Introduction to Signal Integrity

Module 1

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Outline

- Fundamentals (Systems, Signals, Electromagnetism).
- Theory and Applications go hand by hand.
- Learn by doing (gradually build complex systems).
- Animations and Equipment.
- Debugging and Troubleshooting Skills.
- Collaborative learning (learning circles, discussions).

Logistics, timelines

- Six 90 mins classes run on every other Monday (from noon to 1:30 PM).
- Lunch provided.
- A mix between Teaching Modules (TM) and Interactive Modules (IM).
- Collaborative learning highly encouraged.
- Virtual Office hours (Mondays (no classes) from noon to 1 PM.
- Certificate Requirements:
  - Attend at least 80% of the class.
  - Participate in the IM.
  - Complete the assignments.

Assignments

- Three (or Four) short assignments
  - Each assignment builds on previous ones.
  - Should take between 30 mins and 1 hour to complete.
  - Exploration Questionnaire (1st attempt before September 23, final attempt before November 25).
- Purpose
  - Learn by doing.
  - Emphasize the Fundamentals.
  - Bridge fundamentals with applications.
- Mandatory for getting the certificate.
- Programming Languages: Octave, MATLAB, Python or any language of your choice.

Course Objective

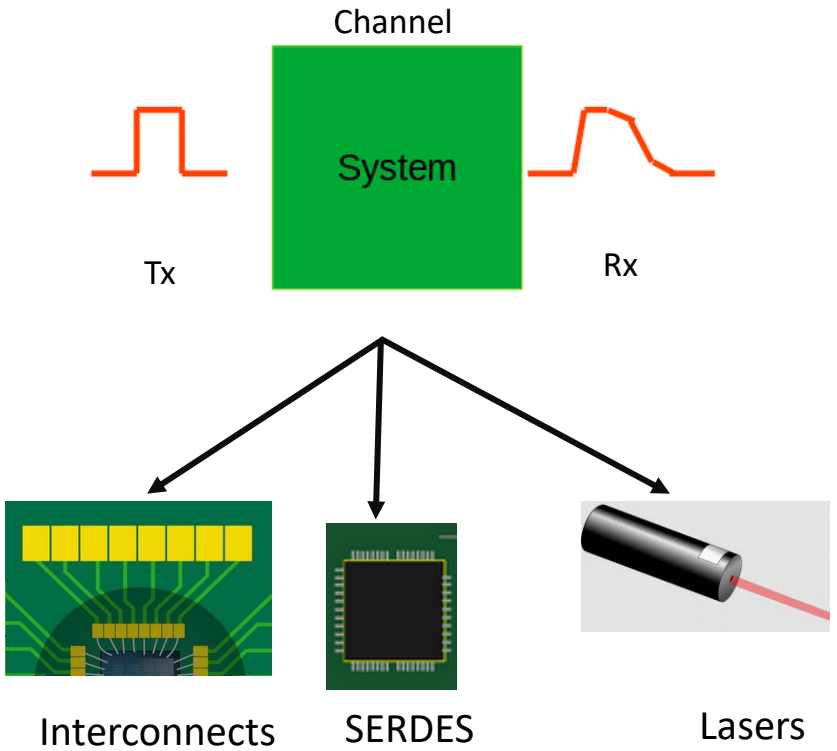
"Bridge the gap between theory and engineering practices in SI"

Challenges

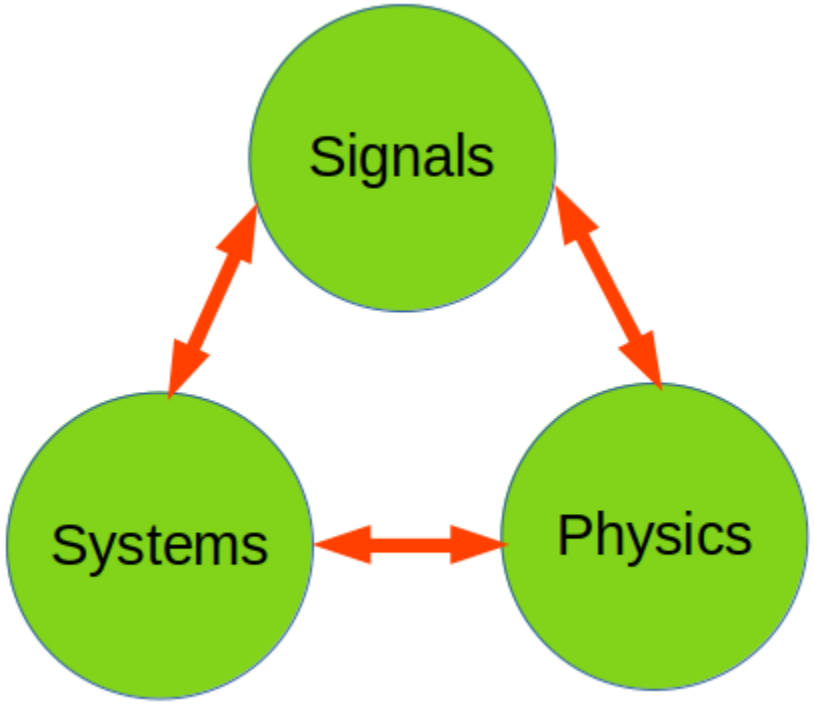
- Wide range of experiences and expectations.
- SI is viewed differently (Circuit Designers, PCB designers, System architects, etc).
- Time limitations.
- Balance between theory and applications.

Workflow conceptual view

- Need to define Signal Integrity first:
  - ChatGPT definition: "Signal Integrity (SI) refers to the measure of the quality and reliability of ~~an electrical~~ (a communication) signal as it travels through a transmission medium"



SI Conceptual View



Module 2

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SI around us

Please try to solve **as a group** the following:

- Mitel is a local telecommunications company founded in 1973, what does "Mitel" mean?
  a. Multimedia Telecommunications
  b. Michael & Terry Lawnmower
  c. Microsoft Telcom.

  Tell us something interesting about the company

- Explain using SI concepts why we tend to raise our voices while talking behind doors.

- Identify SI systems in the room. What do you think the data rate is and what issues you think may affect the signal and how to quickly fix them?

Module 3

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Introduction to Systems

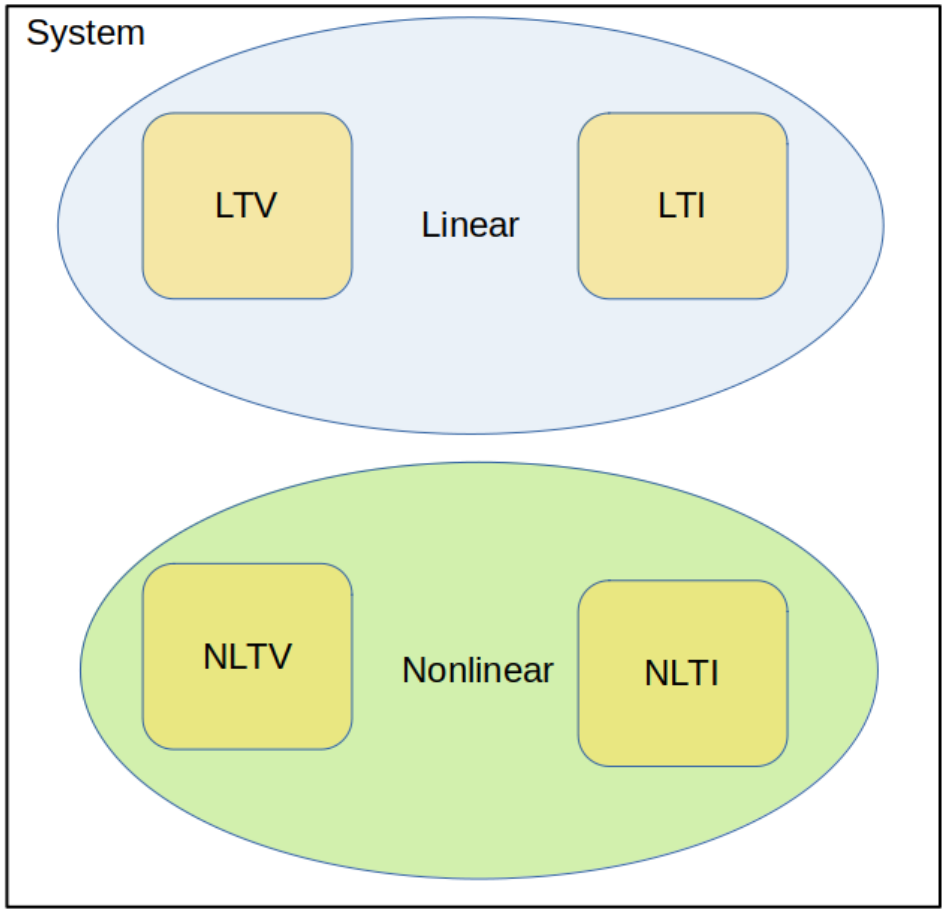
- Data rates double every few years (100 Gbps, 200 Gbps, 400 Gbps).
- Pulses are picoseconds long, i.e., interaction with systems becomes complex.
- Need to describe and characterize systems
  - Physics based characterization
    - Analytical models fit (Optical modulators, Diodes, SERDES, etc.).
    - Physics based Solvers (EM, Heat transfer, mechanical, Photonics, Semiconductors).
  - Behavioral Models
    - Input output characteristics (S parameters)
    - IBIS-AMI (DLL/SO Algorithmic models).

Time delay of light over 1 m (arm distance) is:

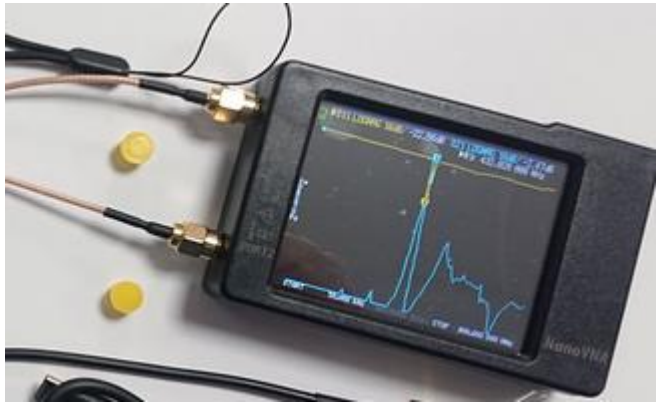
System Types

- Linear systems satisfy Superposition principle:
  - Response to two inputs =Sum of responses of each input.
  - Output is proportional to input amplitude.
- Nonlinear: does not satisfy superposition principle.
- Time variant: Parameters change with time.
- Time invariant: Parameters constant over time.

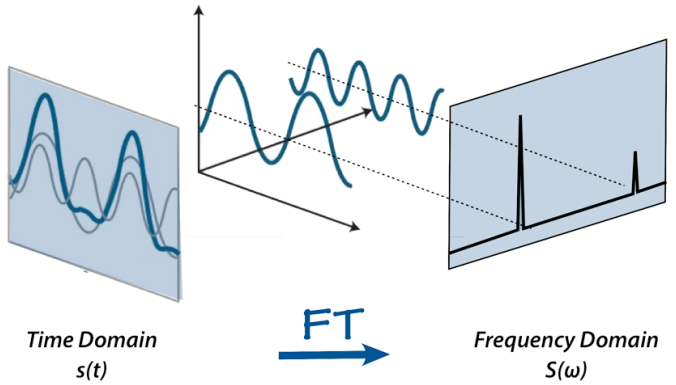
LTI NLTI



Linear Time Invariant Systems

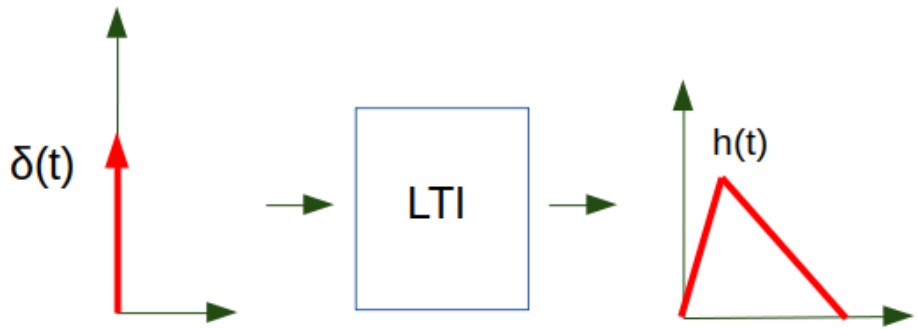


- Many SI blocks are LTI (Cables, PCB traces, connectors, Packages, FIR filters, CTLEs).
- (Relatively) Easy to model
  - Time/Frequency domains.
  - Fitting to rational functions.
- Fast calculations
  - Efficient Frequency domain computations.
  - Interaction is equivalent to direct multiplication.
- Cannot model Lasers, modulators, Limiting amplifiers, DFEs, etc
  - Good first order approximations.
- Measurements are straightforward.



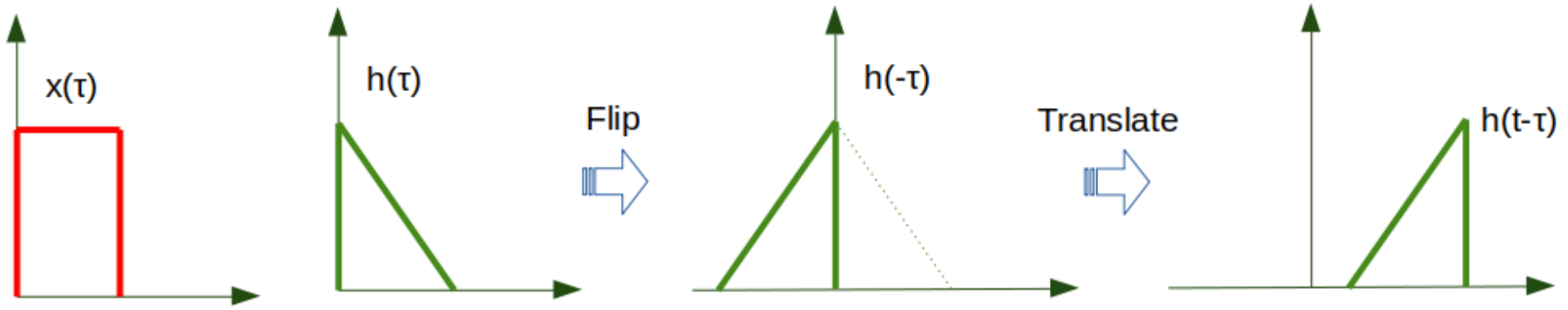
LTI description

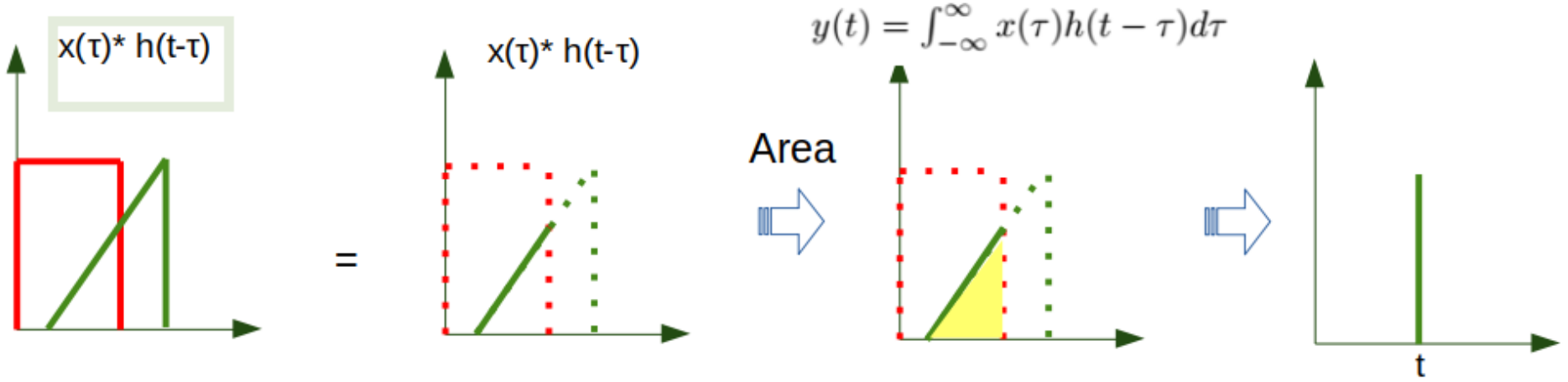
- Combine Linearity and Time invariance, LTI described by its impulse response h(t)
- For any input the output calculated using the convolution operation.
- In the frequency domain, the impulse response becomes the transfer function.



Linearity + Time invariance ⇒ $y(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau$ Convolution

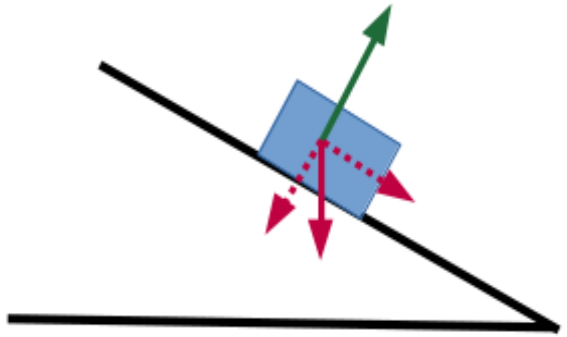
Convolution

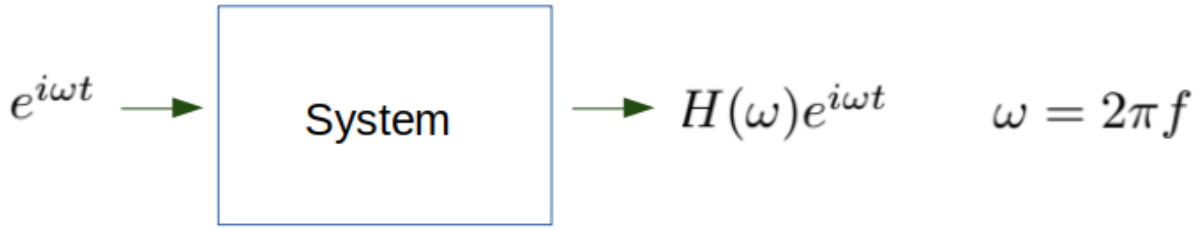




From time to frequency

- Convolution becomes multiplication why?





$$Y(f) = H(f)X(f)$$

$$y(t) = \mathcal{F}^{-1}\{Y(f)\}$$

- Lesson from mechanics: select the coordinate system that is natural to the problem.
- For LTI the"natural coordinate system" is the sinusoids!

Module 4

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Explore as a Group

Topic 1	Topic 2	Topic 3	Topic 4
Challenges with NLTI Systems Modelling	Simulation speed of NLTI vs LTI	Sketch a full system from transmitter to receiver (Does not have to be complete, just do your best)	How LTI systems are measured (frequency or time domain)?

Module 5

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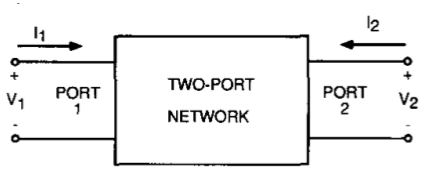
Signal Integrity Metrics – Time Vs. Frequency

Signals = 50 Ohms Characteristic Impedance, Bandwidth of a low frequency to Daylight for digital, Transport information
Powers = 0 Ohms Impedance , Bandwidth ~ 500 MHz on PCB , support the transfer

Domain	Results
Frequency	S-Parameters -> Insertion Loss, Return loss 
Time	Waveforms and Eye Diagrams 



A general two-port network with voltages and currents defined.

Z parameters

$$V_1 = Z_{11} \cdot I_1 + Z_{12} \cdot I_2$$

$$V_2 = Z_{21} \cdot I_1 + Z_{22} \cdot I_2,$$

Y parameters

$$I_1 = Y_{11} \cdot V_1 + Y_{12} \cdot V_2$$

$$I_2 = Y_{21} \cdot V_1 + Y_{22} \cdot V_2,$$

$ABCD$ parameters

$$V_1 = A \cdot V_2 - B \cdot I_2$$

$$I_1 = C \cdot V_2 - D \cdot I_2,$$

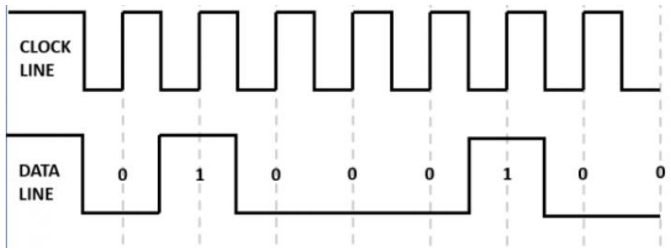
S parameters

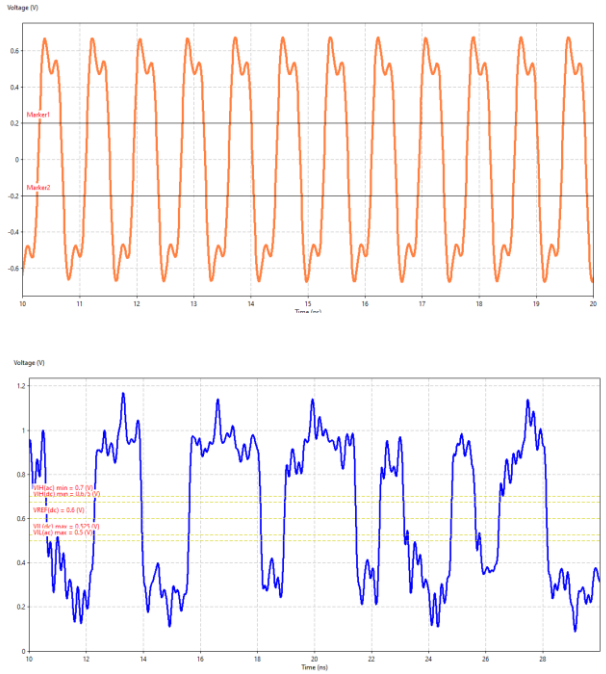
$$b_1 = S_{11} \cdot a_1 + S_{12} \cdot a_2$$

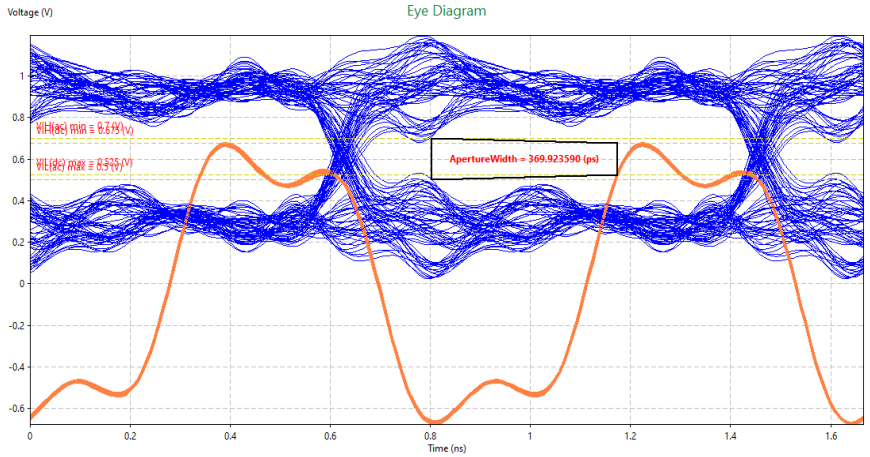
$$b_2 = S_{21} \cdot a_1 + S_{22} \cdot a_2,$$

Time Domain Metrics

RX waveform should look like an amplitude scaled Tx waveform. Metrics define departure from ideal values. Jitter, Overshoot/undershoot, Eye width and height,







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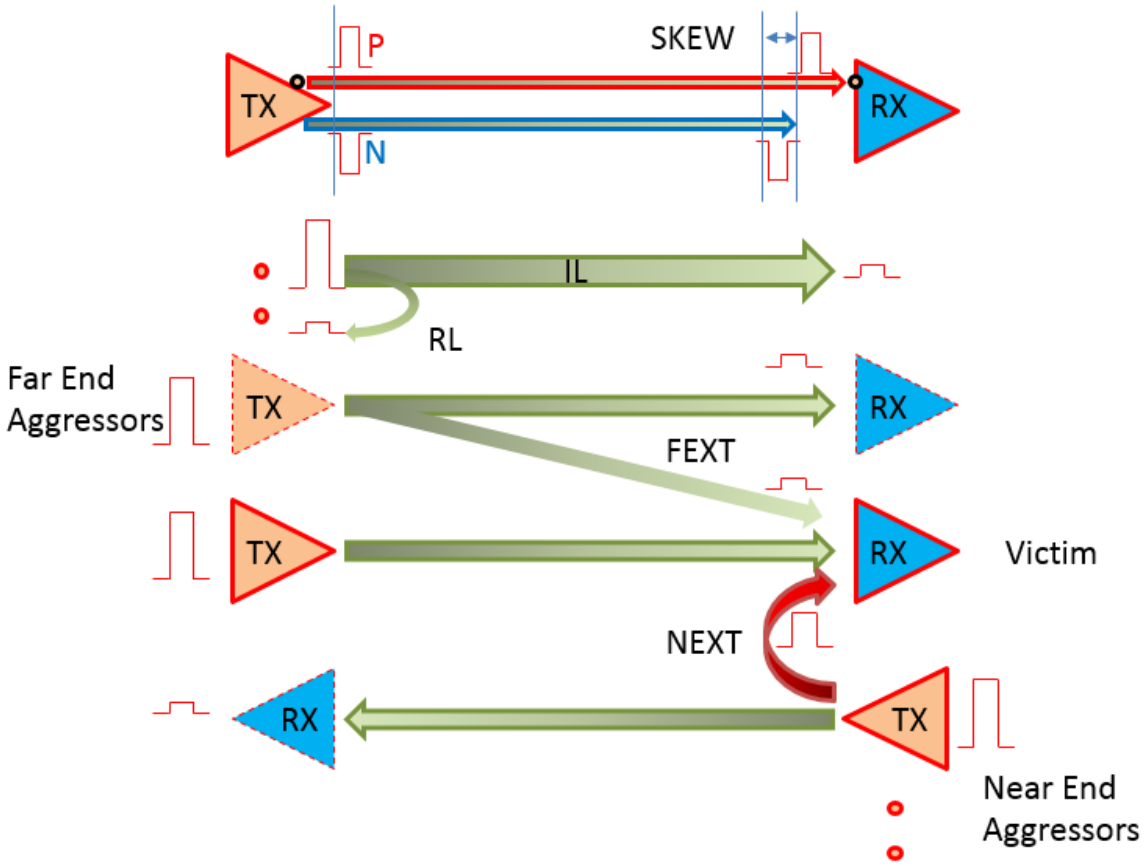
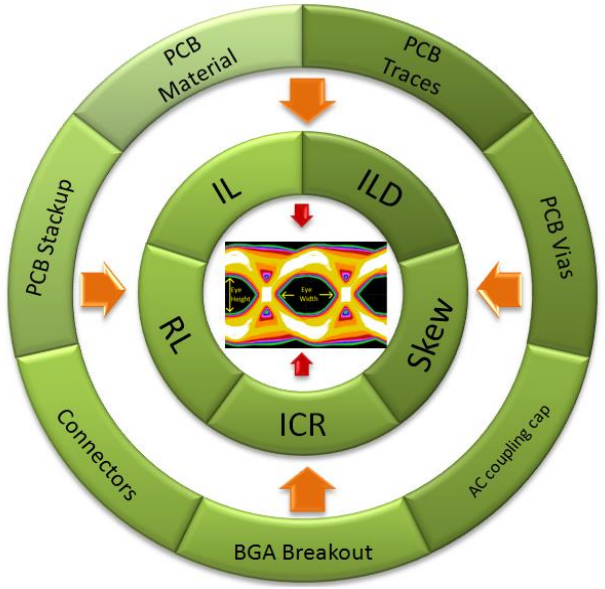
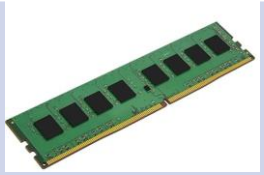
Frequency Domain Metrics – S Parameters





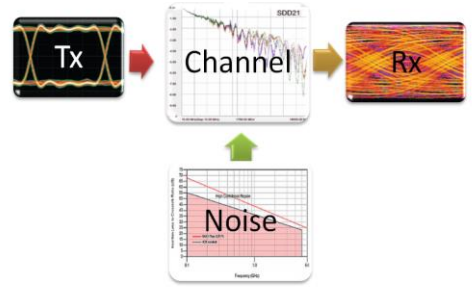
IL- Insertion Loss, RL- Return Loss, ILD-Insertion Loss Deviation,
FEXT – Far end crosstalk, NEXT –Near end crosstalk,
ICR – Insertion loss to crosstalk ratio

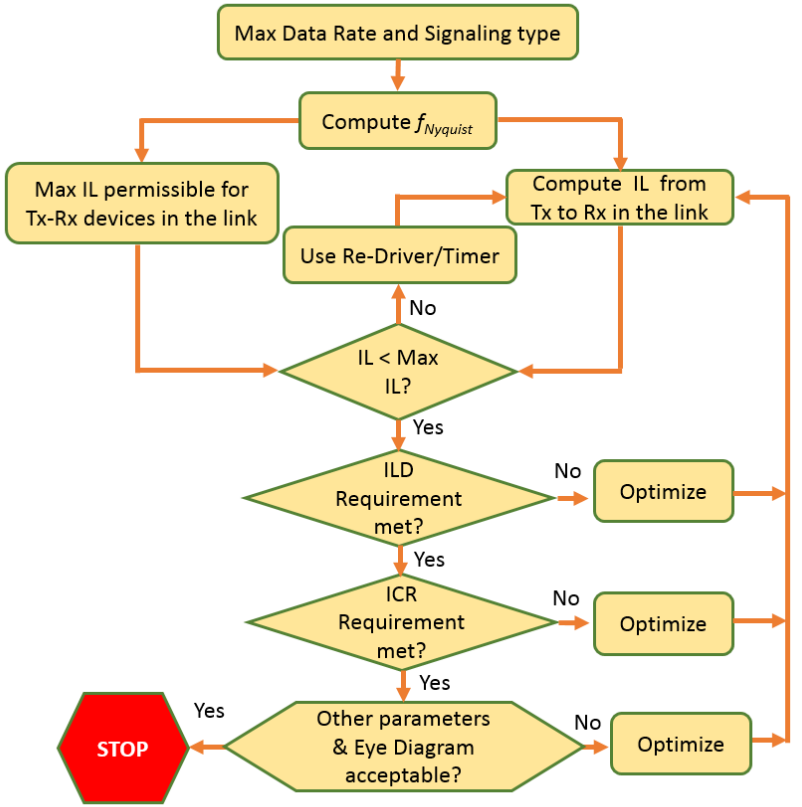
Standards

Standard Name	DDR4	GDDR7	PCI-Express Gen4	PCI-Express Gen7
				
Data Rate (Gbps)	3.2	36	16	128
Signal Type	NRZ	PAM3	NRZ	PAM4
Insertion Loss (dB)	Not specified		25.5	
Return Loss (dB)	Not specified		Mask defined -6dB at 8GHz	
Receiver Eye Height (mV)	Very detailed (~100 mV)		15	
Receiver Eye Width (pS)	Very detailed (~100 pS)		6.25	

Link Budget

	Example: Nyquist Frequency = 8 GHz		
Link Element	Insertion Loss at (dB)	Return Loss (dB)	Cross talk (dB)
Tx Package	1	30	40
TX PCB Interconnect	3	20	35
Tx Connector	1	20	30
Cable	10	20	25
Rx Connector	1	20	39
RX PCB Interconnect	3	20	30
Rx Package	1	30	40
Total	$\sum$ = 20		





References

1. Eric Bogatin, “Signal Integrity Simplified”,
Signal Integrity - Simplified: Bogatin, Eric: 9780130669469: Books - Amazon.ca

Module 6

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Reflect on what we discussed today (5mins)

- Discuss with your Seatmate.

Takeaways Points

- Course Logistics.
- Course Overview.
- Three main components of SI: Signals, Systems and Physics.
- Types of Systems: Linear, Nonlinear.
- Importance of LTI
  - Many SI systems are LTI.
  - Mature analytical and numerical tools.
  - Easy to characterize via measurement.

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•The **Microwave Theory and ~~Techniques~~ Technology Society** (MTT-S) is an IEEE society that focuses on advancing the fields of microwave theory, techniques, and applications.

•It serves as a global community for professionals in **RF**, **microwave**, **millimeter-wave**, and **terahertz technologies**.

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