SWTEST ASIA

Overcoming Challenges for 5G Production Tests

FormFactor™

Choon Beng Sia Ph.D.

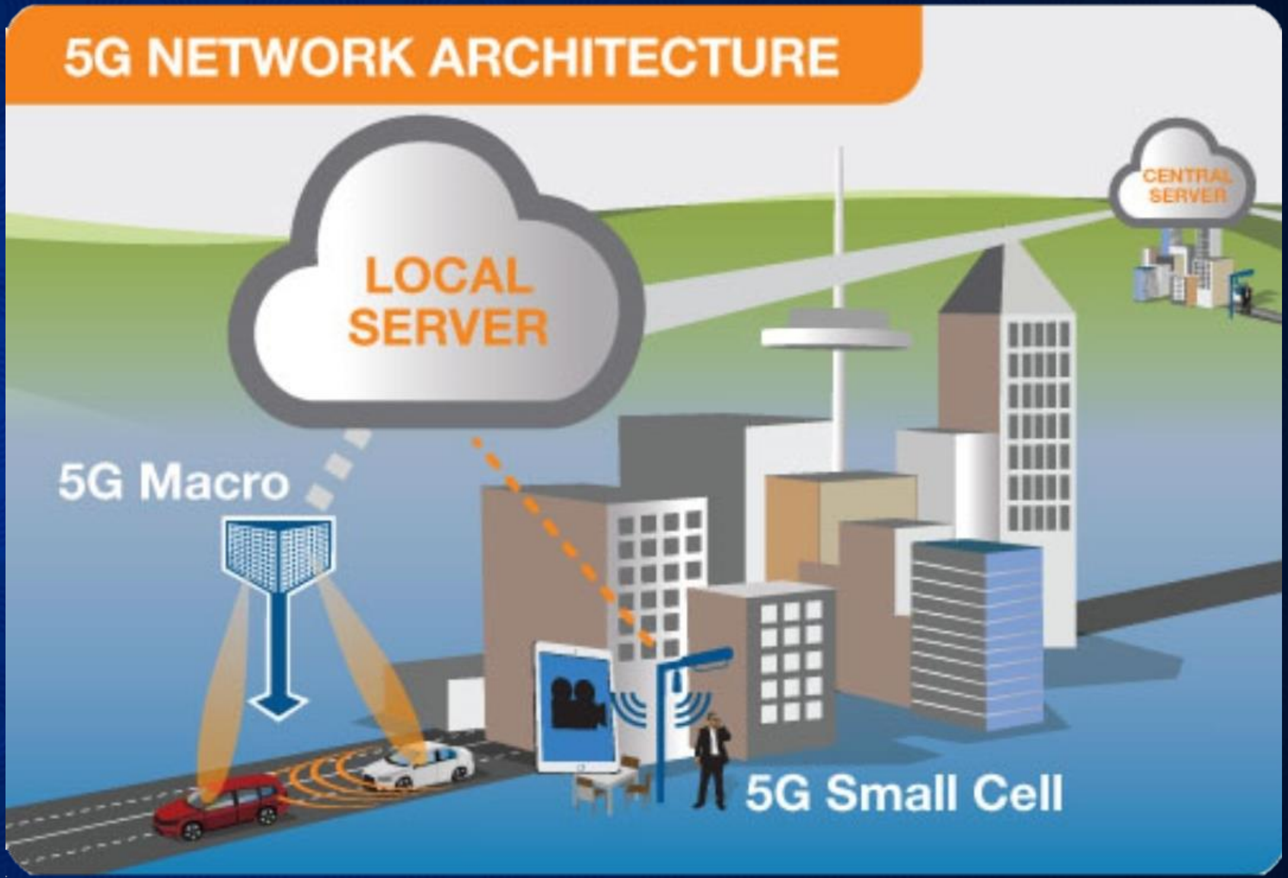
Taiwan, October 18-19, 2018

Overview

- **What is 5G?**
- **Economic Impacts of 5G**
- **Key Challenges for 5G Production Tests**
  - Handling Large Number of RF Test Channels
  - Ensuring Excellent Signal Integrity
- **Possible Solutions**
  - In-membrane Antenna OTA Tests
  - Dedicated Calibration Substrate & Power Calibration
- **Summary**
- **Acknowledgements**

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

5G Use Cases

- **Enhanced Mobile Broadband**
  - Enterprise/Team Collaborations, AR/VR, Enhanced Wireless Broadband, Education, Mobile Computing, Enhanced Digital Signage.
- **Massive Internet of Things (MIoT)**
  - Smart Cities, Energy/Utility Monitoring, Asset Tracking, Smart Agriculture, Physical Infrastructure, Smart Homes, Remote Monitoring, Beacons & Connected Shoppers.

- **Mission Critical Services (Low Latency Requirement)**
  - Autonomous Vehicles, Remote Patient monitoring/TeleHealth, Industrial Automation, Smart Grid, Drones.
    - 4G - braking command makes a car at 100kmph to stop after 1.4m.
    - 5G - Same car stops within 2.8cm due to ultra low latency.

Source: The 5G Economy: How 5G Technology will contribute to the Global Economy, Jan 2017 for Qualcomm
https://www.independent.ie/business/technology/news/the-need-for-speed-is-ireland-ready-for-5g-the-next-big-thing-in-cellular-technology-36629260.html

Economic Impacts of 5G (USA)

- **5G → 3 million jobs, US$275B investments, US$500B economic growth**
- **Smart Cities**
  - US$160B in savings - ↓ Energy Use & ↓ Congestion.
  - Eg. Sensors monitor Health & Safety of critical infrastructure - Buildings, Roads & Bridges.
- **Transportation**
  - Self-driving cars ↓ 90% emissions, ↓ 40% Travel Time & Save 22,000 lives annually.
  - 5G will save US$450B annually in transportation costs.
- **Healthcare**
  - Remote Patient Monitoring & Surgery through connected healthcare devices
  - US$305B in Healthcare Cost-savings Annually.
- **Energy**
  - 5G allow Energy Grid to be more Accurately Monitored, Improving Management, Reducing Costs, adding US$1.8 trillion in revenue to the U.S. economy.

Source: https://www.ctia.org/the-wireless-industry/the-race-to-5g, Accenture

Economic Impacts of 5G (World)

Global 5G value chain output and employment in 2035

	Gross output	Employment
China	$984B	9.5M
United States	$719B	3.4M
Japan	$492B	2.1M
Germany	$202B	1.2M
South Korea	$120B	963K
France	$85B	396K
United Kingdom	$76B	605K
Rest of the world	$800B	3.6M

Global total, 2035

Gross output	$3.5T
Employment	22M

Notes: K = thousand, M = million, B = billion, T = trillion
Source: IHS

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5G will enable $12 trillion of global economic activity in 2035
2016 US$ billions

Industry	Enhanced Mobile Broadband	Massive Internet of Things	Mission Critical Services	5G-enabled output (2016$, M)	Percent of industry output
Ag., forestry & fishing				$510	6.4%
Arts & entertainment				65	3.5%
Construction				742	4.7%
Education				277	3.5%
Financial & insurance				676	4.6%
Health & social work				119	2.3%
Hospitality				562	4.8%
Info. & communications				1,421	11.5%
Manufacturing				3,364	4.2%
Mining & quarrying				249	4.1%
Professional services				623	3.7%
Public service				1,066	6.5%
Real estate activities				400	2.4%
Transport. & storage				659	5.6%
Utilities				273	4.5%
Wholesale & retail				1,295	3.4%
All industry sectors	$4,400	$3,600	$4,300	$12,300	Average: 4.6%

No impact — High impact

Source: IHS

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- By 2035, Value Chain US$3.5T, 20M Jobs
- CEO Qualcomm, "5G Impact similar to Introduction of Electricity or Automobile"

Source: Prepared by IHS, The 5G Economy: How 5G Technology will contribute to the Global Economy, Jan 2017 for Qualcomm Inc.

Global Race to 5G

- **5G Readiness Index**
  - Spectrum Availability
  - Infrastructure Planning
- **CTIA, consortium representing U.S. Wireless Communications Industry**
  - 250 companies

Ranking based on 5G Readiness Index

Source: Analysys Mason Report April 2018 @ https://www.ctia.org/the-wireless-industry/the-race-to-5g

Global Race to 5G

	sub-6GHz						mmWave		
Spectrum	0.6GHz	2.5GHz	3.4 – 3.7GHz			4.4 – 4.9GHz	28GHz		39GHz
GEOGRAPHY									
CARRIERS	T-Mobile	Sprint	Orange Vodafone	China Mobile	NTT DoCoMo SK KT	NTT DoCoMo SoftBank	Verizon AT&T T-Mobile	NTT DoCoMo SoftBank SK | KT	Verizon AT&T T-Mobile
COMMERCIAL SERVICES	2019	Late '19	TBD	2020	2020	Mid-2020	2H18	2020+	2H18

- 2020 appears to be commercialization target for 5G
- Focus on Sub-6GHz, Expect Challenges in mmW Tests

Source:- Keysight World 5G Presentation, Shanghai June 2018

5G Field Trials


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Technology

5G Is Making Its Global Debut at Olympics, and It's Wicked Fast

By Sam Kim and Sohee Kim
13 February 2018 5:00 AM +08 *Updated on 13 February 2018 1:13 PM +08*

- Among the first to experience it will be Korea's wild boars
- 5G technology isn't scheduled to roll out globally till 2020

How to Fend Off Wild Boars With Wicked-Fast 5G Wireless
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Russia will stream the World Cup in VR with 5G

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WRITTEN BY
Bobby Hellard

NEWS

Russia is the latest country to use a sporting event to test 5G

When Morocco takes on Iran at the Russian World Cup on 15 June, supporters will be able to watch the game in VR over a 5G real-time stream.

- **Intel & NTT Docomo 5G Trial at Japan 2020 Summer Olympics:**
  - 8k 360 degree video streams
  - 5, 24-28, 37-40, 64-71 GHz Proposed


Intel makes huge 5G promises for the 2020 Olympics

The Tokyo games will be awash in 5G.

Devindra Hardawar, @devindra
02.25.18 in Internet
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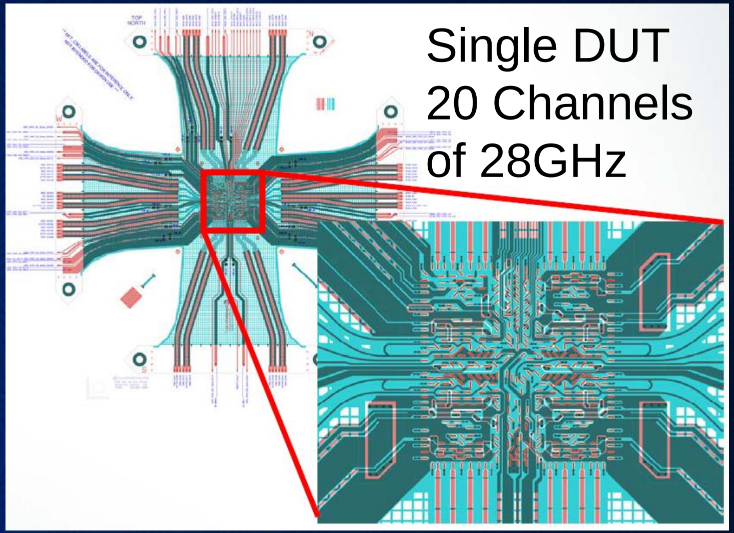
Requirements for 5G Production Tests

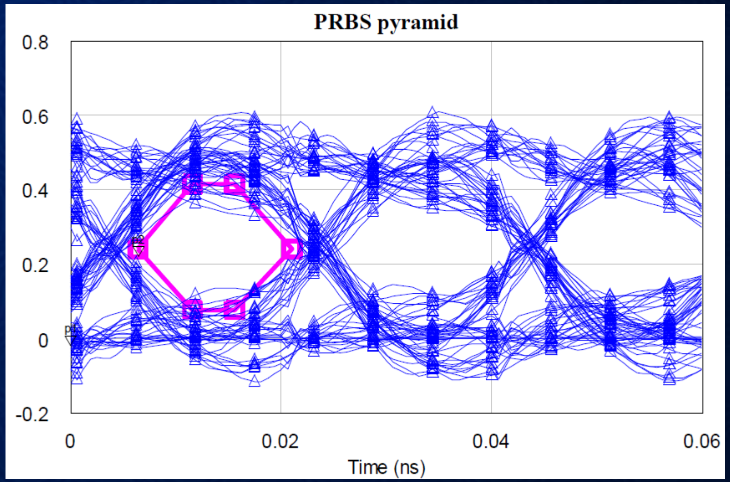
- **New Test Equipment Needed**
  - Higher Test Frequencies (> than most ATE testers can handle)
  - Very Large Number of Channels
- **Short Time of Test with High Throughput**
  - Parallel test (multi-site)
- **High Accuracy is needed to Validate Performance**
  - Good Signal Integrity at high RF frequency
  - Prevent packaging bad devices due to yield

Key Challenges in 5G Production Tests

1. **Handling Very Large Number of RF Test Channels**
   - Parallel Tests require even larger no. of Channels in RF Tester = $$$$
   - Challenges in Routing RF Channels in Parallel Test setup (X8 DUT, >160 Channels, >25GHz)

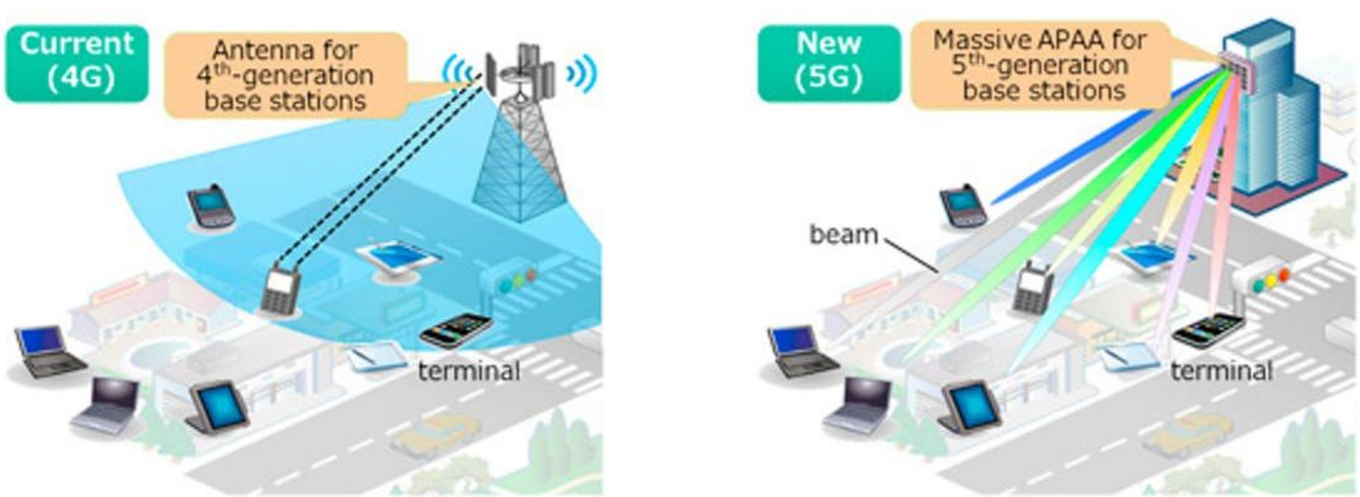


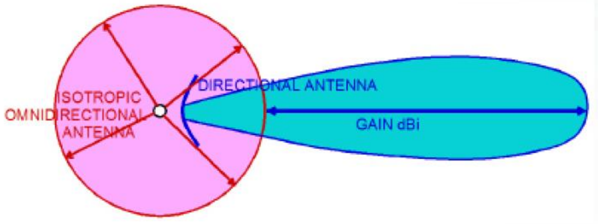
2. **Ensuring Excellent Signal Integrity**
   - Post-Calibration Verifications & Use of Dedicated Calibration Standards Substrates.
   - Maintaining Calibrated State for as long as possible (esp. with Frequency Extenders).
     - Throughput impact if frequent recal. needed.



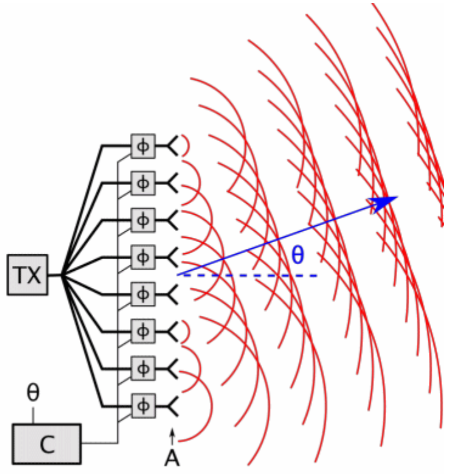
1. Handling Very Large Number of RF Test Channels

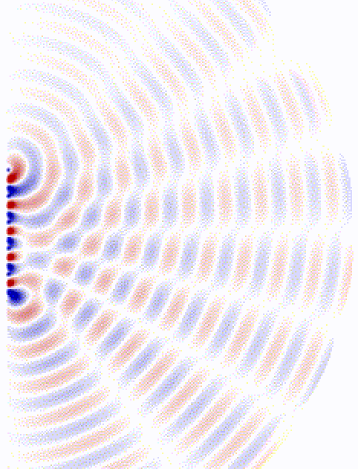
- **5G is using higher freq.**
- **Larger Attenuation at Higher Frequencies.**
  - Omnidirectional Antenna cannot support
- **Directional Antenna needed**
  - Active Phased Arrays & Beamforming
  - Up to 64 lines at 70 GHz in a single device
- **Massive MIMO with Active Phased Array Antennas for 5G.**





Omnidirectional vs Directional Antenna

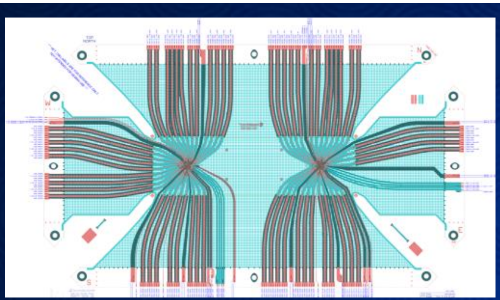
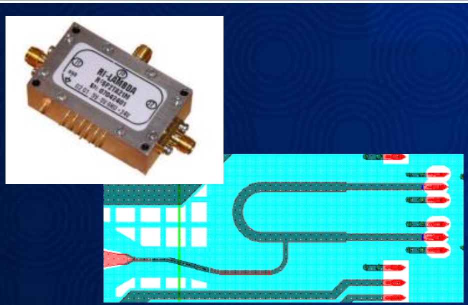
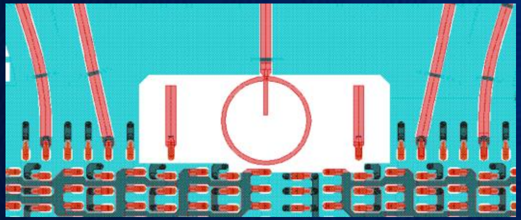




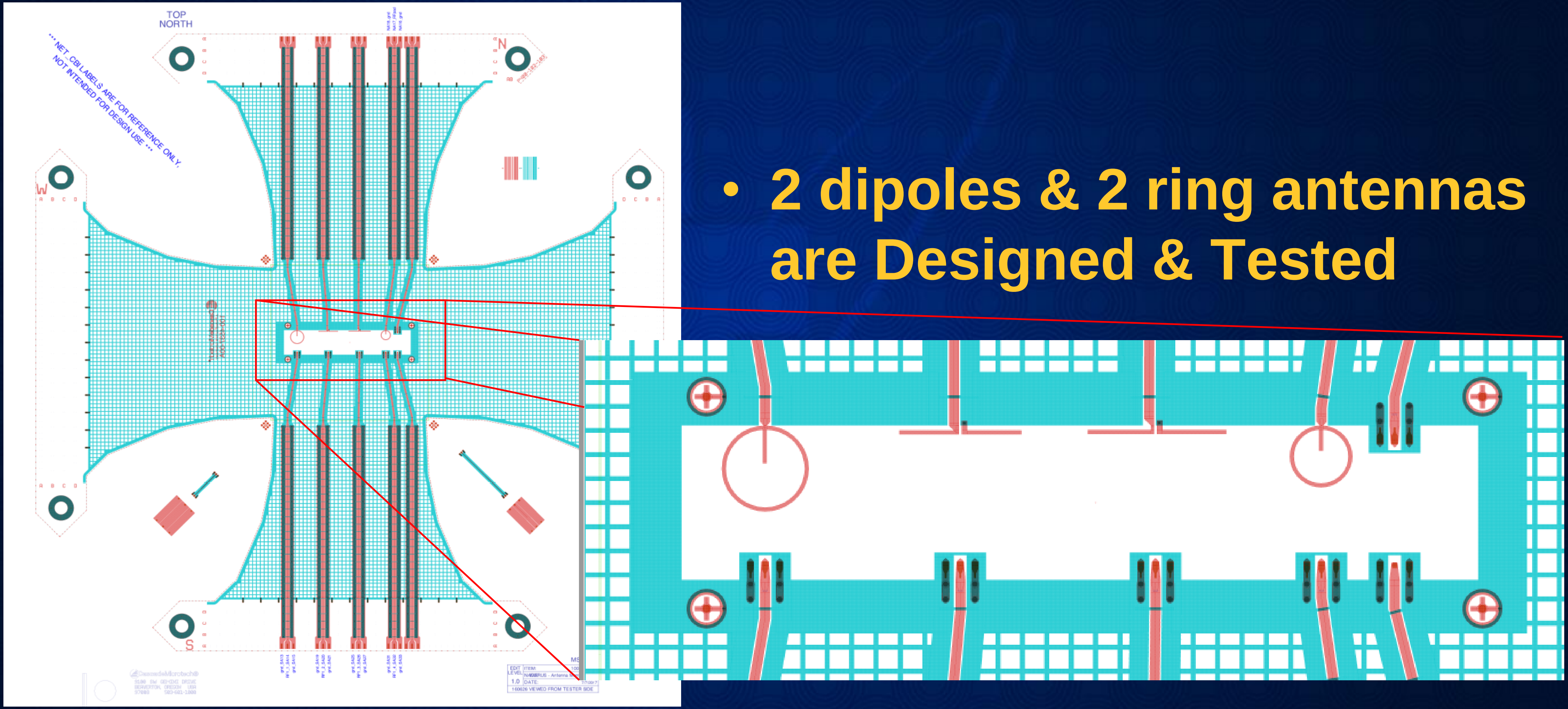
15 Antennas, ¼λ apart
Phase swept -120° to 120°

https://en.wikipedia.org/wiki/Phased_array
https://www.mitsubishielectric.com/en/about/rd/research/highlights/communications/5g.html

1. Handling Very Large Number of RF Test Channels

Test Method	Advantages	Disadvantages
Full Channel 	• Full RF Coverage • Fast	• Expensive Tester • Routing/Space Transformation Difficulties
Balun, Switches, Combiners 	• Established Methods	• Discrete Components – High Loss, Large & Bulky • On-ProbeCard – Narrowband & High Loss
Antenna Coupling 	• Reduce Channel Count (4:1 combining)	• > Loss than Conducted Tests • Space needed for Antenna

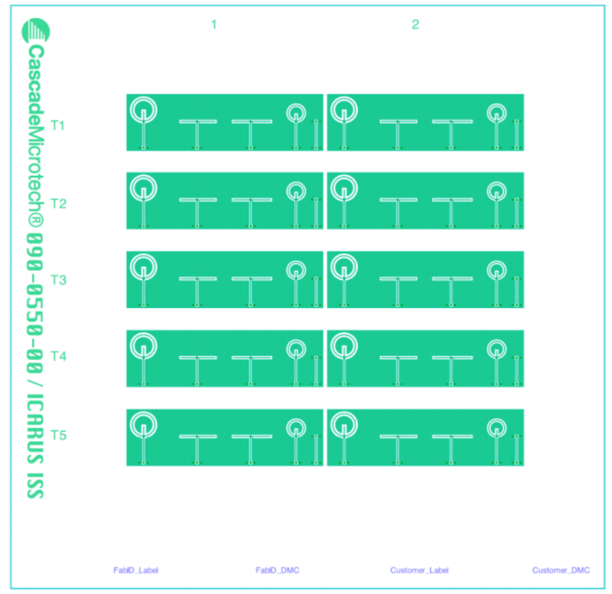
Membrane Probe Head & Antenna Test Structures

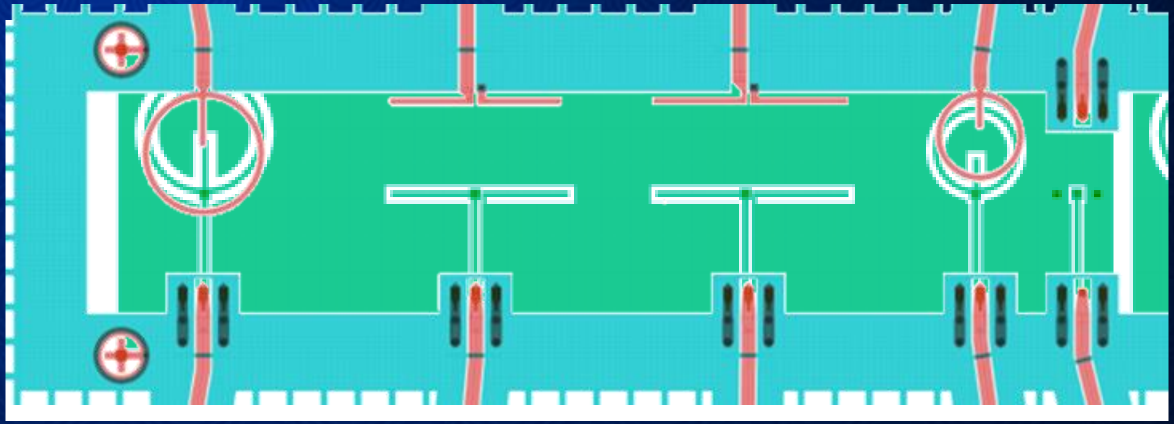


- **2 dipoles & 2 ring antennas are Designed & Tested**

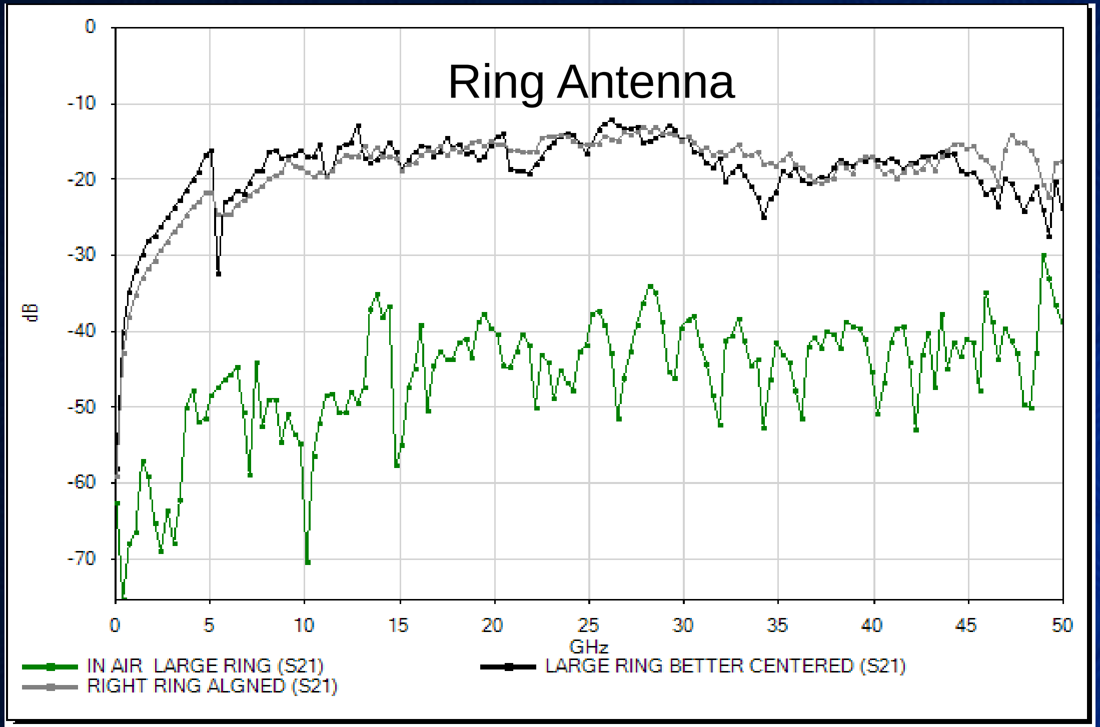
Ceramic Substrate for Reception Tests

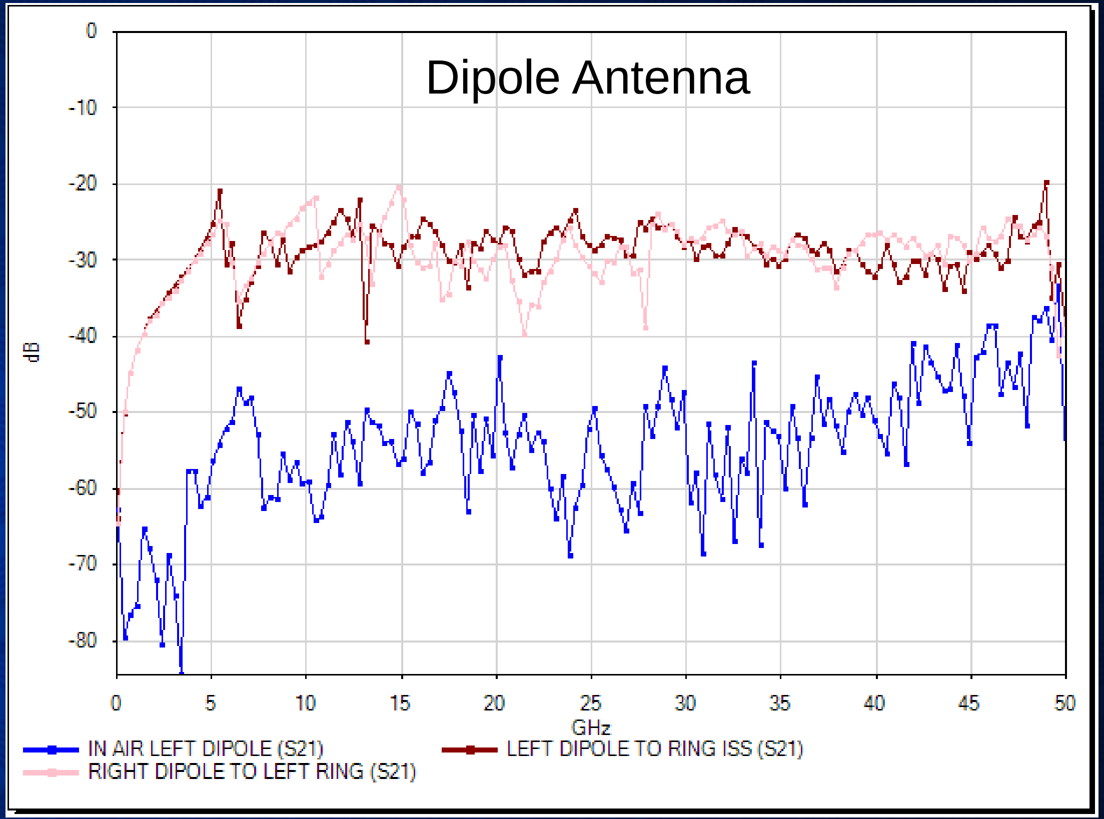
- A substrate was fabricated for reception of the signals.
- Signal goes back to the probe head (membrane) through GSG tips.





Insertion Loss for Ring & Dipole Antenna



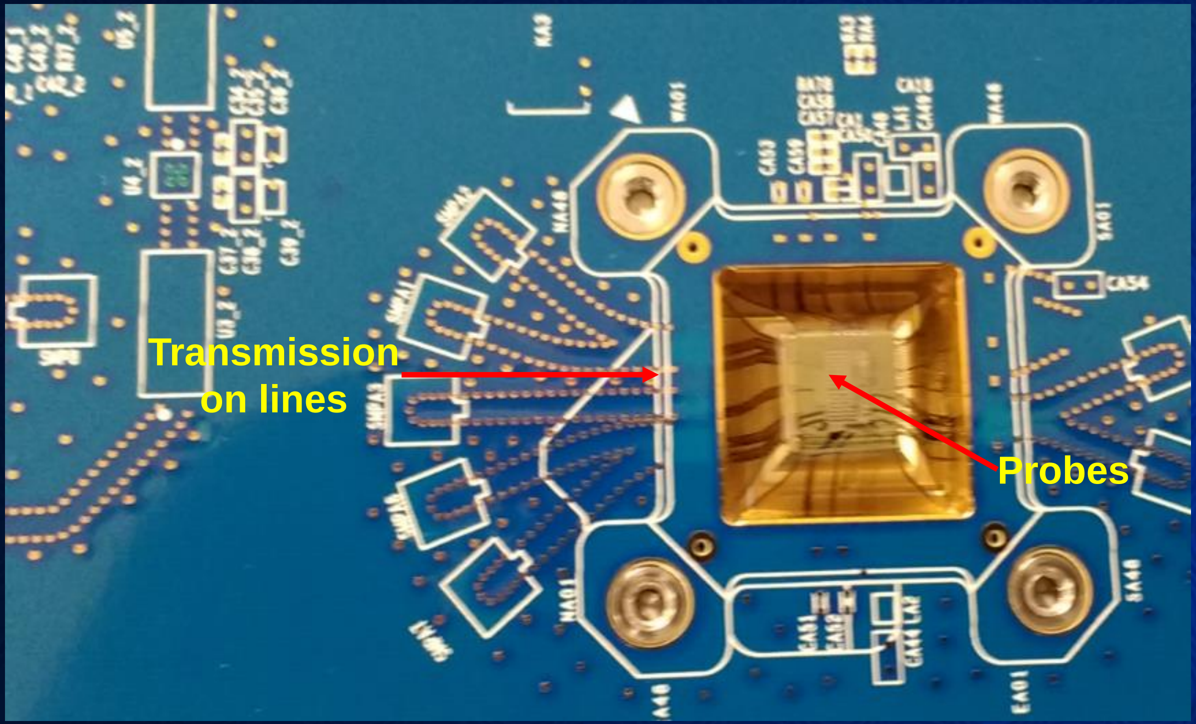


- Insertion Losses higher than noise by about 20dB.
- Wide bandwidth observed due to near field coupling (>100µm).
- Ring Antenna has better performance than Dipole Antenna.

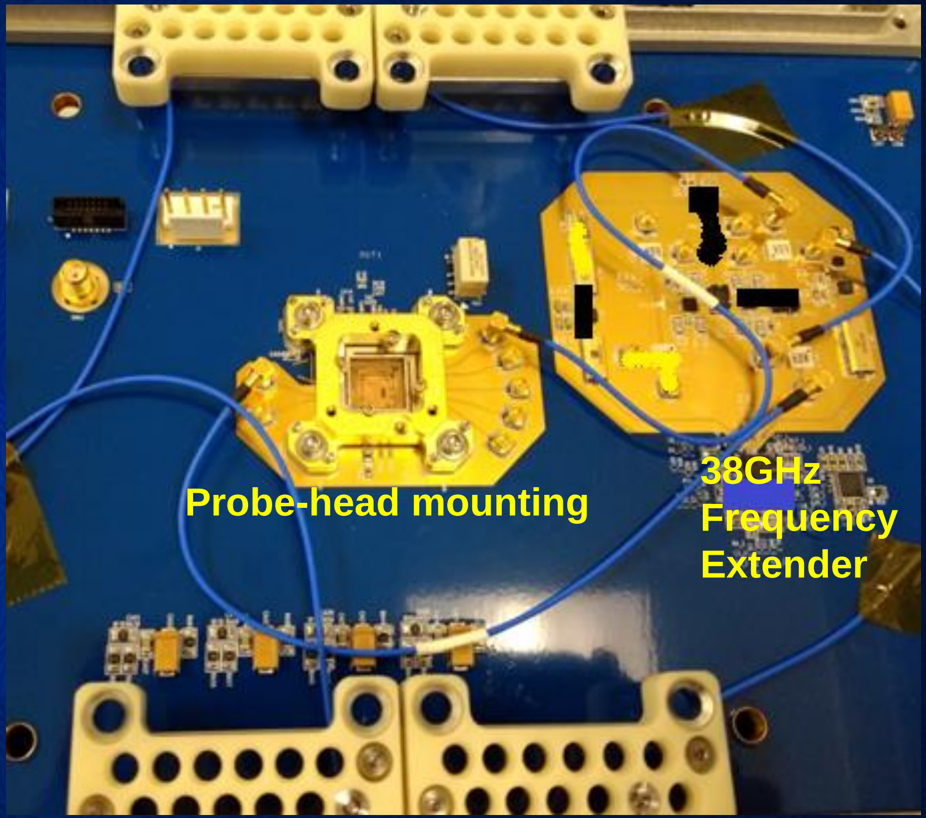
Intel’s ATE mmW Test Setup

- **Advantest 93000 PSRF ATE System**
  - generates 6 GHz for device testing
- **SIU PCB (Wafer Sort Interface Unit)**
  - mmW Frequency Extender developed using off-the-shelf components.
    - Up-converts RF Test Signal from the ATE → 38 GHz CW signal.
    - Down-converts 38 GHz RF signal from the DUT to a signal manageable within the measurement range of the ATE (< 6GHz)

Intel's ATE mmW Tests – Membrane Probe Head



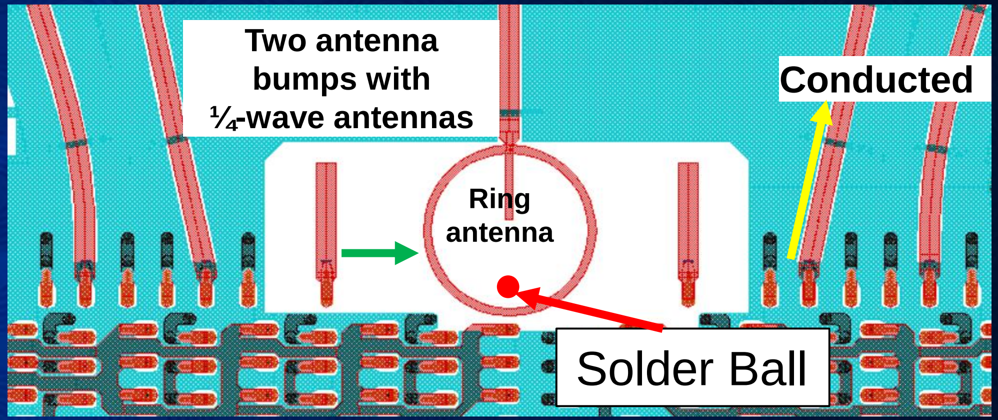
Wafer Side of Wafer Sort Interface Unit



ATE Side of Wafer Sort Interface Unit

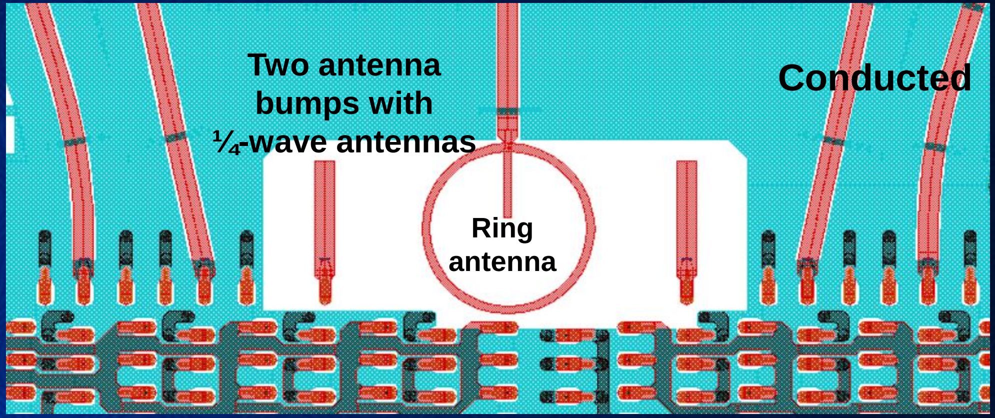
Intel's ATE mmW Test – Test Setup

- **Fully Conducted Test**
  - Electrical contact
- **¼ wave Antenna Transmitting to Ring Antenna**
  - ¼ wave makes contact with solder ball and then transmits to ring antenna
- **Solder Ball Transmit to Ring Antenna**



Intel's ATE mmW Test – Results

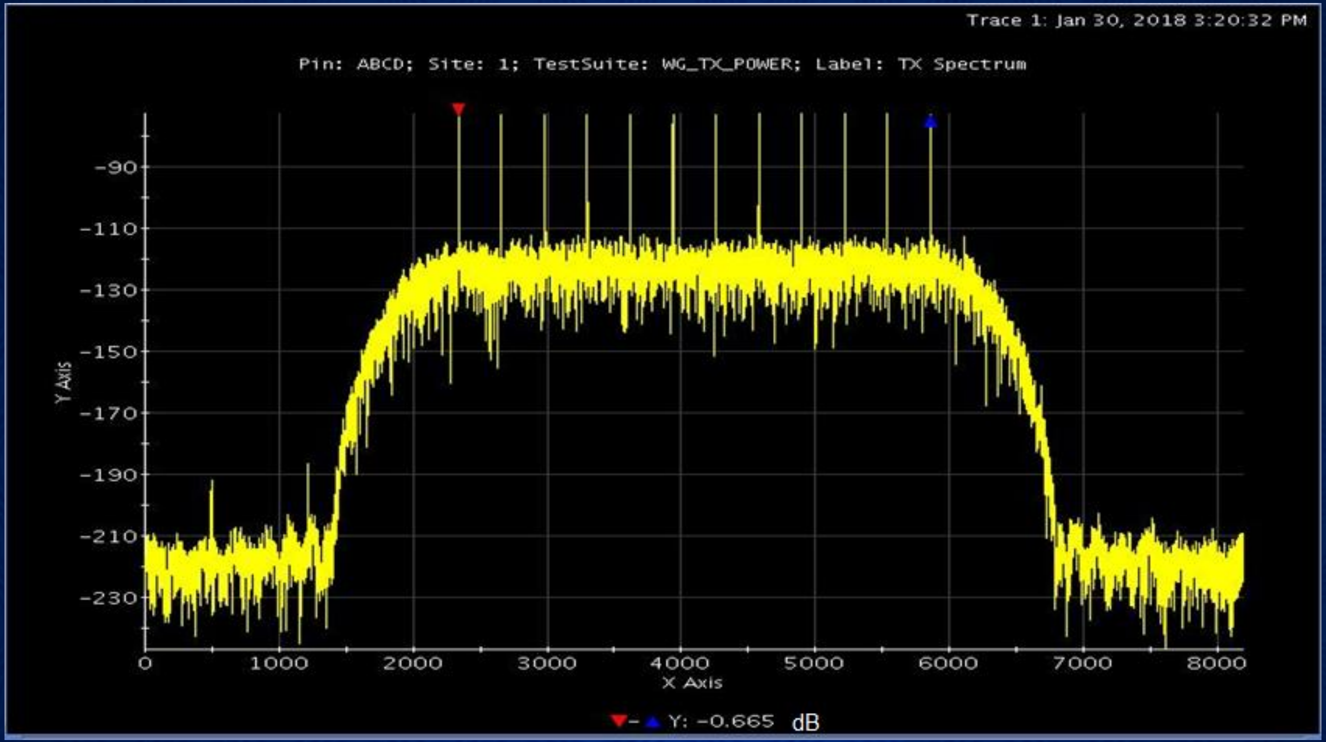
Probe touchdown	Transmit Power from Same DIE (dBm)		
	1/4λ to Ring Antenna	Ring Antenna only	Fully Conducted Path
1	-63.27	-86.67	-38.593
2	-63.169	-85.95	-38.594
3	-63.8	-86.68	-38.588
4	-63.825	-86.62	-38.589
5	-63.636	-85.63	-38.59
6	-63.687	-85.51	-38.597
7	-63.793	-86.62	-38.602
8	-64.043	-86.23	-38.61
9	-64.728	-85.14	-38.616
10	-64.673	-85.98	-38.615
11	-64.955	-86.69	-38.634
12	-64.866	-85.43	-38.649
13	-65.111	-85.95	-38.648
14	-65.785	-84.65	-38.698
15	-65.826	-84.25	-38.711
16	-65.854	-84.13	-38.757
17	-65.748	-84.32	-38.762
18	-65.831	-84.61	-38.766
19	-65.696	-84.21	-38.753
20	-65.692	-84.74	-38.778



mm Wave Probe Connection: 2 to 1 combining with ¼-wave antennas

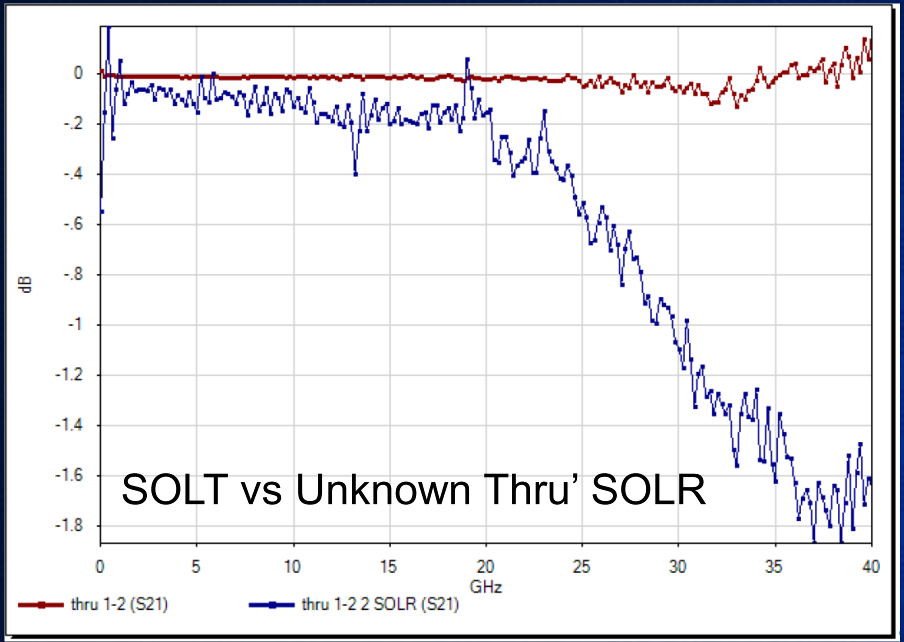
- **Very Repeatable Measurements at 38.56 GHz**

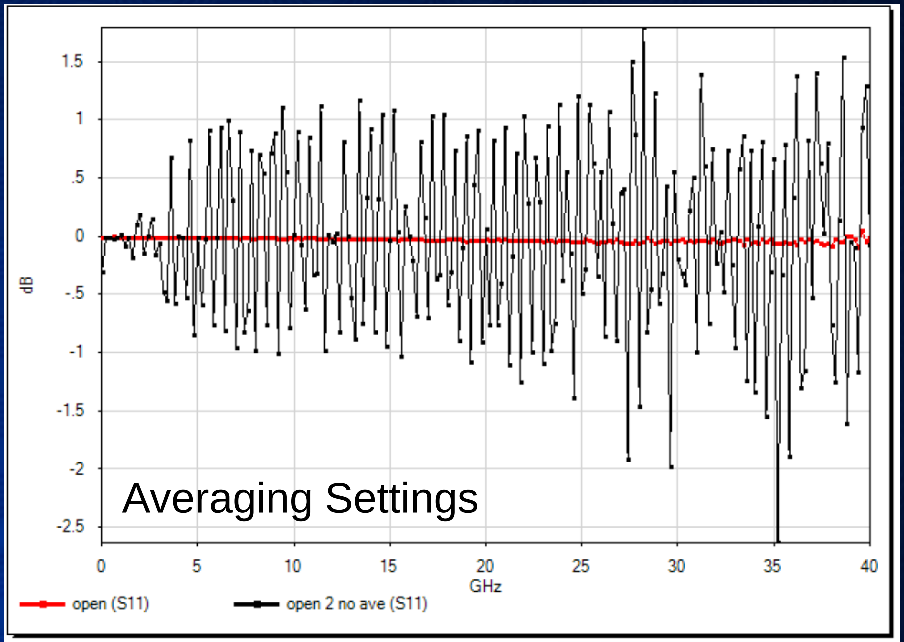
Intel's ATE mmW Test – Results



- **Spectrum measured with the ¼-antenna**
  - Multi-tone Spectra at 38 GHz using an IQ waveform (modulated signal)
- **In-membrane Antennas is feasible for 5G Production Tests.**

2. Ensuring Excellent Signal Integrity

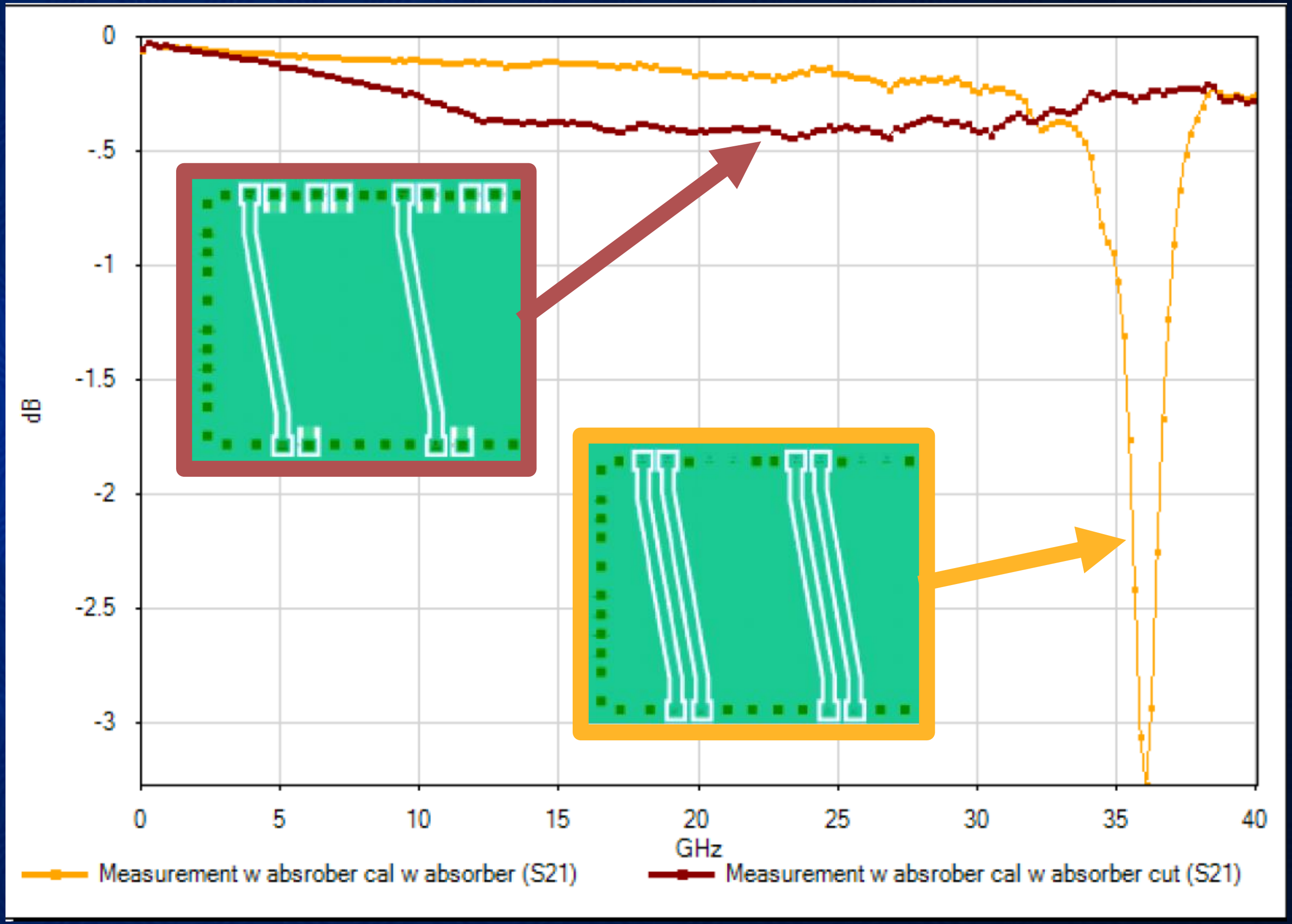




- **Post-Calibration Verification Checks are strongly recommended**
- **It is the only way to reveal Calibration Anomalies**
  - SOLT vs SOLR on thru', SOLT appears better
  - Open check with Gain (Optimize with IFBW settings)

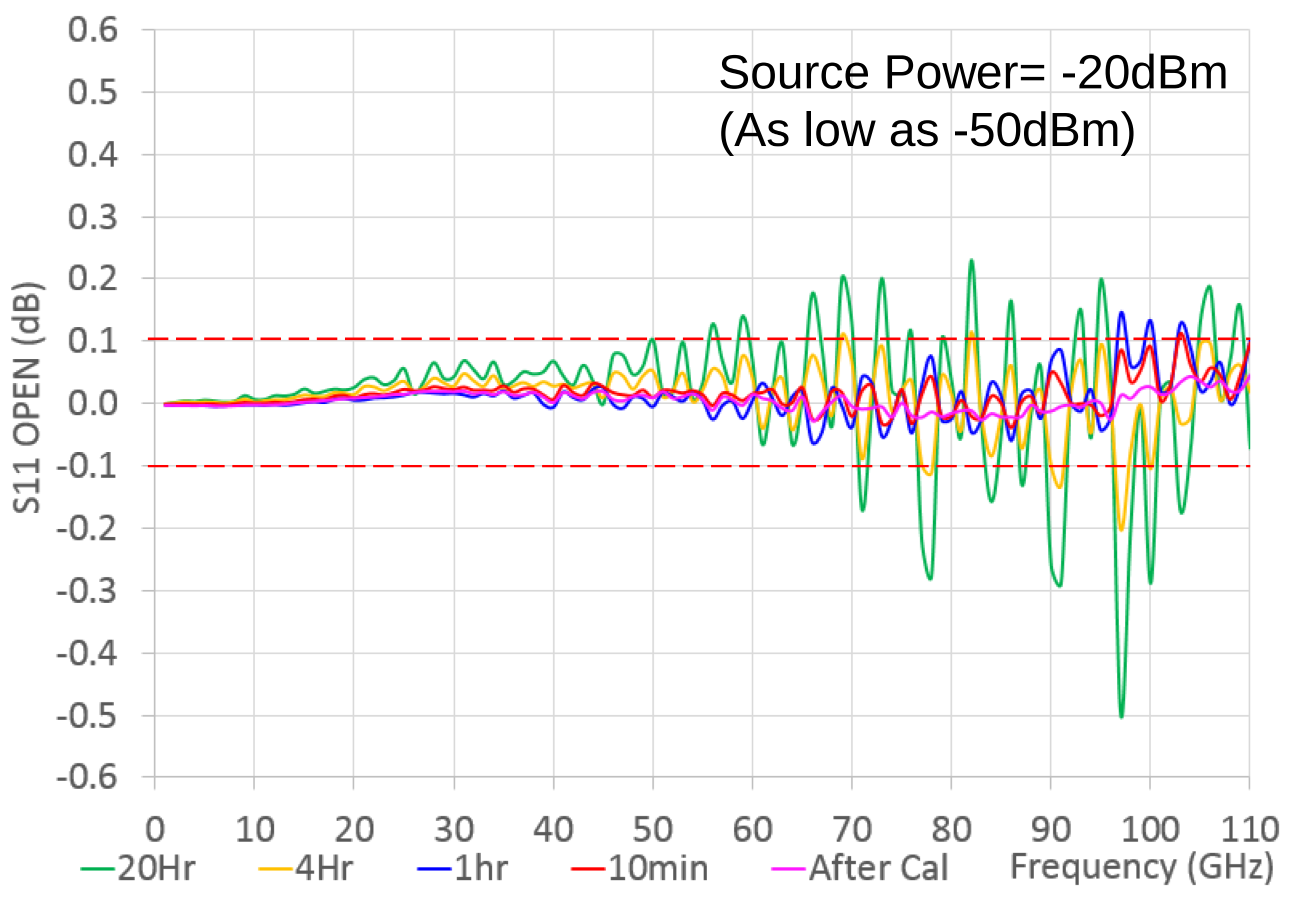
Dedicated Calibration Standards

- **Dedicated Calibration Substrates for 5G**
  - Higher Test Frequencies
- **Narrow Pitch GSSG Layout**
  - Results in 36 GHz resonance for Thru' standards.
  - Calibration fail at 36 GHz.
  - Adjacent thru' removed improves calibration performance.
- **Experience & Know-How are Critical.**



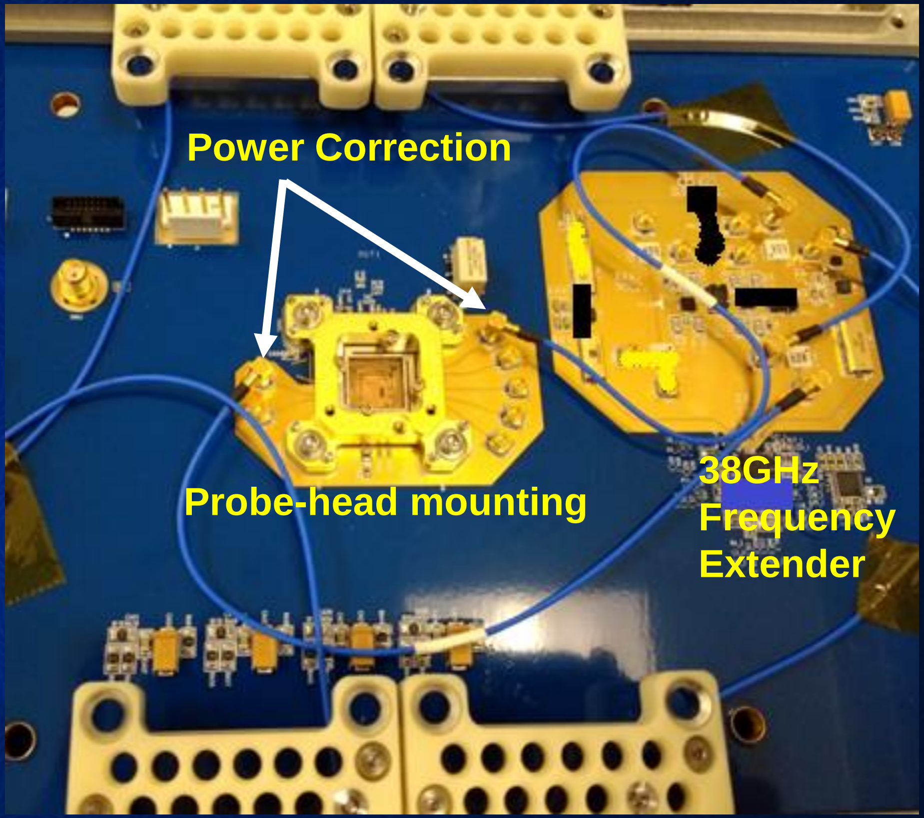
Post-Calibration System Stability

- **As Freq ↑, System Post-Calibration Stability↓.**
- **Worse off when Freq. Extenders are used.**
- **Eg (67-110 GHz Extender)**
  - Open is a Convenient Check.
  - Open After Cal. (< ±0.1 dB).
    - 110 GHz – 10 minutes
    - 90 GHz – 60 minutes
    - 70 GHz – 4 hours
  - Re-calibration is required & Throughput ↓.



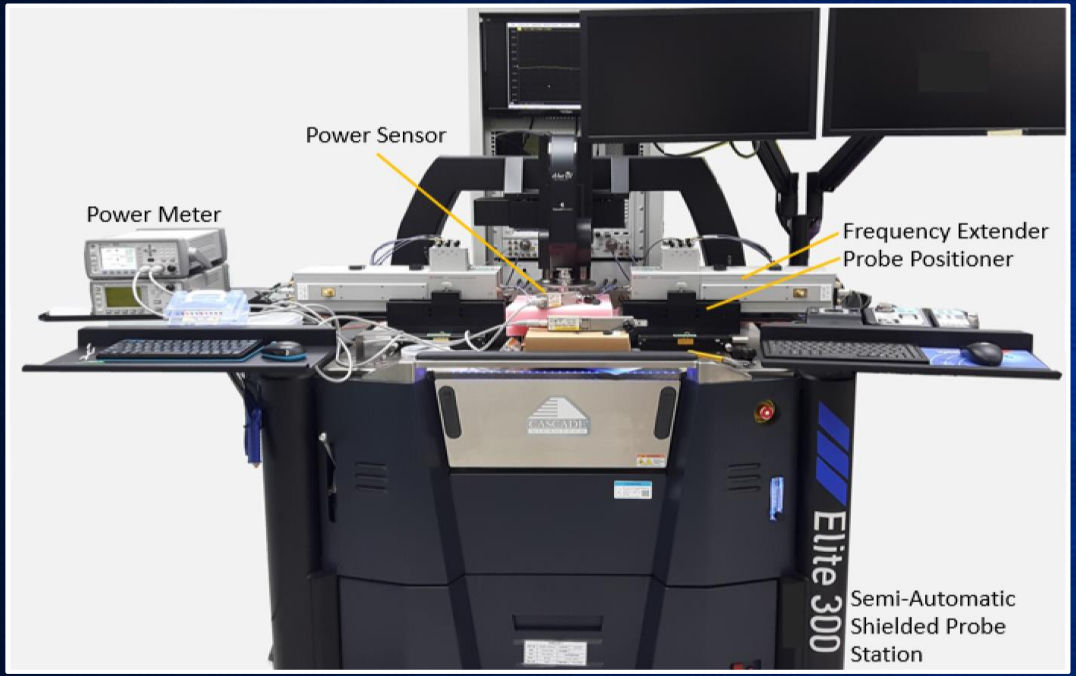
Power Calibration with Frequency Extenders

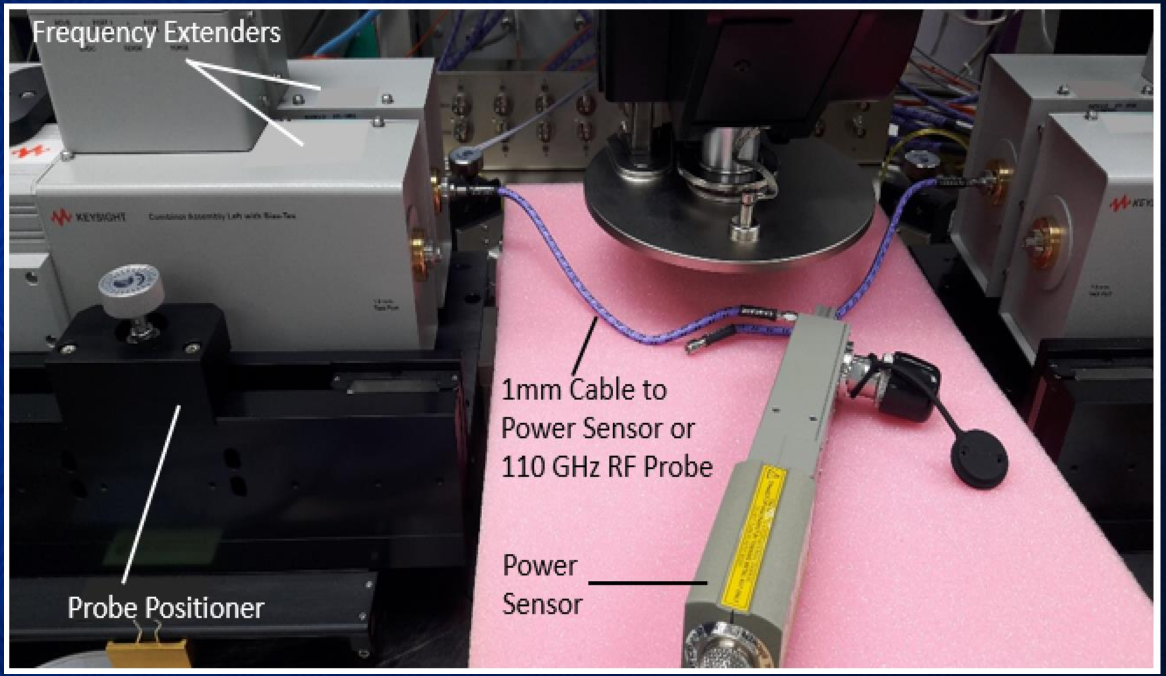
- **Power Cal. not perform on Intel Test Results but if ATE supports…**
- **Source Power Cal.**
  - Characterize Actual Source Power after Frequency Extenders with Power Meter.
  - Account for the Losses of Probecard.
  - Perform Source Power Correction from instrument to probe tips.
- **Receiver Power Cal.**
  - Put Probe Head on Thru' Standard.
  - Perform Receiver power Correction to Probe Tips.



ATE Side of Wafer Sort Interface Unit

Power Calibration with Frequency Extenders

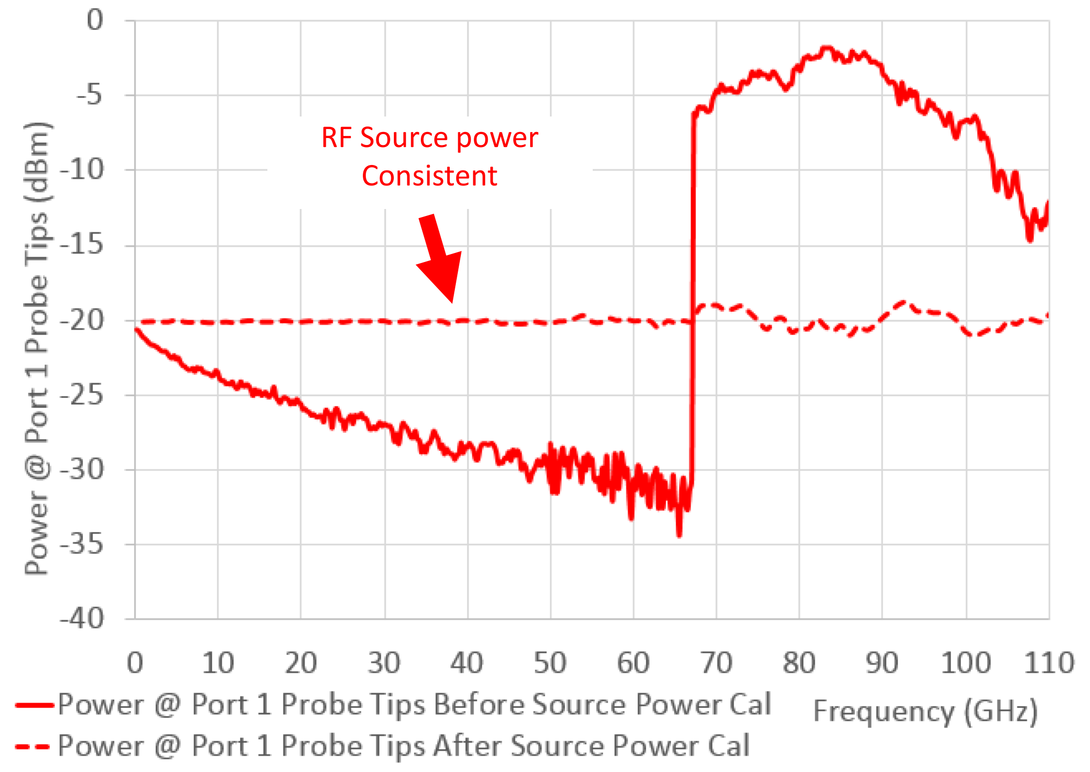




- **110 GHz Engineering Setup for 5G Device Characterization**

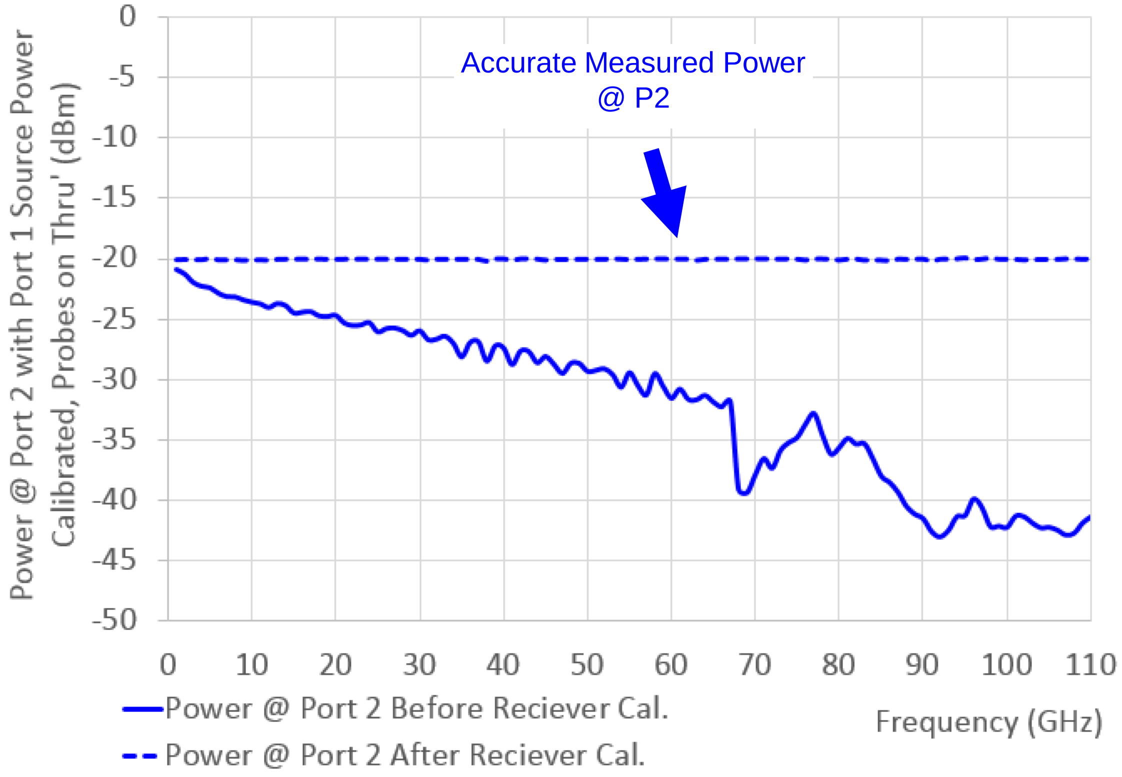
Power Calibration with Frequency Extenders

Source Power @ Tips



- Before Cal. – Loss↑ with freq. & freq. extender Influence power settings.
- After Cal. – Consistent Source Power.

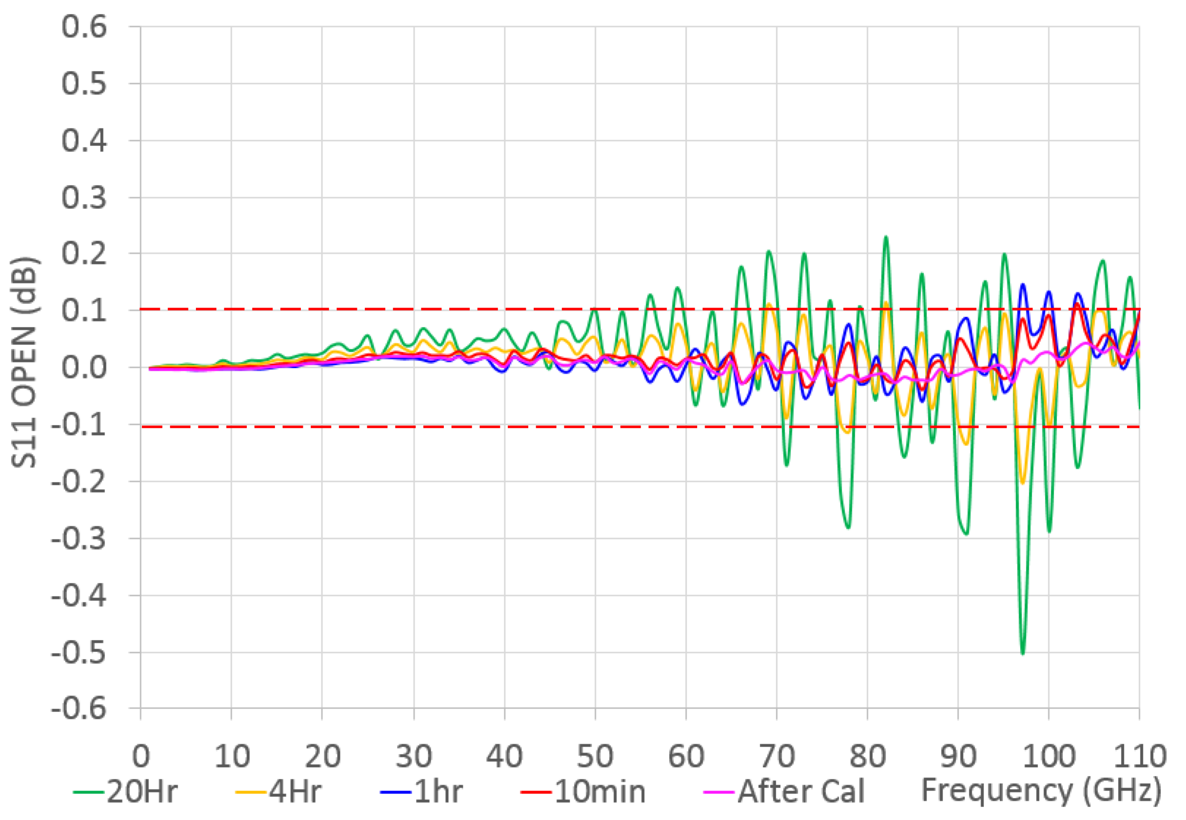
Measured Power @ P2 Receiver



- Before Cal. – Huge Losses at Receiver
- After Cal. – Consistent Power of -20 dBm regardless of freq.

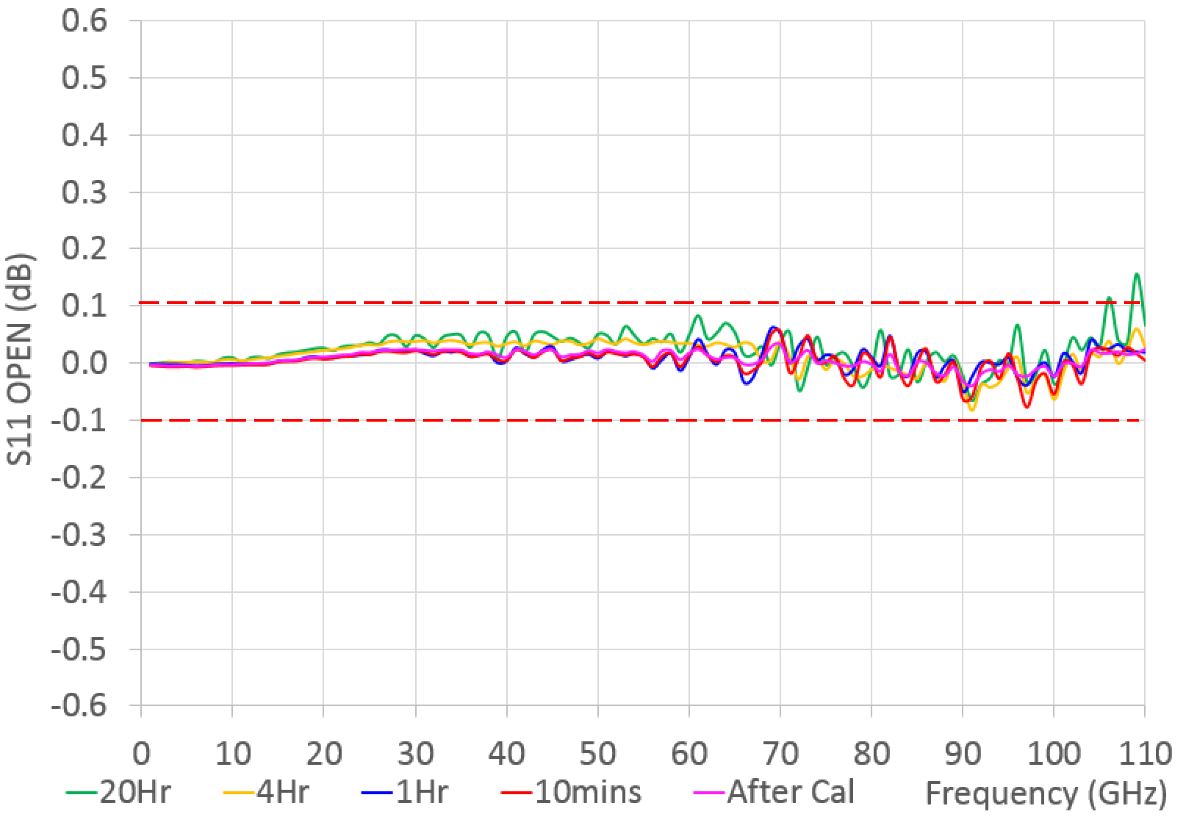
Improved Post-Calibration Stability

S-parameters Calibration



110 GHz – 10 minutes
90 GHz – 60 minutes
70 GHz – 4 hours

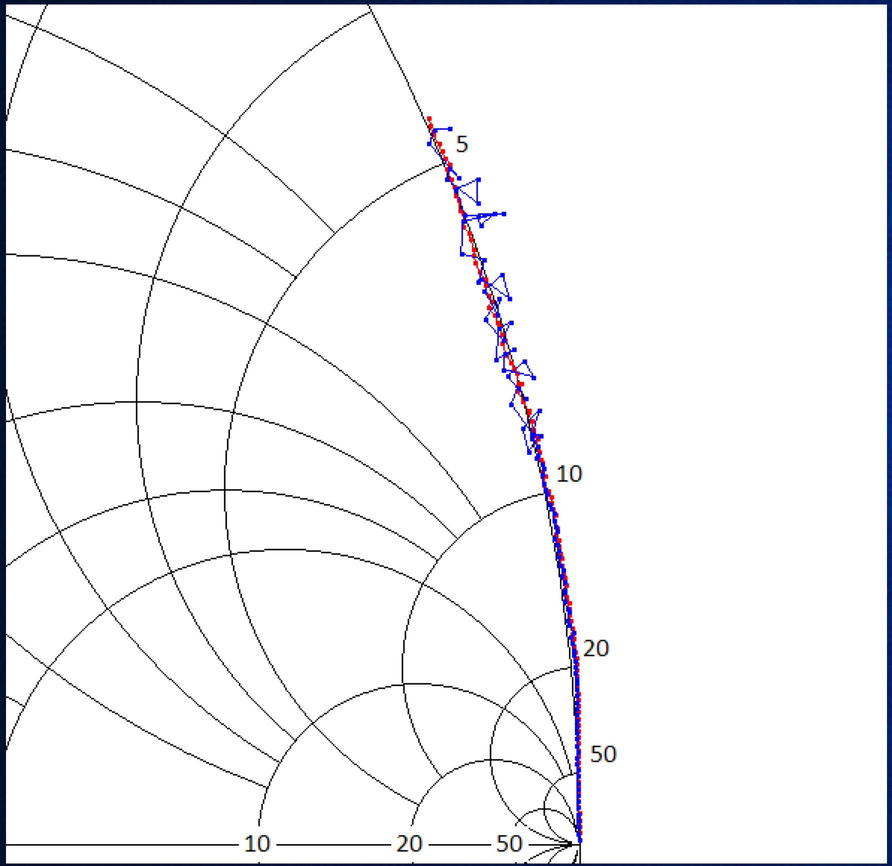
S-parameters+Power Calibration



110 GHz – >4 Hours
90 GHz – >20 Hours
70 GHz – >20 Hours

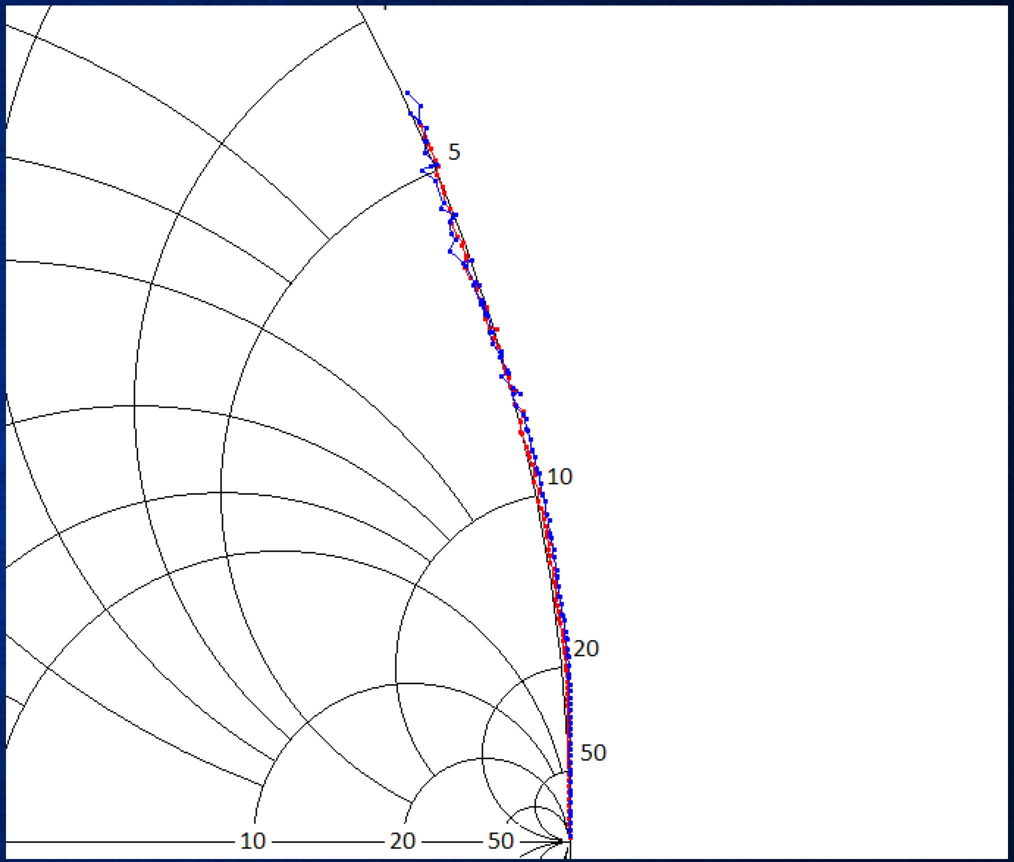
Improved Post-Calibration Stability

S-parameters Calibration



110 GHz Cal. Valid for only 10 mins

S-parameters+Power Calibration



110 GHz Cal. Valid for 4 hours

Summary

- **What is 5G and its Impacts.**
- **Identify 2 Key Challenges for 5G Wafer-Level Tests.**
  - Handling Large RF Channels ; Ensuring Excellent Signal Integrity
- **In-membrane Antennas is feasible for 5G Production Tests.**
  - Reduce RF channels without expensive tester upgrades
  - Good signal integrity that will support 5G production test
    - More designs are now being experimented at Intel
- **Excellent Signal Integrity is Critical for Accurate 5G Tests.**
  - Strongly Recommend Dedicated Calibration Substrates & Post-cal. Verifications.
  - Periodic System Stability Checks are Essential.
    - Power Calibration improves Stability Performance & Test Throughput.

Acknowledgements

- **Colleagues at FormFactor USA**
  - Dr Daniel Bock
  - Amy Leong, Chief Marketing Officer
- **Colleagues at Intel**
  - Michael Engelhardt, Michael Hemena, Robert Murphy and Balbir Singh