5G Boot Camp

PART TWO:
7 KEY MEASUREMENT CHALLENGES AND CASE STUDIES

Keysight Technologies

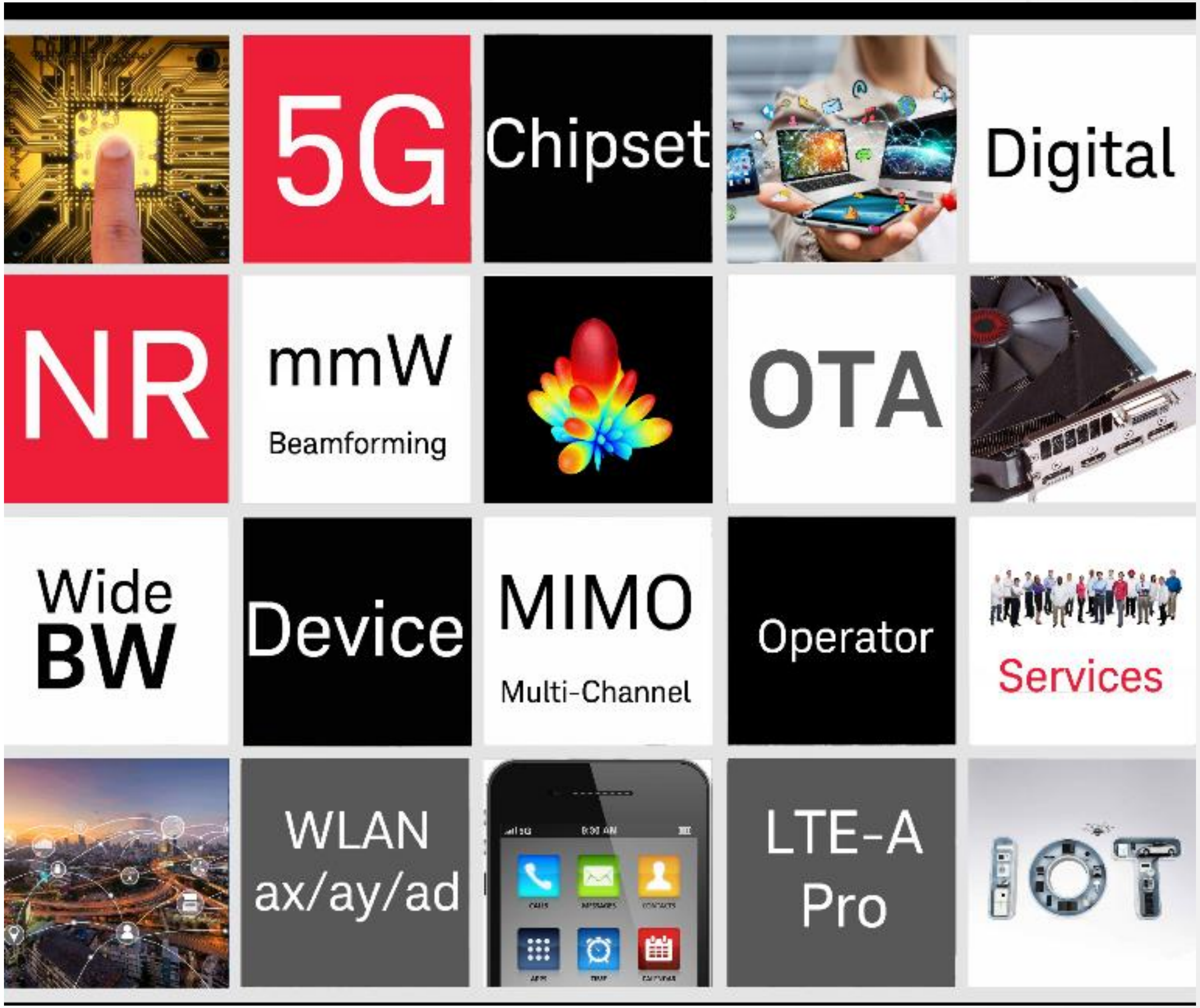
Philip Chang

JAN. 2019

KEYSIGHT TECHNOLOGIES

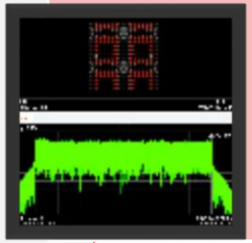
Agenda

- 5G Market Trend, New Radio Specification, and Implications
- 7 Key Measurement Challenges and Case Studies
- Q/A



3GPP Release 15 Specification

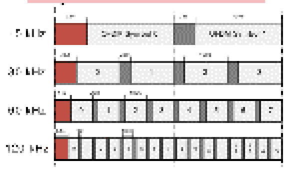
INITIAL RELEASE DEC 2017, FINAL RELEASE LATER 2018



Waveform

CP-OFDM (UL/DL): QPSK, 16QAM, 64QAM and 256QAM

DFT-s-OFDM (UL): π/2-BPSK, QPSK, 16QAM, 64QAM and 256QAM



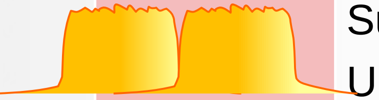
Flexible Numerology

15 kHz*2^n Sub-carrier spacing

1ms subframe

10 ms Frame

Normal & Extended Cyclic Prefix



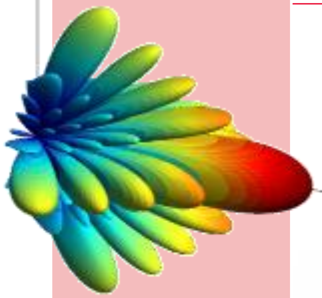
New Spectrum

Sub-6 GHz (FR1) and 24.25 to 52.6 GHz (FR2)

Up to 400 MHz Bandwidth

Up to 8 Component Carriers

Bandwidth Parts enables multiplexing of services



Massive MIMO and Beam Steering

Up to 8x8 MIMO

Much greater # antennas on gNB than UE

Beam sweeping

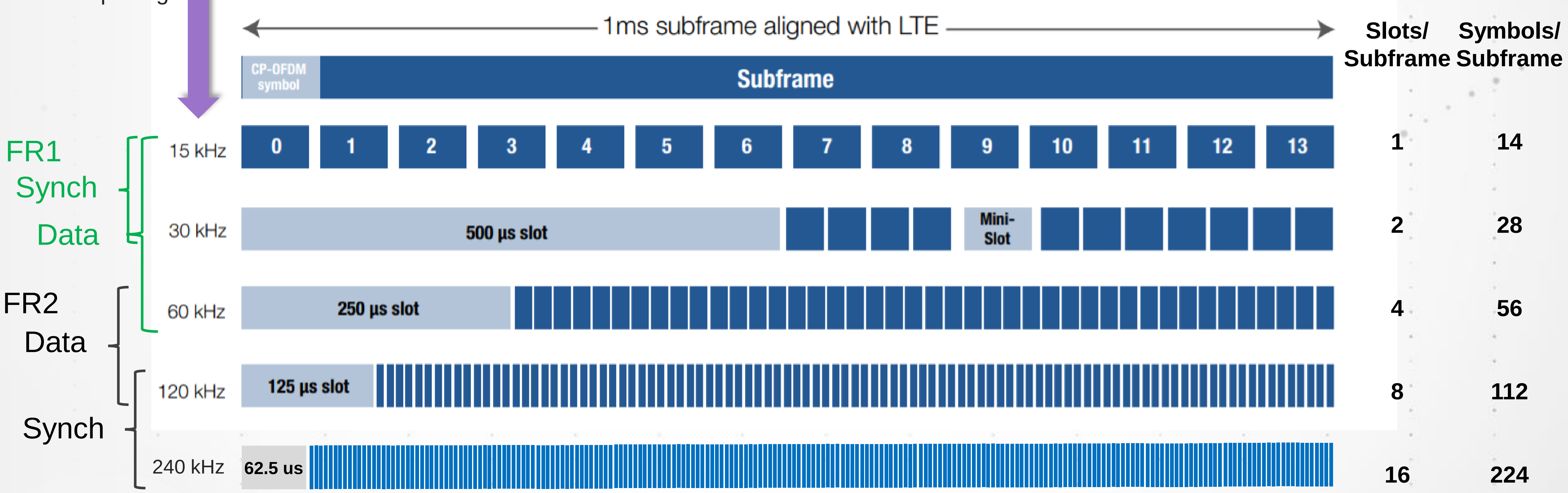
Flexible Numerology

EXPLOSION OF TEST CASES

- 15 kHz*2^n sub-carrier spacing
- 10 ms frame, 1 ms subframe (10 SF/Frame)
  Slot length scales with the subcarrier spacing

$$Slot\ length = {}^{1\ ms}/_{2^{\mu}}$$

- Scheduling – either Slot or mini-Slot
- A slot can be uplink, downlink, or flexible
- Normal slot has 14 symbols, extended has 12 symbols
- New mini-slots can be 2, 4, or 7 OFDM symbols and can start immediately



Spectrum

KEY ATTRIBUTES OF RELEASE 15

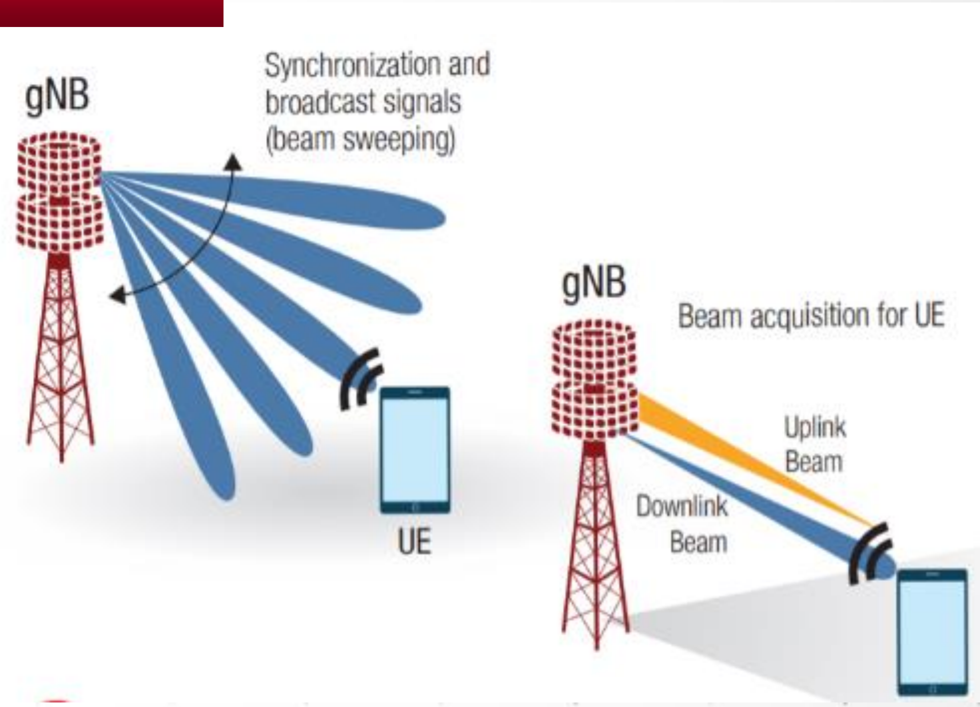
- 5G NR Release 15
- A revolution from LTE-A
- Key challenges
  - Bandwidth
  - mmWave frequency
  - # subcarriers
  - Implementation of 256 QAM and MIMO

Frequency	**Frequency Range 1: 450 MHz – 6000 MHz** **Frequency Range 2: 24.25 to 52.6 GHz**
Transmission Bandwidths (CC)	FR1: 5 to 100 MHz FR2: 50 to 400 MHz
Sub Carrier Spacing	FR1: 15 kHz, 30 kHz, 60 kHz FR2: 60 kHz, 120 kHz, 240 kHz
Maximum number of Subcarriers	3276 (up to 4096 FFTs)
Carrier Aggregation	Up to 8 carriers, maximum BW of 400 MHz (FR1) and 1200 MHz / 1600 MHz (FR2)
Waveform & Modulation	• CP-OFDM (UL/DL): QPSK, 16QAM, 64QAM and 256QAM • DFT-s-OFDM (UL): π/2-BPSK, QPSK, 16QAM, 64QAM and 256QAM
MIMO	Up to 8 layers in downlink, up to 4 layers in the uplink

Spectrum – Massive MIMO and Beam Steering

DIFFERENT IMPLEMENTATIONS UNDER 6 GHZ & MMWAVE

	< 6 GHz (FR1)	mmWave (FR2)
Deployment Scenario	Macro cells High user mobility	Small cells Low user mobility
MIMO Order	Up to 8x8	Less MIMO order (typically 2x2)
Number of Simultaneous Users	Tens of users Large coverage area	A few users Small coverage area
Main Benefit	Spatial multiplexing “Null-forming” for reduced interference	Beam steering for single user
Channel Characteristics	Rich multipath propagation	A few propagation paths
Spectral Efficiency	High, due to the spatial multiplexing	Lower spectral efficiency (few users, high path loss)



Both sub 6 GHz MIMO and mmWave MIMO will require better beam management and over-the-air validation

5G New Radio Challenges Across the Spectrum

SUB 6 GHZ AND MMWAVE

0.6 GHz	2.5 GHz	3.4 - 3.8 GHz	4.4 – 4.9 GHz	ISM	28 GHz	39 GHz	. . .	64 -71 GHz 71 – 76 GHz

Sub-6 GHz

eMBB, URLL - Massive MIMO to increase capacity and throughput

Challenges

- 5G NR coexistence with LTE and Wi-Fi
- Multi-mode devices
- Massive MIMO performance
- RF performance at higher frequencies and bandwidth
- UE battery life

mmWave

eMBB - Fixed wireless broadband or low mobility

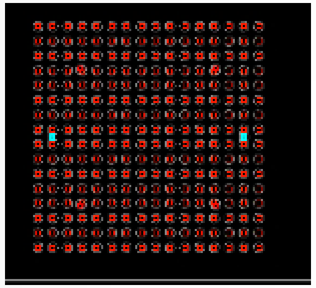
Challenges

- Wideband signal quality, mmWave frequencies and very large bandwidths
- mmWave initial access and beam management QoS
- Measurements without connectors
- 3D spatial channels

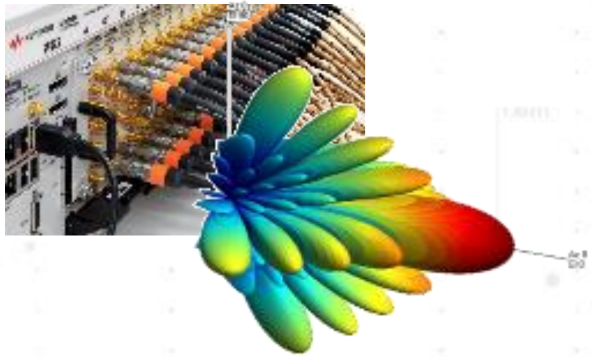
5G New Radio
7 Key Measurement Challenges

7 Key Measurement Challenges

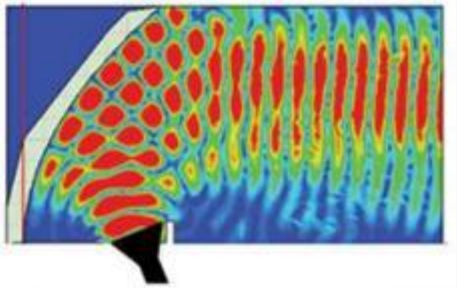
Signal Quality
mmW, Waveform, Fidelity



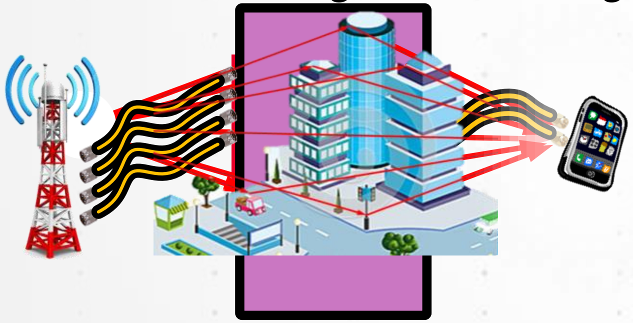
Lots of Channels
MIMO/Beamforming



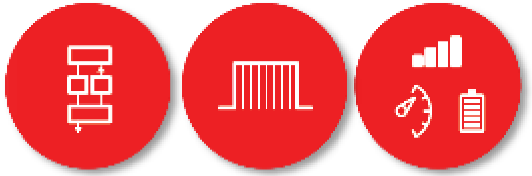
Life Beyond Connectors
Over-the-Air



Channel
Characterizing & Emulating



Performance on the Network
Network Emulation



Protocol R&D
RF / RRM DVT
Functional KPI

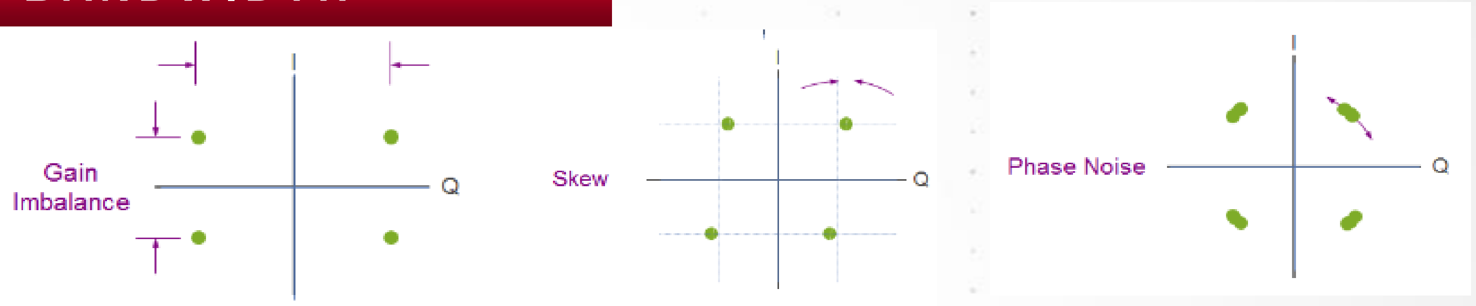
Cost of Test
Assets, throughput

Field Testing and Drive Test

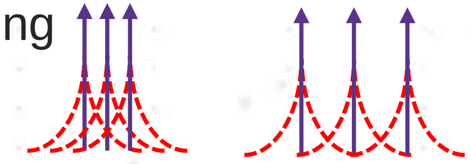
Challenge: Signal Quality and mmWave

CHALLENGES WITH MMWAVE AND BANDWIDTH

- IQ modulator errors

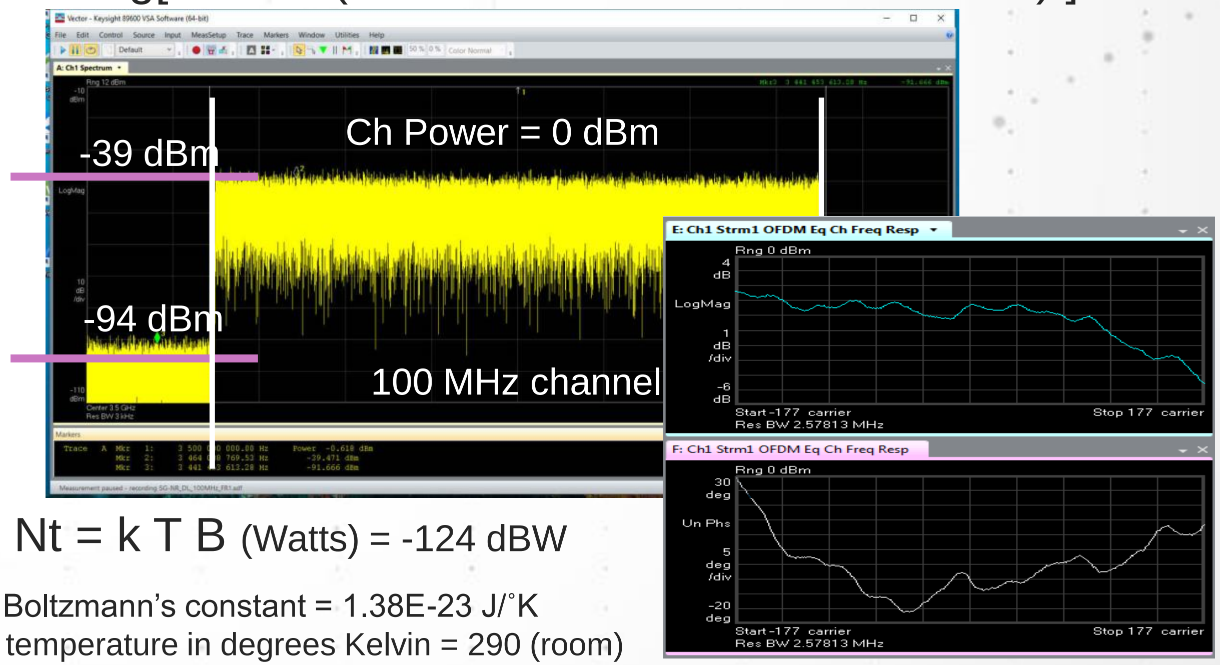


- Phase noise
  - OFDM close subcarrier spacing



- Distortion
  - Overdriving causes compression and distortion
- Signal-to-Noise Ratio
  - Wide BW systems with high noise figure coupled with low RF power levels
- Amplitude flatness and phase linearity
  - Frequency response of cables, gain horn, amplifiers, filters, signal generator, signal analyzer, etc

10xLog[30 kHz/(273 PRB x 12 SC/PRB x 30 kHz)] = -35 dB



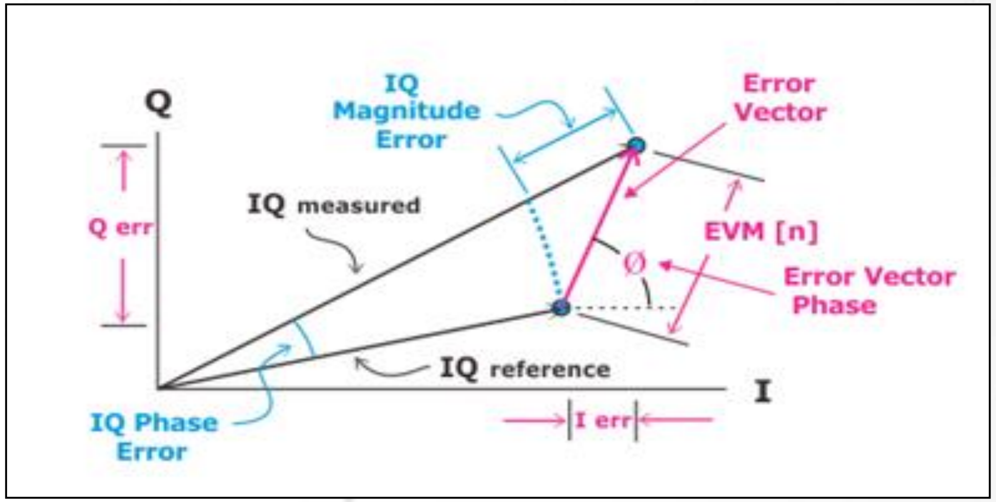
Nt = k T B (Watts) = -124 dBW

k = Boltzmann's constant = 1.38E-23 J/˚K
T = temperature in degrees Kelvin = 290 (room)
B = overall bandwidth = example 100 MHz

How do you Know if the Signal is Good?

EVM IS THE STANDARD MEASURE OF SIGNAL QUALITY

EVM (Error Vector Magnitude): *The normalized ratio of the difference between two vectors: IQ measured signal & IQ reference (IQ reference is calculated value)*

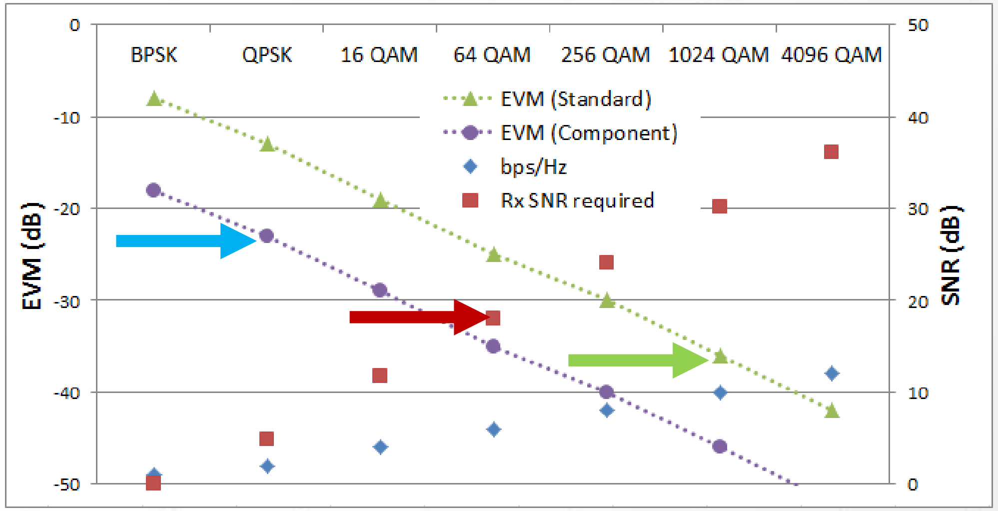


What's considered Good?

- For the link to work: "At the limit for the scenario"
- For component test: "10 dB better than the system as a whole"
- For system test: "3 dB better than the source from radio standard"

5G NR Release 15 EVM Requirements

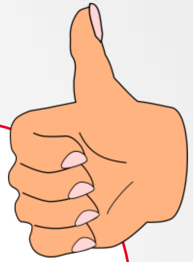
Mod	Required EVM
Pi/2 BPSK	30% (-5.2 dB)
QPSK	17.5 % (-15.1 dB)
16QAM	12.5 % (-18.1 dB)
64QAM	8 % (-21.9 dB)
256QAM	3.5 % (-29.1 dB)



Signal Quality at mmWave Frequencies

CHALLENGES AND TIPS

- IQ modulator errors
- Phase noise
  - OFDM close subcarrier spacing
- Distortion
  - Overdriving causes compression and distortion
- Signal-to-Noise Ratio
  - Wide BW systems with high noise figure coupled with low RF power levels
- Amplitude flatness and phase linearity
  - Frequency response of cables, gain horn, amplifiers, filters, signal generator, signal analyzer, etc



Tips for mmWave Measurements

- ✓ Minimize signal generation impairments correcting for IQ modulation, phase noise, flatness and linearity errors
- ✓ Ensure adequate antenna gain
- ✓ Select test equipment with EVM and Signal-to-Noise Radio better than your DUT
- ✓ Ensure proper use of cables and connectors for the given frequency
- ✓ Perform system level calibration to ensure measurement is at DUT plane

Case Study: Testing for Coexistence

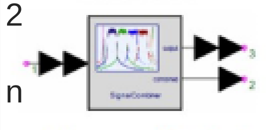
Challenge: Dual-Mode operation. Verify performance in- and out-of-band to reduce interference

- How will the waveforms interact?
- How much out-of-band suppressions will be required?
- How much guard band will be required?
- How can different scenarios be explored?

Solution:

Simulate

Waveform 1
Waveform 2
.
Waveform n



Wideband Source
M9383A

Wideband Analyzer

N9040B

Analysis

Multiple LTE, 5G measurements from 1 acquisition

Challenge: EVM Optimization @ mmWave

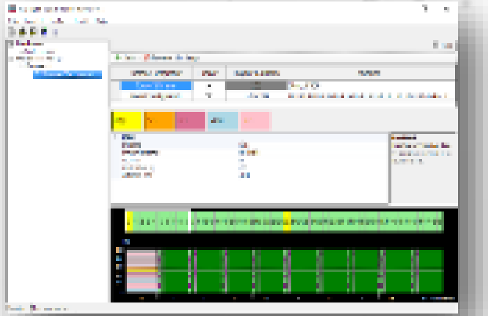
OPTIMIZE EVM USING X-APPS AND VSA

Amplifier EVM performance;

- 5G NR DL 1CC/8CC, 64/256 QAM (high crest factor), 100 MHz bandwidth, 28 GHz & 39 GHz (FR2)

1

Generate 5G NR waveform and playback on wideband vector source



N7631C Signal Studio

2

Use Signal Studio generated .SCP file to configure 5G NR EVM measurement in VSA and X-apps

3

X-App or VSA: ***Optimize*** and measure EVM before and after AUT

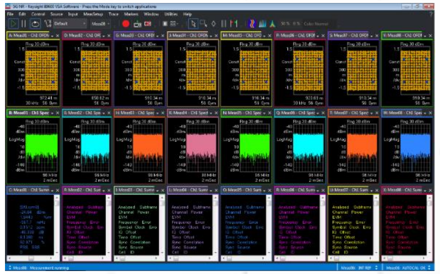
Wideband Source M9383A

Wideband Analyzer

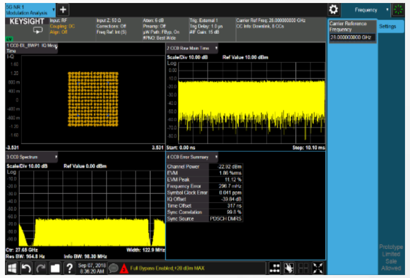
Trigger

N9040B

89601B VSA with opt BHN



N9085EM0E X-Series measurement application



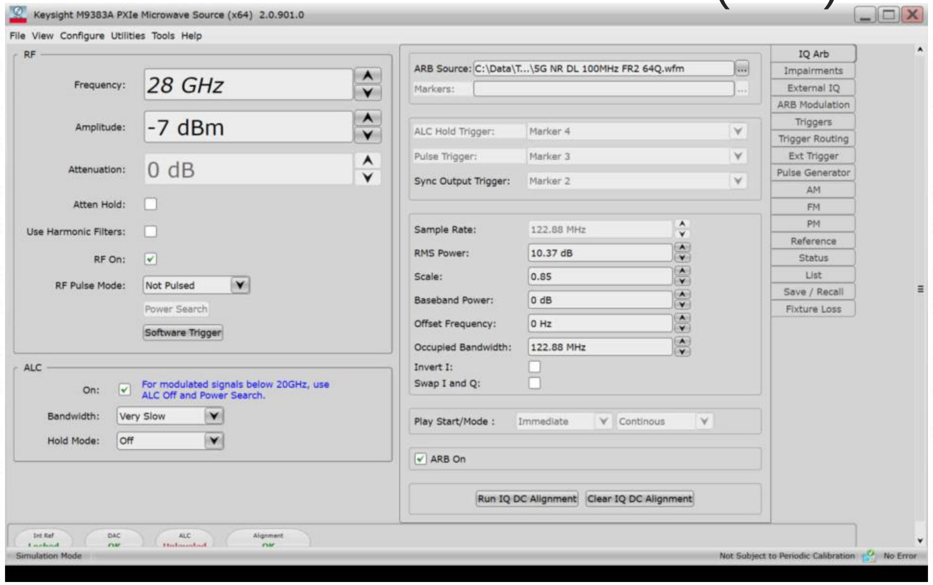
EVM Optimization @ mmWave

M9383A PXI VECTOR SOURCE

M9383A is optimized by default.
Simply do the following:

- Set Frequency
- Set Amplitude
- Set ALC:
  - Freq < 20 GHz: Turn off
  - Freq > 20 GHz: Set to very slow
- Select Waveform
- Turn ARB & RF on

M8393A Soft Front Panel (SFP)



M9383A (MCS) is optimized right out of the box!

Note: you can also use the waveform Markers to trigger the PXA or UXA which greatly speeds up the demodulation measurements.

EVM Optimization @ mmWave

N9040B X-SERIES ANALYZER

Several things you can do to optimize EVM;

- Select *frequency span* that closely captures signal bandwidth
- Optimum phase noise method for wide bandwidth signals: *Best Wide Offset*
- Optimize front end path: if available use *Full Bypass Mode* (particularly at higher frequencies around 28 and 39 GHz) – for EVM only
- Optimize attenuator: find best level at signal analyzer ***mixer input*** for optimum EVM (same for ACLR)
- Optimize attenuator & IF gain: find best combination of both, rather than let Signal Analyzer pick IF gain

EVM Optimization @ mmWave

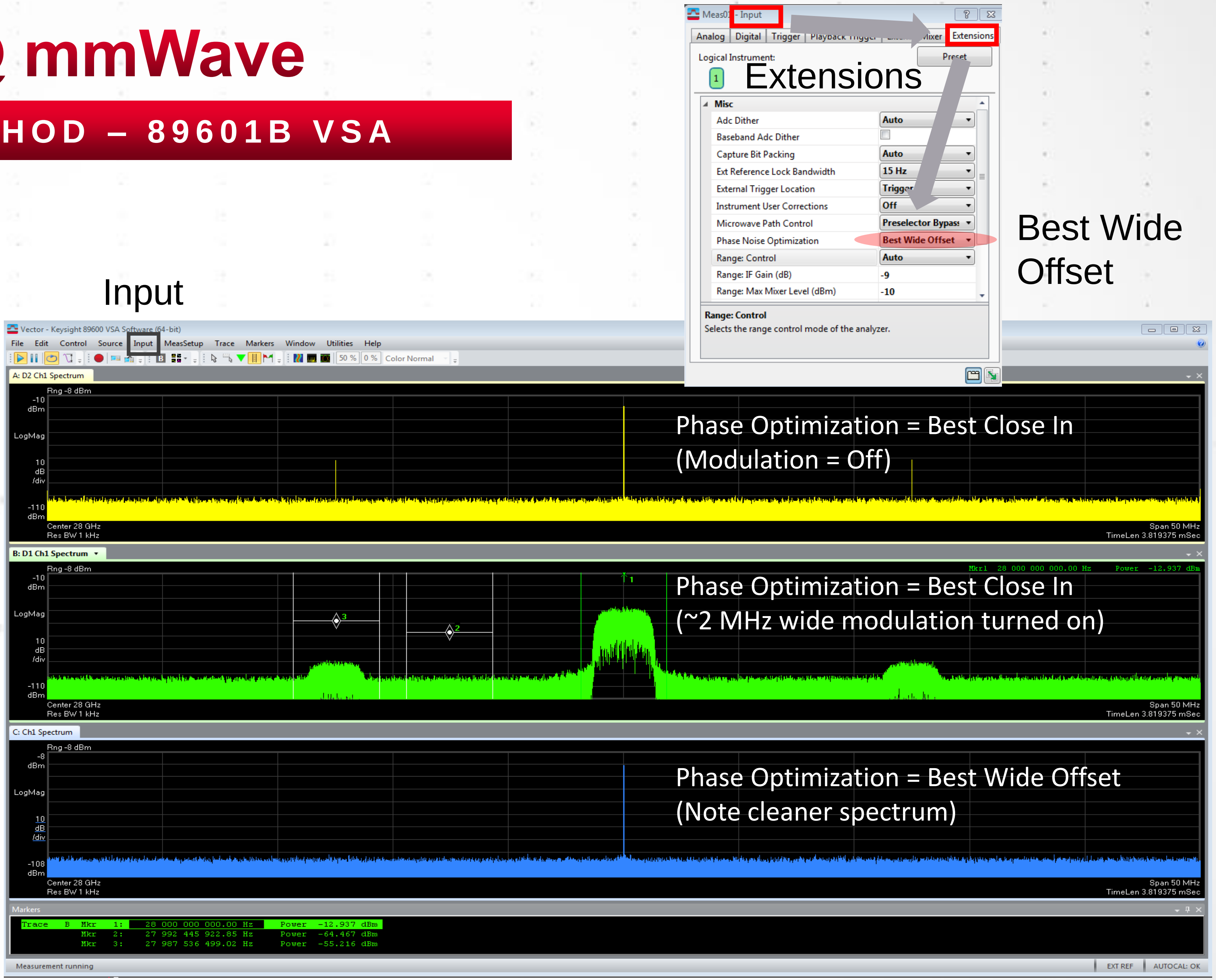
OPTIMIZE PHASE NOISE METHOD – 89601B VSA

For wide bandwidth signals optimize EVM performance by setting phase noise optimization method to ***Best Wide Offset;***

- Input → Extensions → Phase Noise Optimization

Input

Best Wide Offset



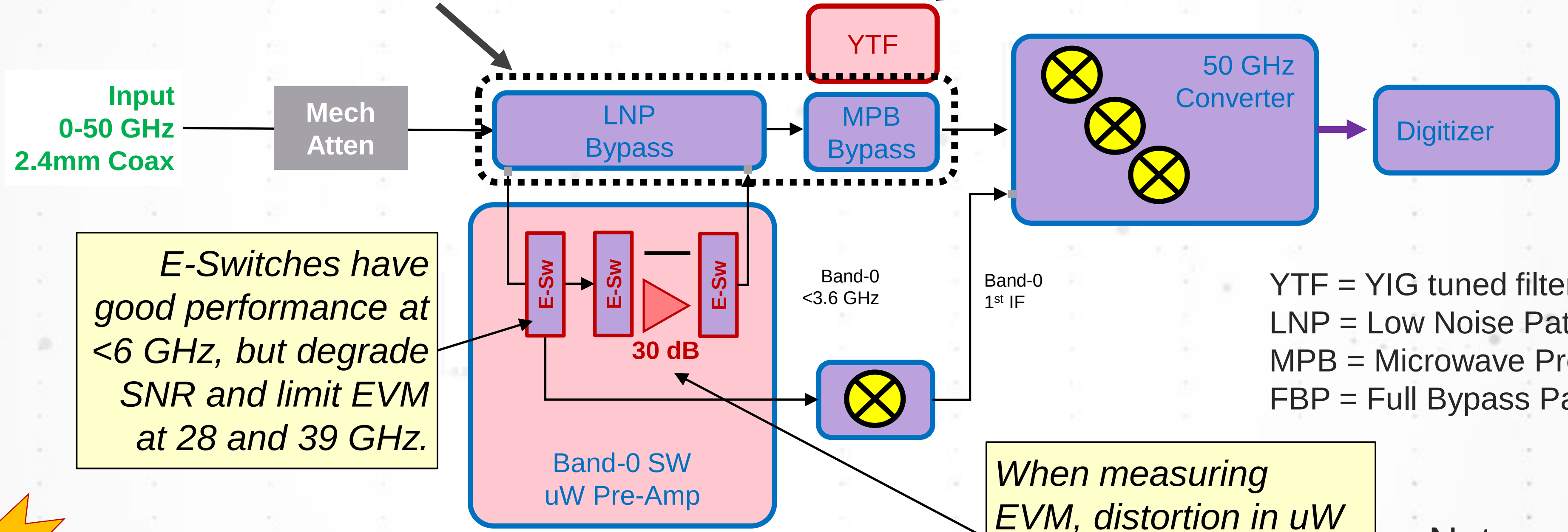
EVM Optimization @ mmWave

OPTIMIZE FRONT END PATH

Things you ***should*** do to optimize signal path and improve EVM at mmWave; MPB, LNP, and FBP

YTF loss at 40 GHz is ~10 dB.

YTF BW is ~40-60 MHz, must bypass for wide-BW EVM measurements. Don't bypass for ACLR



E-Switches have good performance at <6 GHz, but degrade SNR and limit EVM at 28 and 39 GHz.

YTF = YIG tuned filter
LNP = Low Noise Path
MPB = Microwave Preselector Bypass
FBP = Full Bypass Path (LNP + MPB)

When measuring EVM, distortion in uW Pre-Amp will limit EVM floor.

NEW

***FBP** allows by-passing both LNP and MPB at same time. Factory cal data is applied for this new path.*
***UXA with #550 & #H1G only**, start Apr-2018.*

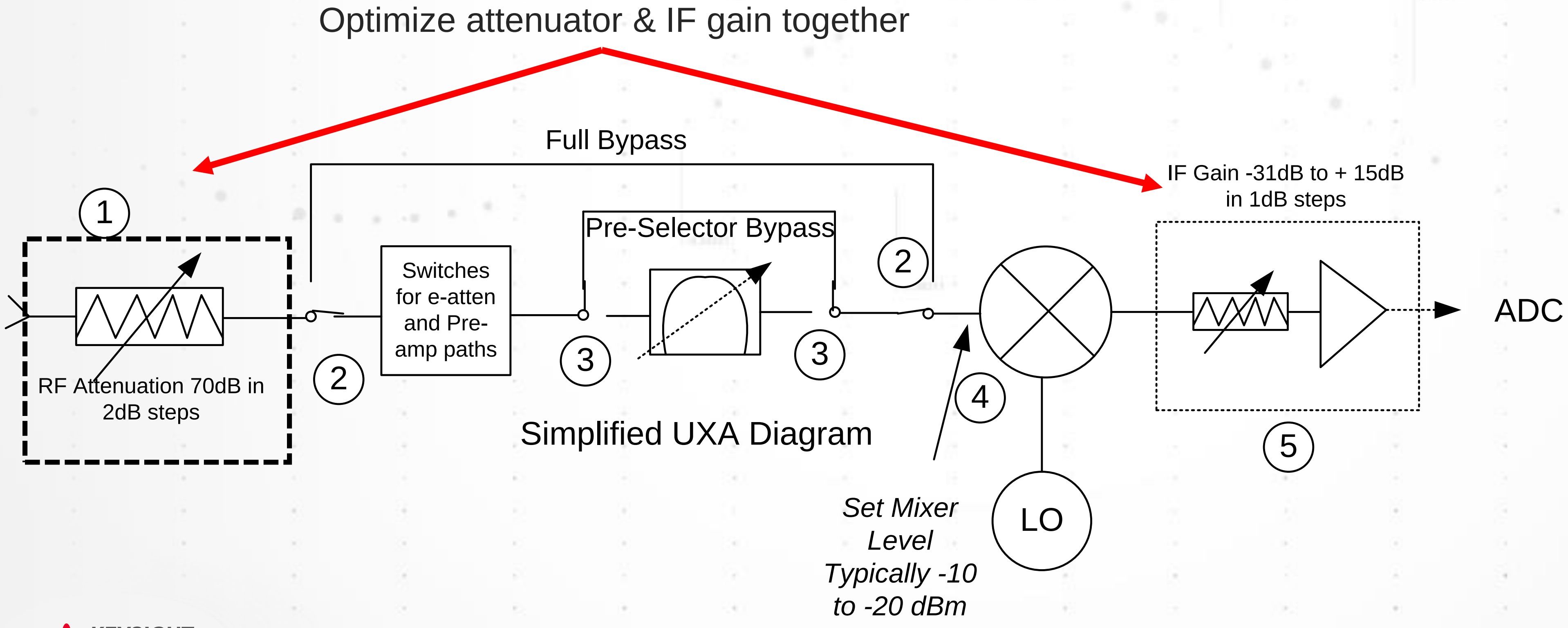
Note: use uWave pre-amp only if signal is low in power **and** improves EVM

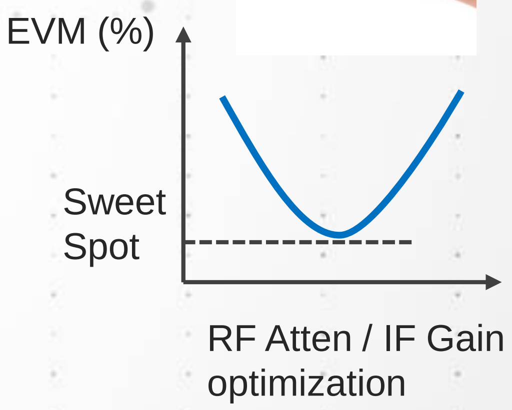
EVM Optimization @ mmWave

UXA FRONT END - SIMPLIFIED VIEW

- Normally, wide BW measurements are noise limited, hence, bypassing both pre-selector & path for electronic attenuator/preamp (Low Noise Path) can improve EVM.

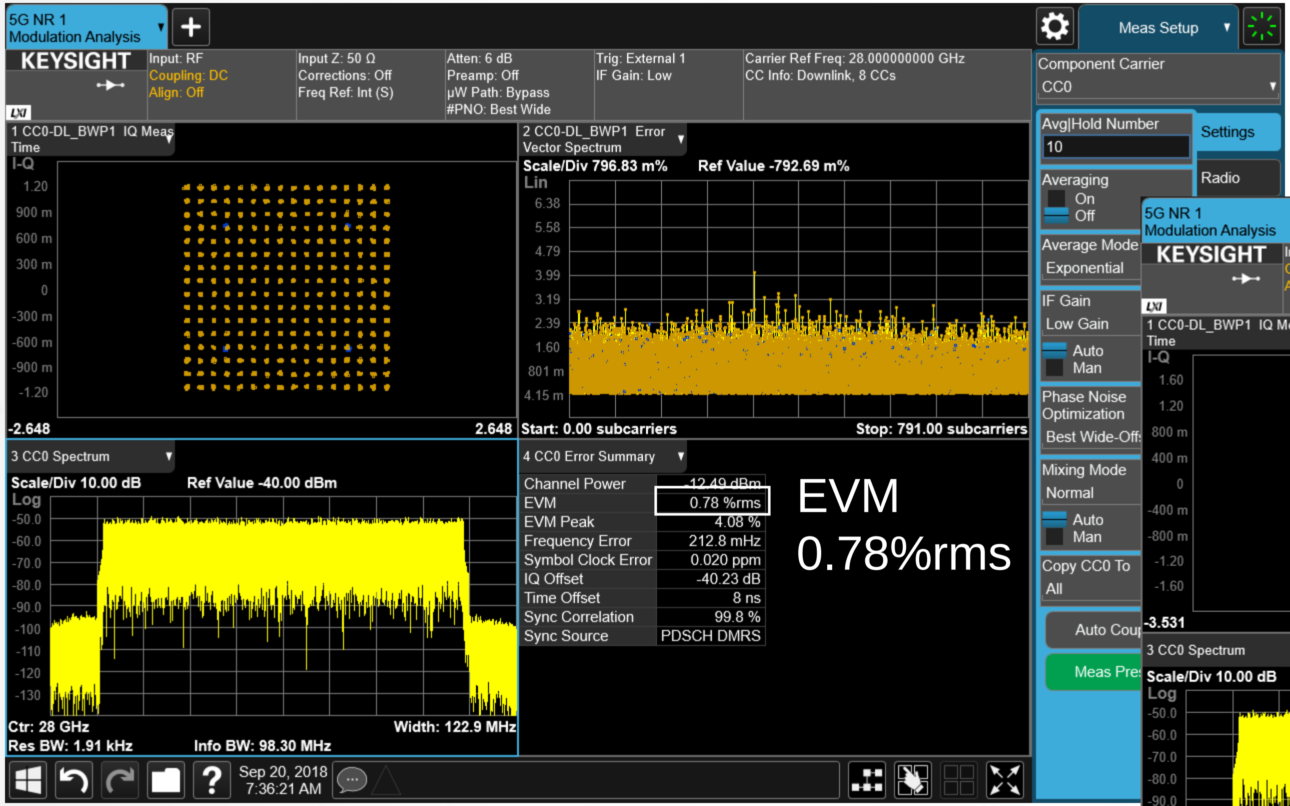
- Normally analyzer selects IF gain depending on other analyzer settings, including the selected RF attenuation. For a given signal BW and crest factor, manually setting both the RF attenuator and IF gain can improve EVM.



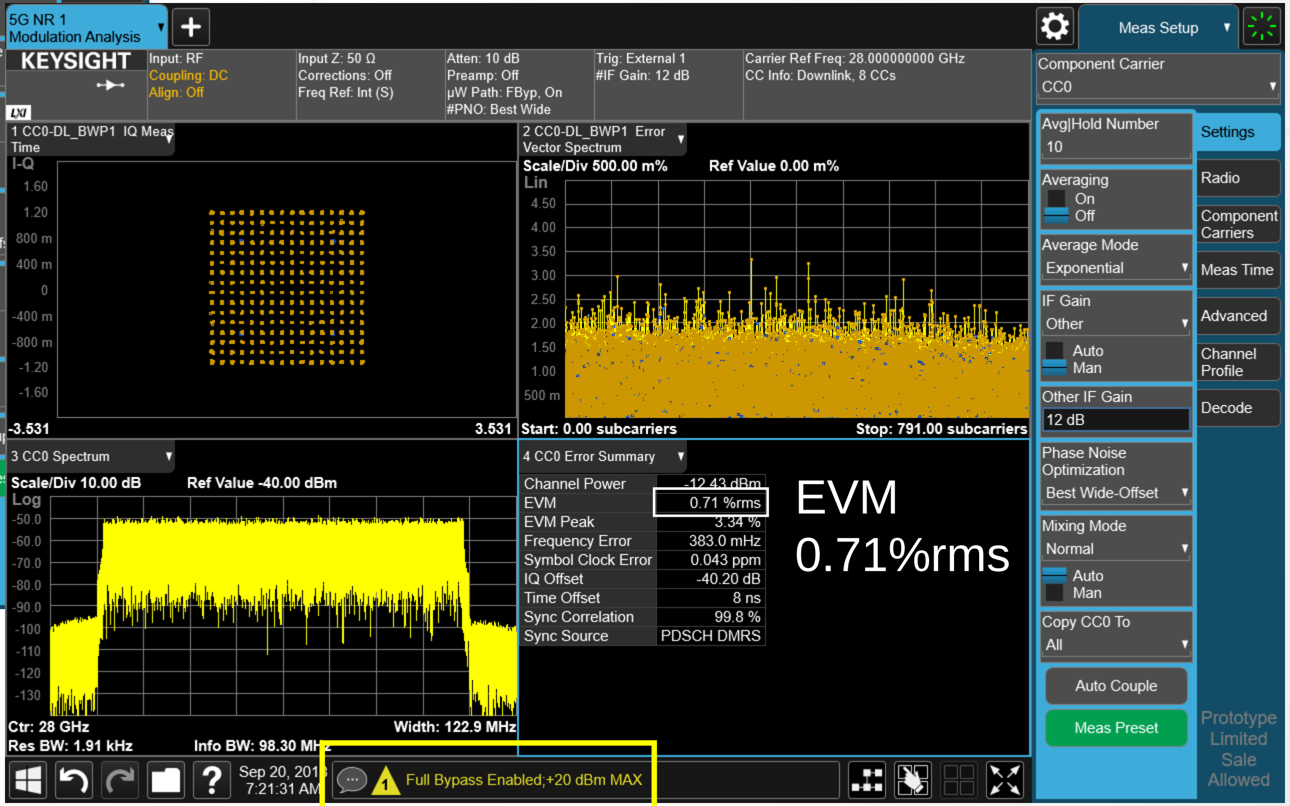


EVM Optimization @ mmWave

5G NR 28 GHZ 100 MHZ 256QAM OPTIMIZED EVM RESULT



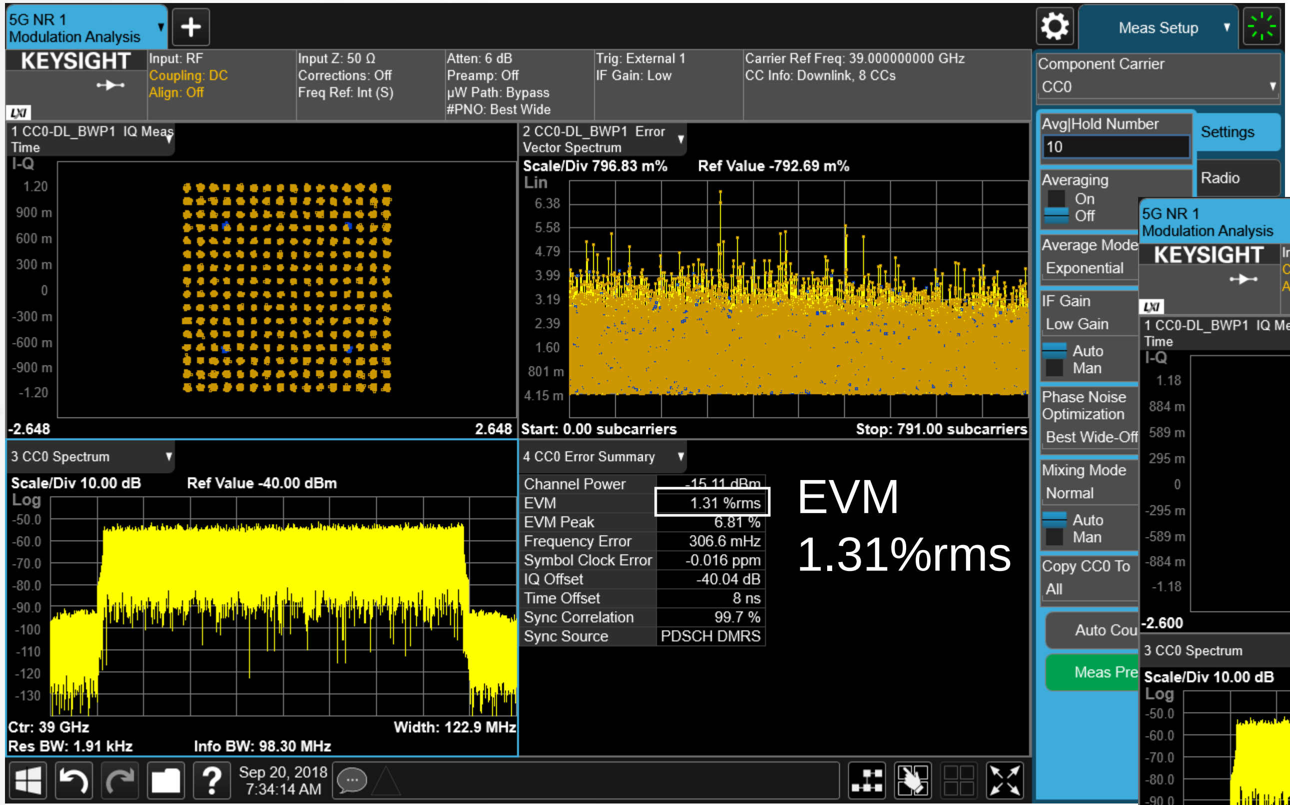
Full Bypass Path and optimized input attenuation/IF gain



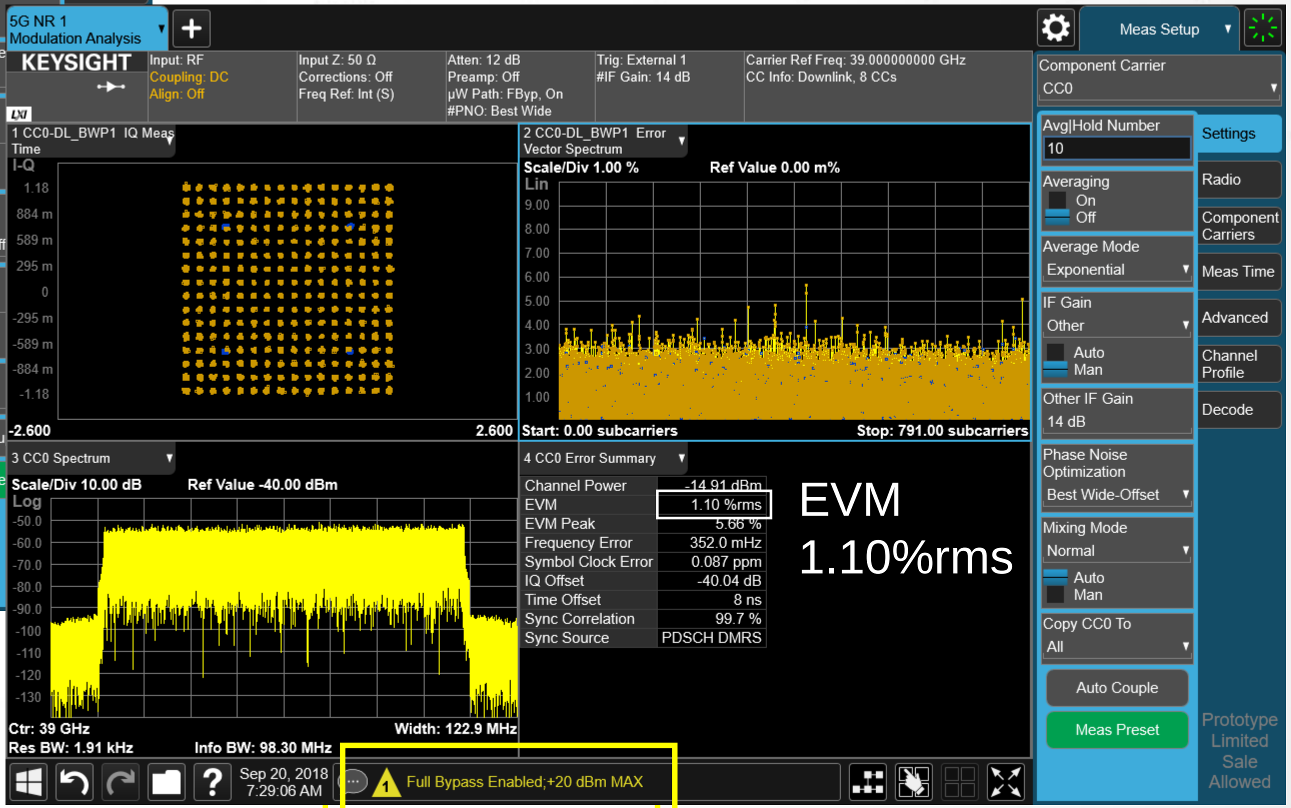
N9040B UXA with options 550 & H1G

EVM Optimization @ mmWave

5G NR 39 GHZ 100 MHZ 256QAM OPTIMIZED EVM RESULT



Full Bypass Path and optimized input attenuation/IF gain

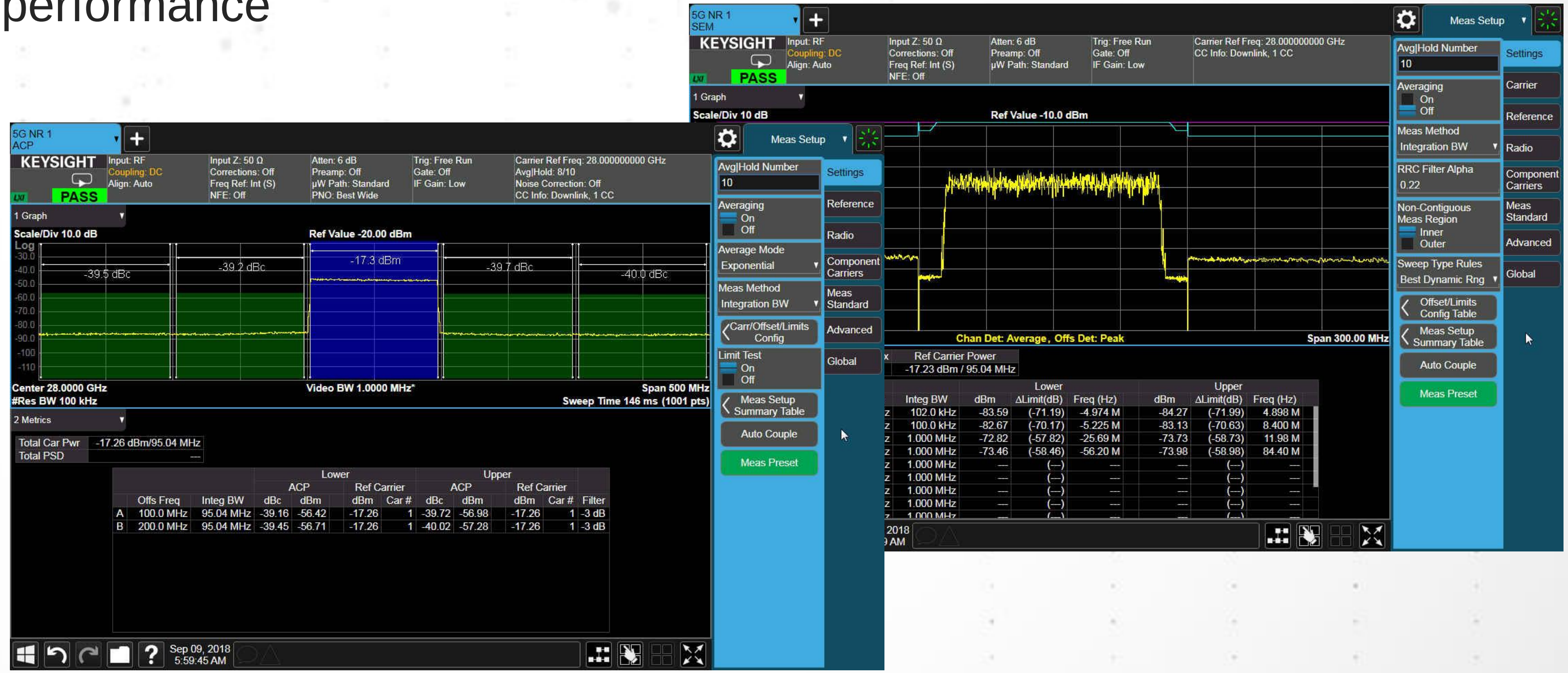


N9040B UXA with options 550 & H1G

ACLR Optimization

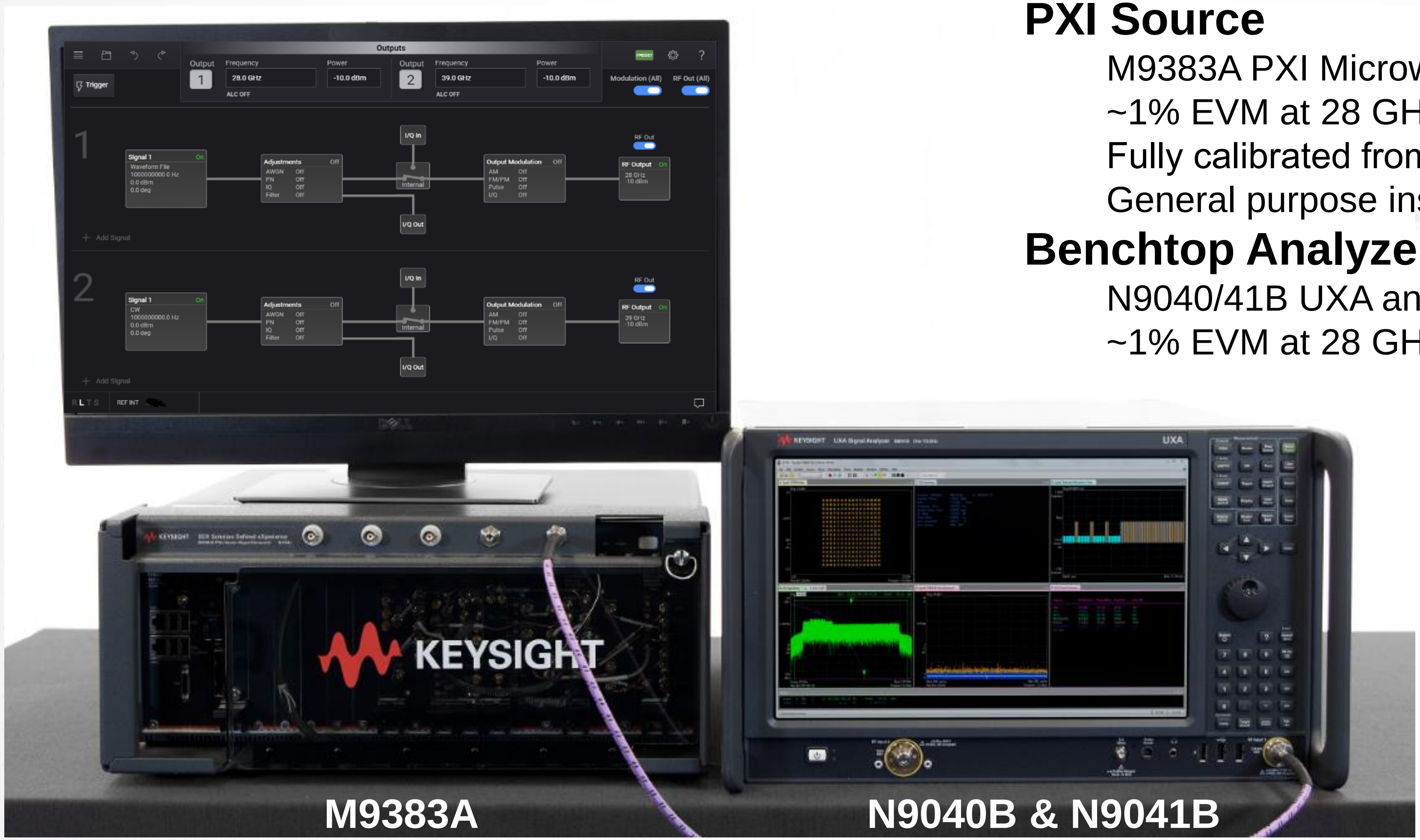
UXA KEY STEPS

- Do not use Full Bypass Path mode - the **microwave preselector filter is needed** for best ACLR performance.
- Above 3.6 GHz enable Low Noise Path (LNP). This bypasses lossy switches.
- Optimize attenuator for best performance
- Turn on Noise Corrections



5G Hardware Configurations: FR1 and FR2

NON-SIGNALING: UP TO 1 GHZ BW SIGNAL GENERATION & ANALYSIS



PXI Source

M9383A PXI Microwave vector source, up to 44GHz
~1% EVM at 28 GHz w/1 GHz BW
Fully calibrated from factory across all BW's
General purpose instruments (not banded)

Benchtop Analyzer

N9040/41B UXA analyzer, up to 50 / 90 / 110 GHz
~1% EVM at 28 GHz w/1 GHz BW (option H1G)

Hardware Configurations: 50-110 GHz, up to 10 GHz wide

NON-SIGNALING: > 1 GHZ BW SIGNAL GENERATION & ANALYSIS

Widest BW Source Config

- M8195 AWG, direct to Low IF
- M9383A or N5183B analog LO
- VDI upconverter

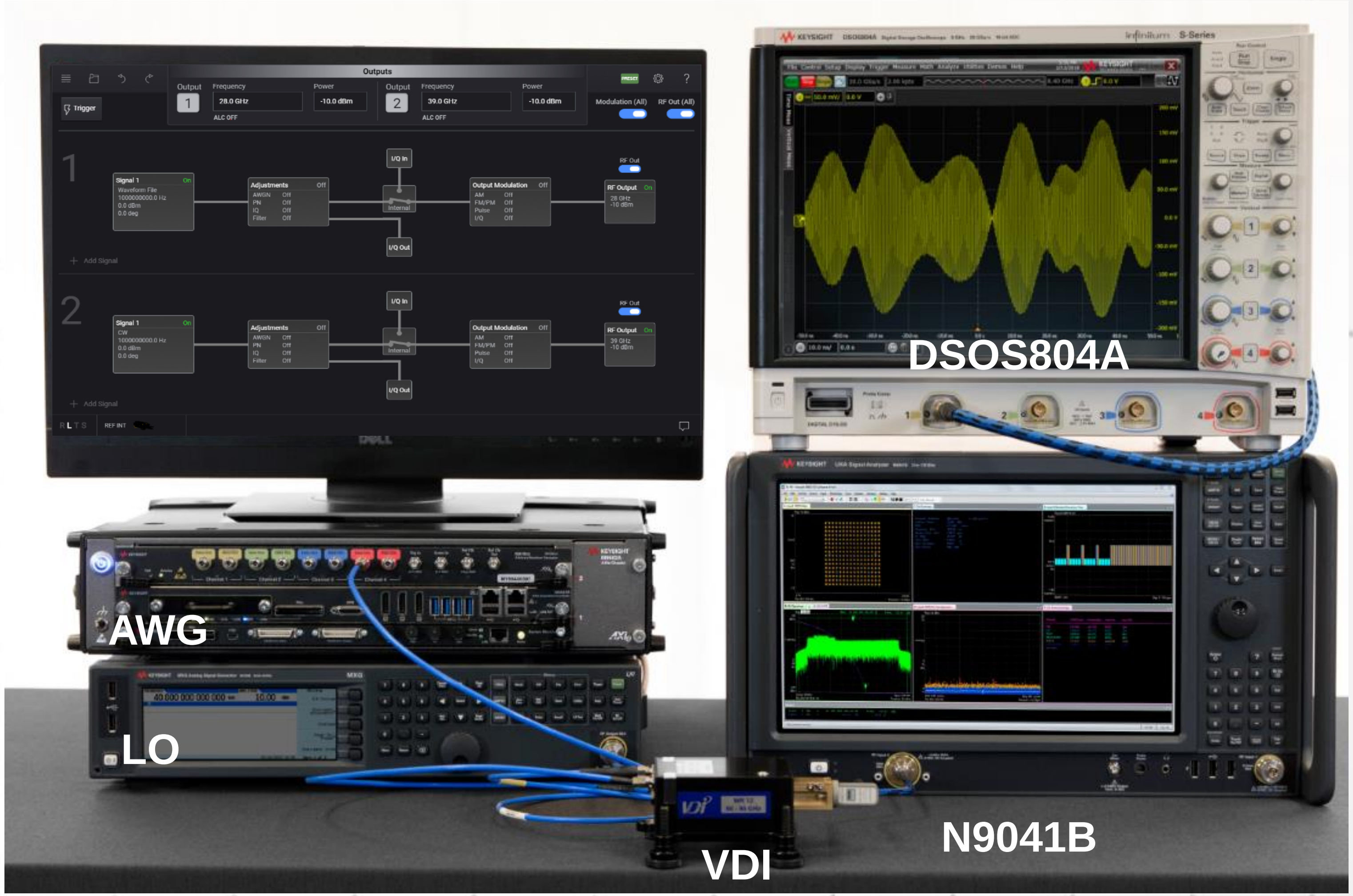
Widest BW Analyzer

N9041B UXA with external WB IF

Extremely low noise & spurs
Excellent for both modulated and SEM testing

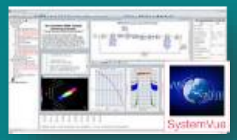
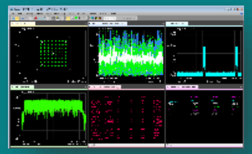
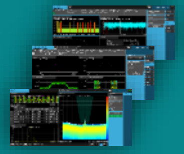
External Digitizer

8, 33, 65 GHz oscilloscope, UXR oscilloscopes (13 to 110 GHz), or M9703/10 AXIe digitizer



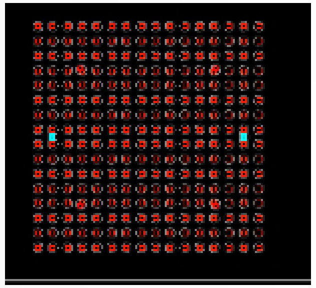
Precede the 5G Race with New Radio

KEYSIGHT 5G NR SOFTWARE SOLUTIONS

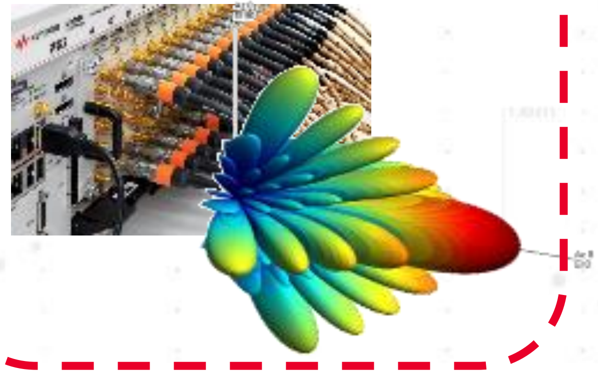
Software:	SystemVue	Signal Studio	89600 VSA	X-Series Apps
				
Category:	**ESL Design & Simulation software**	**Signal Creation software**	**Vector Signal Analysis software**	**Measurement Application software**
Custom OFDM: for 5G proto-typing	**W1461B**	**N7608APPC**	**89601B-BHF**	**N9054EM1E**
Pre-5G: for Verizon	**W1906E**	**N7630APPC**	**89601B-BHN**	
3GPP 5G NR:	**W1906E**	**N7631APPC (N7631C)**	**89601B-BHN**	**N9085EM0E**
Target Customers:	Simulation users who needs the world-best 5G NR PHY simulation	R&D who needs test vector waveforms on receiver or component tests	R&D who wants to get in-depth modulation analysis for transmitter tests	R&D plus early MFG for simple pass/fail tests

7 Key Measurement Challenges

Signal Quality
mmW, Waveform, Fidelity



Lots of Channels
MIMO/Beamforming



3

4

5

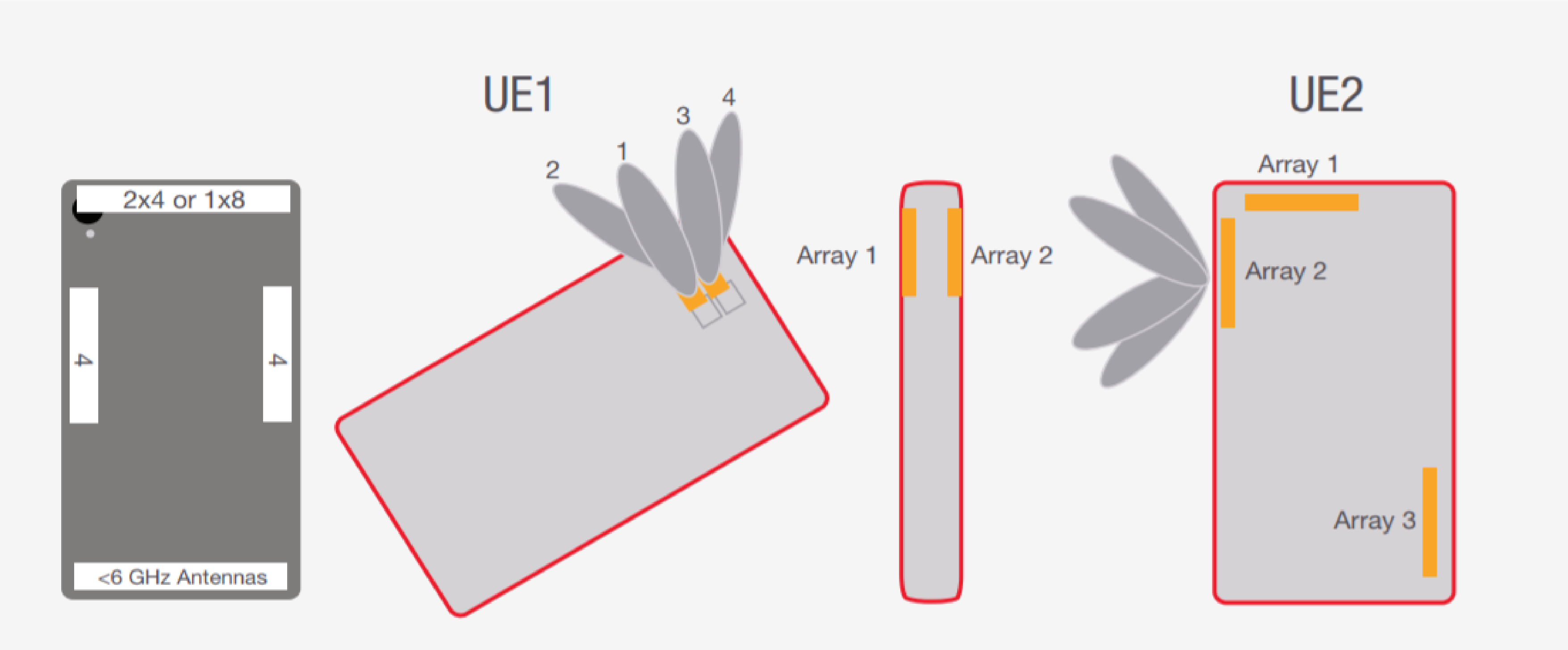
6

7

Challenge: Multiple Antennas

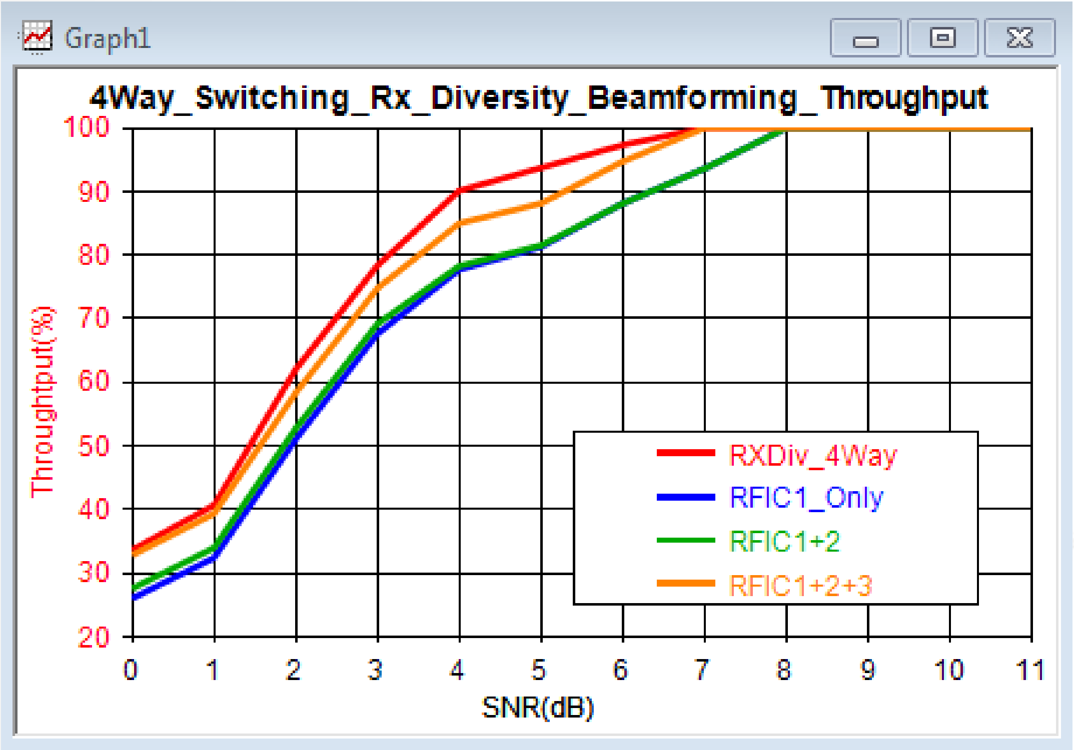
Challenge: Understanding MIMO and Beamforming real-world performance including handover and throughput

- Characterize beam patterns have proper phase and magnitude relationship and beams and nulls are in the correct position
- Emulate real-world conditions in sub 6 GHz or mmWave

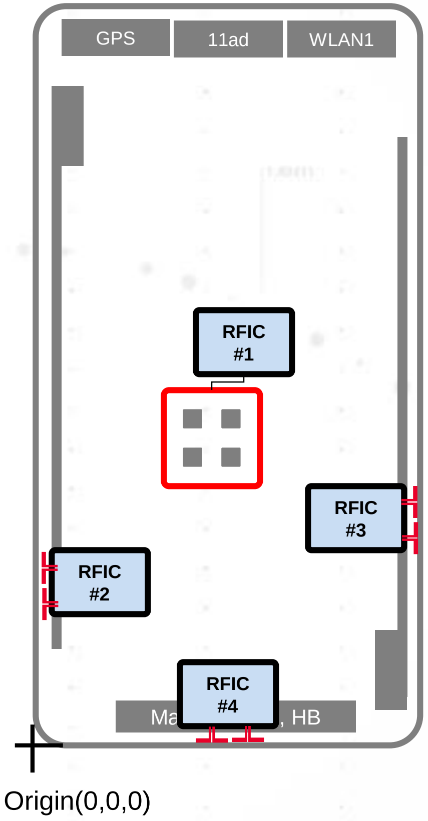


Link-level Mobility Throughput Analysis (28 GHz)

IN 4-WAY SWITCHING RX DIVERSITY WITH BEAMFORMING



Throughput: MCS3, Channel model: TR 38.901



Antenna 1
- Type: microstrip patch array
- Freq: 28Ghz
- # Element: 4
- Dual polarization

Antenna 2
- Type: dipole
- Freq: 28Ghz
- Cover area: left

Antenna 3
- Type: dipole
- Freq: 28Ghz
- Cover area: right

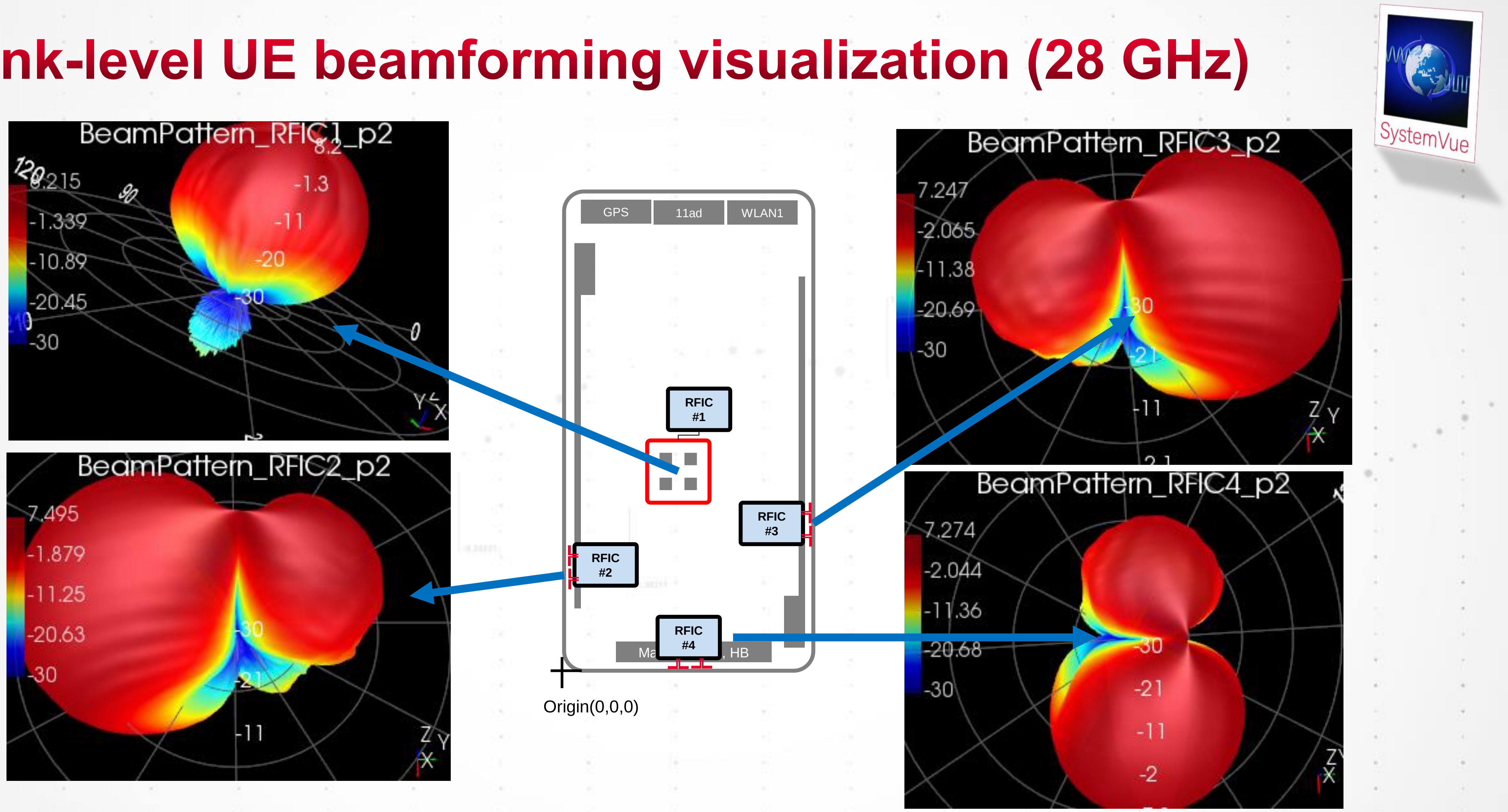
Antenna 4
- Type: dipole
- Freq: 28Ghz
- Cover area: bottom

Receive diversity

SystemVue

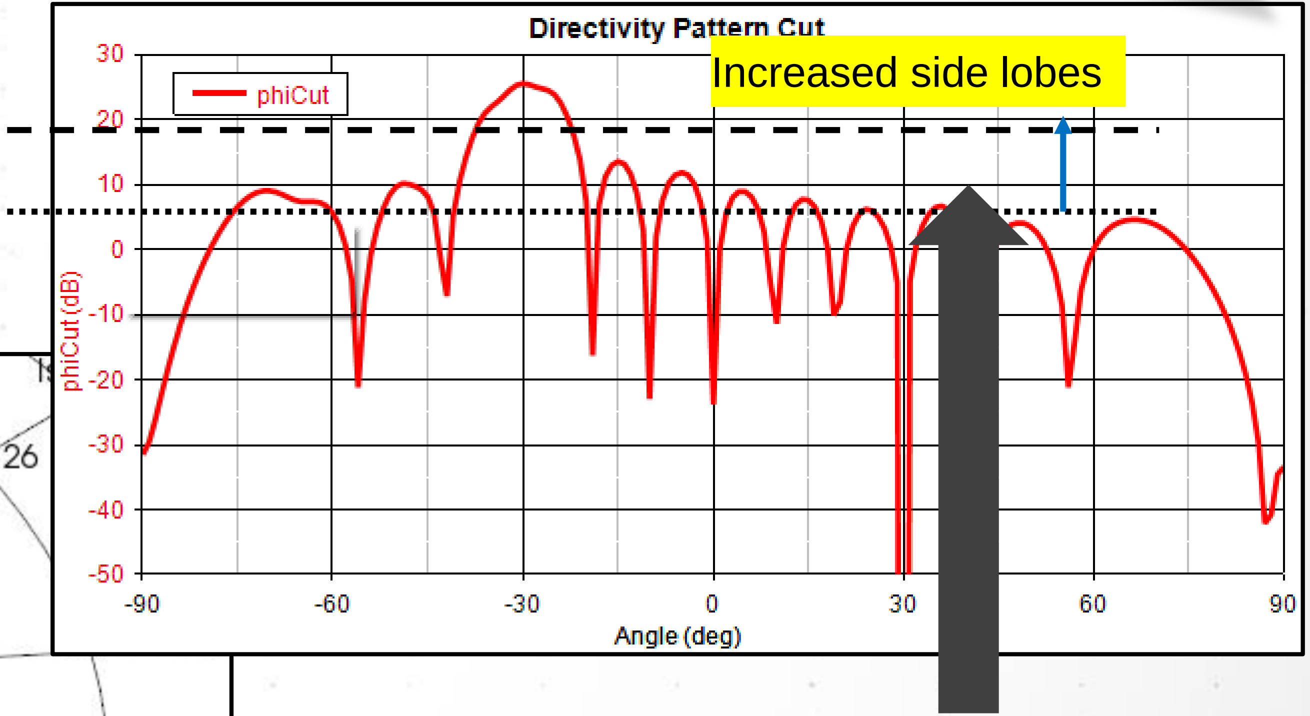
KEYSIGHT TECHNOLOGIES

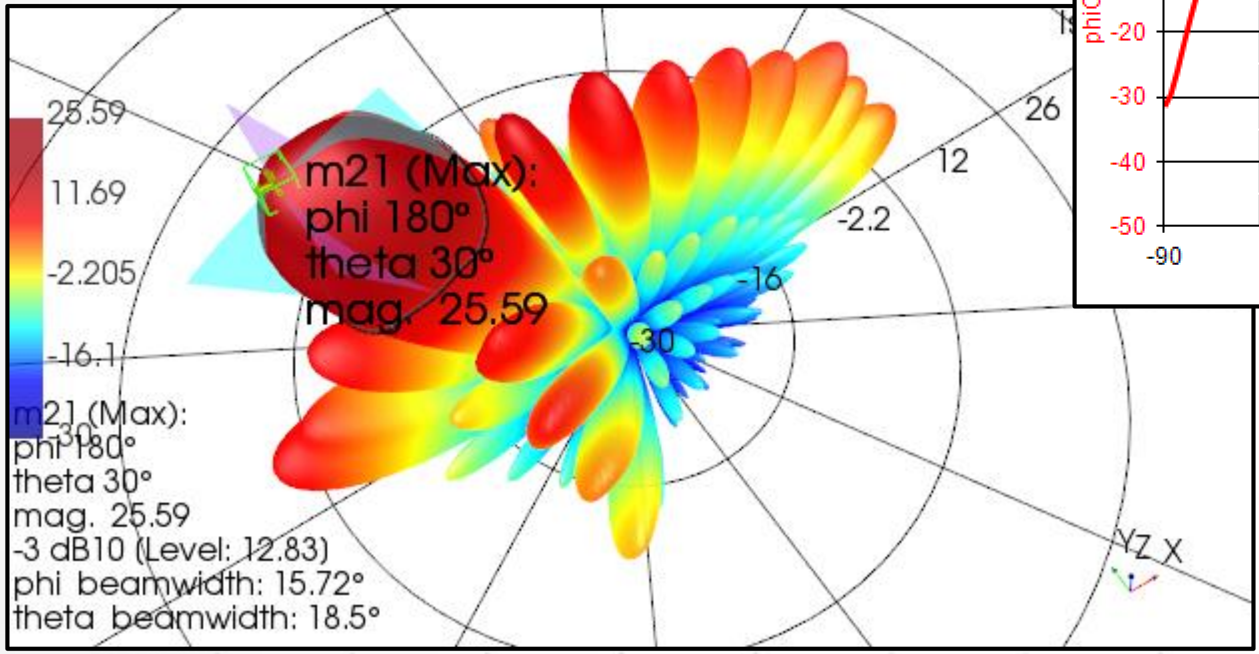
Link-level UE beamforming visualization (28 GHz)



Sidelobe Energy with Nonlinear Array PA's

- To what extent will OTA spatial/sidelobe masks be in the final Conformance docs?
- Even if not, should you still characterize them?

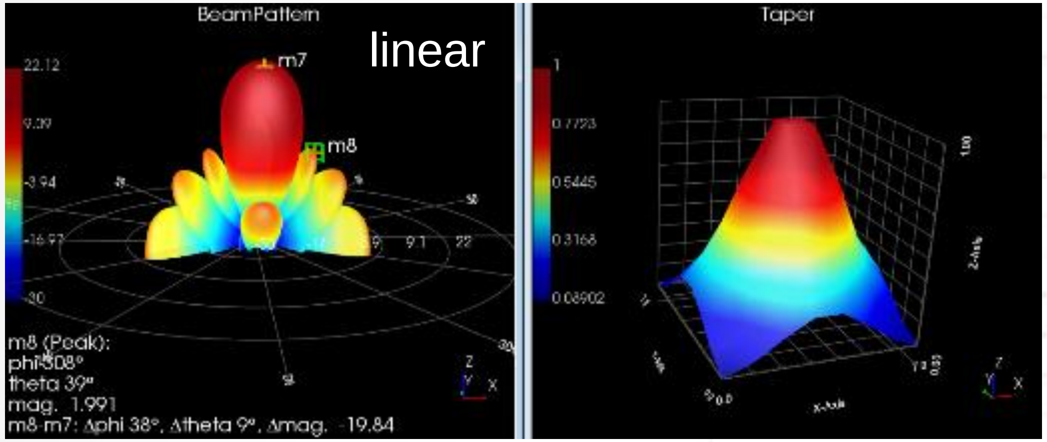


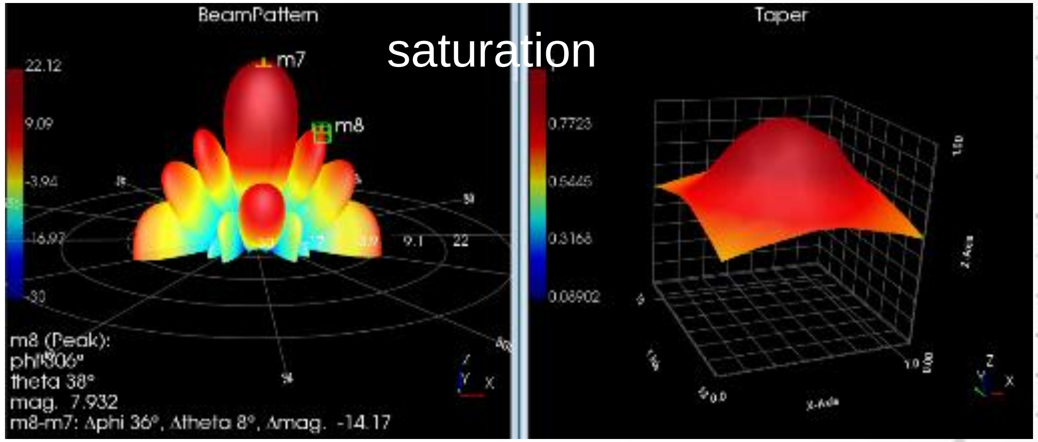


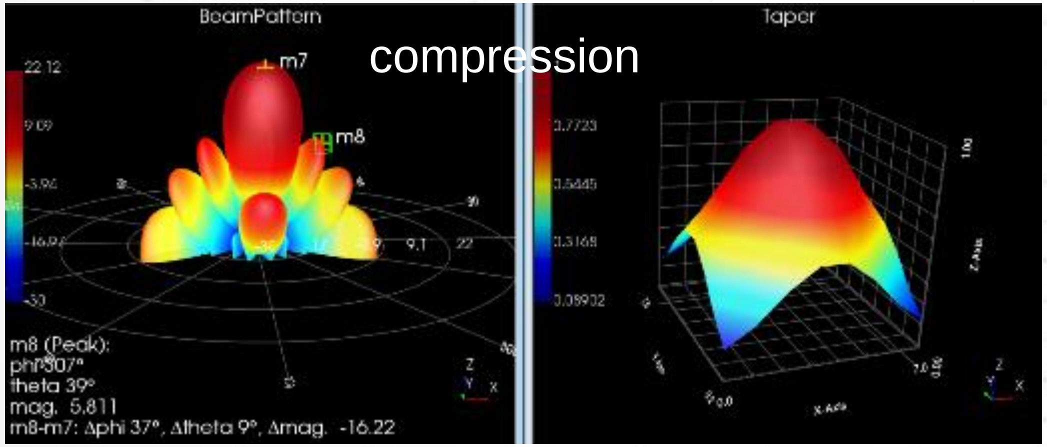
Sidelobes increase +15dBc when Nonlinear instead of Linear. ***Is that ok?***

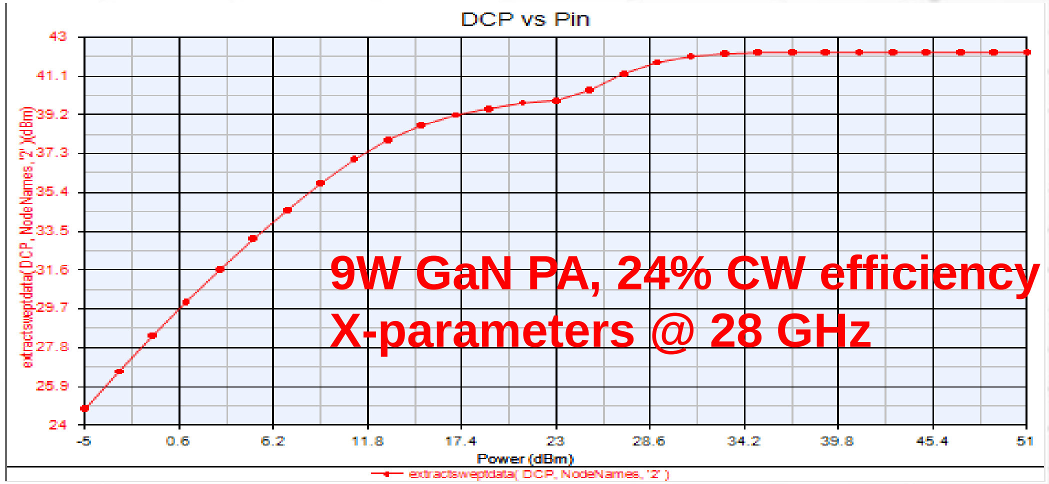
Small vs. Large-signal Sidelobes – GaN PA array @ 28 GHz

8X8 ARRAY, X-PARAMETER DEVICE









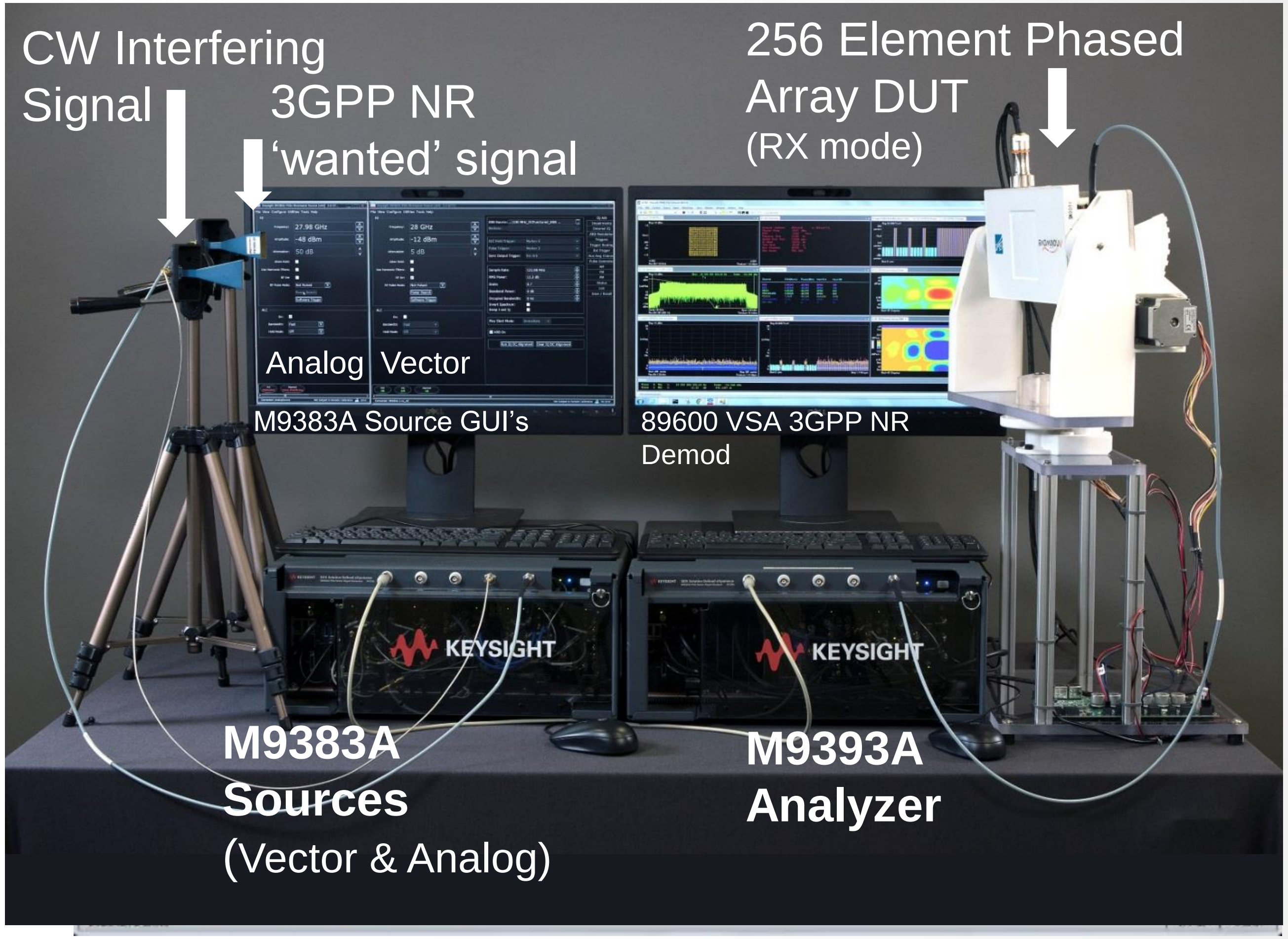
Case Study: Verify Performance on Antenna

Challenge: Base station vendor wanted < 1 % EVM on a Wideband Signal

- Is the waveform created with 5G compliant waveform with numerology, UL, DL scheduling?
- Can the equipment produce clean mmWave signals?
- Performance mmWave measurements?

Solution: Flexible Testbed

- 5G NR compliant waveform generation; N7631C & M9383A
- Best-in-class EVM performance; N9040B or M9393A with 89601B (VSA)
- Flexible configurations can scale as the standards evolve

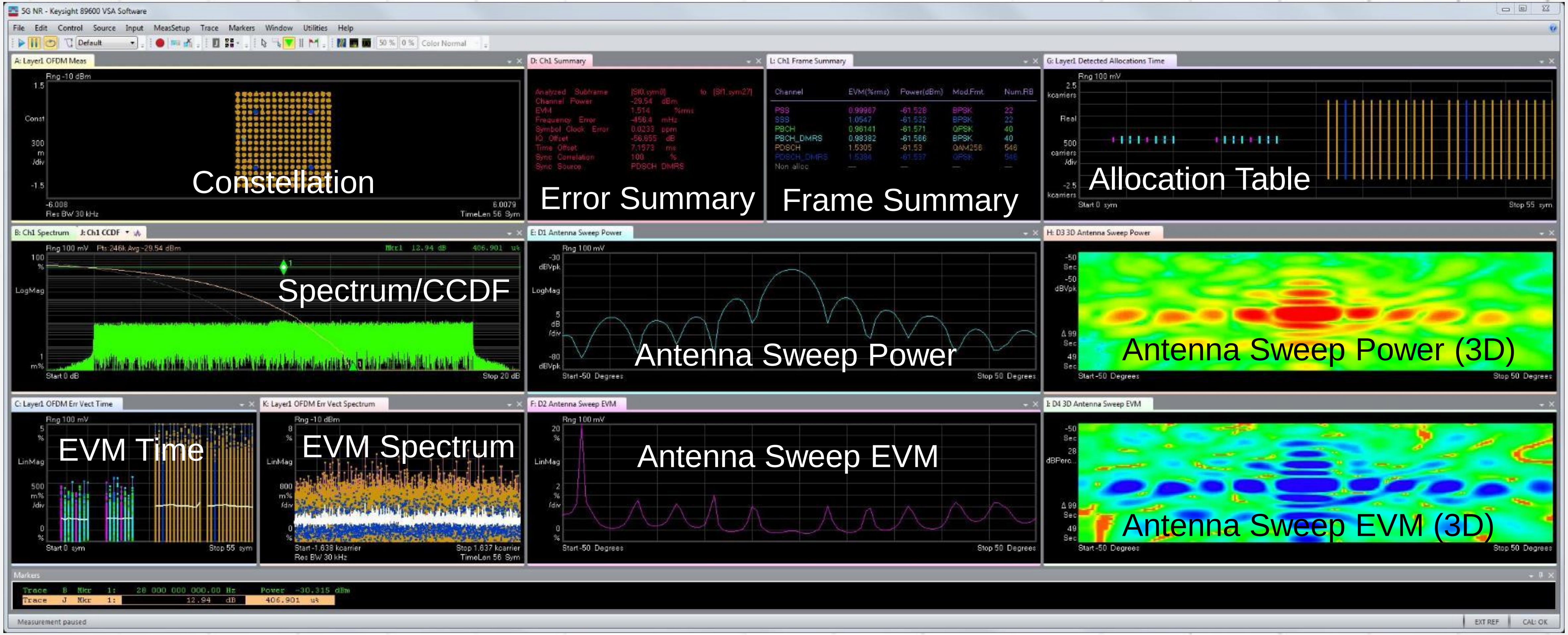


https://www.youtube.com/watch?v=FQBIxIw-nok

Verify Performance on Antenna

3GPP 5G NR MEASUREMENT DETAIL WITH VSA

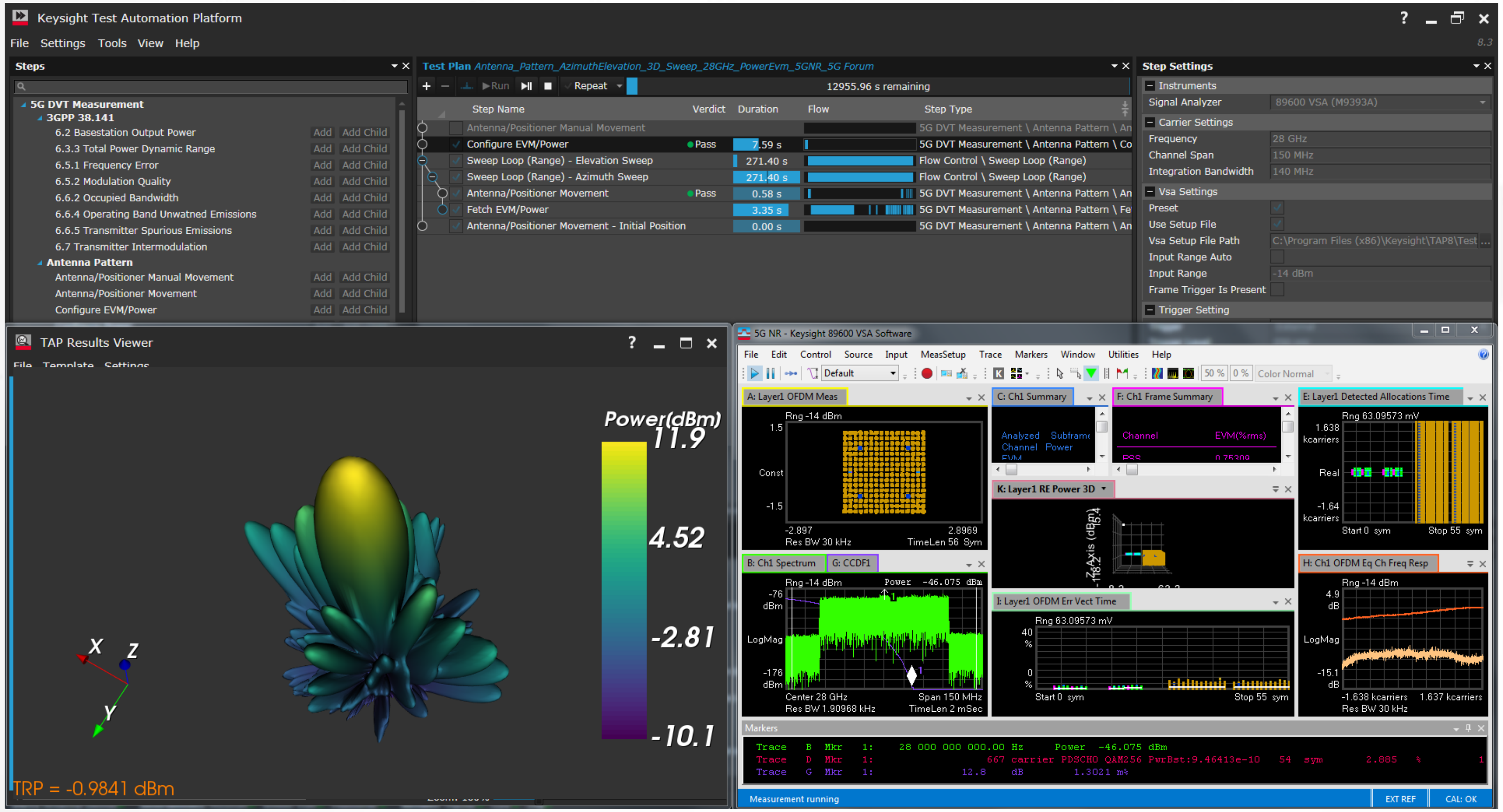
5G NR Downlink
100 MHz BW @ 28 GHz
256 QAM payload



5G Conformance Test SW

TEST AUTOMATION WITH PATHWAVE TEST

Pathwave Test SW User Interface showing results from Phased Array DUT



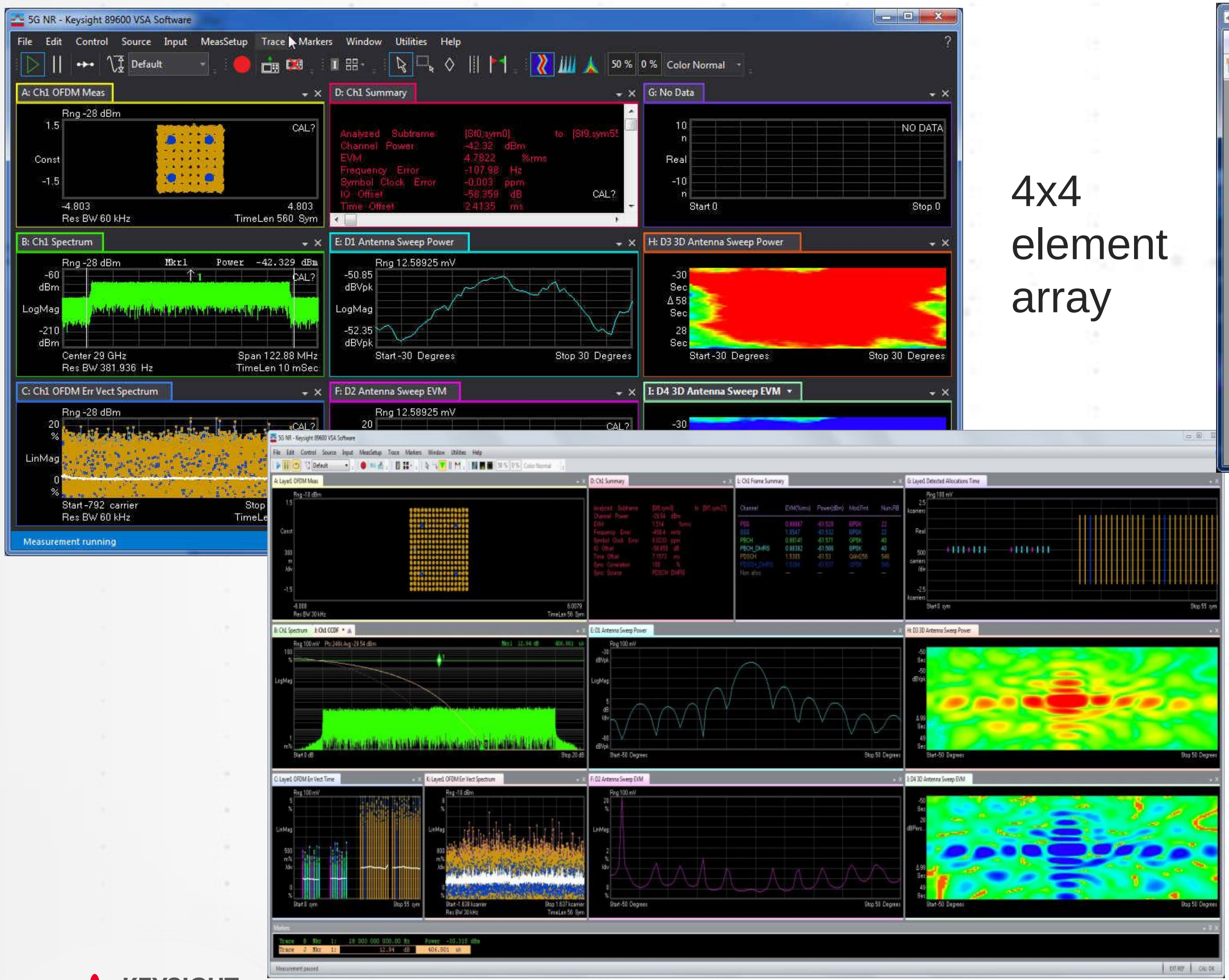
Conformance Test Measurements can be sequenced over frequency/amplitude etc to build specific test plans for a given base station class and configuration

- Create & Playback 5G test waveform
- AUT control
  - Mode; Tx or Rx
  - Beam Steering or Boresight
- Positioning
  - Azimuth
  - Elevation
- Measurements;
  - Power / EVM
  - Antenna beam pattern (at boresight)
  - Antenna beam power surface over azimuth and elevation
  - etc

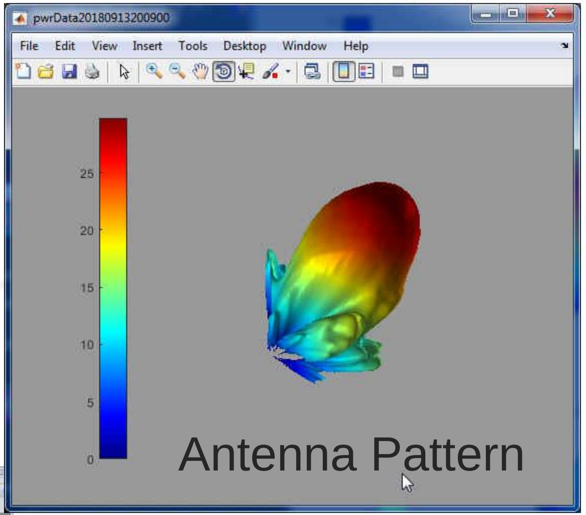
Verify Performance on Antenna

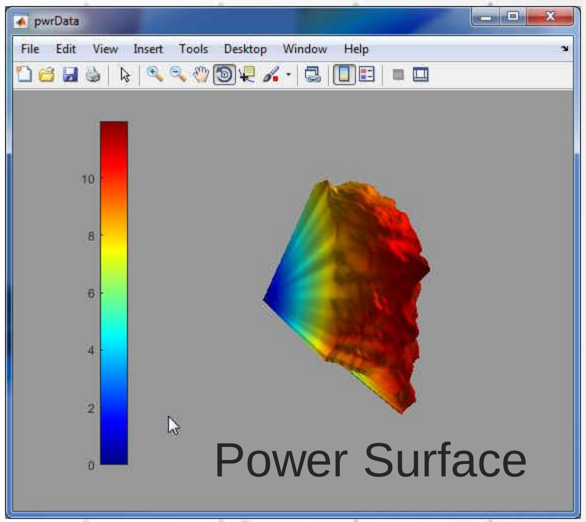
3GPP 5G NR MEASUREMENT DETAIL (EXAMPLES)

5G NR Downlink
100 MHz BW @ 28 GHz
64/256 QAM payload

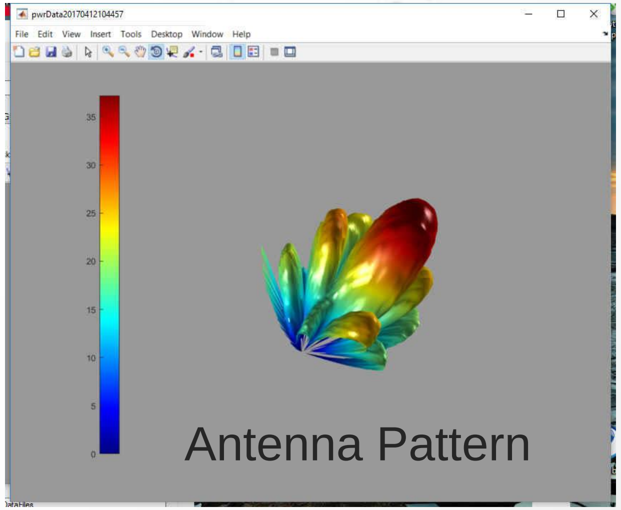


4x4 element array



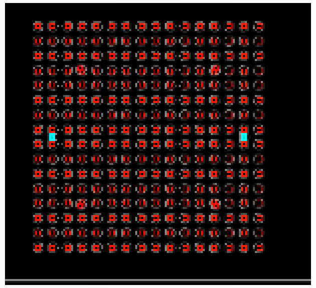


16x16 element array

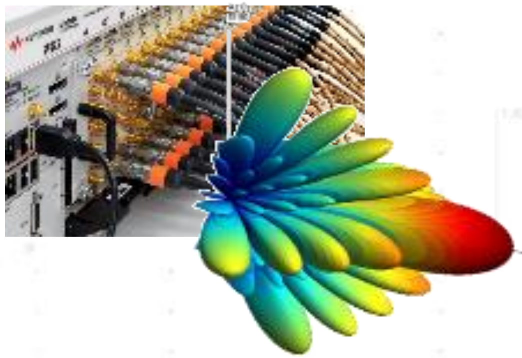


7 Key Measurement Challenges

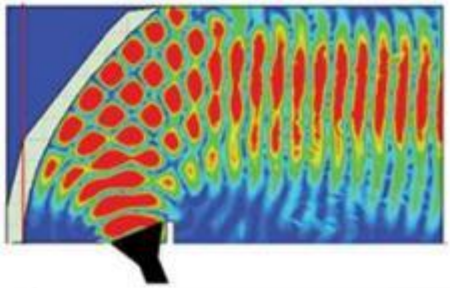
Signal Quality
mmW, Waveform, Fidelity



Lots of Channels
MIMO/Beamforming



Life Beyond Connectors
Over-the-Air



4

5

6

7

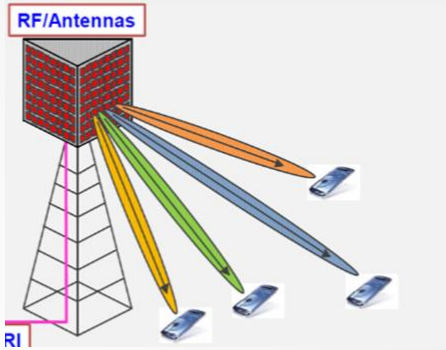
3GPP UE & gNB Tx Conformance Test requirement docs

3GPP NR UE Tx test requirement	Minimum Requirement (2018-06)	Conformance Requirement (2018-09 draft)*	UE
Part 1: Range 1 Standalone	TS38.101-1 v.15.2.0	TS38.521-1 v.1.0.1	FR1, Conducted
Part 2: Range 2 Standalone	TS38.101-2 v.15.2.0	TS38.521-2 v.1.0.0	FR2, Radiated
Part 3: Range 1 and 2 Interworking operation with other radios	TS38.101-3 v.15.2.0	TS38.521-3 v.1.0.0	FR1 and FR2 CA, EN-DC** FR1 Conducted, FR2 Radiated
(*) v.1.0.x is still draft or pre-release status. (Official version should be v.15.x.x) (**) EN-DC: E-UTRA and NR Dual Connectivity			

3GPP NR BTS Tx test requirement	Minimum Requirement (2018-06)	Conformance Requirement (2018-09 draft)*	gNB
Part 1: Conducted testing	TS38.104 v.15.2.0	TS38.141-1 v.1.0.0	FR1, Conducted
Part 2: Radiated testing		TS38.141-2 v.1.0.0	FR1 and FR2, Radiated
(*) v.1.0.x is still draft or pre-release status. (Official version should be v.15.x.x)			

Life Beyond Connectors

Active Antenna System (AAS)



Free-space Path Loss

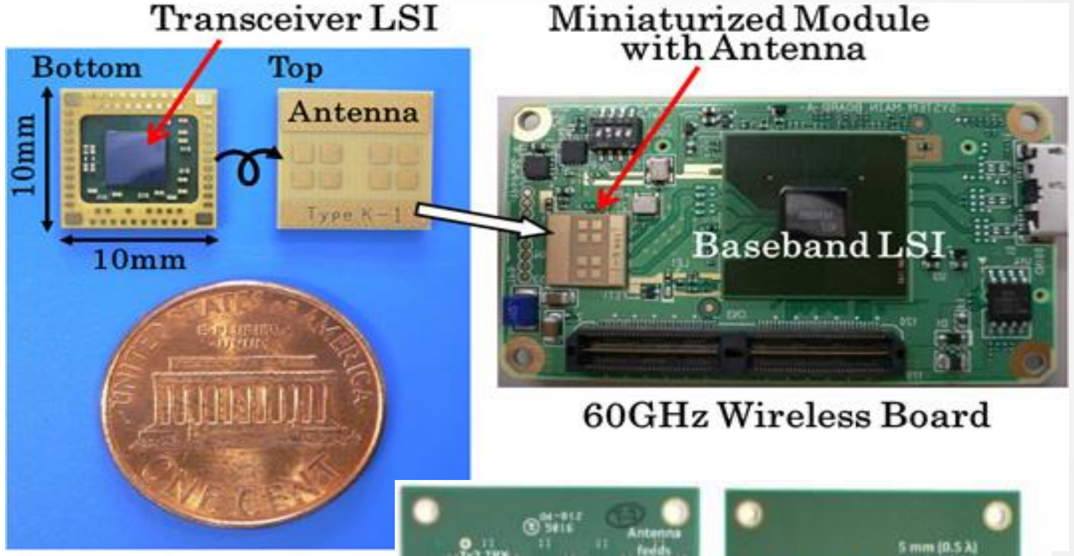
$$Power_{RX} = Power_{TX} + AntGain_{RX} + AntGain_{TX} - 20log_{10}(4\pi R) - 20log_{10}\left(\frac{f}{c}\right)$$

The Good News:

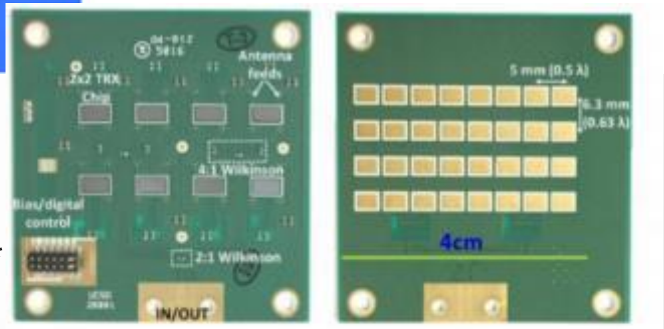
- Higher frequency antenna elements are smaller
- Easier to assemble into electronically steered arrays
- Reduced interference. Energy goes where it's needed
- Improve performance in dense crowds (5G goal)
- Higher frequencies ⟶ wider bandwidths: faster (5G goal)

Challenges:

- Antenna are directional
- Increased complexity with more elements, very small for probing or conducted test
- Multiple antenna arrays required for spherical coverage
- Traditional cabled test methods obsolete – **OTA needed**



28 GHz RFIC*

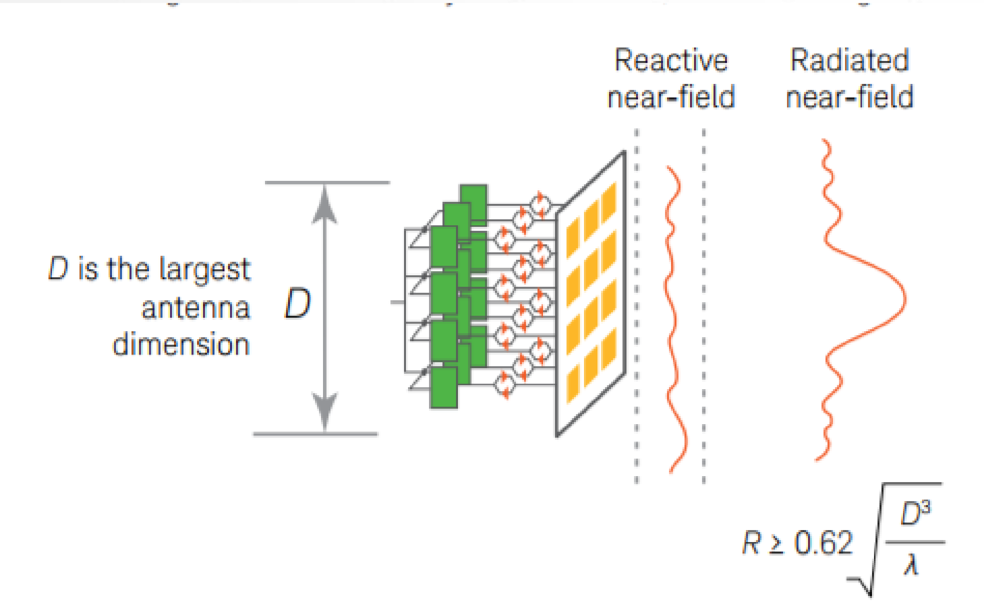


* Image courtesy of Professor G. Rebeiz of U of Ca, SD

Far-Field Test Challenges with mmWaves

LONGER FAR-FIELD AND HIGHER PATH LOSS

From Keysight White Paper: OTA Test for Millimeter-Wave 5G NR Devices and Systems

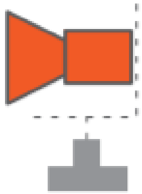


$R \geq \frac{2D^2}{\lambda}$

Fraunhofer distance [R]

Figure 5. Beam evolution as a function of distance from an antenna

Ideal Plane wave is at ∞



What about Path Loss?

Friis Transmission Equation

$$\frac{P_r}{P_t} = \left(\frac{c}{4\pi R f}\right)^2 G_t G_r$$

Path loss proportional to R^2

	Far-Field Distance (m)		
D (mm)	28 GHz	39 GHz	60 GHz
50	0.47	0.65	1
100	1.9	2.6	4
150	4.2	5.9	9
200	7.5	10.4	16
300	16.8	23.4	36.0

What is D?

Fastback Networks V1000

Facebook Terragraph

DFF= $2D^2/\lambda$

DFF= $2 f D^2/c$

D ↑ → DFF ↑

f ↑ → DFF ↑

KEYSIGHT TECHNOLOGIES

FR2 Measurement Challenges

HOW FAR IS THE FAR FIELD?

D (cm)	Freq. (GHz)	Far field (m)	Path Loss (dB)	Freq. (GHz)	Far field (m)	Path Loss (dB)	Freq. (GHz)	Far field (m)	Path Loss (dB)
5	2	0.03	8.93	28	0.47	54.77	43	0.72	62.23
10	2	0.13	20.97	28	1.87	66.81	43	2.87	74.27
15	2	0.30	28.01	28	4.20	73.86	43	6.45	81.31
20	2	0.53	33.01	28	7.47	78.86	43	11.47	86.31
30	2	1.20	40.05	28	16.80	85.90	43	25.80	93.35

TR 38.810 Table 5.3-1: DUT Categories

DUT category	Description
Category 1	Maximum one antenna panel with D ≤ 5 cm illuminated by test signal at any one time
Category 2	More than one antenna panel D ≤ 5 cm without phase coherency between panels illuminated at any one time
Category 3	Any phase coherent antenna panel of any size (e.g. sparse array)

DUT Cat 1 DUT Cat 2 DUT Cat 3

Three Common OTA Methods

SUITABILITY FOR MMW TEST

Direct Far Field simulates behavior of real-world operation—in which DUT receives just a plane-wave. Rayleigh ranged defined as $2D^2/\lambda$.

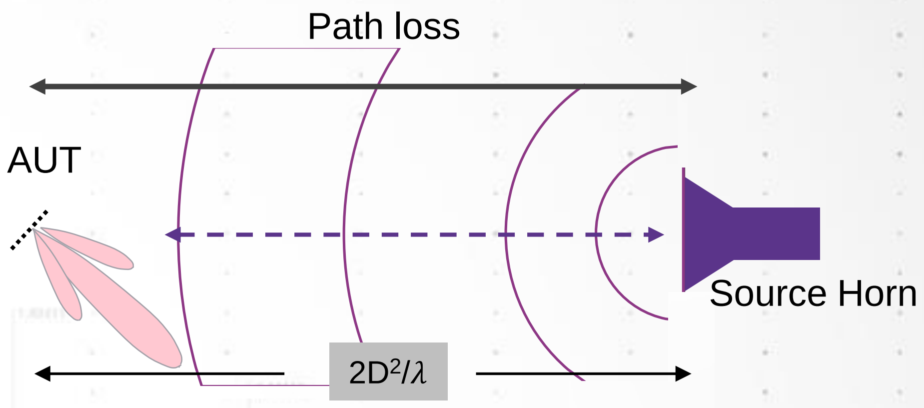
- **Key questions: *what is D? How large is the required chamber?* Path loss.**

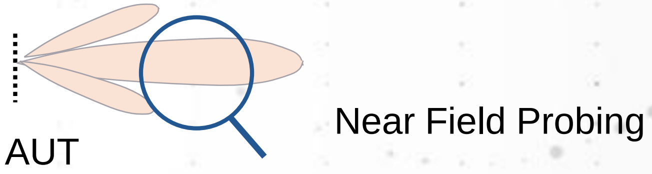
Near-field test systems scan signals in the radiating near-field region and employ mathematical transforms to recover the far-field antenna pattern

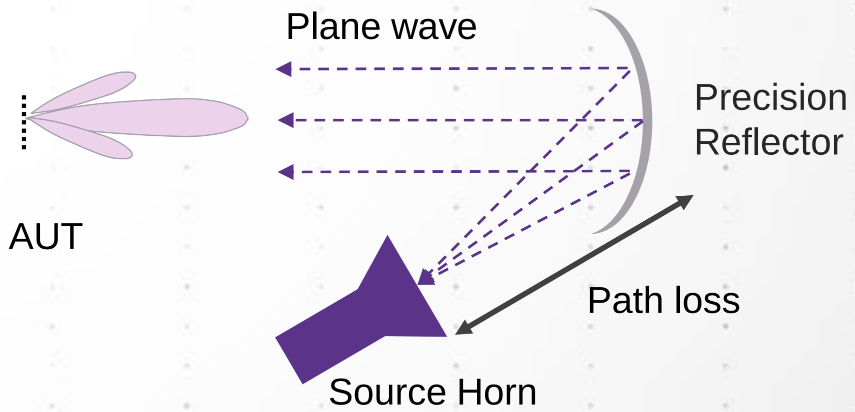
- **Key issues: Device RX, RF parametric, and signaling tests challenging with today's technology.**

Compact Test Range (CATR) or Indirect FF (IFF) uses reflectors to focus the RF energy into a plane wave—enables far-field measurements within a much shorter distance than would normally be required.

- **Key issue: precision reflector design and fabrication required**
- **Key benefit: True far-field in compact footprint**

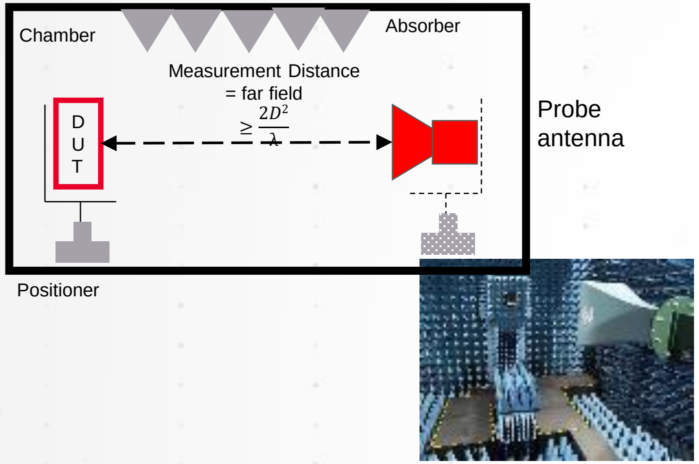






Common OTA Test Methods

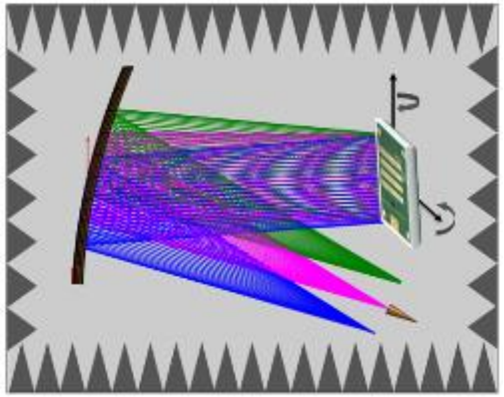
Direct Far Field



- ✓ Simple design, mature
- ✓ Measurement flexibility;
  - ✓ Antenna beam pattern characterization
  - ✓ Beamforming/beamsteering validation
  - ✓ RF parametric tests (if S/N high enough)
- ✓ How devices operate

- × Subject to higher path loss
- × Can get very large for smaller devices at mmWave frequencies
- × Can be slow (mechanical motion), expensive

Indirect Far Field



- ✓ Measurement flexibility
  - ✓ Antenna beam pattern characterization
  - ✓ Beamforming/beamsteering validation
  - ✓ RF parametric tests
  - ✓ End-to-End performance (signaling)
- ✓ Small footprint, even for larger devices
- ✓ Lower path loss, better accuracy

- × Slow (limited by mechanical motion)
- × Expensive (slightly more than DFF)

Near-Field Scanning

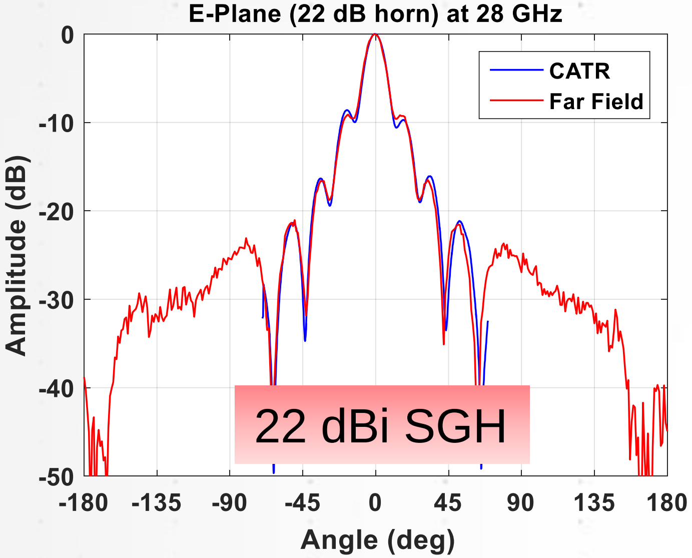
Image courtesy of NSI-MI

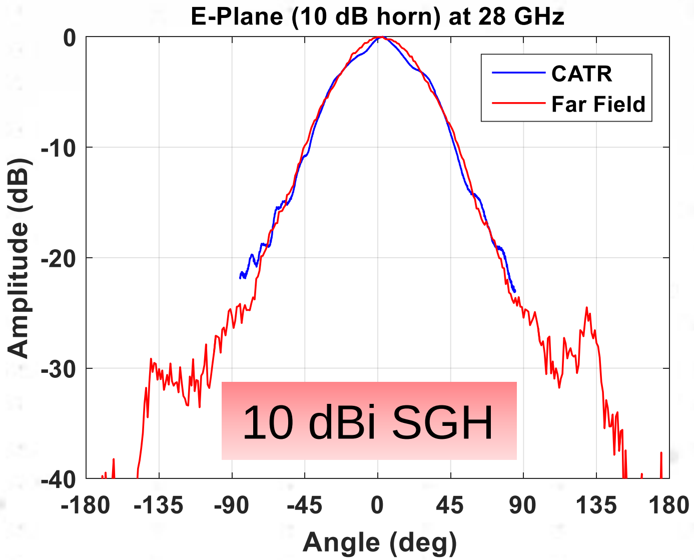
- ✓ Small, lower cost (at mmWave?)
- ✓ Passive antenna;
  - ✓ Antenna beam pattern characterization
  - ✓ Beamforming/beamsteering validation
  - ✓ RF parametric tests (with phase recovery)

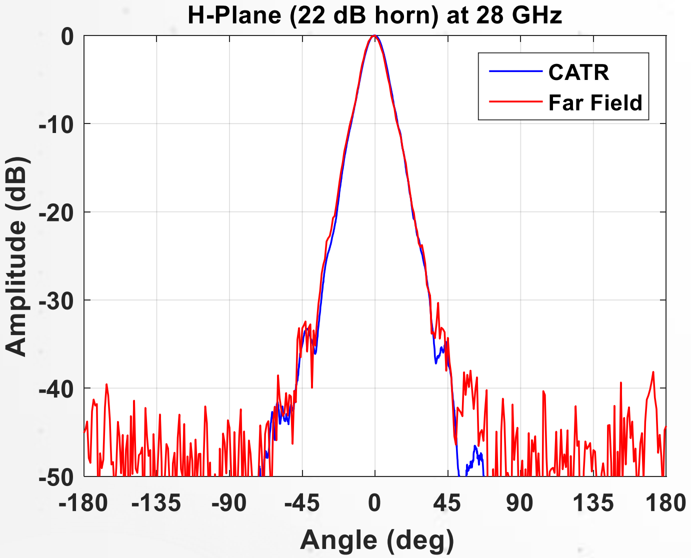
- × Requires highly accurate positioners for mmWave
- × Applicability to modulated signals
- × Tx tests for active devices
- × Rx tests
- × Can be slow

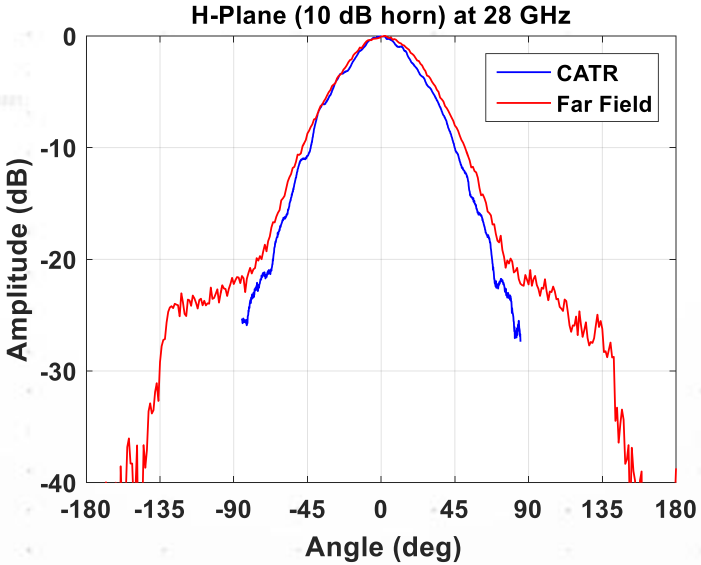
Keysight CATR vs. Far Field Range*

[* http://allwavecorp.com/AntennaMeasurements.php](http://allwavecorp.com/AntennaMeasurements.php)









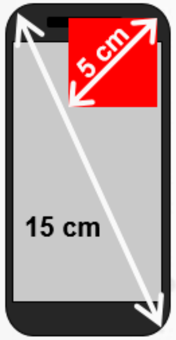
- Comparisons shown for high and low gain horn antennas
- Comparisons show high degree of correlation between the different types of chambers

- 22 dB horn : Sage SAR-2013-34-S2
- 10 dB horn : Pasternack PE9851-10

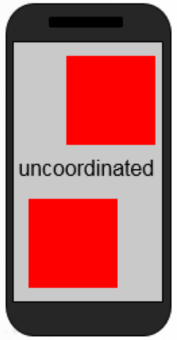
GREAT CORRELATION !

Measurement Systems for NR UE RF Test

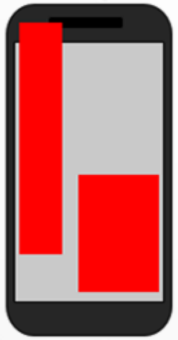
3GPP TR 38.810 STUDY ON TEST METHODS (OTA)



DUT Cat 1



DUT Cat 2



DUT Cat 3

	DFF (Direct Far Field)	IFF (CATR)	NF-TF (Near Field with Transform)
Single panel (Cat 1)	• Tx / Rx • High MU • Max D= 5cm • UE Declaration Required	✓ Tx / Rx ✓ Lowest MU ✓ No Declaration (Blackbox)	• Tx Only • N/A for RX tests • Max D= 5cm • UE Declaration required
Multi-panel with no coherence (Cat 2)	• Tx / Rx • Additional MU factor on Rx • Max D= 5cm • UE Declaration Required	✓ Tx / Rx ✓ Lowest MU ✓ No Declaration (Blackbox)	Not Applicable/Approved
Multi-panel with coherence (Cat 3)	Not Applicable/Approved	✓ Tx / Rx ✓ Lowest MU ✓ No Declaration (Blackbox)	Not Applicable/Approved

MU = Measurement Uncertainty

Newly Approved Indirect Far Field OTA for UE Test

BASED ON CATR / IFF

- The IFF test method based on compact antenna test range (CATR) uses a parabolic reflector to collimate the signals transmitted by the probe antenna.
- Creates a far-field test environment in a much shorter distance and with less path loss than the DFF method.
- Verizon over-the-air (OTA) testing solution using Compact Antenna Test Range Chamber (CATR)

  https://www.youtube.com/watch?v=IJOVIHHB9bw

3GPP gNB Conformance Tests (TS 38.141-1,2)

CHAPTER 6,7,8 MEASUREMENT DETAILS

3GPP NR gNB Conformance Test Summary
(Conducted & Radiated)

Chap 6, Tx Characteristics

- Output Power
- Output Power Dynamics
  (RE Power Control DR / Total Power DR / ...)
- Transmit On/Off Power
  (TX Off Power / TX Transient Period)
- Signal Quality
  (Freq Error / EVM / Time Alignment Error /...)
- Unwanted Emissions
  (Occupied BW / ALCR / Spurious /...)
- Transmitter Intermodulation

Summary
- Requires time aligned digitizers
  Or digitizers with wide BW

Chap 7, Rx Characteristics Tests

- Reference sensitivity level
- Dynamic range
- Adjacent Channel Selectivity (ACS)
- Blocking characteristics
- Intermodulation characteristics
- In-channel selectivity
- Spurious emissions

Summary
- Tests are performed open loop
- Tests require interfering signals
- Performance metric = BLER
  (calculated by eNB)

Chap 8, Rx Performance Requirements Tests

- Performance requirements for PUSCH
  - Multipath fading propagation conditions
  - UL timing adjustment
  - HARQ-ACK multiplexed on PUSCH
  - High speed train conditions
- Performance requirements for PUCCH
  - ACK missed detection for single user PUCCH format 1a
  - CQI missed detection for PUCCH format 2
  - ACK missed detection for multi user PUCCH format 1a
- Performance Requirements for PRACH

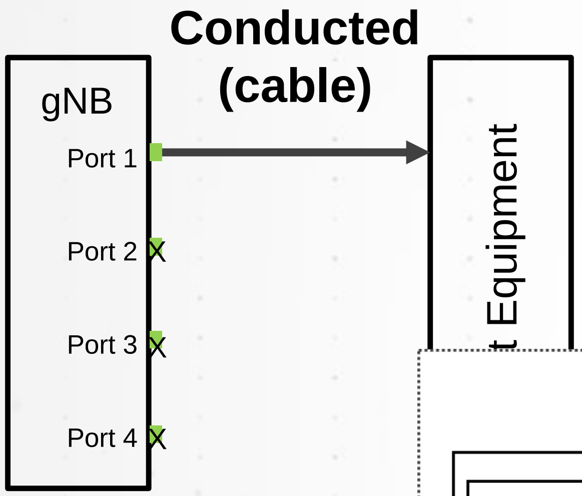
Summary
- 3 tests performed closed loop (implies real-time sig gen)
- Tests require fading of 'wanted' & 'interfering' signals
- Performance metric = throughput
  (calculated by eNB)

Chap 8 Structure not defined yet

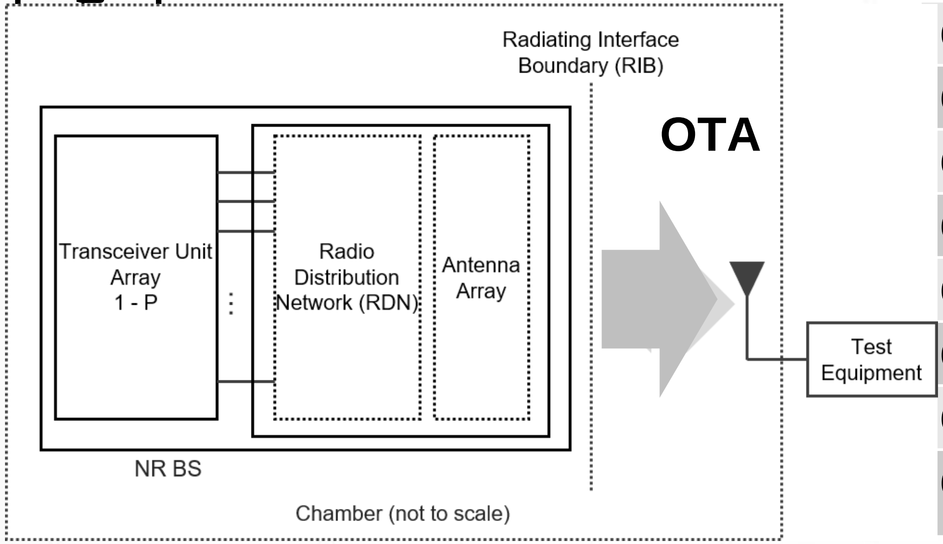
3GPP gNB Transmitter Tests (Chap 6)

BASIC CONFIG FOR MOST TESTS

3GPP TS 38.141-1 (Conducted)
3GPP TS 38.141-2 (Radiated)



FR2 DUTs will require OTA



gNB transmits appropriate **Test Model (NR-TM)**

	Parameters	Metric
6.2, 6.3	OTA Base Station Output Power	EIRP TRP
6.4	OTA Output Power Dynamics	EIRP
6.5.1	OTA Transmit OFF Power	EIRP/TRP
6.5.2	OTA Transient Period	EIRP
6.6.2	OTA Frequency Error	EIRP
6.6.3	OTA modulation quality	EIRP
6.6.4	OTA Time alignment error	EIRP
6.7.2	OTA Occupied Bandwidth	EIRP
6.7.3	OTA ACLR	TRP
6.7.4	OTA Out of band Emissions	TRP
6.7.5	OTA Transmitter Spurious Emissions	TRP

*gNB tests will likely follow the eNB very closely with changes added for **FR2 OTA testing***

OTA Power Measurements

TRP AND EIRP

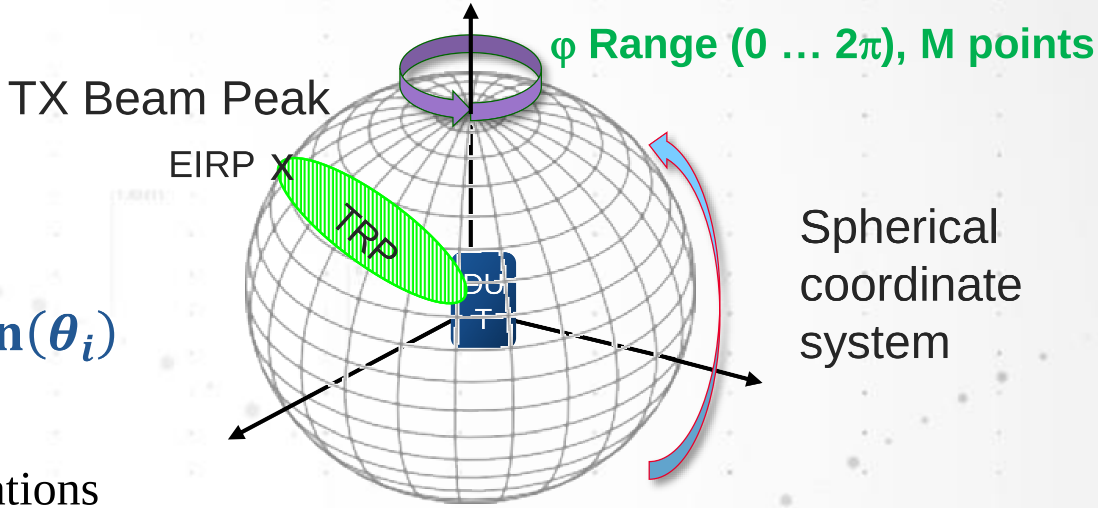
Beam Position:
- gNB – declared
- UE - beam locked

BTS: 3GPP TR37.842 & 843
UE: 3GPP TR38.810

Total Radiated Power (TRP) value for the uniform measurement grid:

$$TRP = \frac{\pi}{2NM}\sum_{i=1}^{N-1}\sum_{j=0}^{M-1}\underbrace{\left[EIRP_{\theta}(\theta_i,\varphi_j) + EIRP_{\varphi}(\theta_i,\varphi_j)\right]}_{\text{EIRP measured at two orthogonal polarizations}}\sin(\theta_i)$$

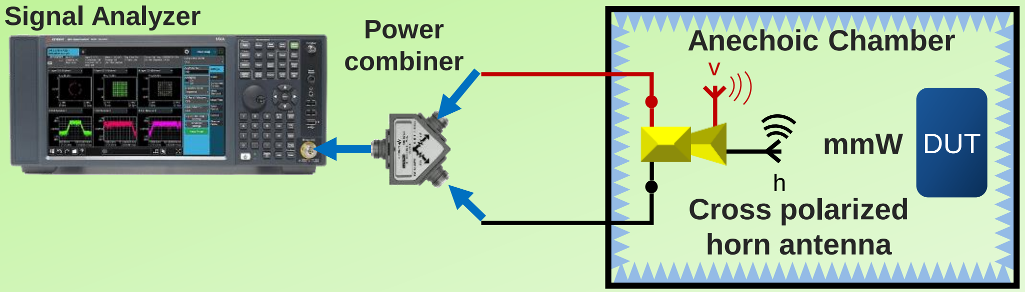
EIRP measured at two orthogonal polarizations



where **N** is the number of angular intervals in the nominal θ range from 0 to π and **M** is the number of angular intervals in the nominal φ range from 0 to 2π.

EIRP = Effective (or Equivalent) Isotropic Radiated Power (usually in dBi).

Measurement taken at one setting of θ and φ



This case, SA can make power/spectrum measurement with the Total EIRP directly

OTA Measurement – gNB Spatial Requirements

OTA AAS BS DECLARATION

Example from 3GPP TR 37.843

Example declarations of an OTA Active Antenna System (AAS) BS with multiple beam widths and beam steering capability;

- For the minimum beam width case: beam width (θ and ϕ) =10°, maximum steering (θ and ϕ) = ±32.5°
- For the maximum beam width case: beam width (θ and ϕ) =35°, maximum steering (θ and ϕ) = ±25°

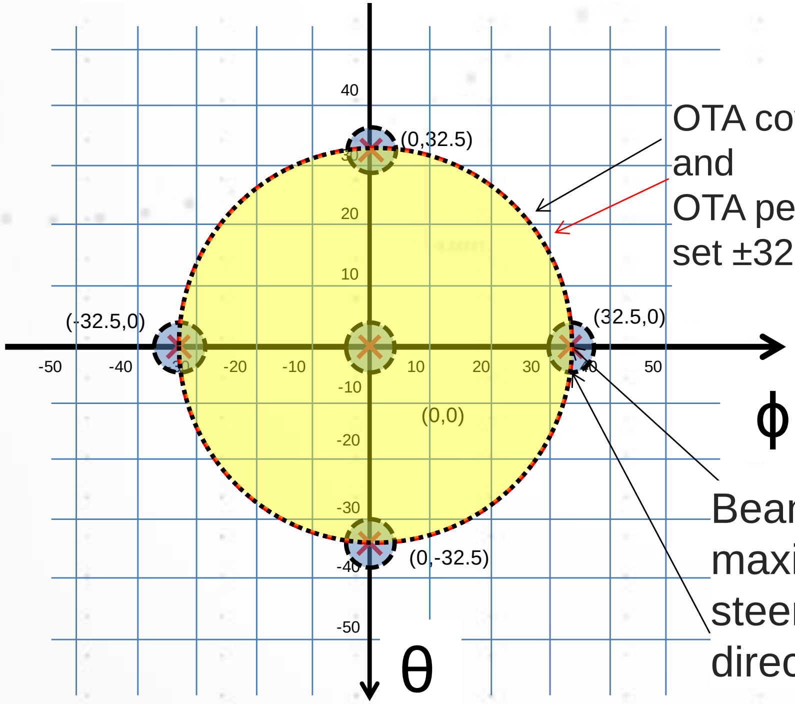
Some Tx measurements made at peak beam position and/or max steering direction;

- Tx Power
- Freq Error
- EVM

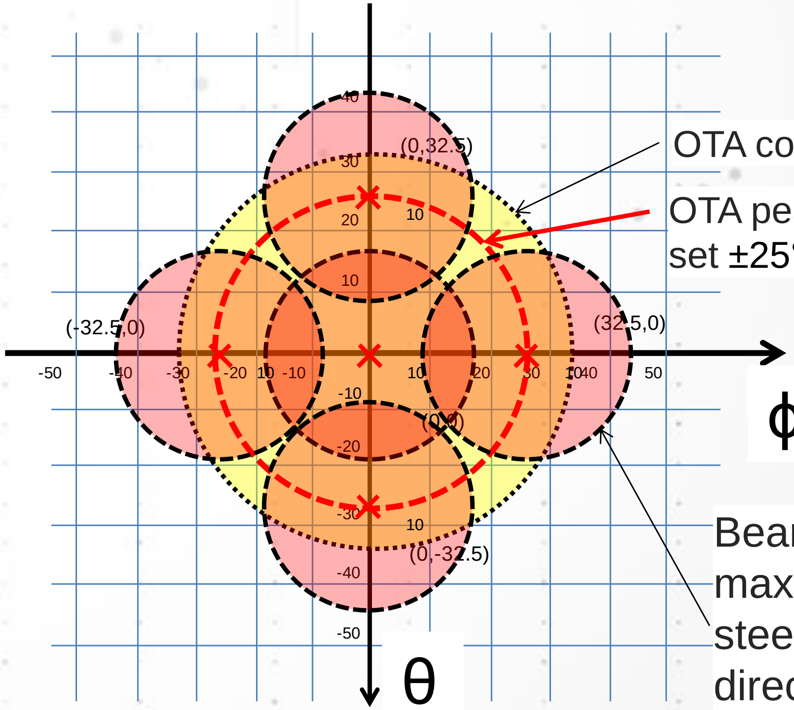
Other measurements made at peak beam position and over grid (TRP);

- Tx Power
- ACLR
- Out-of-Band

Minimum beam width case



Maximum beam width case



What about those NR gNB Test Models?

TS38.141-1 V1.0.0 SEC. 4.9.2 AND TS38.141-2 V.1.0.0 SEC. 4.9.3

- Duration: 1 radio frame (10 ms) for FDD, 2 radio frames (20 ms) for TDD
- Normal CP
- Virtual RB: Localized type

Test Model	TS38.141-1		TS38.141-2	
NR-TM1.1	4.9.2.2.1	BS Output power, OBW, ACLR, OBUE, Spur, Intermod	4.9.3.2.1	BS output power, OBW, ACLR, OBUE, Spur
NR-TM1.2	4.9.2.2.2	ACLR, OBUE		
NR-TM2	4.9.2.2.3	Total power dynamic range (min pwr), 64QAM EVM, Freq error (min pwr)	4.9.3.2.2	Total power dynamic range (min pwr), 64QAM EVM, Freq error (min pwr)
NR-TM2a	4.9.2.2.4	Total power dynamic range, 256QAM EVM, Freq error		
NR-TM3.1	4.9.2.2.5	Total power dynamic range (max pwr), 64QAM EVM, Freq error (max pwr)	4.9.3.2.3	Total power dynamic range (max pwr), 64QAM EVM, Freq error (max pwr)
NR-TM3.1a	4.9.2.2.6	Total power dynamic range (max pwr), 256QAM EVM, Freq error (max pwr)		
NR-TM3.2	4.9.2.2.7	Freq error, 16QAM EVM		
NR-TM3.3	4.9.2.2.8	Freq error, QPSK EVM		

PHY channel parameters have not been defined yet.

Editor's note: Physical channel parameters for TM2 to be added.

What about those NR gNB Test Models?

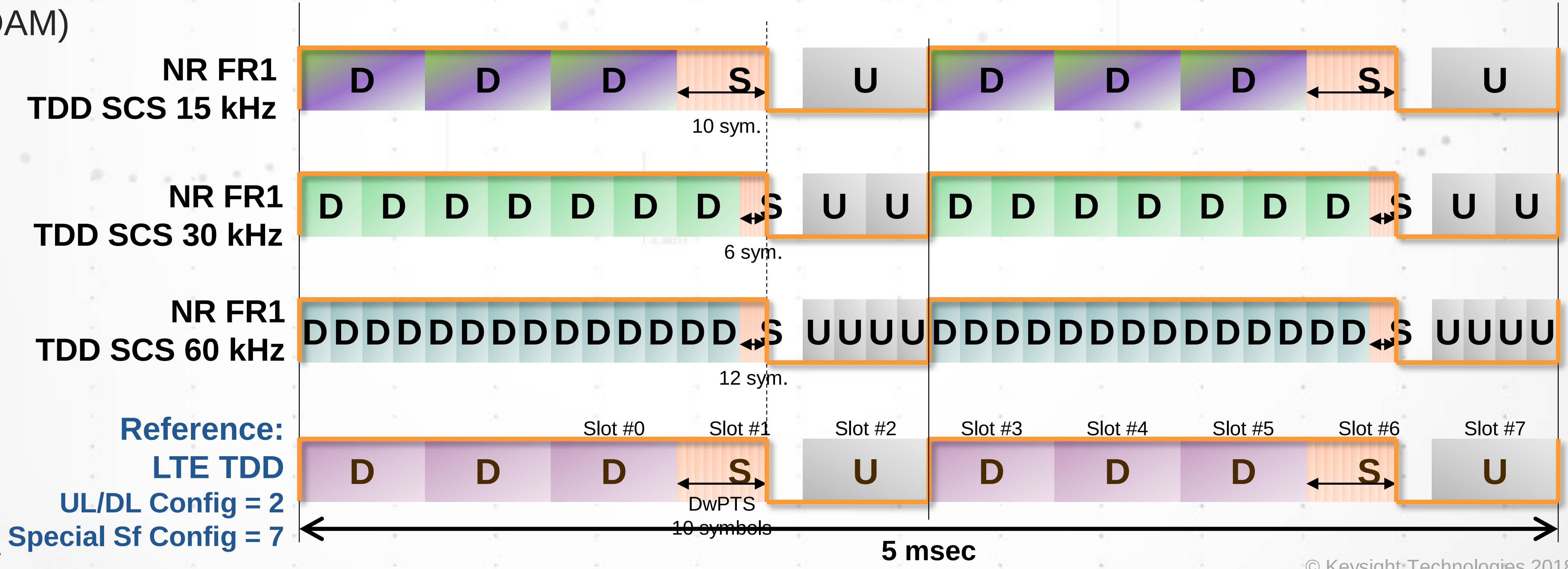
TS38.141-1 SECTION 4.9.2 NR TEST MODELS FOR FR1 TDD

Test model for FR1 TDD frame structure is defined but not the physical parameters.

We can generate this frame structure and populate PRB with any modulation type (eg 64 QAM)

Table 4.9.2.2-1: Configurations of TDD gNB test models for NR FR1

SCS [kHz]	Number of DL slots	Number of DL symbols in S slot	Number of UL symbols in S slot	Number of UL slots
15	3	10	2	1
30	7	6	4	2
60 (Note)	14	12	8	4
Note: There are two S slots. First S slot has 12 DL symbols followed by 2 flexible symbols; second S slot has 6 flexible symbols followed by 8 UL symbols.				



KEYSIGHT TECHNOLOGIES

What about those NR gNB Test Models?

TS38.141-2 SECTION 4.9.3.2 NR TEST MODELS FOR FR2 TDD

Test model for FR2 TDD frame structure is defined but not the physical parameters.

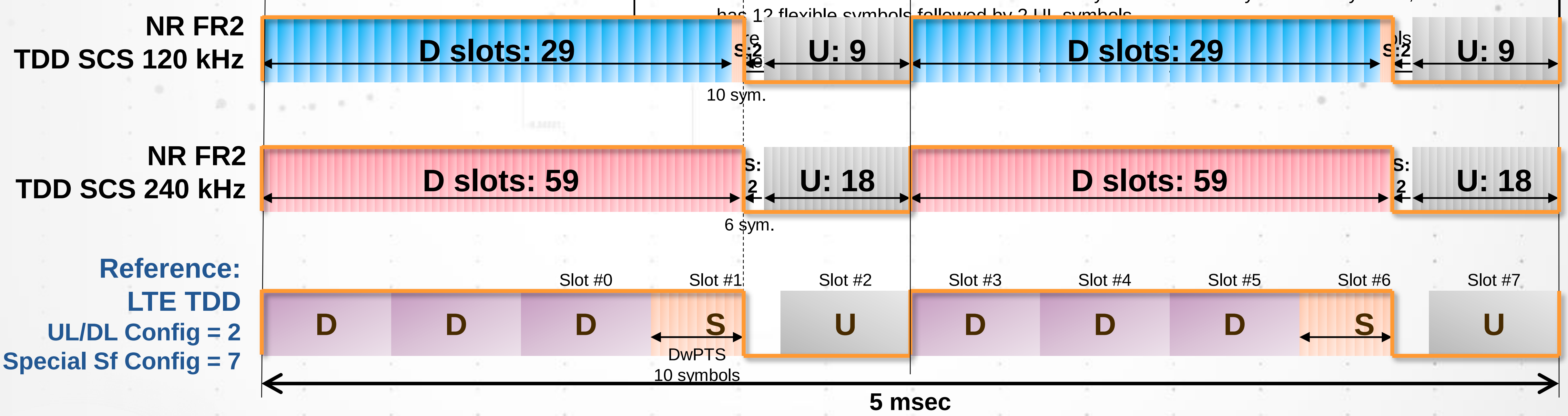
We can generate this frame structure and populate PRB with any modulation type (eg 64 QAM)

Table 6.1.2-1: Configurations of TDD gNB test models

SCS [kHz]	Number of DL slots	Number of DL symbols in S slot	Number of UL symbols in S slot	Number of UL slots
15	3	10	2	1
30	7	6	4	2
60 (Note 1)	14	12	8	4
120 (Note 2)	29	10	2	9
240 (Note 3)	59	6	4	18

Note 1: There are two S slots. First S slot has 12 DL symbols followed by 2 flexible symbols; second S slot has 6 flexible symbols followed by 8 UL symbols.

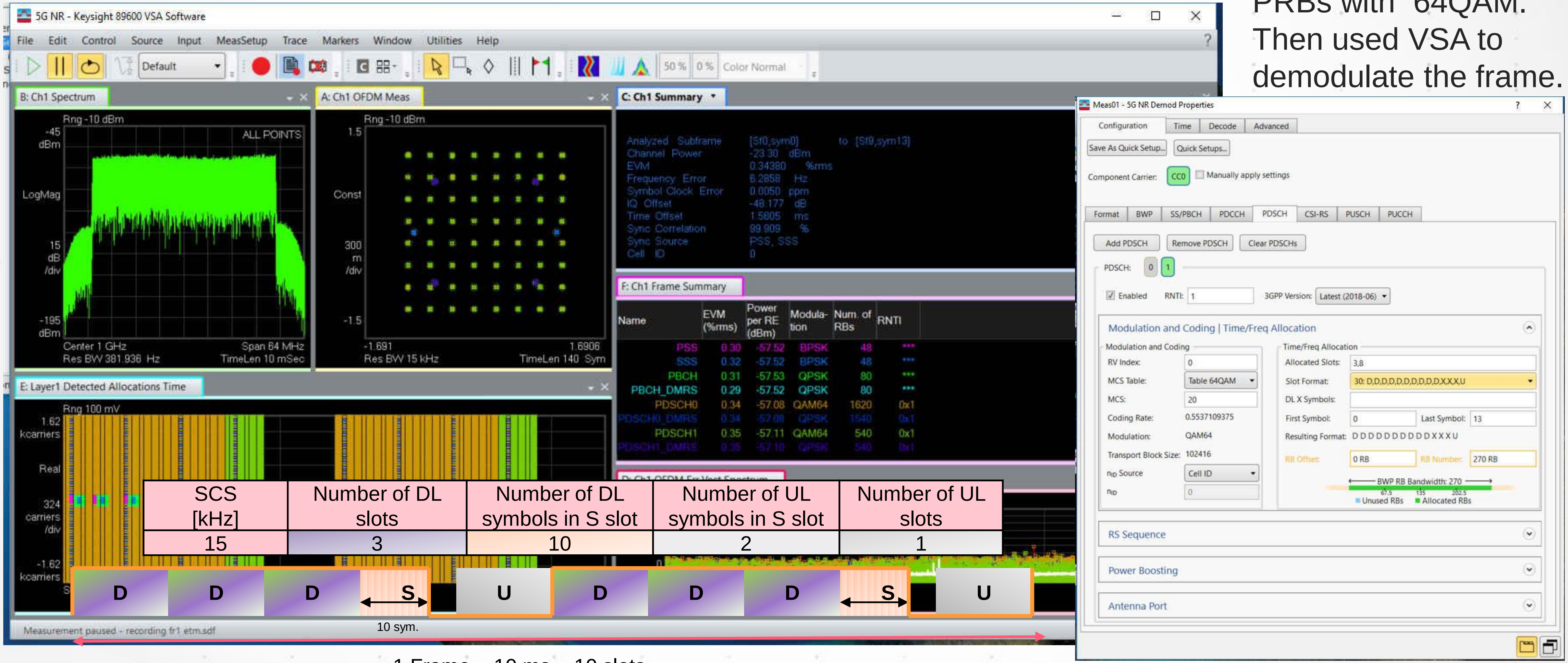
Note 2: There are two S slots. First S slot has 10 DL symbols followed by 4 flexible symbols; second S slot has 12 flexible symbols followed by 2 UL symbols.



What about those NR gNB Test Models?

VSA DEMOD OF NR TEST MODEL FOR FR1 50 MHZ TDD 64QAM

Used signal studio for 5G NR to generate a FR1 TDD **NR-TM** frame and filled all PRBs with 64QAM. Then used VSA to demodulate the frame.



SCS [kHz]	Number of DL slots	Number of DL symbols in S slot	Number of UL symbols in S slot	Number of UL slots
15	3	10	2	1

1 Frame = 10 ms = 10 slots

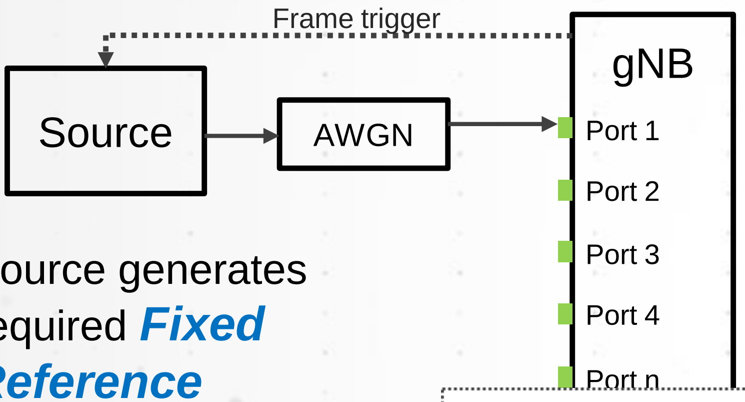
KEYSIGHT TECHNOLOGIES

3GPP gNB Receiver Characteristics (Chap 7)

BASIC TEST CONFIG

3GPP TS 38.141-1 (Conducted)
3GPP TS 38.141-2 (Radiated)

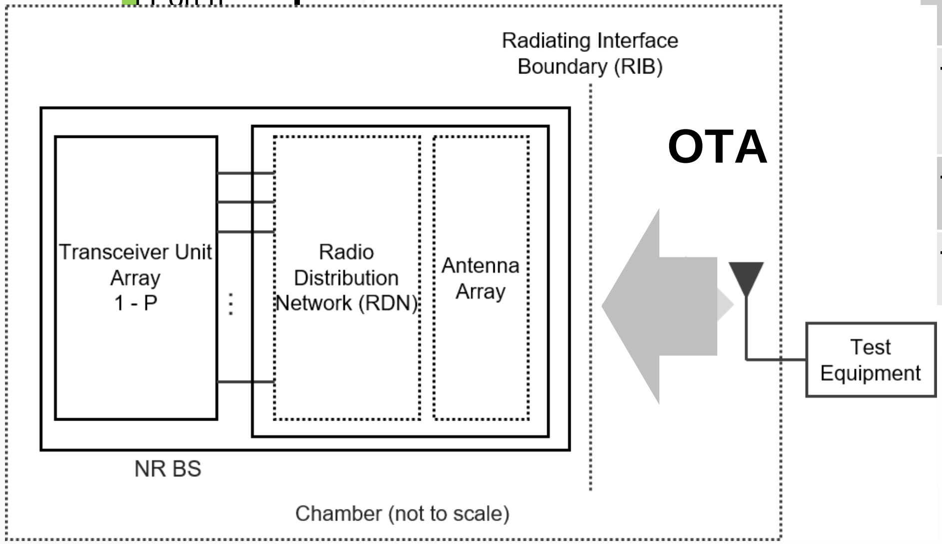
Conducted (cable)



gNB Calculates throughput based on received CRC

Source generates required ***Fixed Reference Channel (FRC)***

FR2 DUTs will require OTA



Receiver Sensitivity & Dynamic Range Tests

	Parameters	Metric
7.3	OTA Reference Sensitivity Level	EIS
7.4	OTA Dynamic Range	EIS
7.5.1	OTA adjacent channel selectivity	EIS
7.5.2	OTA in-band blocking	EIS
7.6	OTA Out-of-band Blocking	EIS
7.7	OTA Receiver Spurious Emissions	TRP
7.8	OTA Receiver Intermodulation	EIS
7.9	OTA In-channel Selectivity	EIS

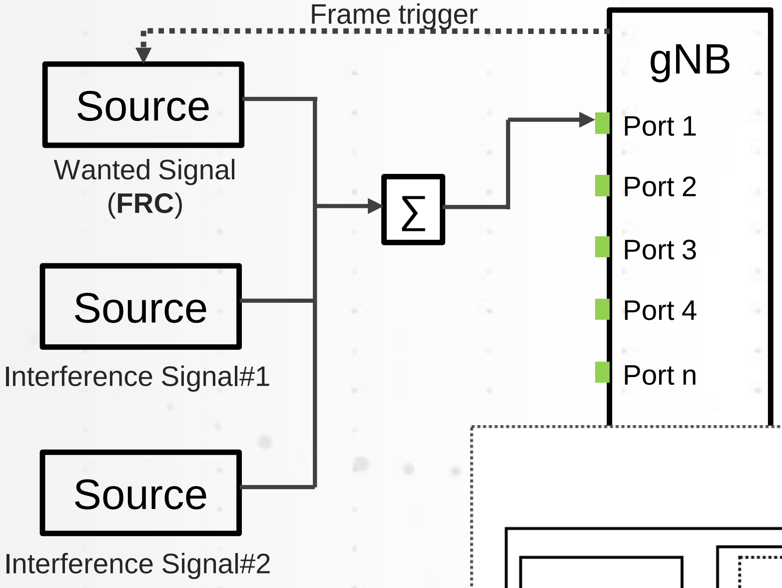
EIS = Effective (or Equivalent) Isotropic Sensitivity

3GPP gNB Receiver Characteristics (Chap 7)

ADDITIONAL TEST CONFIGS

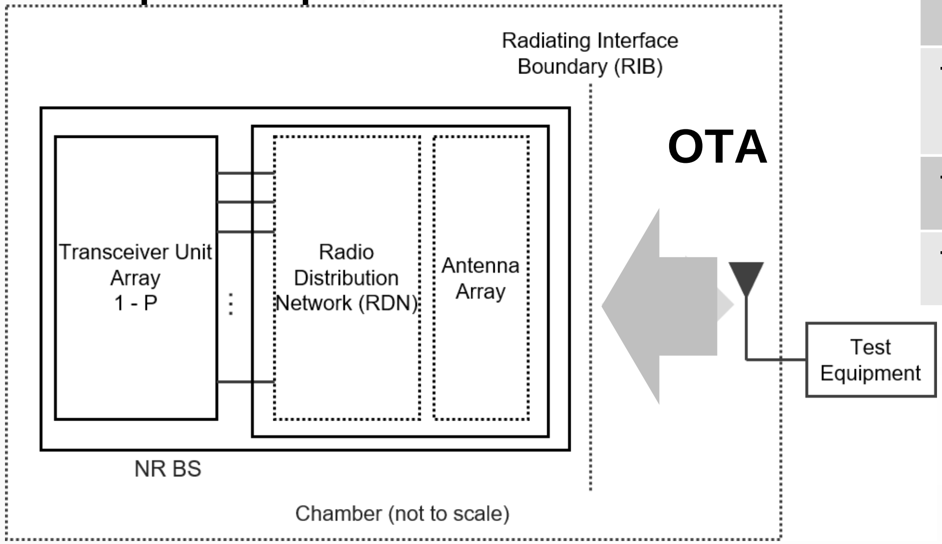
3GPP TS 38.141-1 (Conducted)
3GPP TS 38.141-2 (Radiated)

Conducted (cable)



gNB Calculates throughput based on received CRC

FR2 DUTs will require OTA



Intermodulation Tests
(Blocking & Selectivity tests similar)

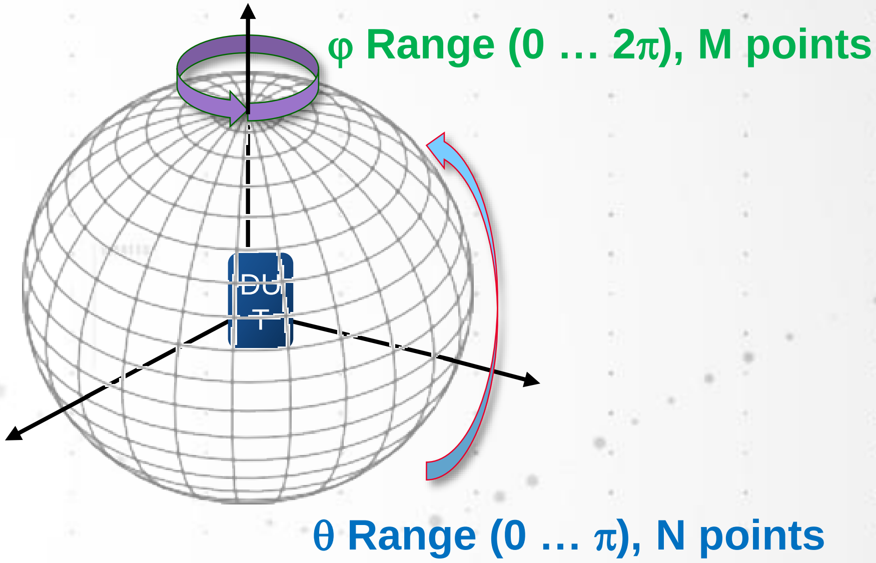
	Parameters	Metric
7.3	OTA Reference Sensitivity Level	EIS
7.4	OTA Dynamic Range	EIS
7.5.1	OTA adjacent channel selectivity	EIS
7.5.2	OTA in-band blocking	EIS
7.6	OTA Out-of-band Blocking	EIS
7.7	OTA Receiver Spurious Emissions	TRP
7.8	OTA Receiver Intermodulation	EIS
7.9	OTA In-channel Selectivity	EIS

OTA Sensitivity Measurements

TIS AND EIS

Effective Isotropic Sensitivity (EIS) is the measured sensitivity in a single direction (fixed θ and φ). Usually expressed in dBm.

Total Isotropic Sensitivity (TIS) value for the uniform measurement grid:



$$TIS = \frac{2NM}{\pi \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} \left[\frac{1}{EIS_{\theta}(\theta_i, \varphi_j)} + \frac{1}{EIS_{\varphi}(\theta_i, \varphi_j)} \right] sin\theta_i}$$

$$TIS = \frac{4\pi}{\int_0^{2\pi} \int_0^{\pi} [\frac{1}{EIS_{\theta}(\theta_1, \phi_1)} + \frac{1}{EIS_{\phi}(\theta_1, \phi_1)}] \sin\theta_1 d\theta_1 d\phi_1}$$

This summation approximation is valid for TIS in the same way as for TRP.

Fixed Reference Channels (FRC) for gNB Rx Testing

DEFINED IN ANNEX A.X IN TS 38.141-1 & 38.141-2

Annex A (normative):
Reference measurement channels

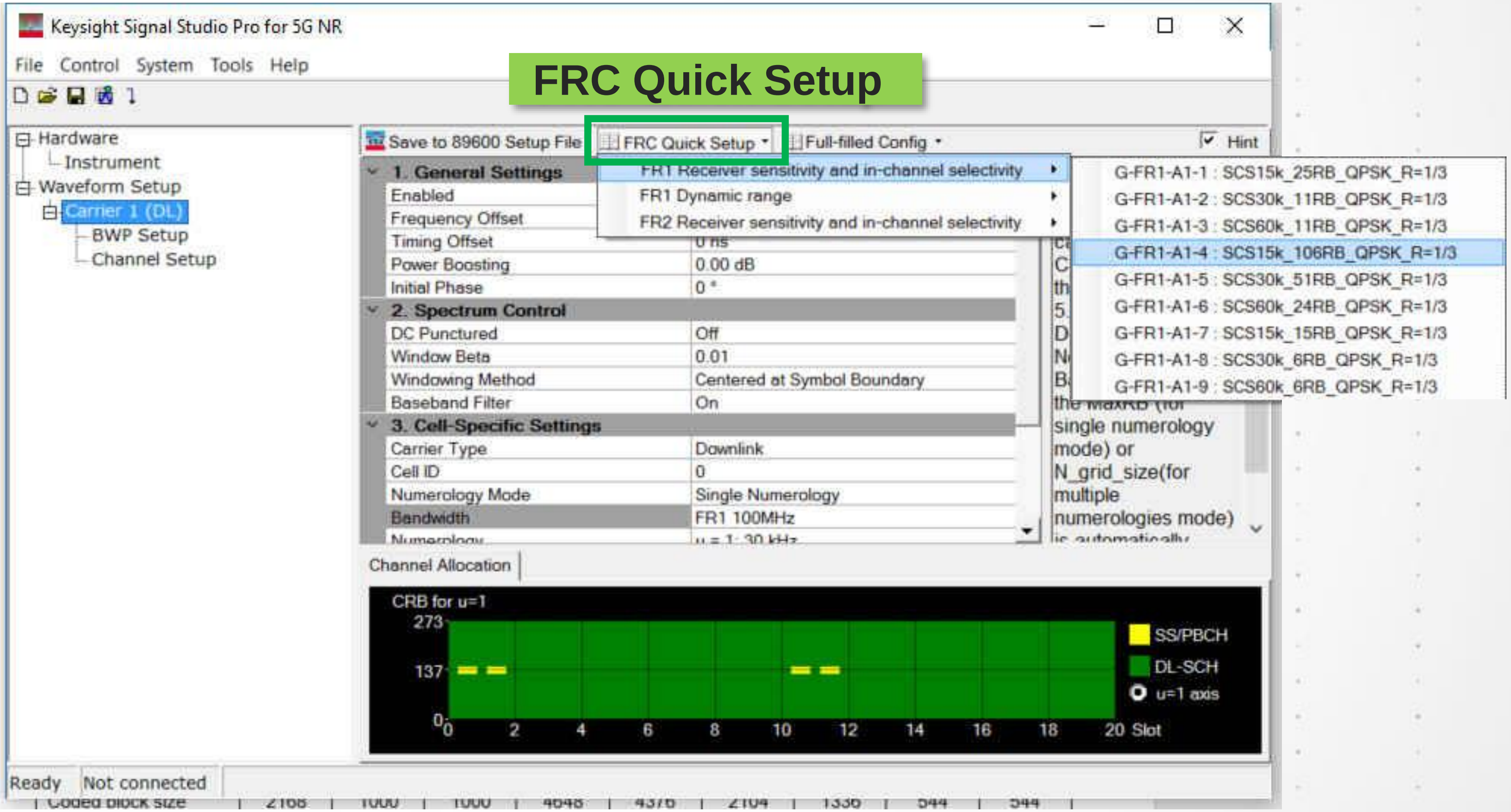
A.1 Fixed Reference Channels for recei
and in-channel selectivity (QPSK, R

The parameters for the reference measurement channels are specified in table A.1-1 f
channel selectivity.

The parameters for the reference measurement channels are specified in table A.1-2 f
channel selectivity.

Table A.1-1: FRC parameters for FR1 receiver sensitivity and ir

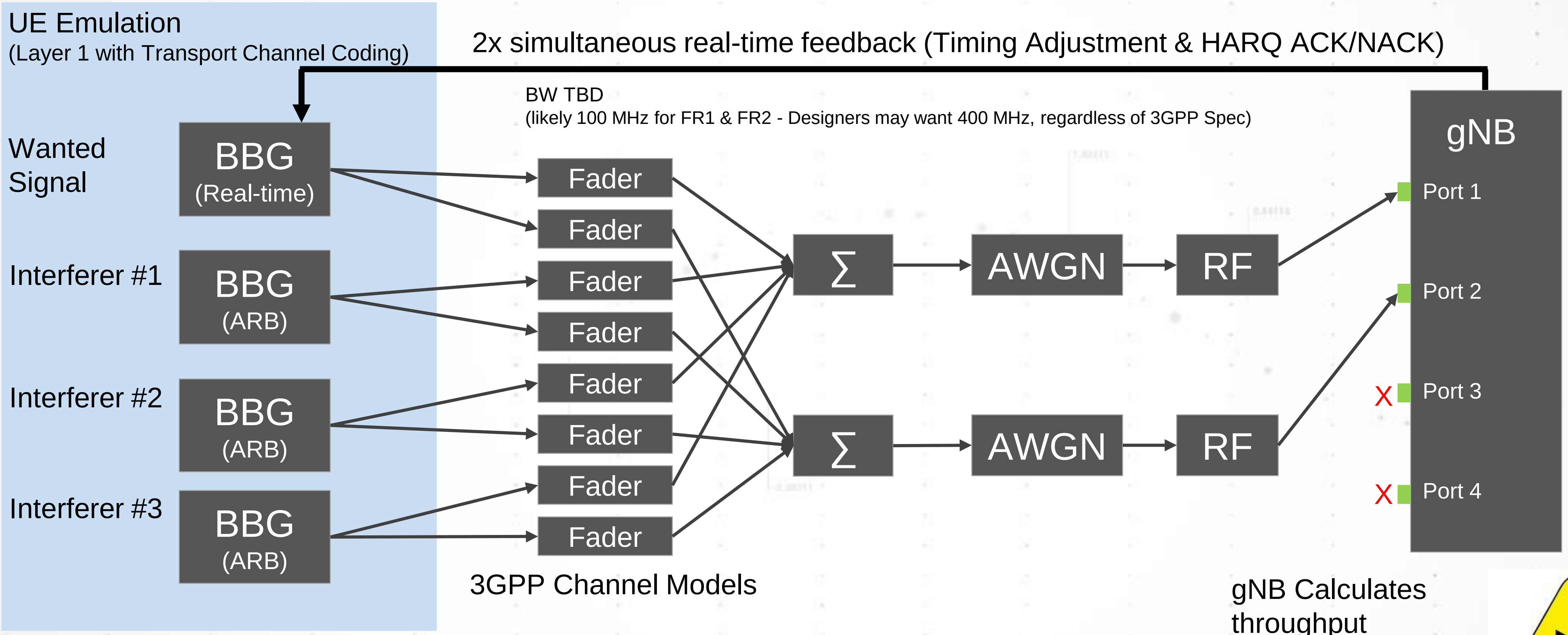
Reference channel	G-FR1-A1-1	G-FR1-A1-2	G-FR1-A1-3	G-FR1-A1-4	G-FR1-A1-5	G-FR A1-
Subcarrier spacing[kHz]	15	30	60	15	30	60
Allocated resource blocks	25	11	11	106	51	24
CP-OFDM Symbols per slot (Note 1)	12	12	12	12	12	12
Modulation	QPSK	QPSK	QPSK	QPSK	QPSK	QPS
Code rate (Note 2)	1/3	1/3	1/3	1/3	1/3	1/3
Payload size (bits)	2152	984	984	9224	4352	208
Transport block CRC (bits)	16	16	16	24	24	16
Code block CRC size (bits)	-	-	-	24	-	-
Number of code blocks - C	1	1	1	2	1	1
Coded block size	2168	1000	1000	4648	4376	210



Signal Studio Pro for 5G NR N7631C

3GPP gNB Receiver Performance Requirements (Chap 8)

EXAMPLE 4X2 TEST CASE



gNB Calculates throughput
(based on CRC)

Do this OTA!

- FR2 DUTs will require OTA
- Legacy LTE supports 8x8 spatial multiplexing (not required in conformance test but of interest in R&D)
- Depending on gNB capability, some tests require: 1x2, 4x2, 2x2, 3x2, **3x4, 3x8**

3GPP UE Conformance Test Requirements: Radiated

TS38.521-2 V.1.0.0 (V.2018-09) - DRAFT

TS38.521-2	Transmitter Test	Measurement	OTA
6.2.1	UE maximum output power	Chan Power	EIRP, TRP
6.2.2	UE maximum output power reduction (MPR)	Chan Power	<FFS>
6.2.3	UE maximum output power with additional requirements	Chan Power	<FFS>
6.2.4	Configured transmitted power	Chan Power	EIRP, TRP
6.3.1	Minimum output power	Chan Power	EIRP
6.3.2	Transmit OFF power	Tx On/Off Power	TRP
6.3.3	Transmit ON/OFF time mask	Tx On/Off Power	EIRP
6.3.4	Power control		EIRP?
6.4.1	Frequency error	Mod Analysis	q- & j- each
6.4.2.1	Error Vector Magnitude	Mod Analysis	q- & j- each
6.4.2.2	Carrier leakage	Mod Analysis	EIRP?
6.4.2.3	In-band emissions (IBE)	Mod Analysis	<FFS>
6.4.2.4, 6.4.2.5	EVM equalizer spectrum flatness, EVM spectrum flatness for pi/2 BPSK with spectrum shaping	Mod Analysis	<FFS>
6.5.1	Occupied bandwidth	OBW	EIRP
6.5.2.1, 6.5.2.2	Spectrum emission mask Additional Spectrum emission mask	SEM	TRP
6.5.2.3	Adjacent channel leakage ratio	ACP	TRP
6.5.3	Spurious emissions	Spur Emissions	TRP

3GPP TS 38.521-2 (Radiated) – UE FR2

TS38.521-2	Receiver Test	Metrics	Assumed Link Direction
7.3	Reference sensitivity level	EIS CDF	Each beam peak search grid
7.4	Maximum input level	Beam peak	RX beam peak direction
7.5	Adjacent Channel Selectivity (ACS)	Beam peak	RX beam peak direction
7.6.2	In-band blocking	Beam peak	RX beam peak direction
7.6.3, 7.7	Out-of-band blocking and Spurious response	FFS	FSS
7.9	Receiver Spurious emissions	FFS	TX beam peak direction
7.10	Receiver image	FFS	FFS

FFS – For Further Study

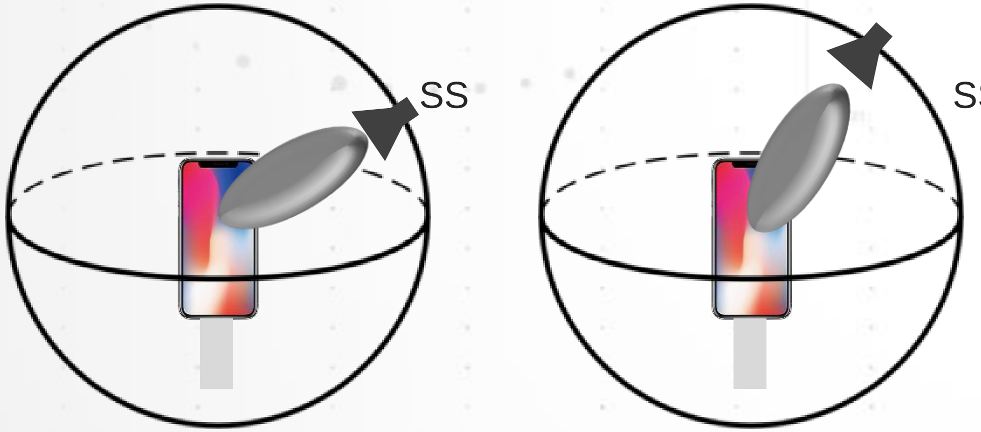
3GPP UE Test Requirements: Radiated

UE BEAMLOCK FUNCTION (UBF)

3GPP TS 38.521-2 (Radiated) – UE FR2

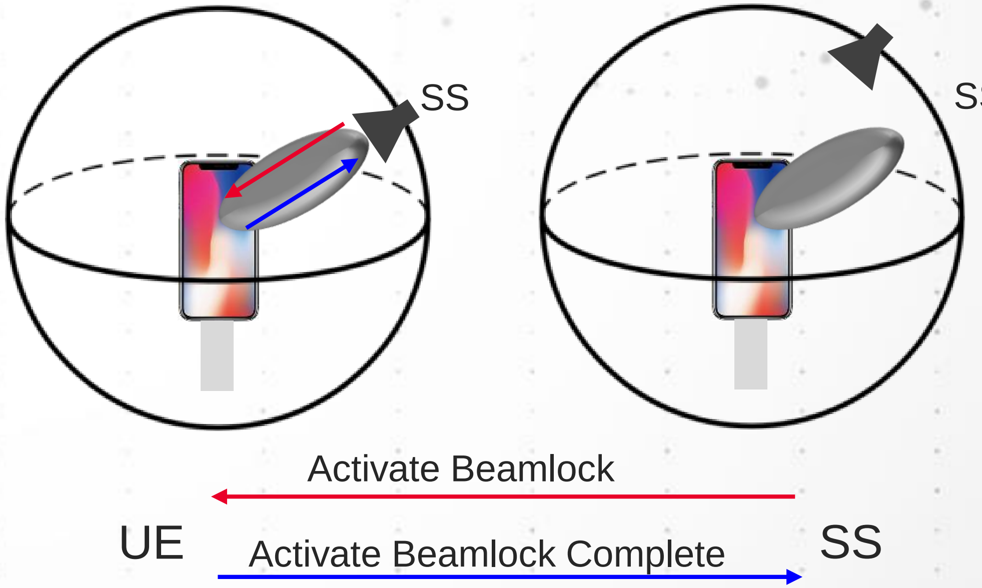
Without UE Beamlock Function (UBF), the UE keeps forming the beam towards the SS

- Required for Spherical Coverage, TX & RX Beam Peak Searches, EIS, EIRP measurements



The **UBF** is intended for making the UE to lock the UE antenna pattern once it has formed a beam towards the base station (SS) direction

- ***Required for <u>TRP</u> measurements***
- Recommended to prevent the beam from moving when performing measurements at low SNRs



Keysight OTA Solutions for mmWave UE Test

FROM R&D TO CONFORMANCE TO CARRIER COMPLIANCE

Rack Mount Test Chamber (RMTC)

- Fits in 19" rack
- 5-cm QZ size
- Single AoA
- Direct far-field
- 1x dual-polarized probe

Light weight, Cable replacement

UE Calibration / Array Calibration / Functional / Protocol Signaling / Performance / Demod tests

Compact Antenna Test Range (CATR) or IFF

- Multiple sizes
- Single AoA
- Indirect Far-field
- 1x dual polarized probe

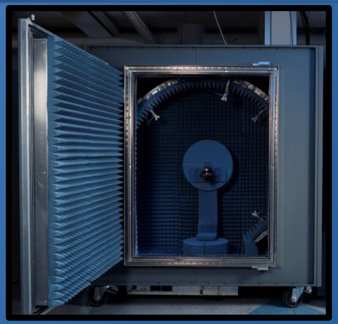
Black-box testing - 3GPP Approved Solution for RF Test

Antenna / RF Parametric / TRP & TIS / Functional (incl. beam tracking) / Protocol testing / Throughput (clean channel)

2D MPAC

- Multiple AoA
- Far-field
- 3-4 dual polarized probe
- 45º 2D arch
- Benchtop installation

Functional (beam forming/ Protocol testing



3D MPAC

- Multiple AoA
- Far-field
- 4 out of 6 X-polarized probes
- 180º basic 3D or sectorized

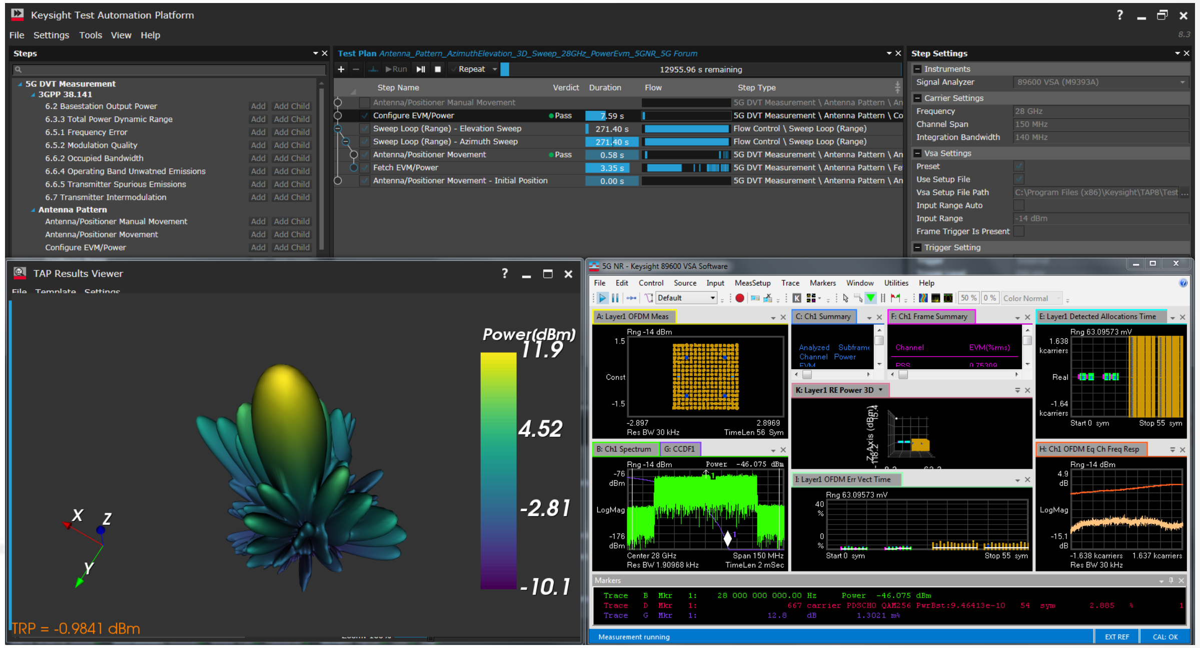
Performance test (with fading – 38.901) / RRM (HO & Throughput) / Virtual drive test / Beam Management

3GPP Conformance Test Solution for gNB

KEY VALUES

5G Testbed Hardware

5G Testbed Software



Solution Value

- Validated gNB conformance tests
- Test Automation Platform enables testing over wide range of conditions
- Flexible solution upgradable as standard continues to evolve

5G Non-Signaling mmWave Transceiver OTA Solution

COVERING THE 28 AND 39 GHZ MMWAVE BANDS

Wideband Transceiver Test Solution

- One Vector Signal Analyzer (VSA), one Vector Signal Generator (VSG) in 2U form factor saves precious rack space
- Simultaneous signal generation and analysis with independent frequency and power
- Two bi-directional IF ports
- Six RF ports for multiple device testing

mmWave Transceiver, 28 GHz and 39 GHz

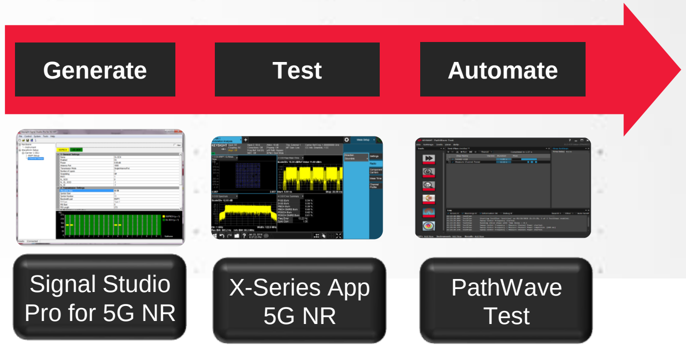
- Tunable between 24 GHz and 43.5GHz bands
- EVM < 1% (depending on number of component carriers)
- Two full duplex ports

Software

- 5G NR and 5G TF measurements based on X-Series measurement applications integrated in the wideband transceiver
- Keysight Signal Studio applications for signal creation

mmWave RF Performance Test Solution

- Over-the-air (OTA) characterization and validation of mmWave device under test.
- EIRP, TRP, TRS, RF parametric measurements



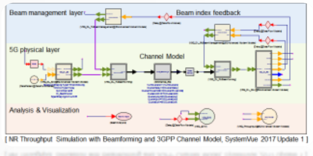
5G Software: "*First in 5G*" & full use of "*Automation*"

ACROSS ENTIRE PRODUCT DESIGN CYCLE

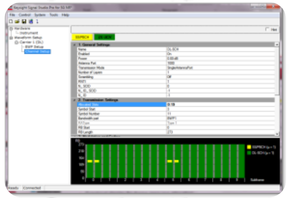
PATHWAVE

Simulate | Generate | Analyze | Test | Automate | IST Solutions

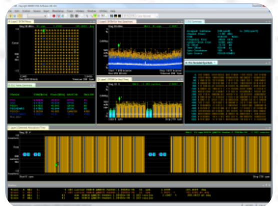
Open.
Scalable.
Predictive.



SystemVue 5G Library

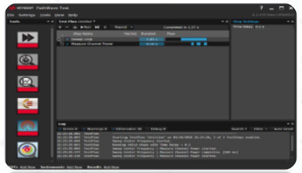


Signal Studio Pro for 5G NR

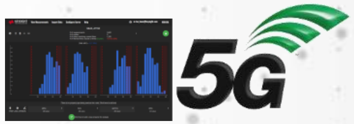


89600 VSA 5G NR

X-Series App 5G NR



PathWave Test



Cloud, KMF and more

EMERGING HW
EMERGING SW
KEY EXPERTISE

PathWave is uniting these areas int a flow

KEYSIGHT
TECHNOLOGIES