SWTEST

PROBE TODAY, FOR TOMORROW

5G Wafer Test and the New Age of Parallelism

FormFactor™

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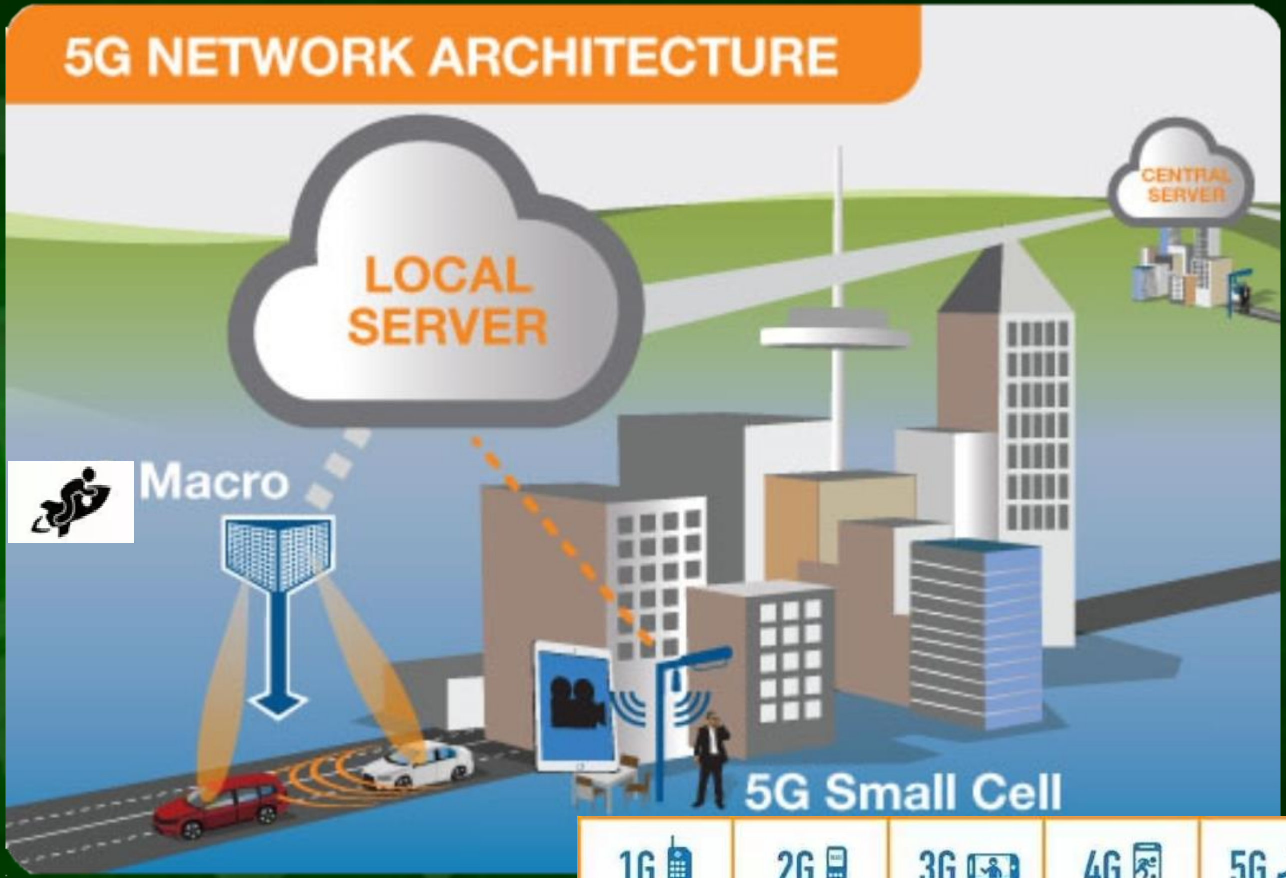
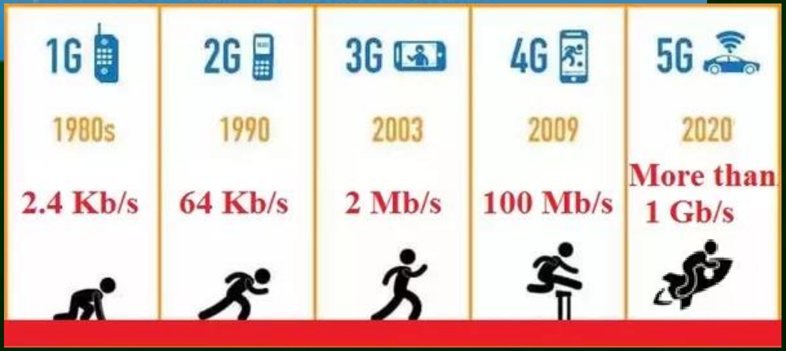
Overview

- 5G – What do you know now?
- What Probing Technology can you use at these frequencies?
- What should you think about for probe head inductance (or everything you know is wrong)?
- What are some of the Figures Of Merit (FOM) important for 5G probe cards?

What is 5G?

- **Communication Network for 4th Industrial Revolution**
  - 5G RF, Optical, High Speed Digital
- **Extremely Fast Data Rates**
  - 10Gbps (5G) vs 100Mbps (4G)
- **Ultra Low Latency**
  - 1ms (5G) vs 50ms (4G)
- **Huge No. of Connections**
  - 100 billion (5G) vs 1000 (4G)
- **Higher Energy Efficiency**
  - Always Stay Connected
- **Connect Everyone, Everything**





Sources: https://www.quora.com/What-is-5G-Will-5G-technology-bring-new-dimensions-to-wireless ; http://www.emfexplained.info/?ID=25916 ; https://en.wikipedia.org/wiki/Fourth_Industrial_Revolution

What does 5G Production Test Require?

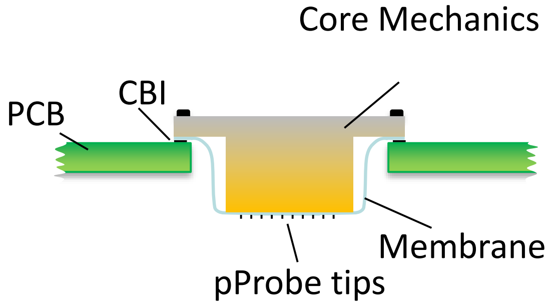
- **What we know 5G components testing will require:**
  - New test equipment for the higher frequencies and more channels
  - Time of test as low as possible with high throughput and multi-site capability on the probe card
  - High accuracy is needed to validate performance with high measurement repeatability to verify modulation

What does this mean for Probe Cards?

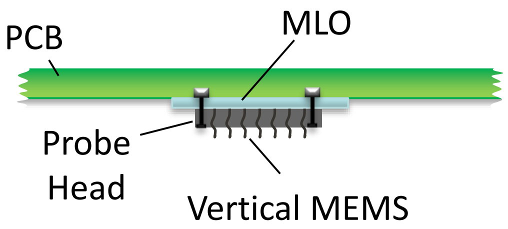
- **The net result is that any probe card technology needs to be capable in the test environment**
- **Including:**
  - Signal integrity
  - Multi-Site Capability
  - High channel count capable in arrays (RF lines are not in the periphery)
  - Lowest cost of test possible for the use case

Pyramid, Katana-RF, Pyrana & ePyrana Comparison:

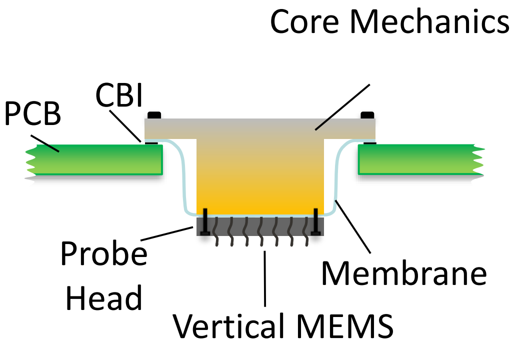
pProbe Probe Card



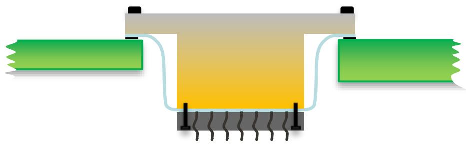
Katana-RF Probe Card



Pyrana Probe Card



ePyrana Probe Card



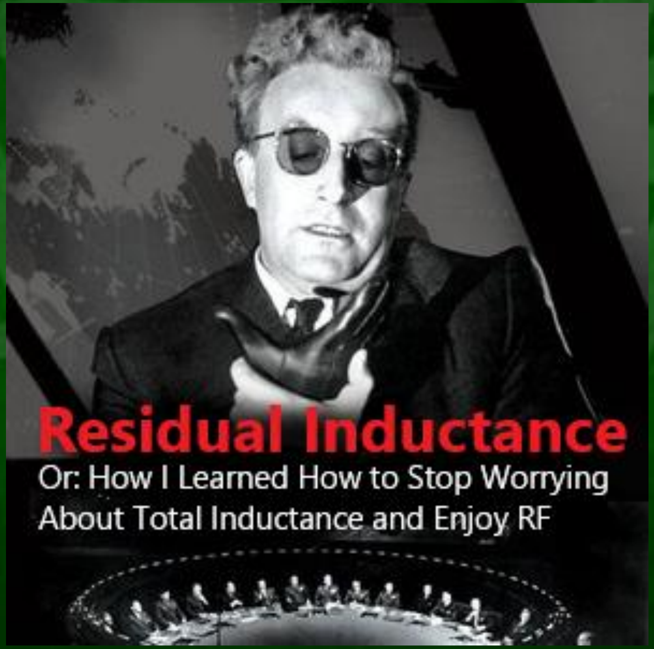
	Pyramid Probe Card	Katana-RFX Probe Card	Pyrana Probe Card	Pyrana Probe Card
RF Performance	**80 GHz**	<10 GHz	<10GHz	**<45GHz**
Space Transformer	Membrane to CBI	MLO or Direct Attach	Membrane to CBI	Membrane to CBI
Max Probe Area	10 x 38mm	**~ 75 x 75mm**	**12 x 75mm**	**12 x 75mm**
Common PCB	**Yes (standard CBI)**	No	**Yes**	**Yes**
Pin repair	No	**Yes**	**Yes**	**Yes**
Pin-Pin Compliance	<10µm	**+/- 150µm**	**+/- 150µm**	**+/- 75µm**

Daniel Bock

Probe Residual Inductance (L_r)

- **When looking at probe head inductance, people confuse the definition of the time delay and the residual inductance**

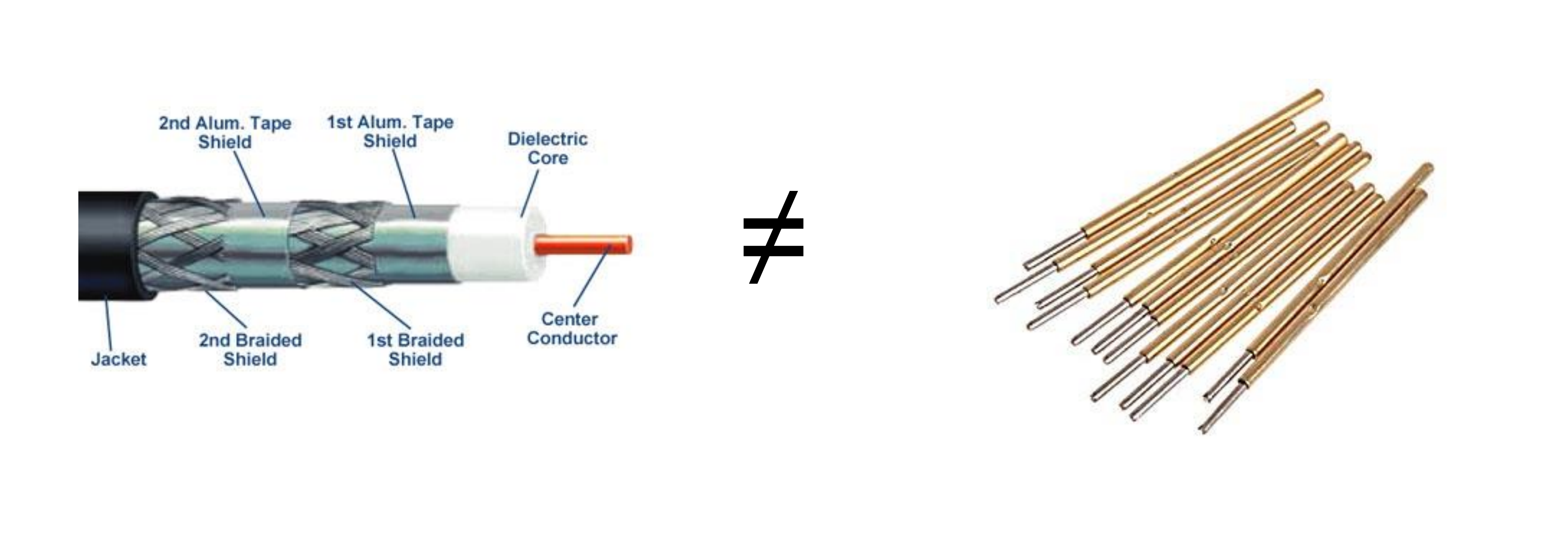
- **Delay Inductance**
  - Inductance can be defined by the delay in the signal vs. input signal
  - But even with a delay, a properly designed transmission line will not have a substantially degraded signal
  - E.g. A good 50 Ω cable can have inductance of µH, but it is compensated with capacitance



- **Residual Inductance**
  - Inductance can be looked at as the amount of voltage drop due to ‘uncompensated’ inductance
  - This is what affects the overall signal integrity

Probe Residual Inductance (L_r)

- **When looking at probe head inductance, people confuse the d**



- **Del … e**
  - Ir … t as d … due
  - B … ance d … rall h
  - E … inductance of µH, but it is compensated with capacitance

How to Calculate the L_r?

- **Looking at the voltage drop due to the inductance from the two sides of the probe head was done to estimate L_r**
  - The definition of voltage drop for inductance goes as
    - $\Delta V = -Lr\frac{dI}{dt}$
  - Within Microwave Office, voltage probes were used to measure the ΔV across a probe head S-parameter model and then calculate the residual inductance

Residual Inductance Estimates

- **Based on available data, the residual inductance of various probe head technologies is:**

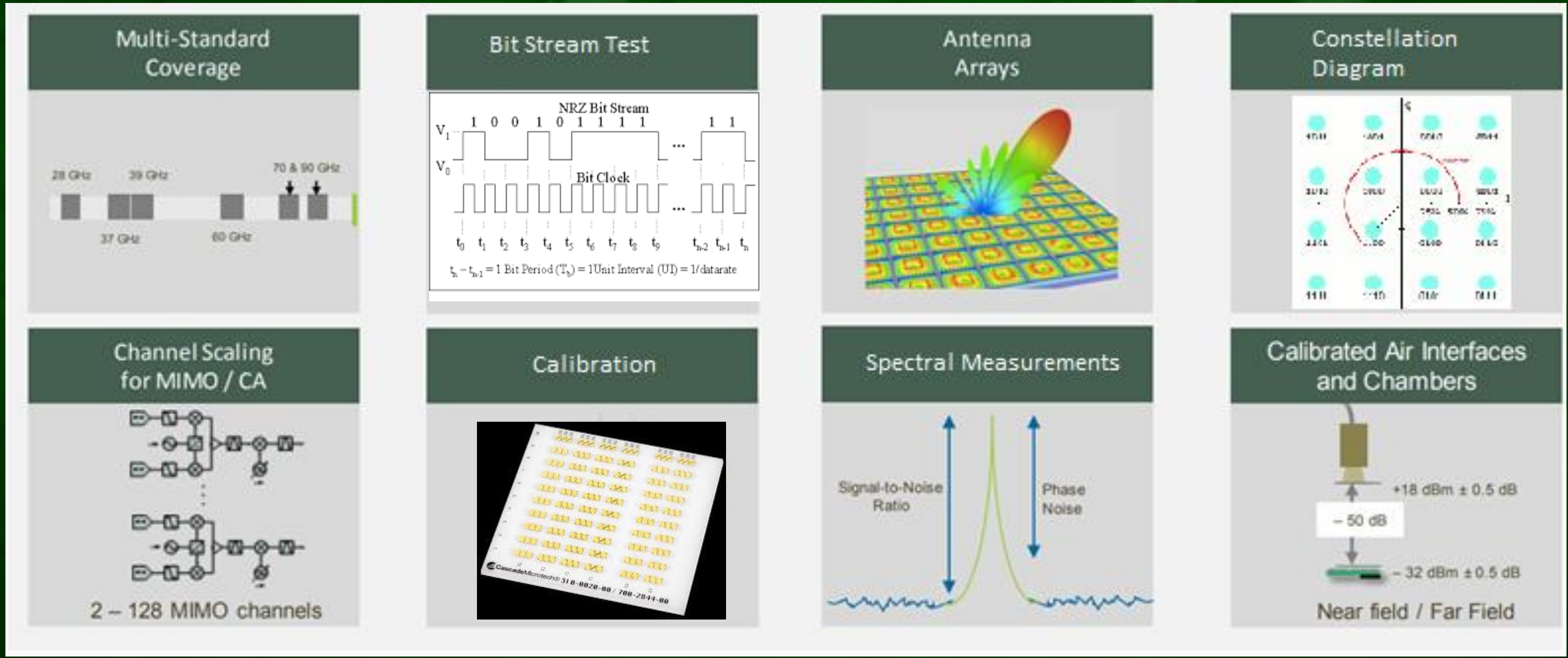
	L_r (pH)	Uncompensated length (µm)
Needle Card with Epoxy ring (1)	10,000-20,000	>10,000
Vertical	~1,000	2,900
Pyrana/Katana	500	2,800
ePyrana	50	225
Pyramid	40	50

- **The residual inductance is an important FOM that dictates the maximum operational bandwidth of each probe head technology**

Ref 1: http://www.accuprobe.com/services.php

What Type of Tests does 5G Require?

- 5G components testing, the industry hasn't agreed upon what are the best wafer test measurements:



Modified from: http://www.5gsummit.org/hawaii/docs/slides/Panel-slides.pdf

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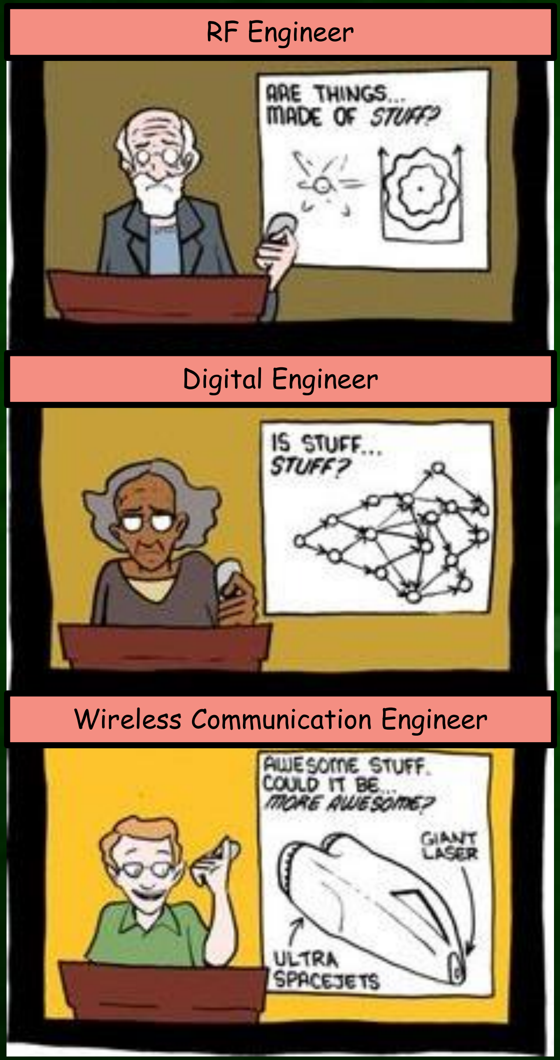
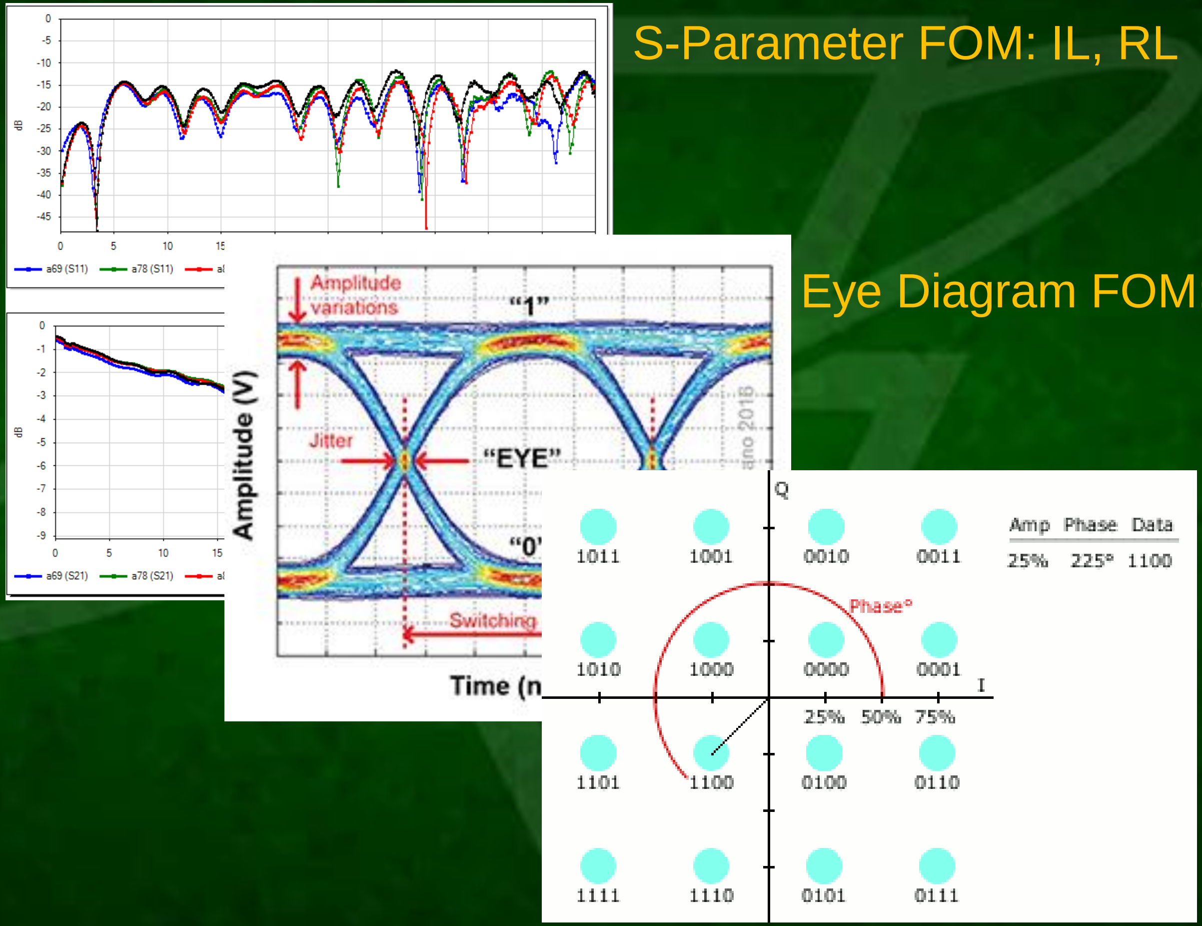
What RF Figure of Merit quantifies the quality of your device?





S-Parameter FOM: IL, RL

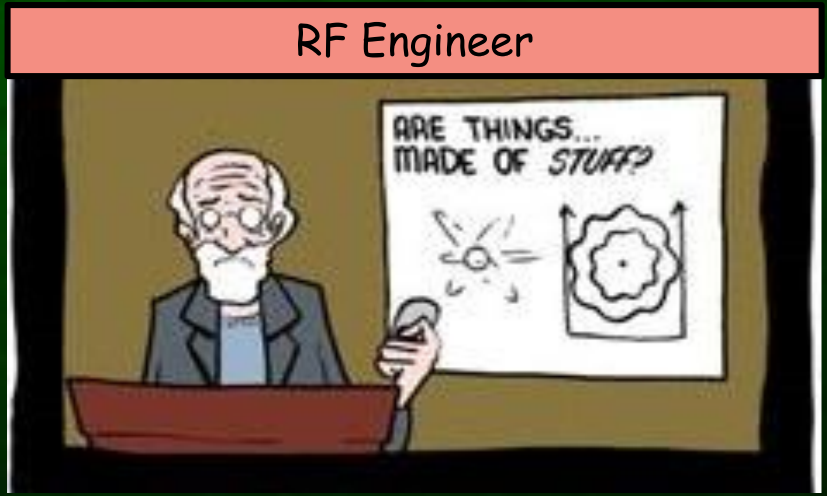
Eye Diagram FOM: Eye Amplitude

Constellation Diagram FOM: EVM

Reference: https://www.pinterest.com/michigantech/engineer-and-scientist-humor/

First Test Method: S-Parameters

- **S-parameter FOM includes: measurement accuracy and repeatability of S-parameter measurements**
  - There a multiple ways to do RF calibration. Two of the simpler methods that can be used in a full production environment were evaluated
    - 1-port SOL
    - Automatic Fixture Removal (AFR)
  - We compared the absolute value of the measurements and repeatability for IL and RL



What is the difference between SOL and AFR?

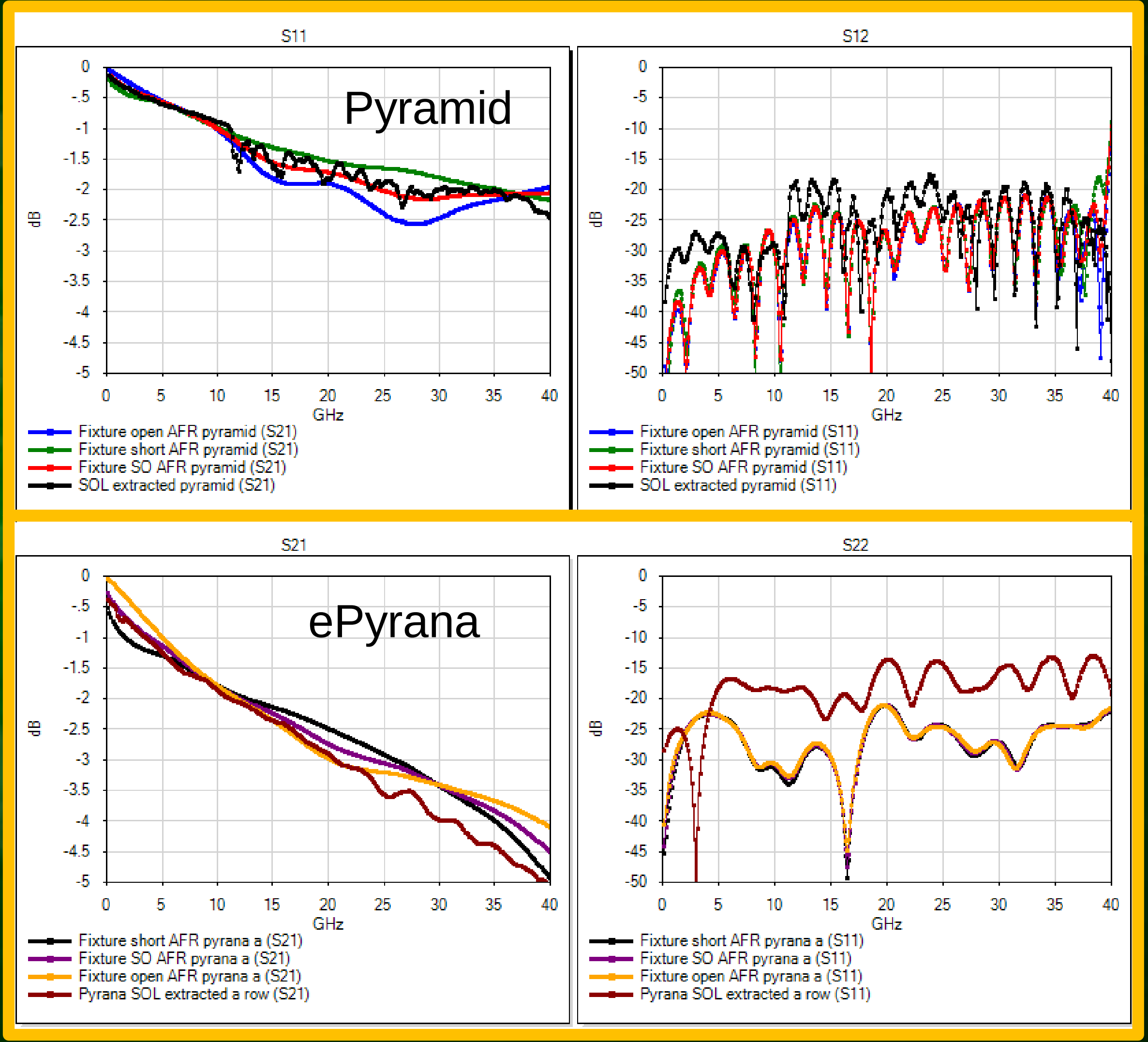
- **Both methods can be used to generate 2-port S-parameters for the Probe Card**
  - **SOL:** generates 2-port parameters based on Short-Open-Load measurements
    - Accepted to have good accuracy for characterizing a probe card

$$\begin{pmatrix} S_{11} \\ S_{22} \\ \Delta\mathbf{S} \end{pmatrix} = \begin{pmatrix} 1 & M_S \cdot \Gamma_S & \Gamma_S \\ 1 & M_O \cdot \Gamma_O & \Gamma_O \\ 1 & M_L \cdot \Gamma_L & \Gamma_L \end{pmatrix}^{-1} \cdot \begin{pmatrix} M_{1S} \\ M_{1O} \\ M_{1L} \end{pmatrix}$$

  - **AFR:** uses 1 port measurements in order to isolate the performance of only the probe card and then generates representative 2-port parameters of the device
    - Note: AFR can be done three different ways:
      - Use Short only, Open only, and Short-Open combined

Comparison of the RF Measurements

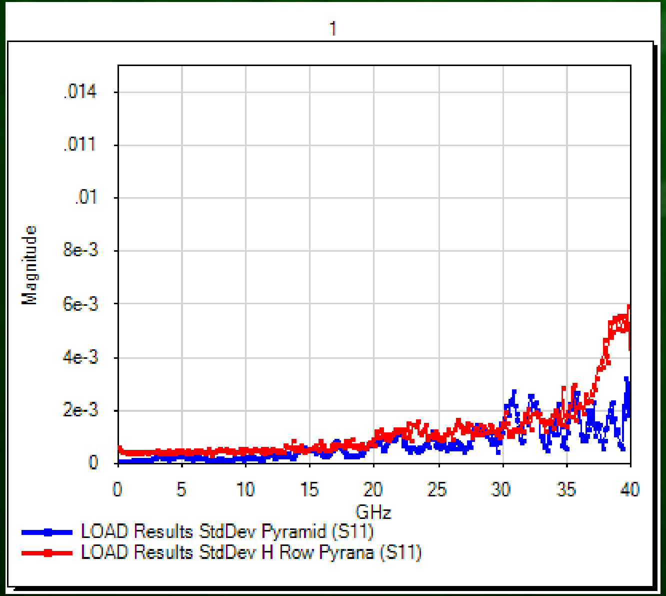
- **AFR is able to get some of the 'basic' features of the probe card performance**
  - However, it does lose some of the more detailed variations in performance for IL
  - Larger difference in RL, with AFR calculating better than actual performance

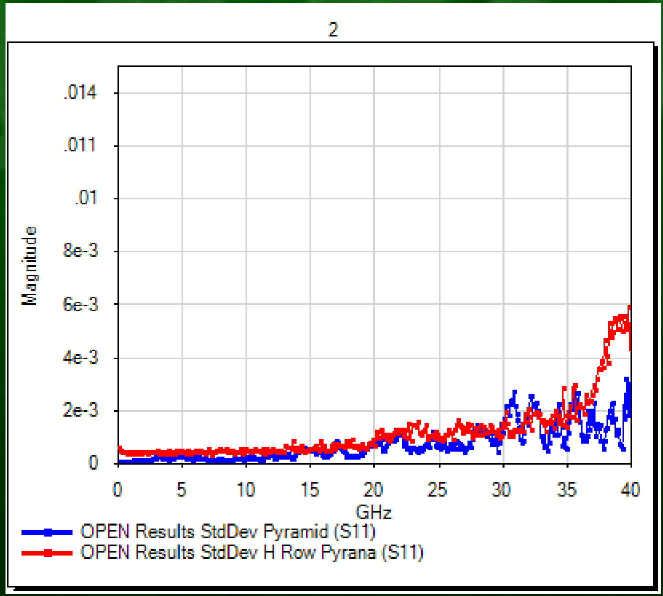


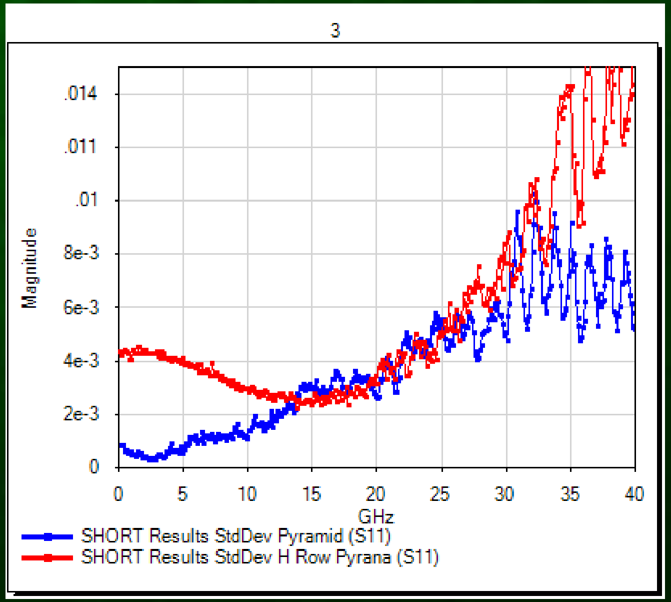
Insertion Loss Return Loss

RF Repeatability of SOL

- **One key consideration post calibration is what is the measurement standard deviation from touchdown to touchdown**
  - These measurements are done with a single SOL calibration, and then remeasuring the standards 10 times each
  - Each plot is the std dev of the measurements (Blue = Pyramid; Red = ePyrana)

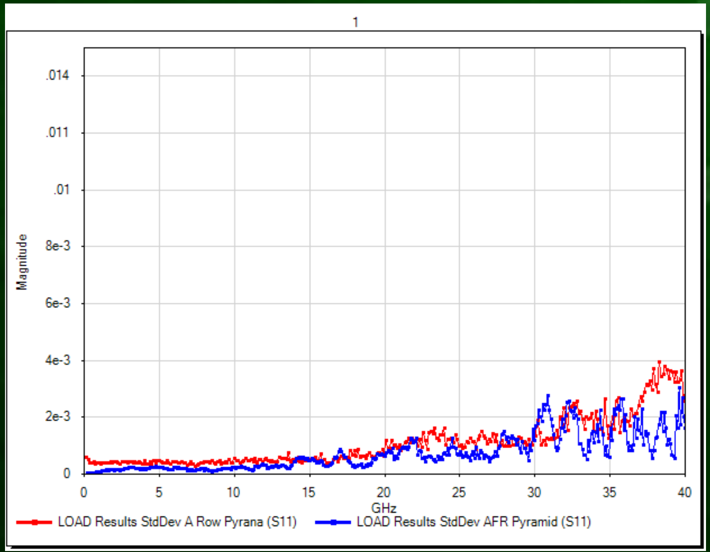


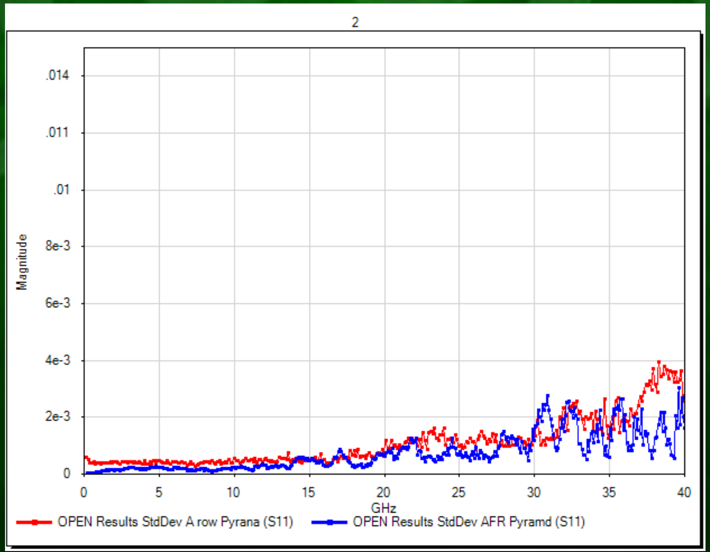


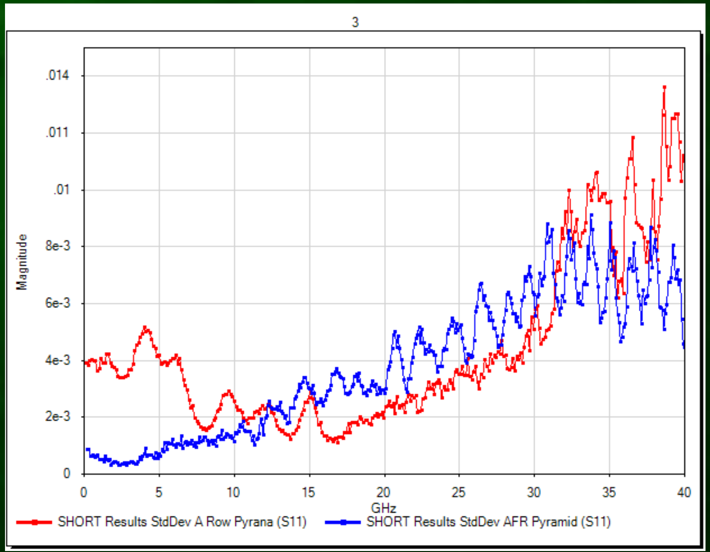


Repeatability of AFR

- **AFR, in comparison, has similar repeatability**
  - This indicates that the cal method doesn't necessarily dictate the repeatability
    - Blue = Pyramid; Red = ePyrana

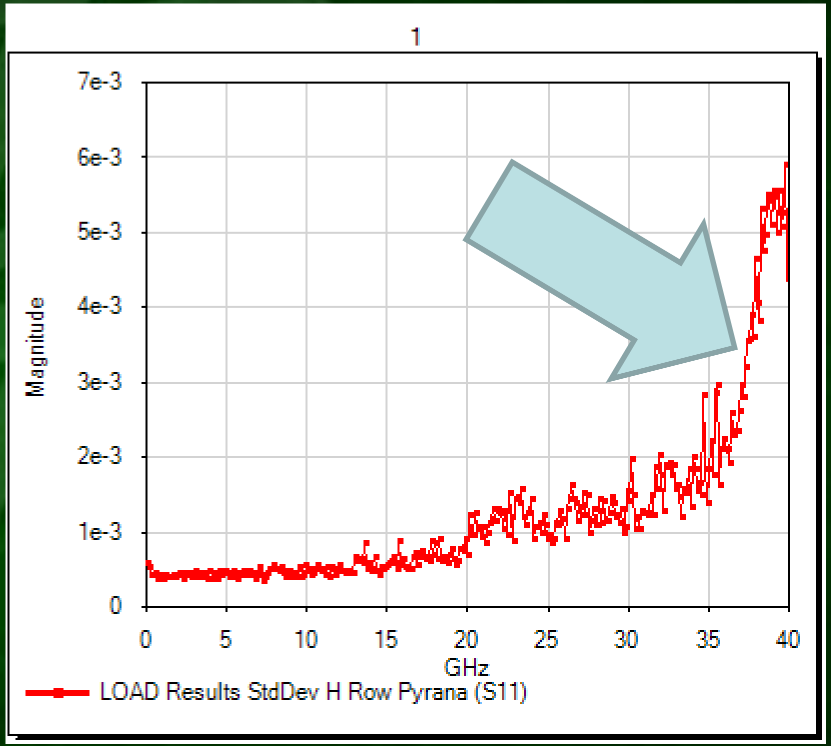






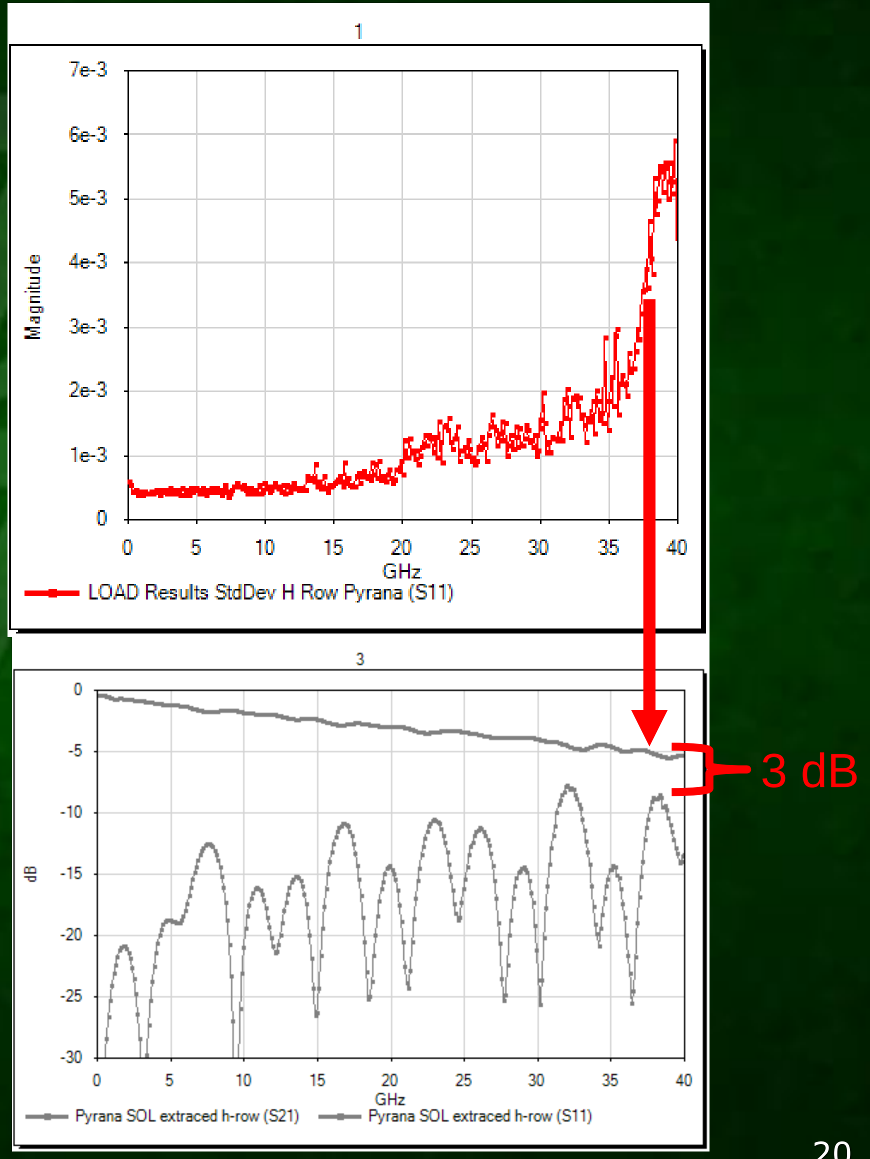
Calibration and IL-RL difference

- **It has been accepted that as the RL-IL difference gets smaller, measurements get worse**
  - Characterization work has generally maintained that the difference between IL and RL should be more than 10 dB
  - For production, it can operate much closer in difference
  - Our measurements found a point were repeatability began to degrade suddenly



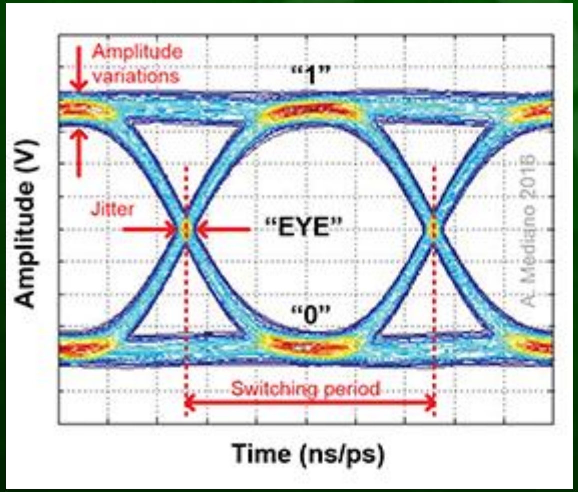
RF Measurement FOM

- **At 37 GHz, the IL and RL difference just reached the critical point of about 3 dB difference (or 50%)**
  - It appears to be that an important FOM for probe cards is that IL-RL difference should be > 3 dB
  - Pyramid meets this out to 81 Ghz
  - ePyrana is good in 45 GHz

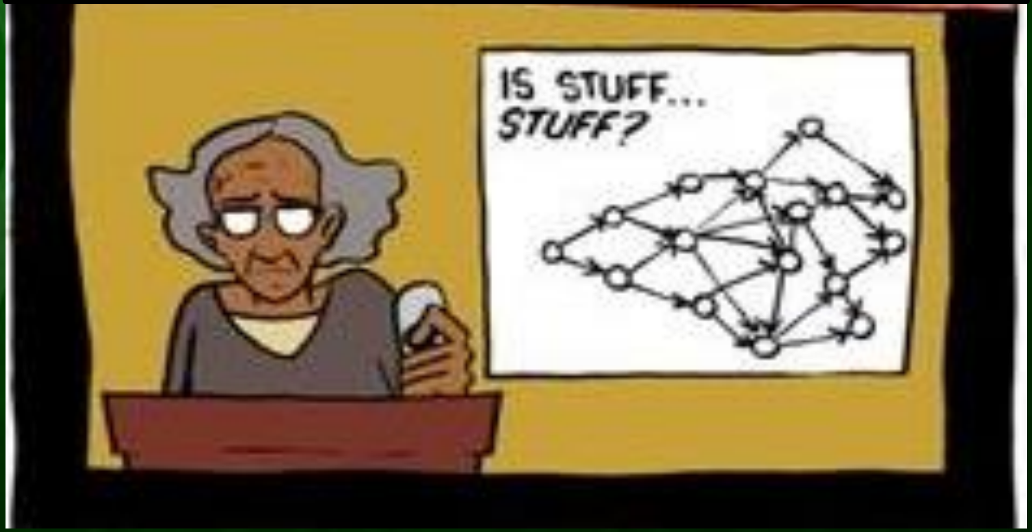


Next Test Method: Eye Diagrams

- **Eye Diagram FOM includes: the eye amplitude, jitter, and all characteristics that differentiate 0 and 1s**
  - For example TIAs, CDRs

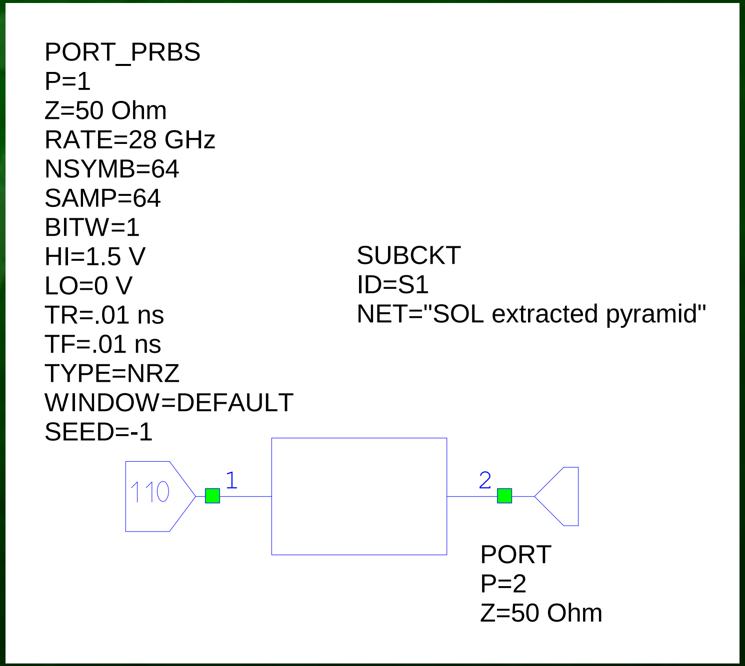


Digital Engineer



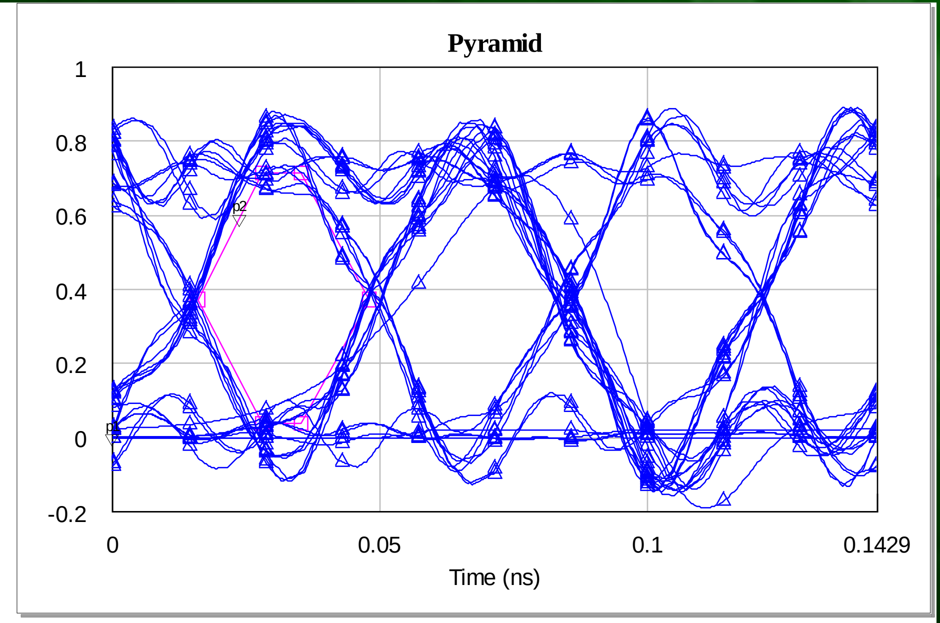
Eye Diagram Test

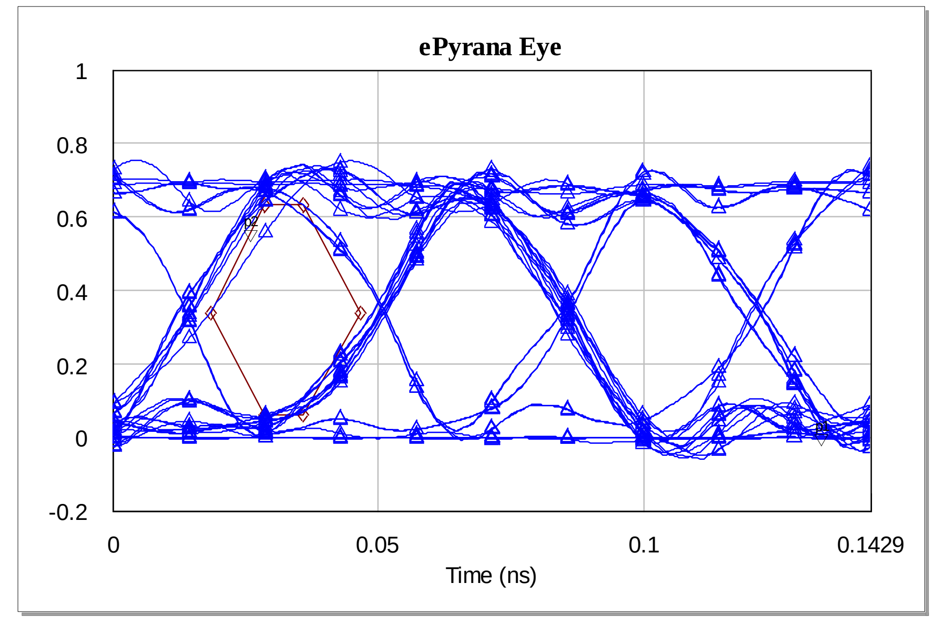
- A digital signal (pseudo-random bit stream) through the probe head S-parameters
- A representative signal with the following characteristics was generated:
  - Data Rate: 28 Gbps
  - Rise Time/Fall Time: 10 ps
  - V_high : 1.5 V
  - V_low: 0.0 V



Eye Diagram Comparison

- **The Eyes are different, with the biggest difference being the eye in ePyrana being smaller than that in Pyramid**
  - A reduction in eye size of about 14% with ePyrana compared to Pyramid
  - Pyrana was also simulated, with a 40% reduction in the eye



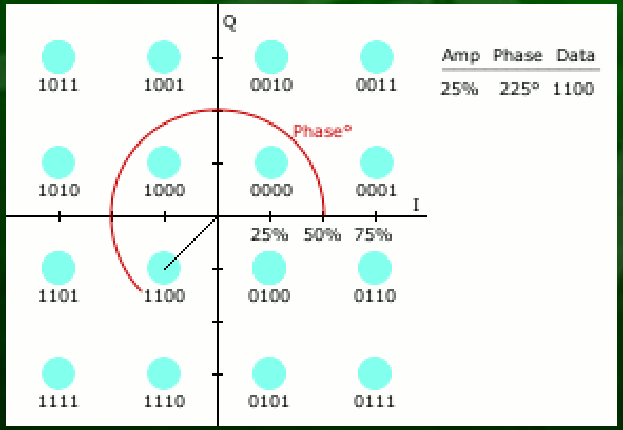


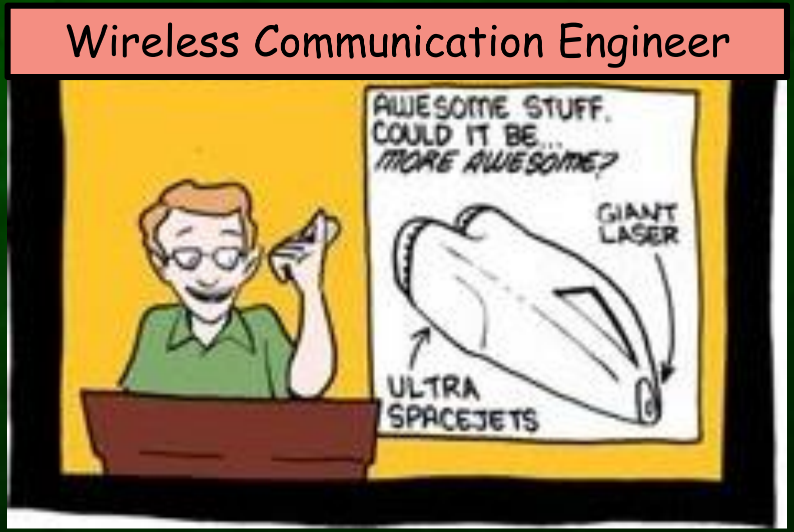
Eye Diagram FOM

- **Pyramid maintains the best amplitude because of its lowest loss**
- **ePyrana will generally be good enough, with only a 14% reduction**
- **Pyrana has the largest reduction in the eye, with about 40% smaller eye**

Next Test Method: Modulated Signals

- **Modulated Signal FOM: EVM**
  - 5G will primarily use QAM type of signal modulation and you need to be able to recover the bits
    - The more symbol definitions (like QAM126 vs QAM256), the more bits that can be encoded in each symbol, but the required accuracy of the measurement goes up, which is quantified as Error Vector Magnitude (EVM)

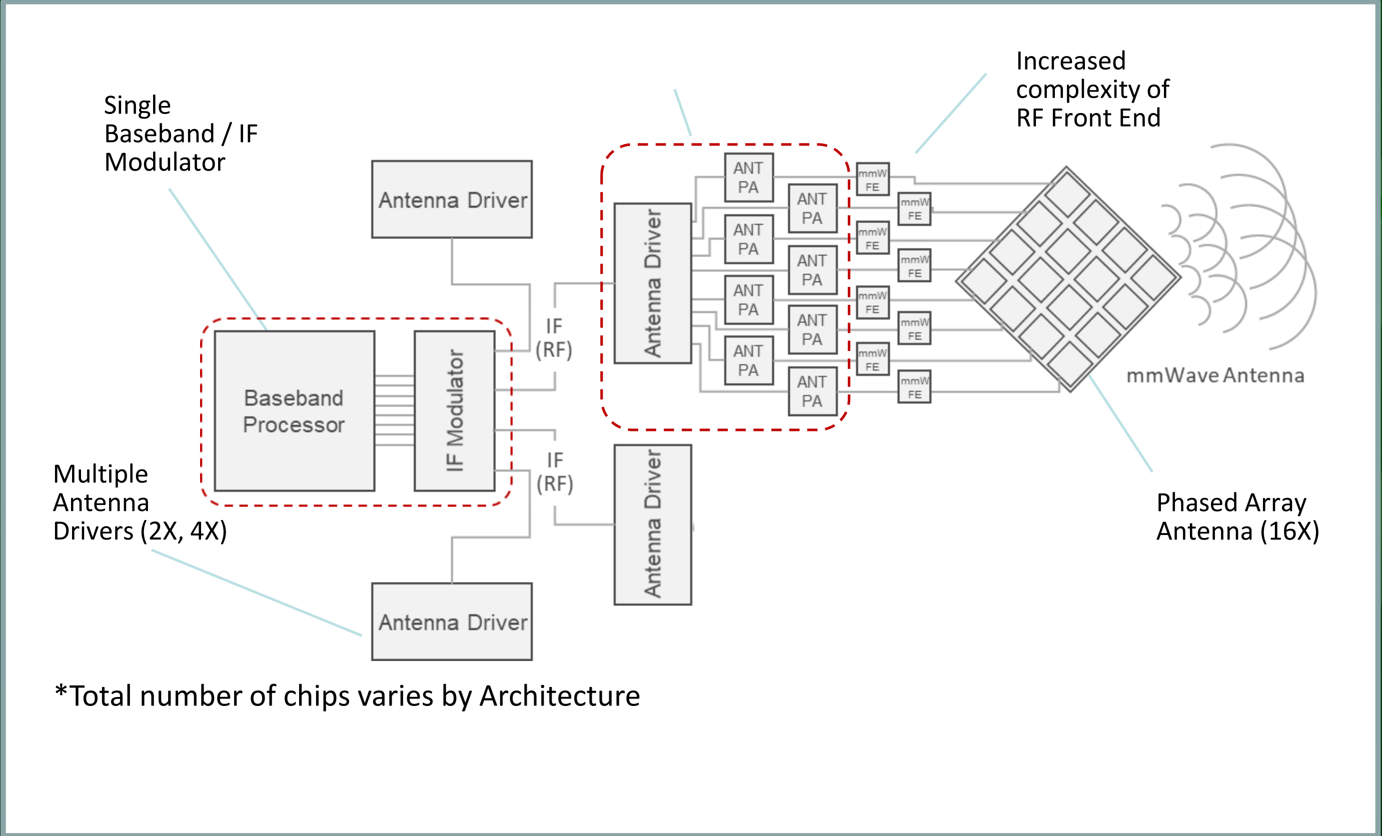




Source for Table: https://literature.cdn.keysight.com/litweb/pdf/5992-2997EN.pdf?id=2979328

What is EVM?

- **EVM is a measure of the how the signal is distorted from the proper magnitude-phase location on the constellation diagram**



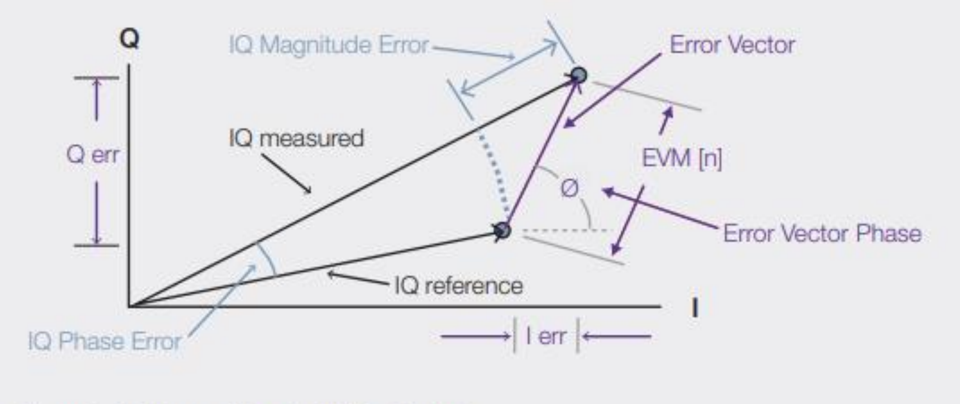


Figure 1. Understanding the EVM calculation

What is the required EVM for 5G?

- **The governing body for the requirements in 5G (3GPP) has released direction on what the EVM requirements look like**
  - This is the EVM for the total system, where the higher bit-encoding requires lower EVM

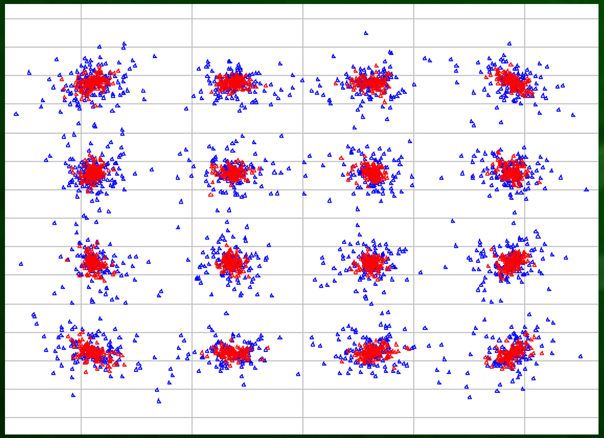
Table 3. 3GPP TS 38.101-1 EVM requirements for different 5G modulation schemes

Modulation scheme for PDSCH	Required EVM
QPSK	17.5 %
16QAM	12.5 %
64QAM	8 %
256QAM	3.5 %

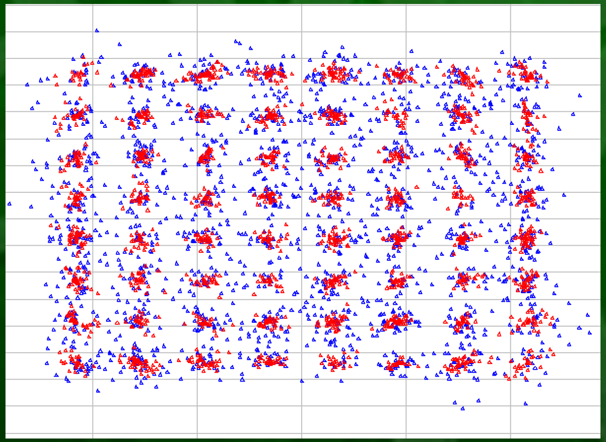
5G NR Radio Specification for the System; Rev. 15

EVM FOM

- We then looked at what is the EVM for the FFI's three RF probe card technologies



16-QAM



64-QAM

	Pyramid	Pyrana	ePryana	3GPP
16-QAM	3.1	8.7	4	12.5%
64-QAM	2.7	7.7	3.5	8%
256-QAM	2.56	7.2	3.3	3.5%

EVM % of the three different probe heads vs QAM

Red Pyramid and Blue is Pyrana

Summary

- **We have discussed:**
  - A new probe head FOM for L_r
  - What are the appropriate FOM for the different types of tests to evaluate the capability of probe cards for:
    - S-parameters
    - Eye Diagrams
    - Constellation diagrams

Questions