different rise time in time and frequency domain using DSO and Spectrum Analyzer.



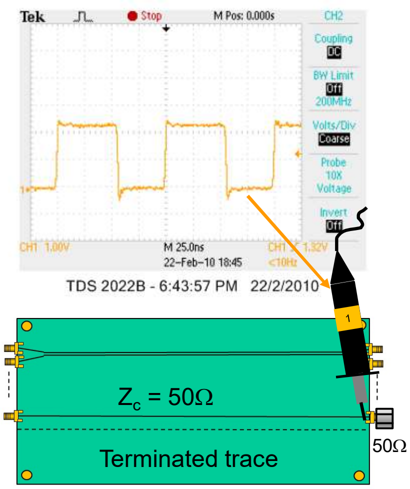
TD **Time-Domain Transmission Measurement of PCB Trace**

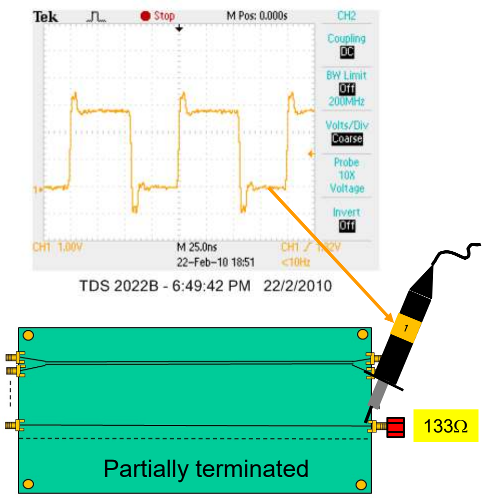
- Illustrating the propagation delay of electrical signal along the PCB trace.



TD Effect of Rise/Fall Time and Termination on Digital Signal (1)

- Long PCB trace (10 cm) driven with 1.2 ns rise/fall time 10MHz pulses.

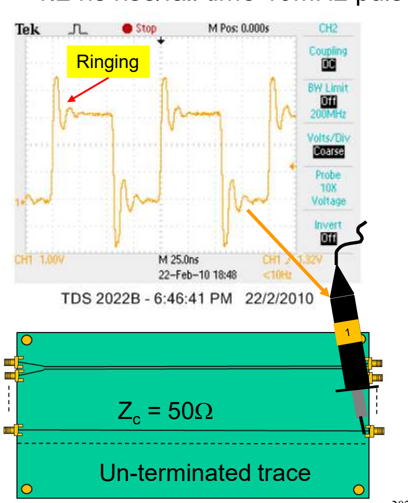


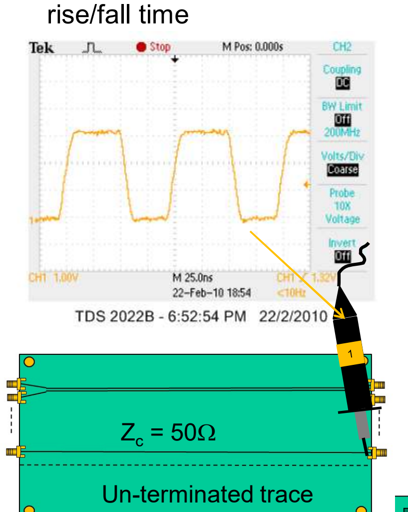


TD Effect of Rise/Fall Time and Termination on Digital Signal (2)

- Long PCB trace (10 cm) driven with 1.2 ns rise/fall time 10MHz pulses.

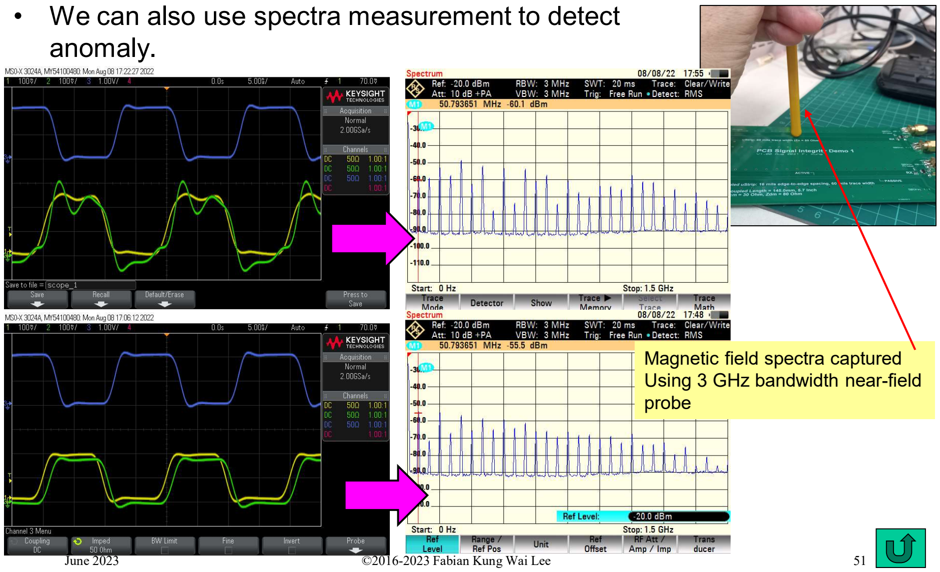
For comparison with 6 ns rise/fall time





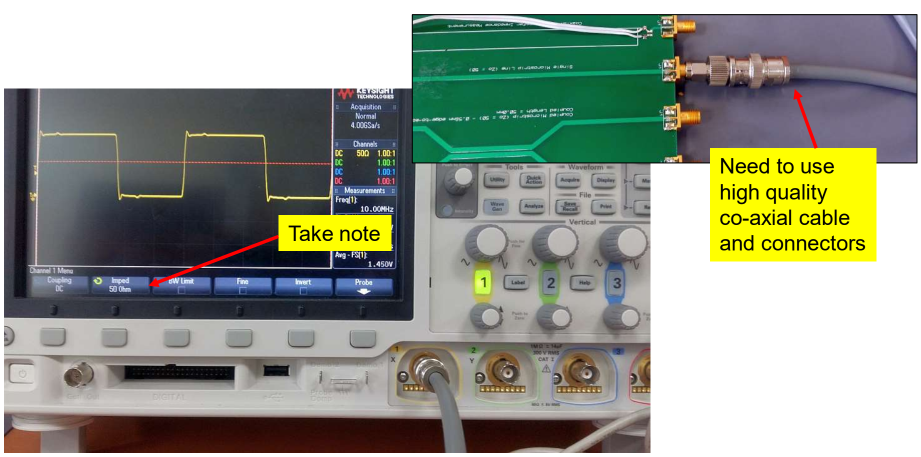
TD Effect of Ringing on Near-Field Magnetic Spectra

- We can also use spectra measurement to detect anomaly.



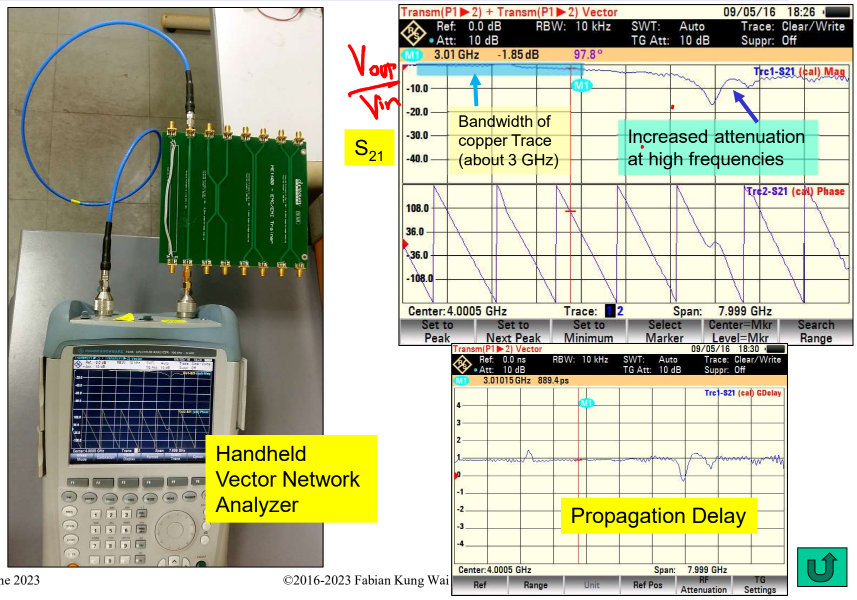
TD Direct Measurement on Oscilloscope without Probe

- Sometimes we do not need to use a probe with oscilloscope. This approach is used for probing the output of systems with connectors.



FD

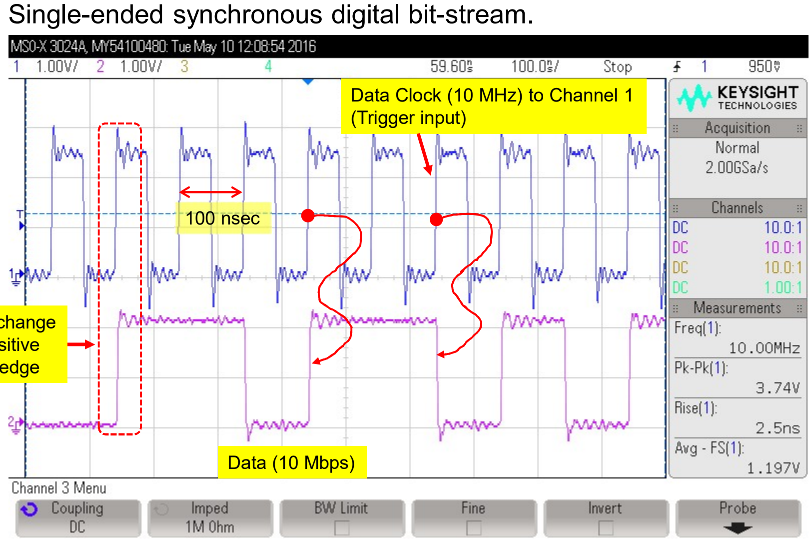
Measuring Copper Trace Transmission Loss and Dispersion



TD

Measuring Random NRZ Bit-Stream (1)

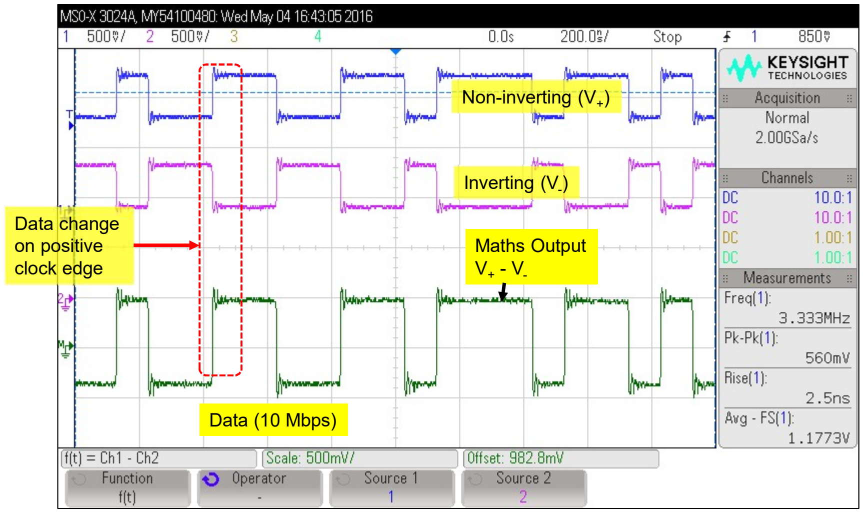
- Single-ended synchronous digital bit-stream.



TD

Measuring Random NRZ Bit-Stream (2)

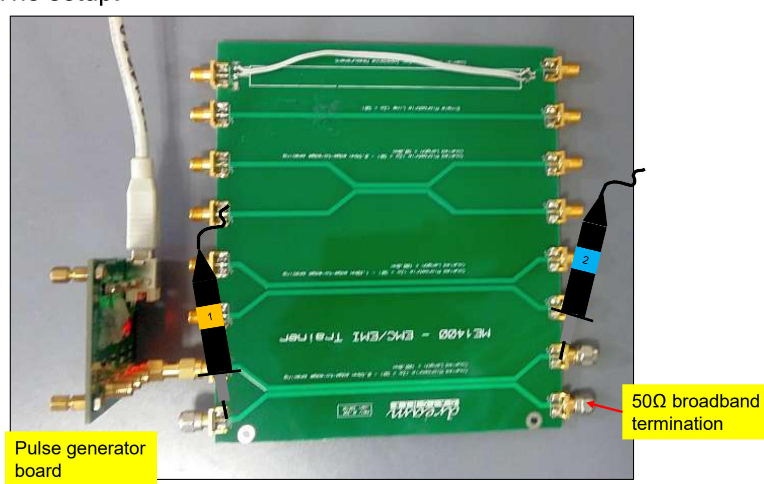
- Differential synchronous digital bit-stream.



TD

Crosstalk Measurement (1)

- The setup.



TD

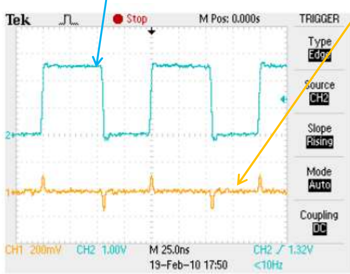
Crosstalk Measurement (2)

- Time-domain measurement sample results.

10 Mbps ‘high-speed’ signal on active trace

Near-end crosstalk

Can see significant drop in crosstalk level as trace separation increases



TDS 2022B - 5:48:24 PM 19/2/2010

Crosstalk level captured with DSO
0.5 mm trace spacing

TDS 2022B - 5:53:37 PM 19/2/2010

Crosstalk level captured with DSO
1.0 mm trace spacing

TD

Extra

Generating an Eye Diagram

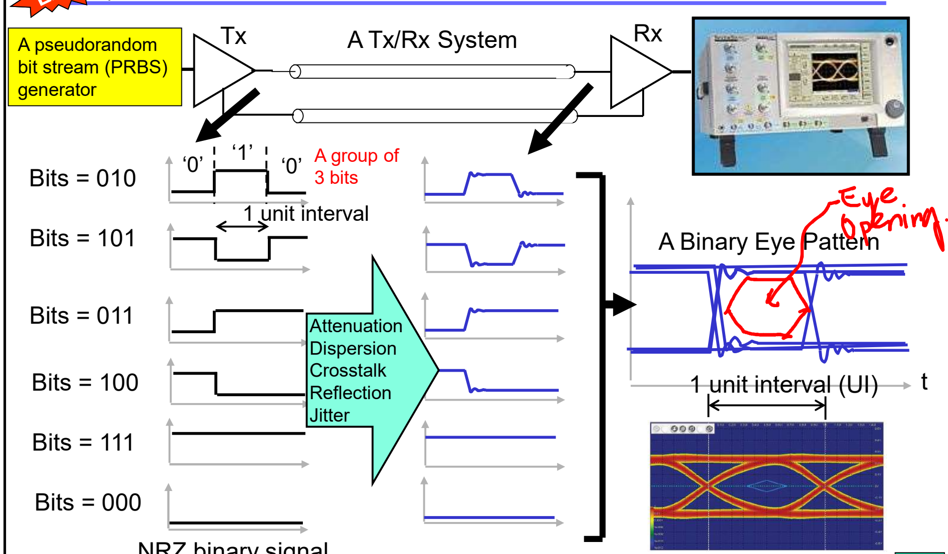
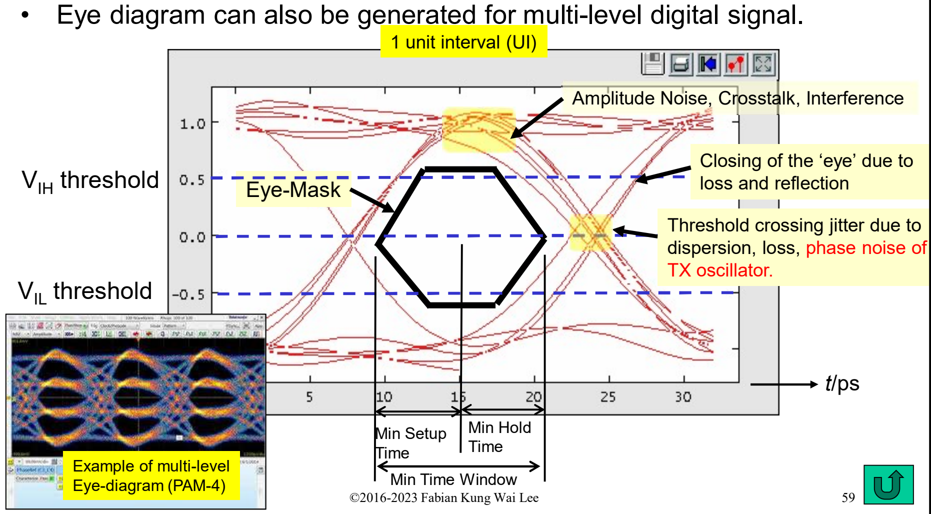


Image Source: C. Filip, “Overview of channel equalization techniques for serial interfaces”, Siemens 2021.

TD Extra

Eye-Mask and Jitter

- The opening of the eye-mask indicates 1) The max. bit-rate achievable 2) The optimum level of sampling and 3) The threshold levels.
- Eye diagram can also be generated for multi-level digital signal.

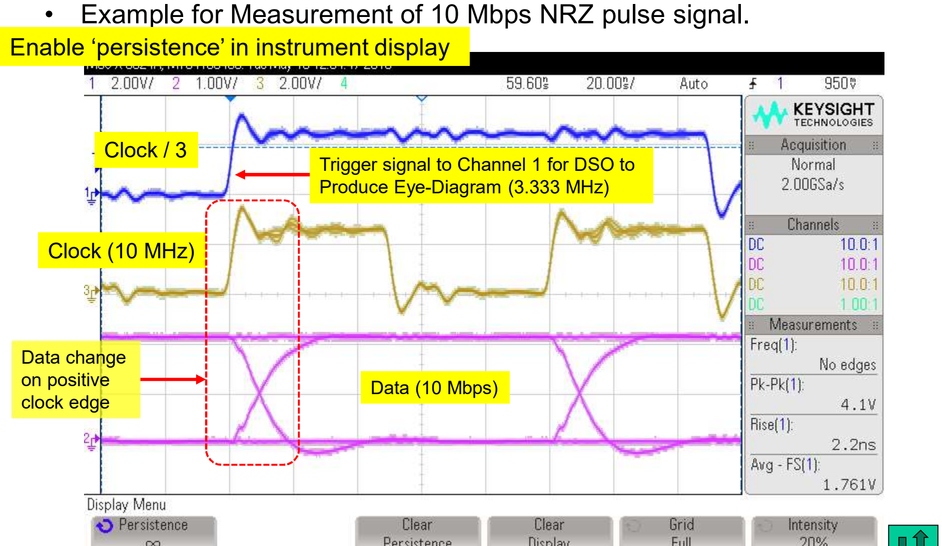


TD Extra

Eye-Diagram Measurement Using Triggered Method

Note: To show R&S high-speed design poster

- Example for Measurement of 10 Mbps NRZ pulse signal.

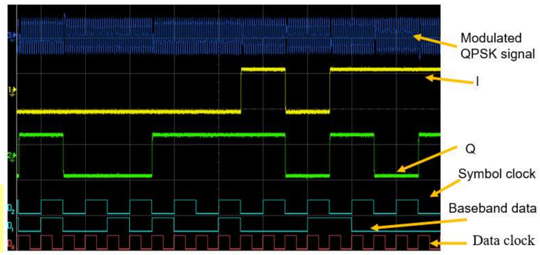


TFD

Extra

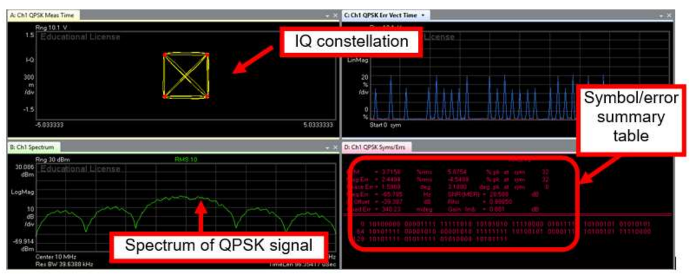
Modulated Signals Measurement with VSA

- An example of QPSK (Quadri-Phase Shift Keying) modulated sine wave measurement.



TD measurement using Oscilloscope

FD measurement using VSA



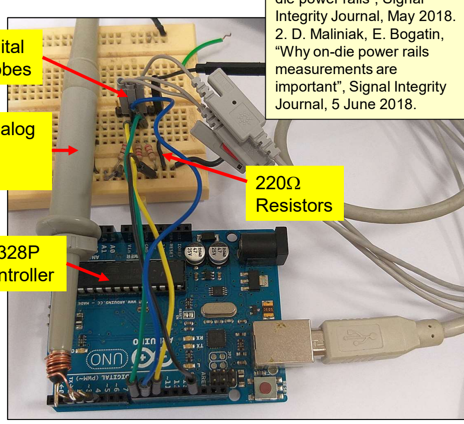
TD

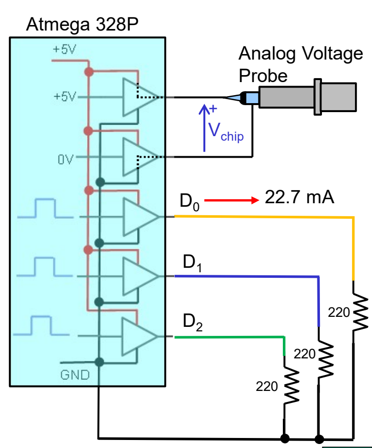
Extra

Ground Bounce/Power Bounce Measurement (1)

- Here we demonstrate a simultaneous switching noise (SSN) or ground bounce on an 8-bits micro-controller, based on the method suggested by *Maliniak* and *Bogatin*.

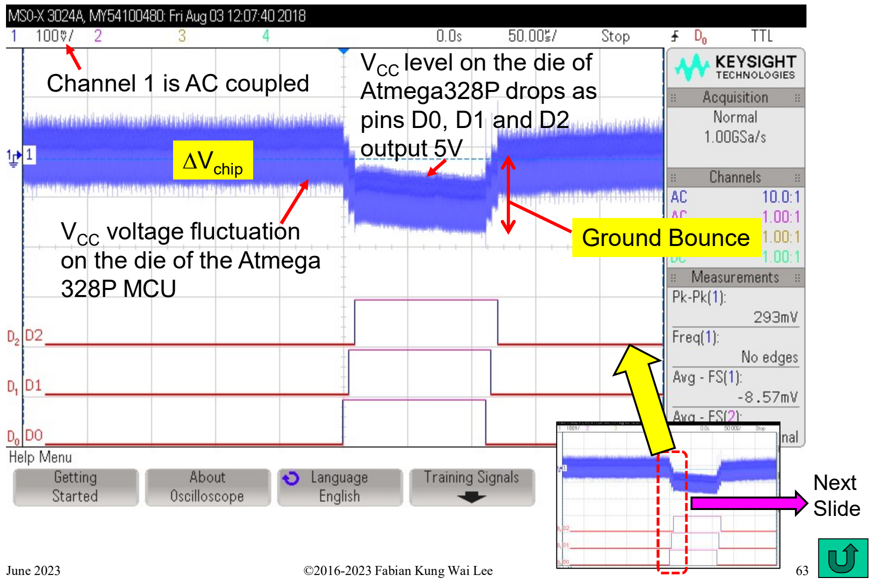
1. D. Maliniak, E. Bogatin, "How to measure shared on-die power rails", Signal Integrity Journal, May 2018.
2. D. Maliniak, E. Bogatin, "Why on-die power rails measurements are important", Signal Integrity Journal, 5 June 2018.





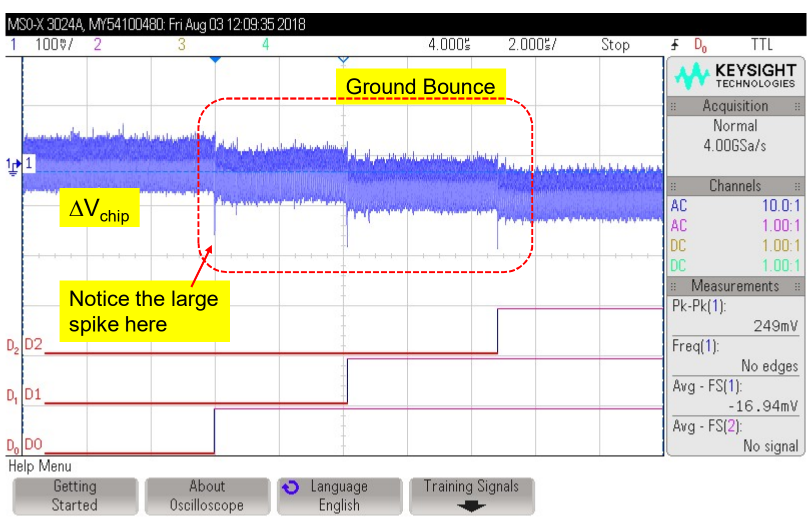
TD Extra

Ground Bounce/Power Bounce Measurement (2)



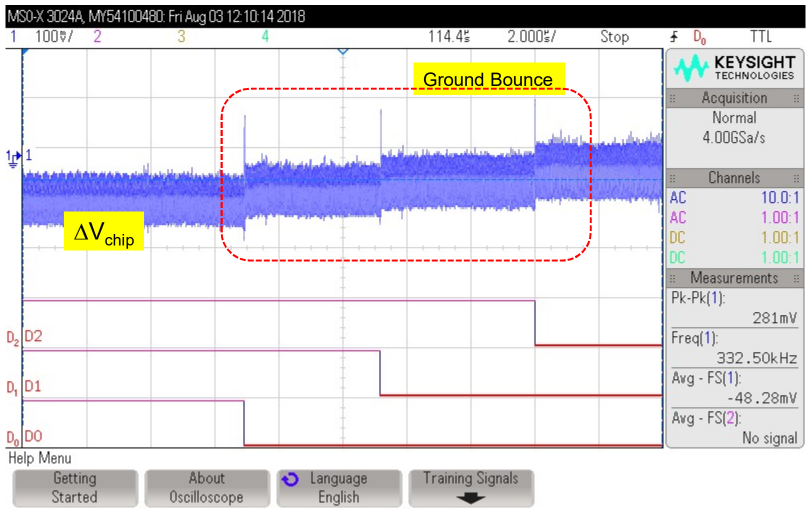
TD Extra

Ground Bounce/Power Bounce Measurement (3)

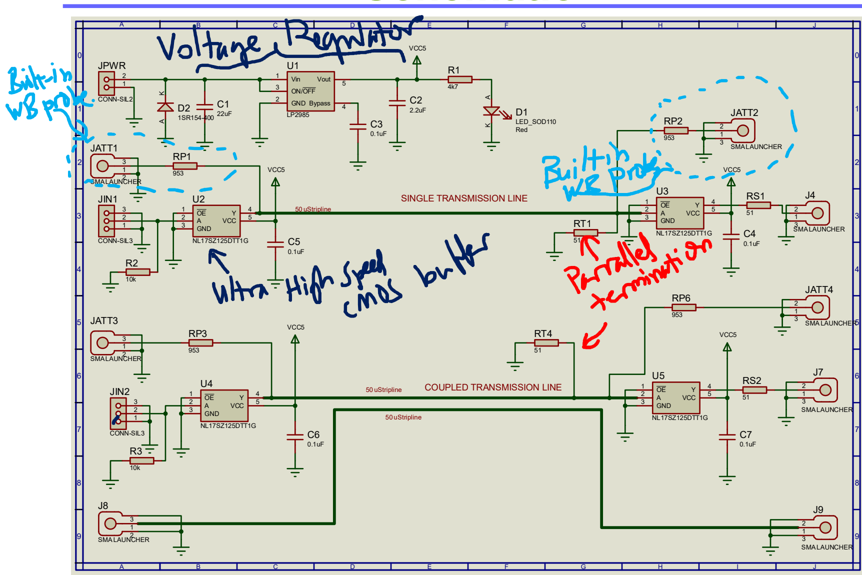


TD
Extra

Ground Bounce/Power Bounce Measurement (4)

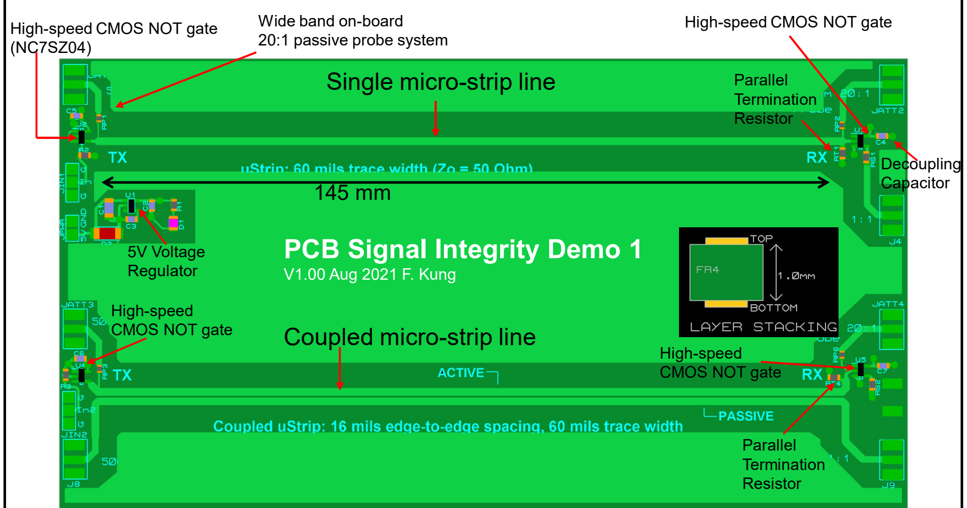


Crosstalk and 'Ringing' Demo – The Schematic



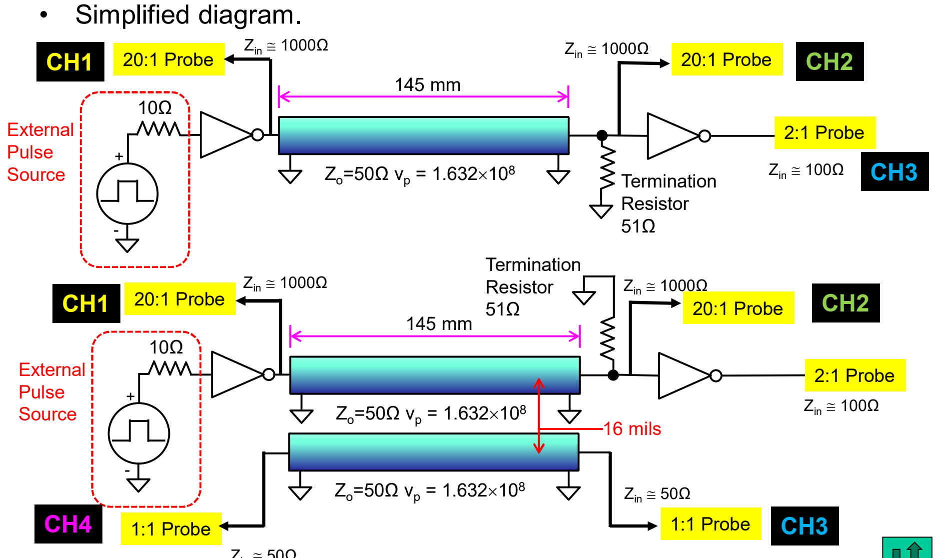
Crosstalk and ‘Ringing’ Demo – The PCB

- Our demo PCB.



Crosstalk and ‘Ringing’ Demo – Block Diagram

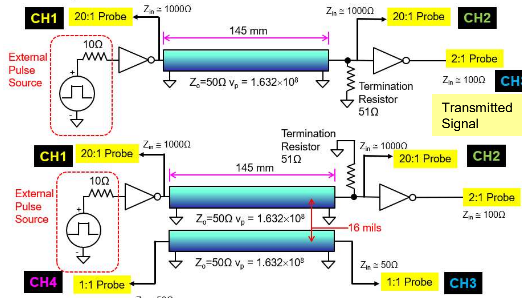
- Simplified diagram.

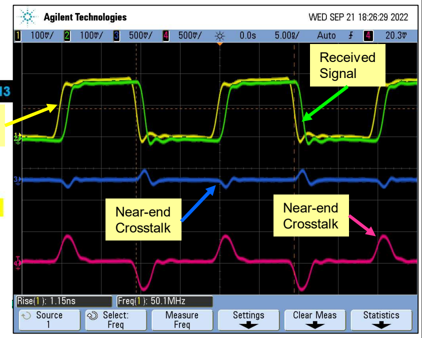


Crosstalk and 'Ringing' Demo – Captured Waveforms

- Driven with 50 MHz square wave generator.

- Simplified diagram.

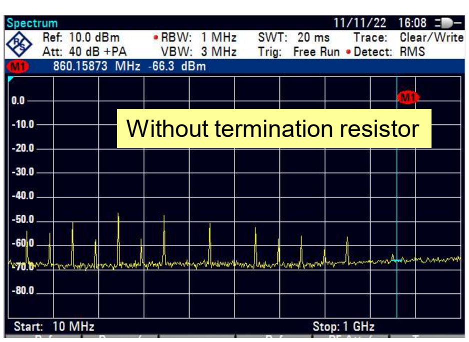


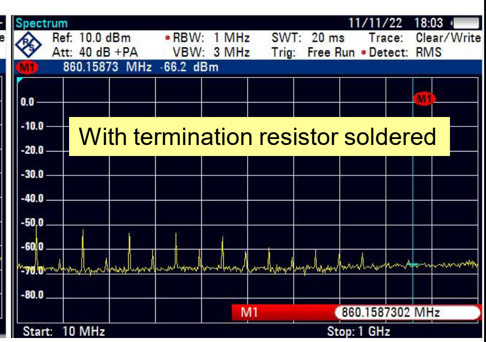


With 500 MHz bandwidth oscilloscope

Crosstalk and 'Ringing' Demo – Captured Spectrum for Single Tline

- Driven with 50 MHz square wave clock generator.
- Using near-field magnetic probe to pick up spectra of the of magnetic field.





To Show…

- Time-domain waveforms and spectra.
- Probing method in time-domain.
- Time delay due to signal propagation.
- Impedance matching.
- Using near-field probe with spectrum analyser.
- Comparing measurement with circuit simulation.

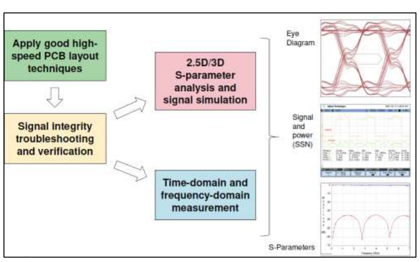
5. Conclusion

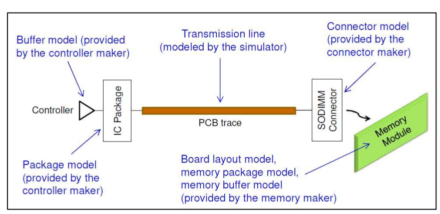
Important Considerations

- Interference sources and signal integrity mechanisms can be divided into narrow-band and wideband.
- Mitigation and defensive design approaches can also be divided into narrow-band and wideband methods.
- Matching the correct method to the source or mechanisms is thus crucial.
- Examples of narrow-band method – Band-pass filtering, notch filter, tuning, or usage frequency dependent network. Some bypass and decoupling capacitors only work within a range of frequencies. Also interaction between components and system physical structures can result in narrow-band response.
- Examples of wideband method – Shielding with metallic enclosure, isolation using physical separation, termination with resistor, physical design of signal transmission path.

Before a System is Build

1. Use computer simulation software to model and simulate the behaviour of the interconnection and physical system, for example modern full-wave electromagnetic field solver can create an electrical model of the PCB with assembled component.





Slides from Day 1 by CC Chai

2. Built test PCB with test structures and traces, with built-in high bandwidth probe, then check the performance of the test structures.

Trouble-Shooting Sequences After a System is Build (1)

1. Check stability and integrity of on-board power supply, probe using oscilloscope.
2. Write a test program for the controller to generate a known periodic signal at TX, then:
   – Probe the transmitter and receiver side with oscilloscope and suitable probes to check the integrity and shape of the signal.
   – If oscilloscope bandwidth is not sufficient, we can measure the spectra of the signal using SA and observe for anomaly spectra.
   – Validate functionality of system.
3. Write a test program for TX to generate pseudo-random bit sequence, with very high bandwidth oscilloscope we can perform BER test and capture eye diagram at the receiver at the same time. Use eye diagram to detect for interconnection loss, crosstalk and reflection.

Trouble-Shooting Sequences After a System is Build (2)

- For complex interfacing systems, such as USB3, PCI Express etc., a protocol analyzer, interposer board with build-in probe system, in conjunction with high-bandwidth digital oscilloscope is necessary to trouble-shoot the system.
- At bandwidth above 1 GHz, probing with oscilloscope probe is virtually impossible due to signal attenuation, thus we need to use an interposer board, which is a special PCB with build-in probes, that connects between the processor/motherboard and the device-under-test.
- A protocol analyzer is needed to determine the correct timing to trigger acquisition of the analog signals from the interposer board.

Note: To show the setup diagram for PCI-Express debugging from LeCroy's Webinar "How to debug PCI Express® Link Training and other dynamic link behaviors" March 2023

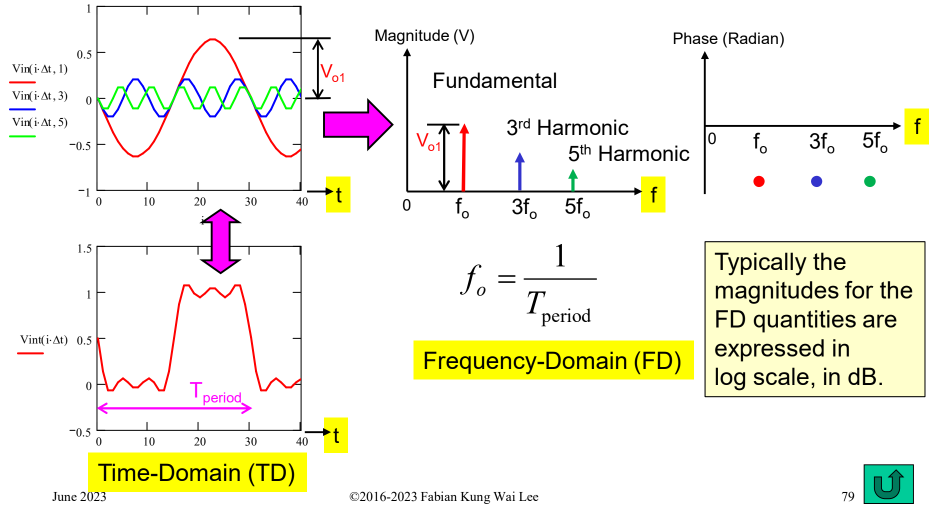
APPENDIX

Good Basic Tutorials

- How to solve signal integrity problems: The basics by Keysight Technologies (Sep 2018)
  https://www.youtube.com/watch?v=mpyMWuVrKKc&feature=youtu.be

The Importance of Magnitude and Phase Integrity in Frequency Domain (1)

- By combining sinusoidal signals of frequencies f_o, $3f_o$, $5f_o$ and so forth with the correct **magnitude** and **phase** we can create a periodic square wave.

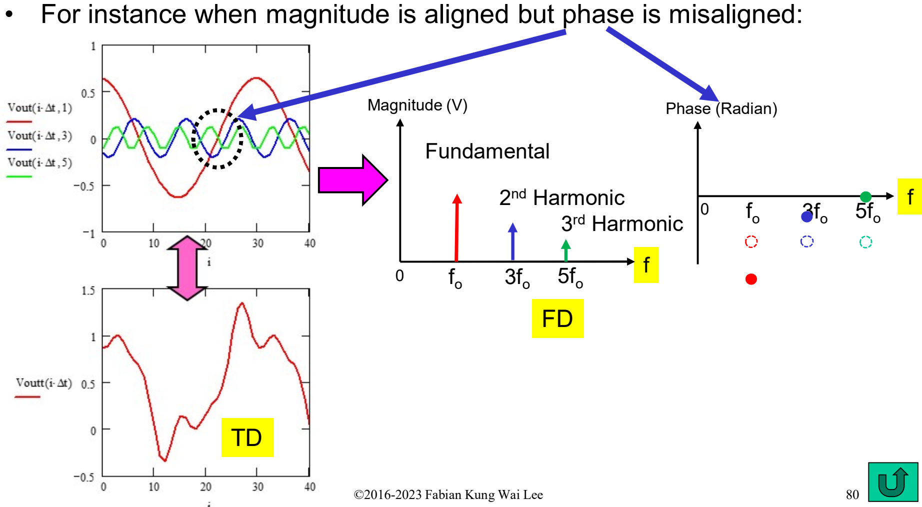


$$f_o = \frac{1}{T_{\text{period}}}$$

Typically the magnitudes for the FD quantities are expressed in log scale, in dB.

The Importance of Magnitude and Phase Integrity in Frequency Domain (2)

- Both magnitude and phase of each frequency must be perfectly ‘aligned; to produce the square wave.
- For instance when magnitude is aligned but phase is misaligned:

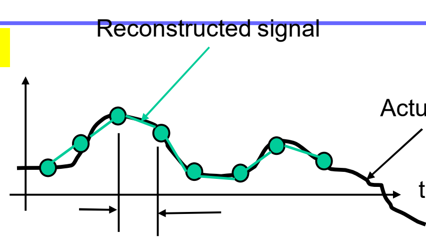


Co-Axial Probes

- Co-axial probes from Pasternack.

Equivalent and Real-Time Sampling

Real-time



Sampling interval, τ = 1/(Sampling Rate)

If sampling rate = 1 Gs/s, τ = 1nsec

Equivalent-time

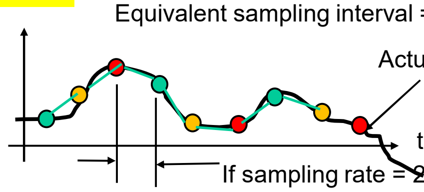
Actual sampling interval = 150 psec

Equivalent sampling interval = 50 psec

1st pass

2nd pass

3rd pass



If sampling rate = 20 Gs/s, τ = 50 nsec

Microstrip Trace Design

- Calculations for microstrip line.

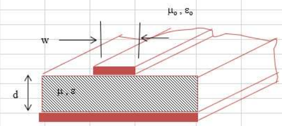
$$\varepsilon_{eff} = 1 + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{1}{\sqrt{1 + \frac{10d}{w}}}\right]$$

$$Z_c = \frac{377}{\sqrt{\varepsilon_{eff}}}\left[\frac{w}{d} + 1.98\left(\frac{w}{d}\right)^{0.172}\right]^{-1}$$

$$v_p = \frac{1}{\sqrt{\mu\varepsilon_{eff}\varepsilon_o}}$$

Microstrip Line Design

Based on lecture notes of "RF Circuit Design"



Usage: Key in the parameter values in cells with YELLOW color, follow the unit.
Read out the results under "Results" section.

Parameters		Unit	Remarks	
Er	4.6		Relative permittivity of substrate	4.600E+00
d	1	mm	Thickness of substrate	1.000E-03
t	0	mm	Thickness of trace	0.000E+00
W	1.524	mm	Width of trace	1.524E-03
uo	1.2566E-06	H/m	Free space permeability	1.257E-06
eo	8.8541E-12	F/m	Free space permittivity	8.854E-12
f	1000	MHz	Frequency	1.000E+09

Results

W/d	1.524		Trace width over dielectric thickness ratio
Eeff	3.455		Effective dielectric constant
Zc	55.528	Ohm	Lossless characteristic impedance
vp	1.613E+08	m/s	Phase velocity
Beta	38.954		Phase constant

S. Ramo, J.R. Whinnery, T.D. Van Duzer, "Field and waves in communication electronics" 3rd edition, 1993 John-Wiley & Sons.

Coupled Microstrip Trace Design

- Calculations for coupled microstrip.

Garg R., Bahl I. J.,"Characteristics of coupled microstriplines", IEEE Transaction on Microwave Theory and Techniques, MTT-27, No.7, pp. 700-705,July 1979.

Coupled Microstrip Line Design

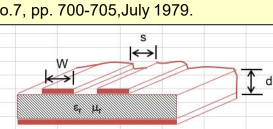
Based on lecture notes of "High-speed PCB Design"
Usage: Key in the parameter values in cells with YELLOW color, follow the unit.
Read out the results under "Results for coupled transmission lines" section.

Parameters		Unit	Remarks	
Er	4.6		Relative permittivity of substrate	4.600E+00
d	1	mm	Thickness of substrate	1.000E-03
t	0	mm	Thickness of trace	0.000E+00
W	1.524	mm	Width of trace	1.524E-03
uo	1.2566E-06	H/m	Free space permeability	1.257E-06
eo	8.8541E-12	F/m	Free space permittivity	8.854E-12
f	1000	MHz	Frequency	1.000E+09
s	0.4064	mm	Trace-to-trace spacing	4.064E-04
c	3.00E+08		Speed of light in vacumn	3.00E+08

Results for single transmission line

W/d	1.524		Trace width over dielectric thickness ratio
Eeff	3.455		Effective dielectric constant
Zc	55.528	Ohm	Lossless characteristic impedance for single microstripline
vp	1.613E+08	m/s	Phase velocity
Beta	38.954		Phase constant

Cp	6.20709E-11	F/m	A1	2.453259896	Cpo	1.34937E-11	F/m
Cf1	2.47885E-11	F/m	A2	-0.02174644	Cf1o	9.41256E-12	F/m
Cf2	8.41182E-12	F/m	k	0.117647059	Cf2o	2.768E-12	F/m
Zc1	103.2079792	Ohm	k1	1.996521686			
			k2	0.003478314			
			Cga1	1.98574E-11	Cgdo	3.6131E-12	F/m
			Cga2	1.97541E-11			
			Cga	1.98574E-11			
			B1	3.238650899			
			B2	1.058290286	B2o	0.049212598	
			Cgd	3.22869E-11			



Results for coupled transmission lines

Ce	9.52712E-11	F/m	Even mode distributed capacitance
Ceo	2.56742E-11	F/m	Even mode distrbuted capacitance when Er=1
Co	1.39004E-10	F/m	Odd mode distributed capacitance
Coo	4.63768E-11	F/m	Odd mode distributed capacitance when Er=1
Zoo	41.5436575	Ohm	Odd mode characteristic impedance
Eeffo	2.997271299		Odd mode effective dielectric constant
Zoe	67.44328656	Ohm	Even mode characteristic impedance
Eeffe	3.710771228		Even mode effective dielectric constant
Zdm	83.08731499	Ohm	Differential mode characteristic impedance
Zcm	33.72164328	Ohm	Common mode characteristic impedance

Pre-Emphasis, De-Emphasis And Equalization (1)

- **Pre-emphasis** is applied at the transmitter (TX).
- **De-emphasis** in principle can be applied at transmitter and receiver (RX), but for modern digital system it is also applied at the TX (more effective if applied at TX).
- Pre-emphasis amplifies the high-frequency component of the digital signal, and can be viewed as a active high-pass filter.
- High-frequency component of a signal is associated with transition, so pre-emphasis magnifies the signal transition.
- De-emphasis attenuates the low-frequency component of the digital signal, and can be viewed as a low-pass filter.
- Low-frequency component of a signal is associated with the steady-state voltage level, so de-emphasis attenuate the steady-state voltage level.
- Both pre and de-emphasis operations are usually implemented in discrete time, with interval similar to unit interval (or fractional internal) using FIR (finite impulse response) blocks.

Pre-Emphasis, De-Emphasis And Equalization (2)

- **Equalization** is to compensate for the frequency dependent characteristics of the channel frequency response.
- Equalization network can be applied anywhere in the TX-RX path, but is usually applied at the RX and implemented as continuous time analog network*, for instance using RC networks with optional linear amplifier integrated in the RX integrated circuit.
- It some instance equalization can also be built into the cable or interconnection.
- Because a physical channel is always low-pass, equalization always has high-pass characteristics.

*Note: in signal integrity this continuous time analog network is usually called Continuous Time Linear Equalization (CTLE).

Pre-Emphasis, De-Emphasis And Equalization (3)

- A sample equalization network frequency response employing one zeros and two poles.

$$H_{ctf}(s) = k * \frac{(s+\omega_z)}{(s+\omega_{p1})(s+\omega_{p2})}$$

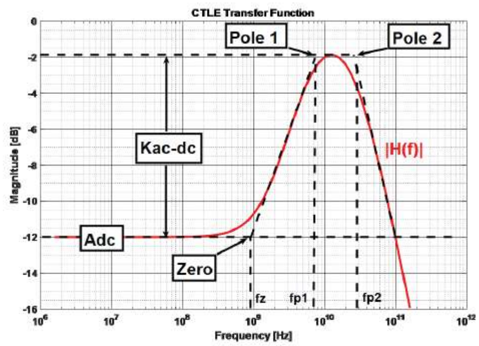


Figure 20 – Bode plot of a CTLE filter

Pre-Emphasis and De-Emphasis of Digital Signal

Pre-emphasis
(emphasize the positive and negative edges, boost High-frequency components)

Boosting the high-frequency content of the signal

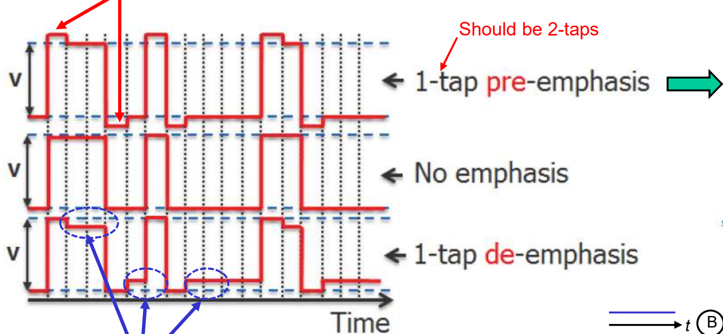
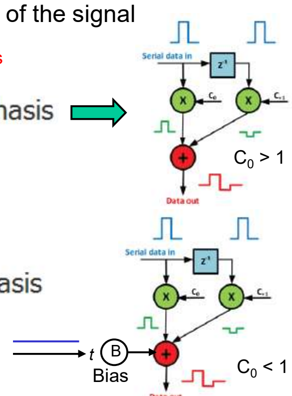


Figure 3 – Transmitter pre- and de-emphasis



De-emphasis
(de-emphasize the steady state value, smaller than the no emphasis value)

Decreasing the low-frequency content of the signal

Typical Usage of Emphasis, Equalization and Other Compensation in Digital Transmission

Slicer means the decoder

DFE: Decision Feedback Equalization
FFE: Feed Forward Equalization

For bit-rate < 2.5 Gbps

For bit-rate between 2.5-5 Gbps

For bit-rate between 5-50 Gbps

Latest for bit-rate above 50 Gbps

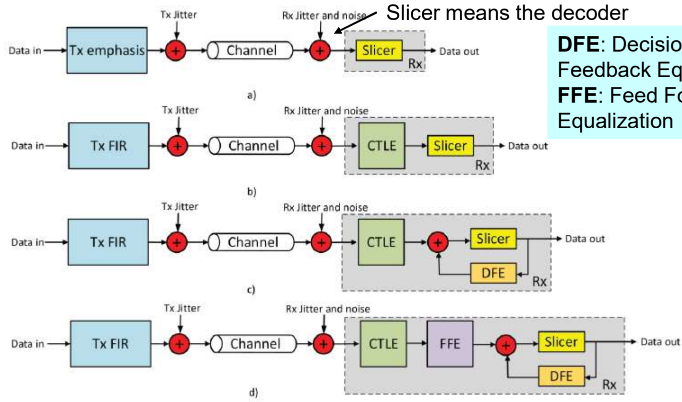
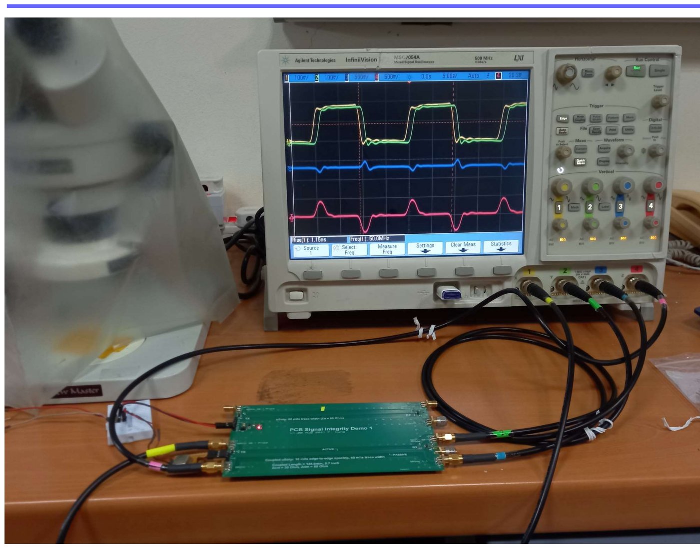


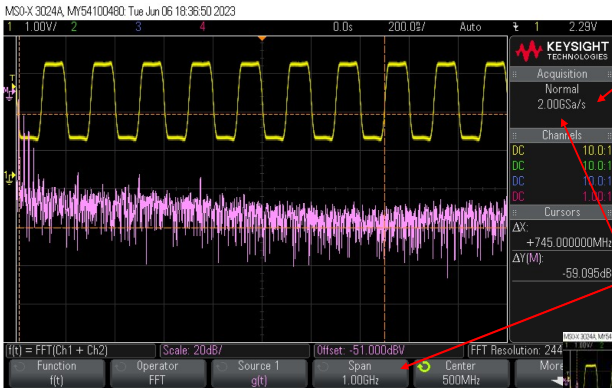
Figure 1 – Typical equalization architectures: Tx emphasis or FIR only a), Tx FIR and Rx CTLE b), Tx FIR and Rx CTLE + DFE c), and Tx FIR and Rx CTLE + FFE + DFE d)

Source: C. Filip, “*Overview of Channel Equalization Techniques for Serial Interfaces*”, White paper by Siemens, 2021.

Demo Setup



Using FFT Function of Keysight MSOX Oscilloscope



The default sampling rate is determined by the horizontal time-base selected by user

The maximum span is associated with the sampling rate

Press [Math] -> [FFT]

We can adjust the Span and Center frequencies to zoom into the spectra