Advances in Millimeter Wave and Terahertz Applications

Suren Singh / Application Development Engineer
Keysight Technologies Inc.

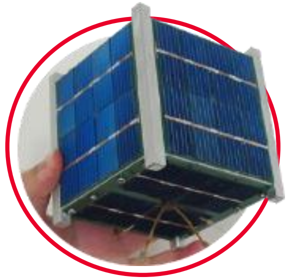
Background

INDUSTRY MOVE TO MM-WAVE

Broader
Frequency coverage

Satellite systems are demanding
higher bandwidth

Offers faster, higher density, secure and safe communications

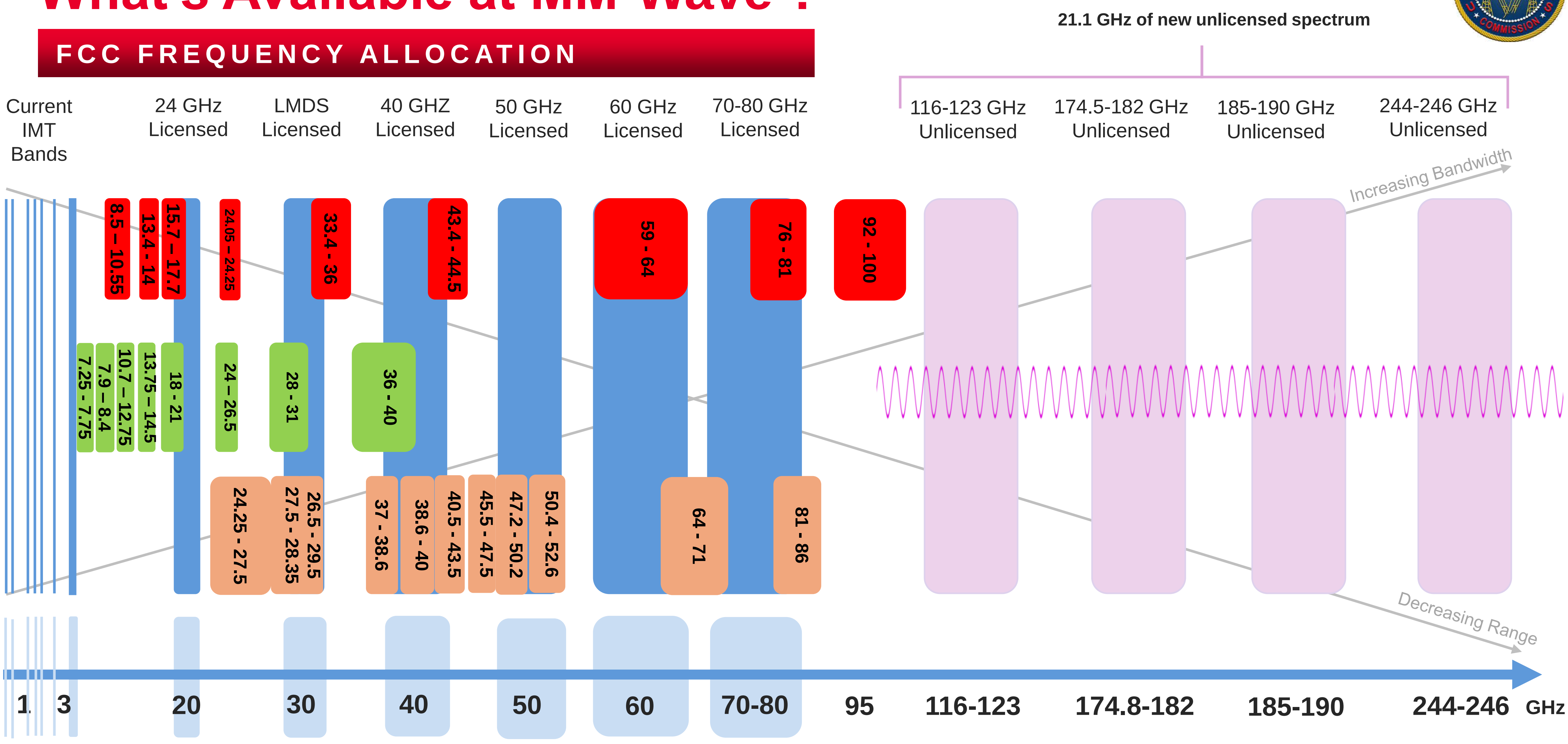


Higher densification of
communications satellites

Faster higher sensitivity
communication systems

What's Available at MM-Wave ?

FCC FREQUENCY ALLOCATION



10 yr. Experimental license use on any frequencies between (95 GHz – 3 THz)

*Gigabit LTE and beyond: Mobilizing millimeter wave

Impact On Wireless Communication

ENABLES NEXT-GENERATION BROADBAND ACCESS

	5/6G	SatComm	802.11ay
Complex Modulations	OFDM 256 QAM	OFDM 256 QAM	Single-Carrier 64 QAM
Wider Bandwidth	100/400 MHz 1.2 GHz (CA)	0.5-2 GHz	4-8 GHz
Higher Frequencies	FR1: <6 GHz FR2: 24 - 52 GHz FR3 & 4: 260 GHz ??	Ka Band 27-40 GHz	57-71 GHz
Multiple Antennas Techniques	Phased array antenna MIMO FR1: 8x8 MIMO FR2: 2x2	Phased array antenna	Phased array antenna MIMO

Space and Satellite

IMPACT ON COMMUNICATION SYSTEMS

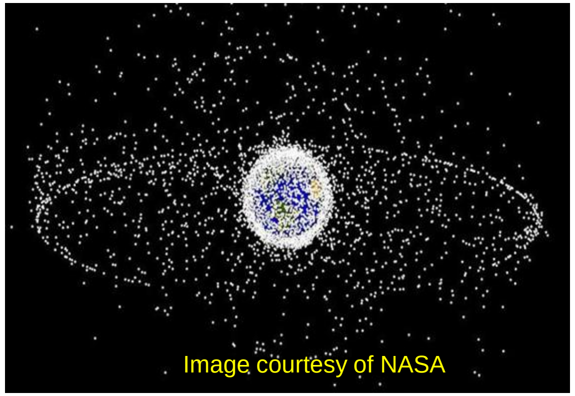
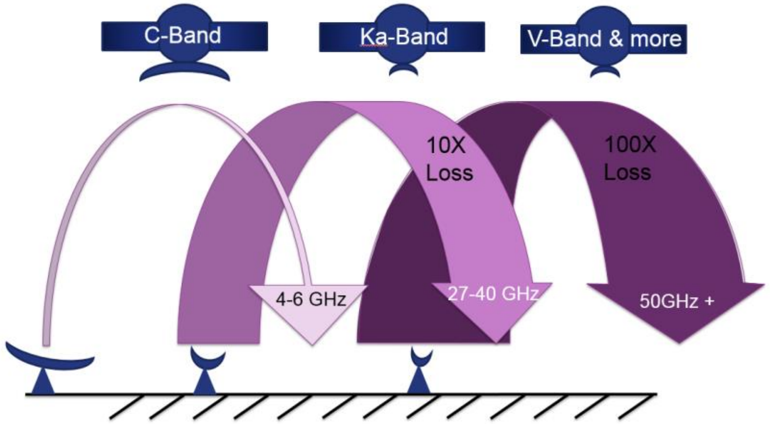


Image courtesy of NASA

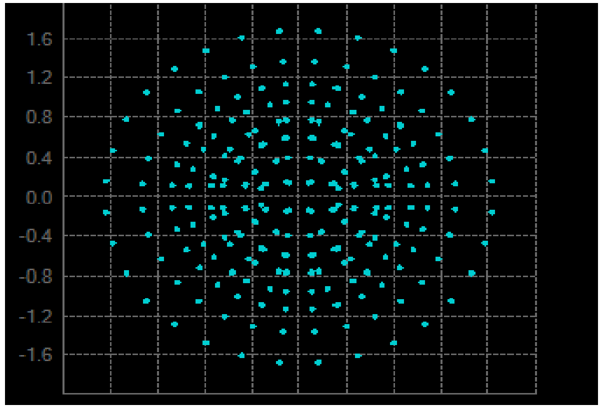
Higher Frequency Space

- Lowering costs
- 18,000 proposed LEOs
- Increasing electrical interference
- Hostile environment (TVAC) and radiation?
- COTs HW in space



Higher Densification

- Move to Ka-band and looking higher to V-band (more available bandwidth)
- Smaller antennas
- Spot beams and phased array antenna (satellite)
- Flat antenna, phased array (mobile, ground)

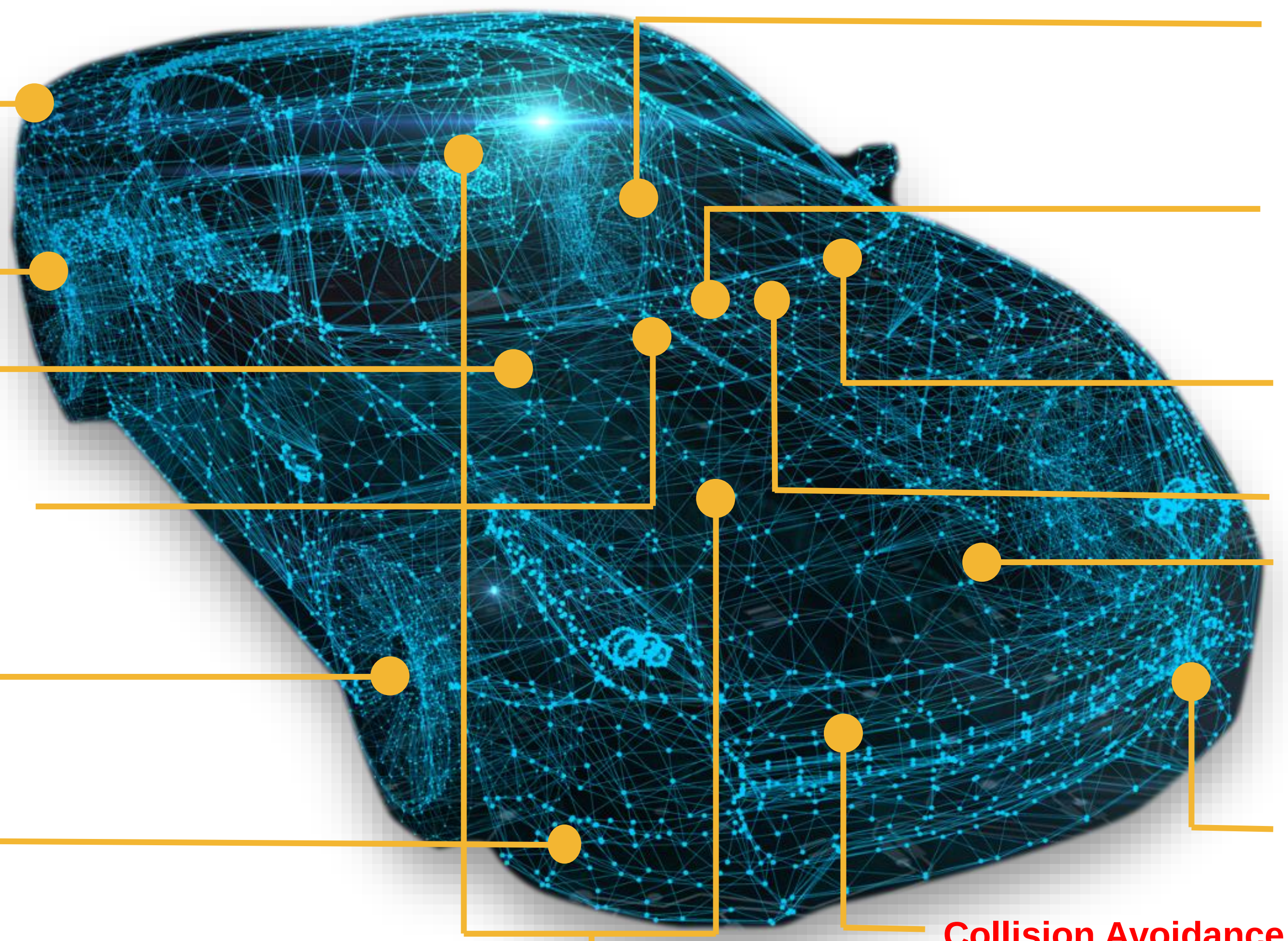


Higher Data Rates

- High throughput satellite (HTS)
- Frequency reuse
- Higher order modulation
- Wider bandwidth signals
- DVB-S2X, 2014 standard (up to 256 **A**mplitude **P**hase **S**hift **K**ey or APSK)

Automotive Electronics

INNOVATIONS THROUGH MULTIPLE TECHNOLOGY DOMAINS

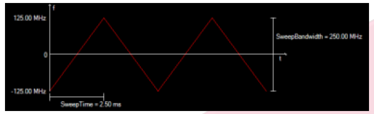


Automotive Radar Evolution

RADAR MODULATION AND MIMO EVOLUTION

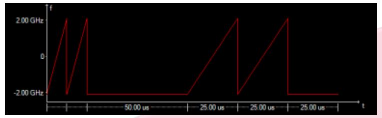
Pulse radar

- 2D (Azimuth and Doppler)
- Close-in blind-range issues (only for LRR/MRR)
- High Peak to Average Power Ratio (PAPR)



Slow LFM, FMCW (chirp)

- 3D (Azimuth, Elevation, and Doppler)
- SISO
- Constant power with low PAPR
- Prone to interference
- Narrow-band (several MHz) IF processing with simple homodyne receiver



Fast LFM, FCM (chirp)

- 4D High resolution (Azimuth, Elevation, Doppler, Depth)
- Small scale MIMO (3x4)
- Few strategies for interference
- IF ADC sample rate : several 10's MHz
- Complex analog RF Tx and Rx with PLLs
- Simple digital processing with multiple FFTs

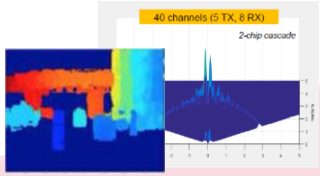
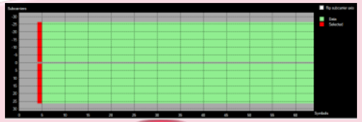
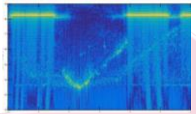


Image Radar with Large Ant and massive MIMO

- 4D UHD Ultra high resolution (Azimuth, Elevation, Doppler, Depth)
- FCM
- TDM Cascade multiple MIMO transceivers for large and massive MIMO
- Big Ant size for high angular resolution
- Complex analog RF Tx and Rx with phase synchronization between transceivers and arrays
- Additional image processing with A.I and M.L

SAR





Coded PMCW

- Phase coded waveform by Pseudo random code
- Hadamard code for orthogonal array channel
- More virtual Arrays and massive MIMO
- More resistant to interference
- Chip rate: several Gbps, IF bandwidth: several GHz
- Simple analog RF Tx and Rx with PLLs
- Complex digital processing

Component & Device Level Impacts

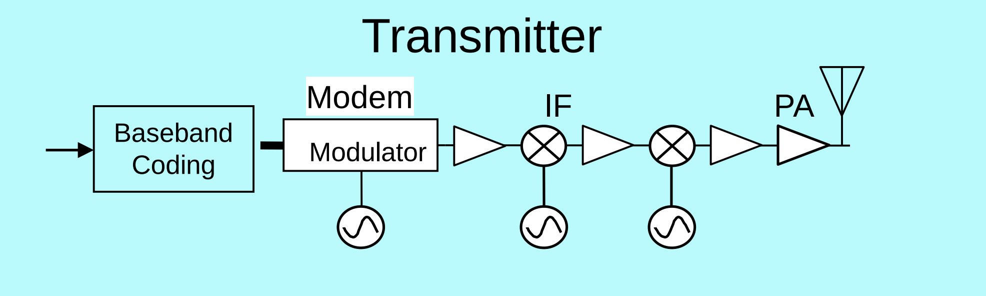
RF TEST METHODS ARE BEING CHALLENGED

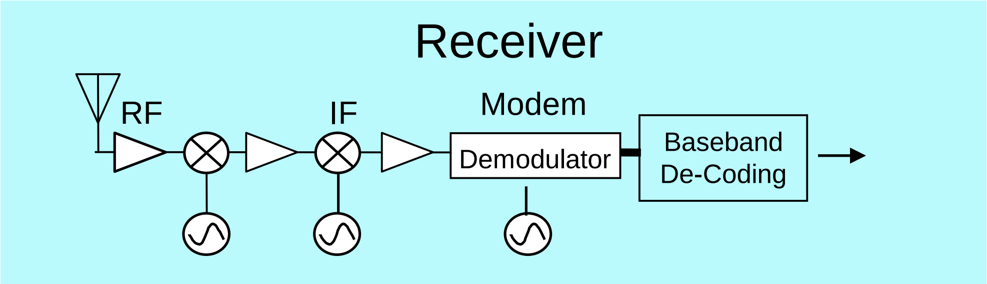
- Increased frequencies smaller wavelengths demands better stability
- Increased demands on the designs being more stable mechanically and thermally
- Traditional wave propagation methods are being replaced by E-M field theory
- Move from RLC to Transverse Electric modes of propagation
- Connector sizes are becoming smaller
- Current coaxial propagation methods have higher losses move to waveguide and microstrip designs

Contributes to degradation of quality of communication systems at millimeter wave frequencies

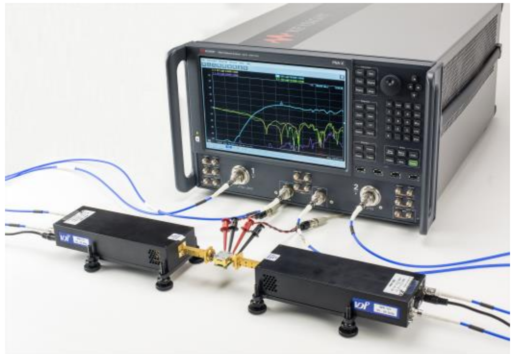
Evolution of Device Characterization

MEASUREMENT CHALLENGES AT MM-WAVE





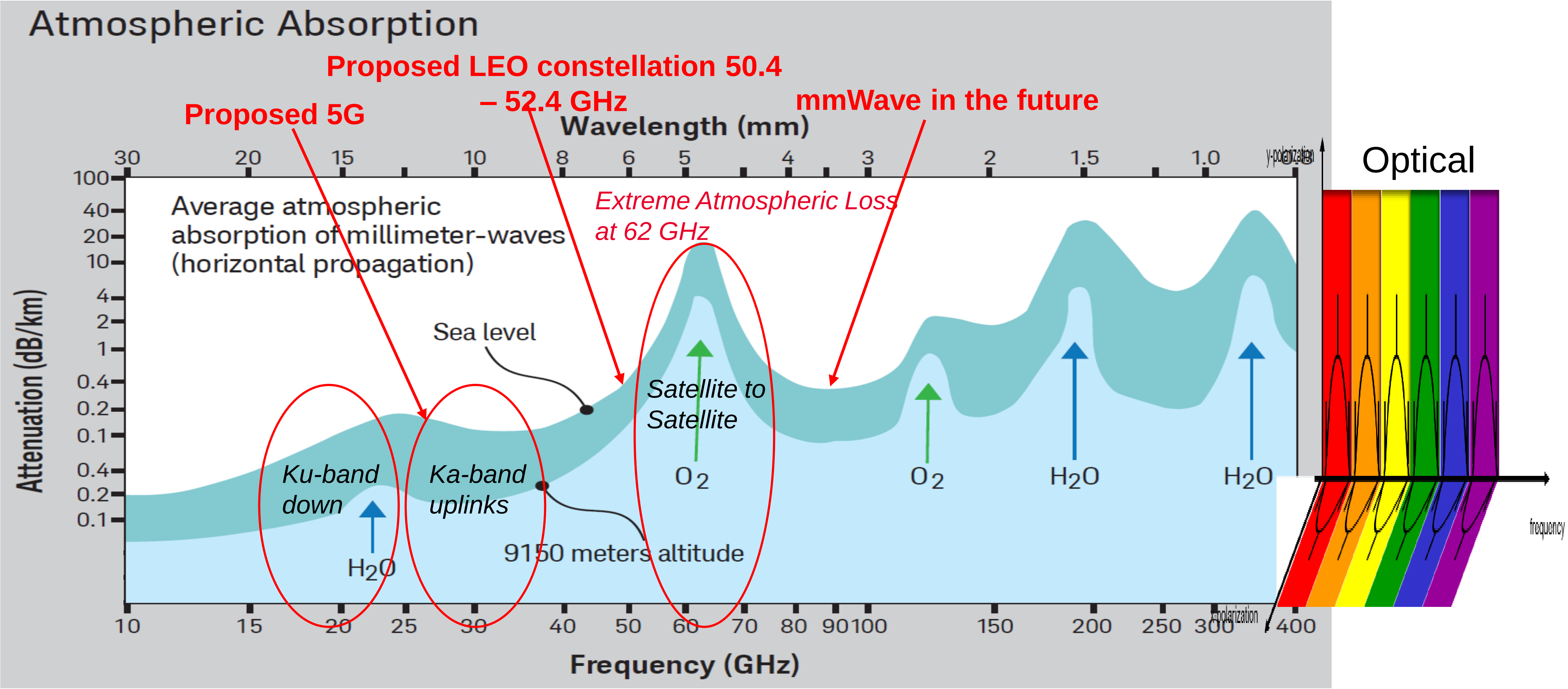
- Wideband devices at mm-wave frequencies
- On-Wafer devices high levels of integration
- Device performance parameters at mm-wave
  - Millimeter wave amplifier Noise figure
  - Inter-modulation distortion performance
  - I-Q performance measurements
  - System level ACPR and EVM measurements at mm-wave



Wireless Communication Application

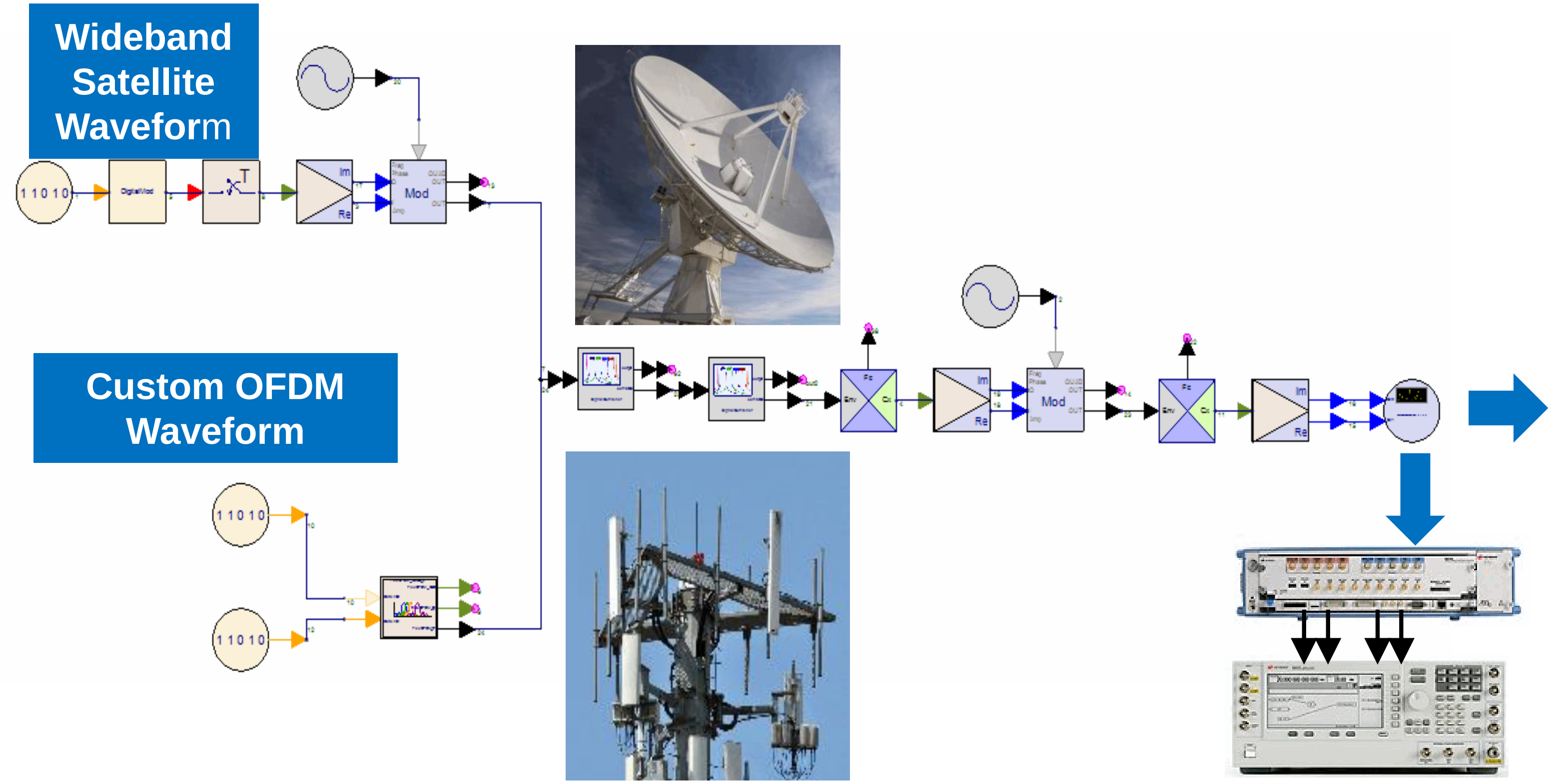
Satellite Communications at Higher Frequencies

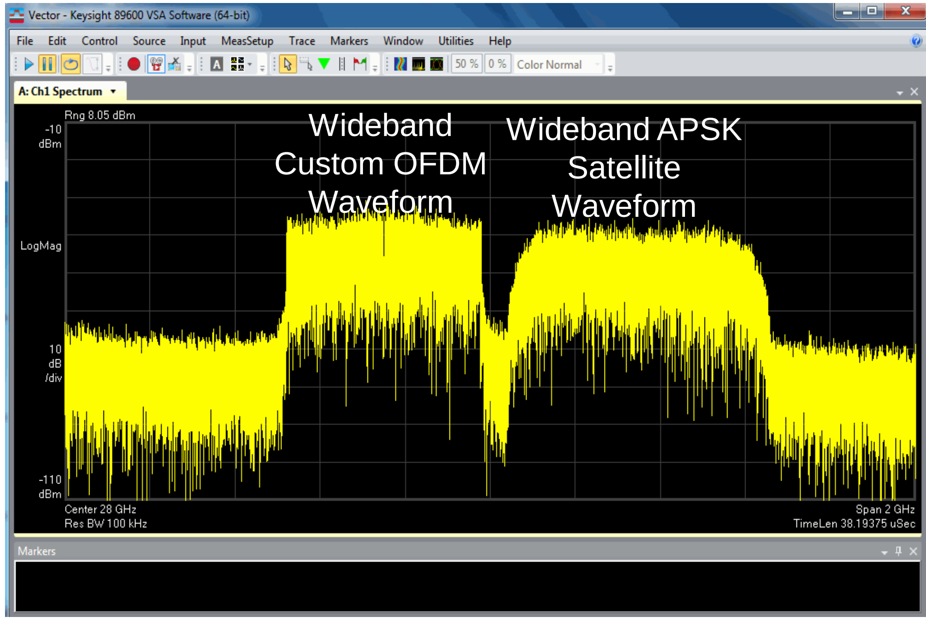
GAIN BECOMES A KEY ENABLER AS LOSS INCREASES

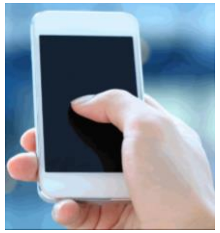


Example 1: Frequency Band Sharing

POTENTIAL INTERFERENCE & COEXISTENCE @ 28 GHZ



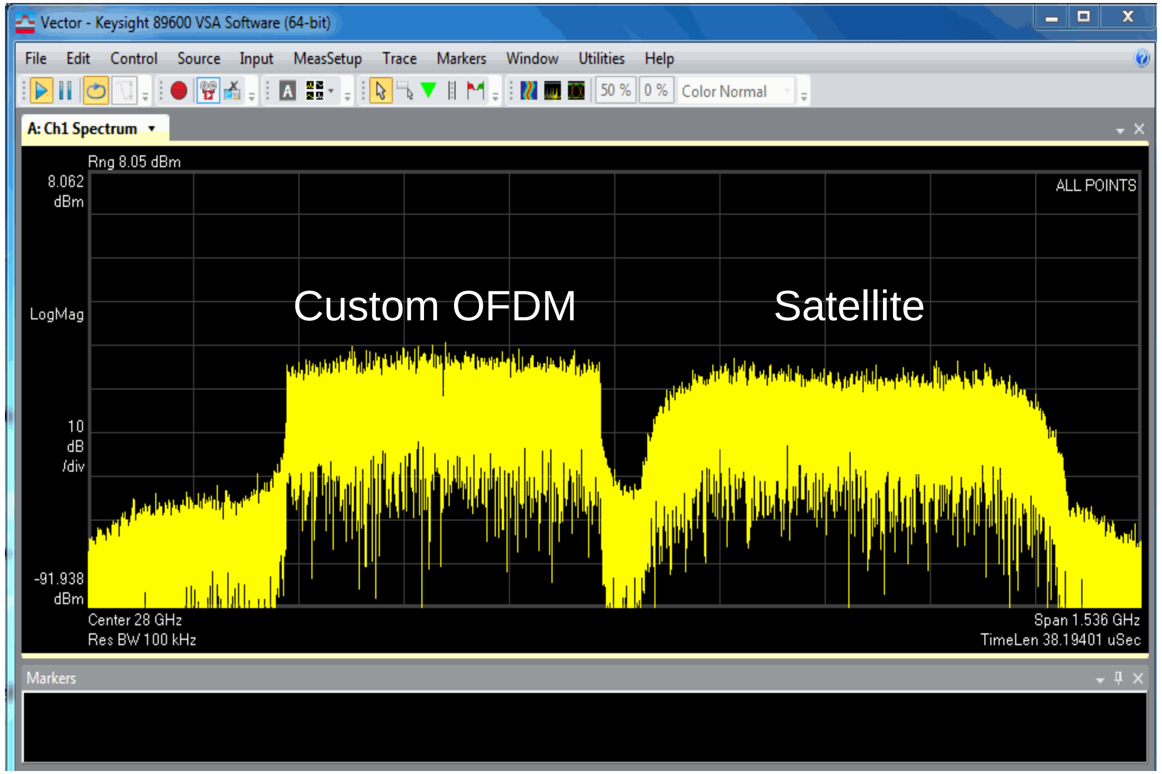


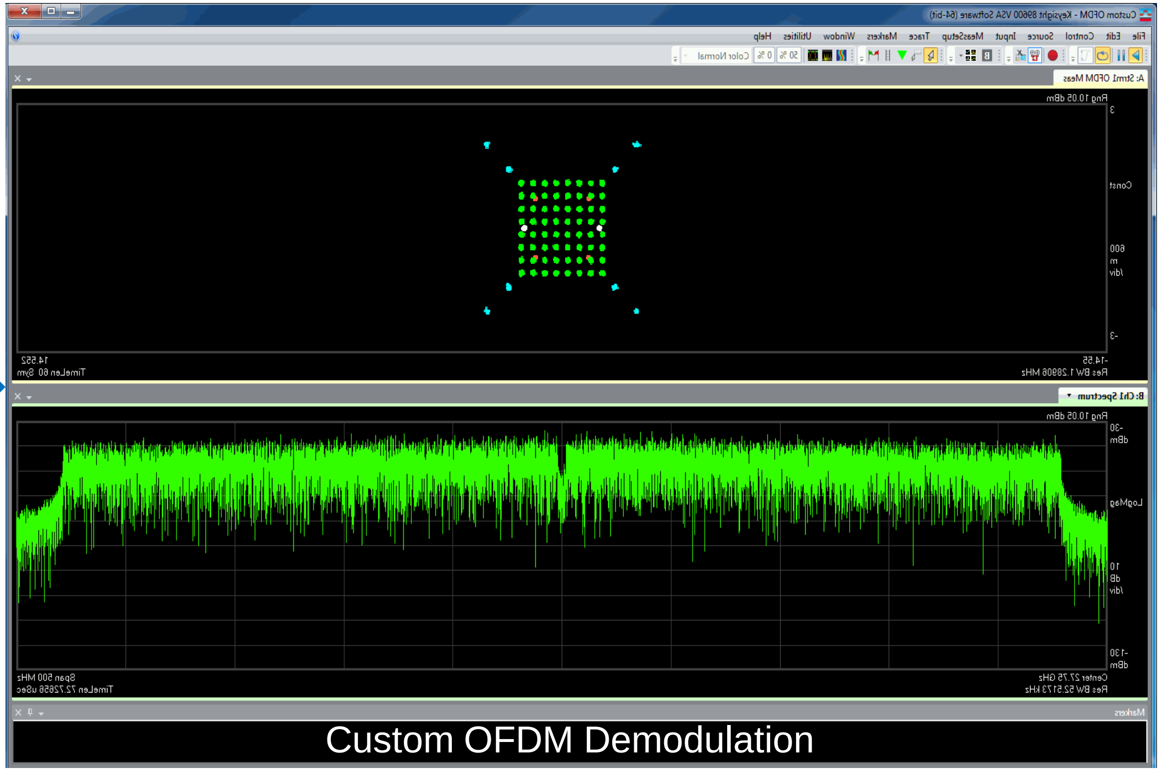


Source: https://apps.fcc.gov/edocs_public/attachmatch/FCC-15-138A1.pdf

Frequency Band Sharing

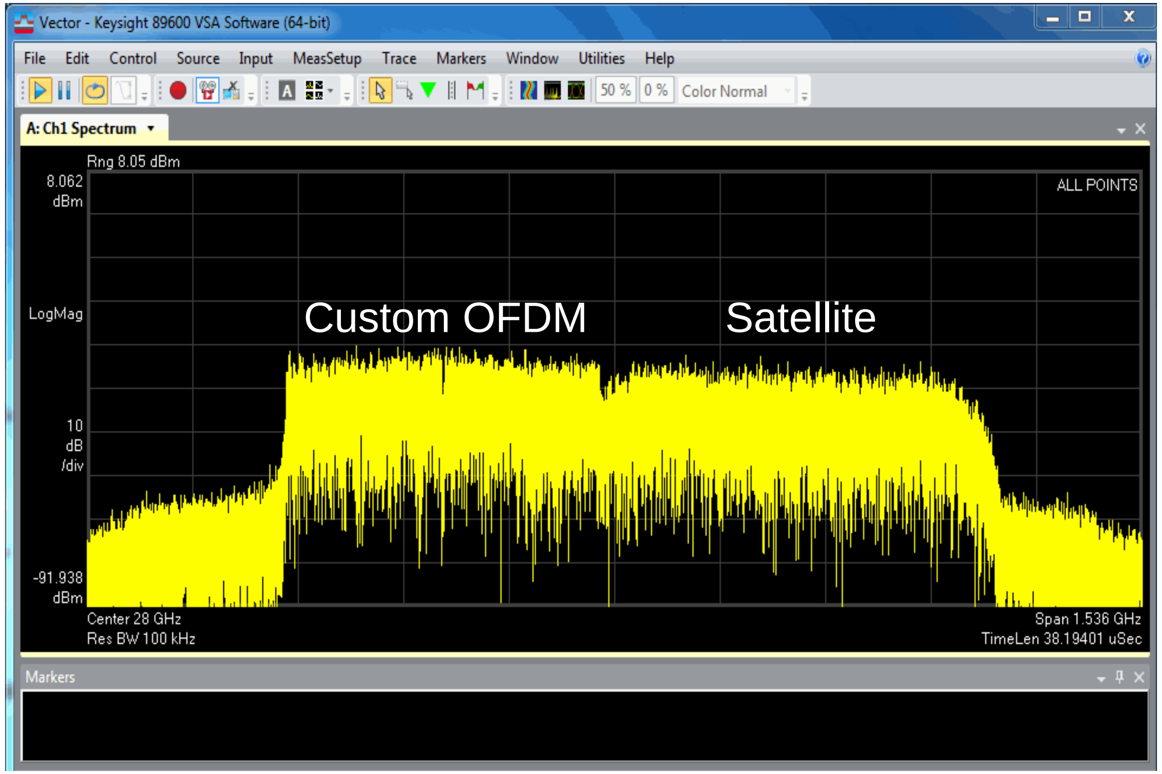
GOOD COEXISTENCE WITH SATELLITE AND CUSTOM OFDM

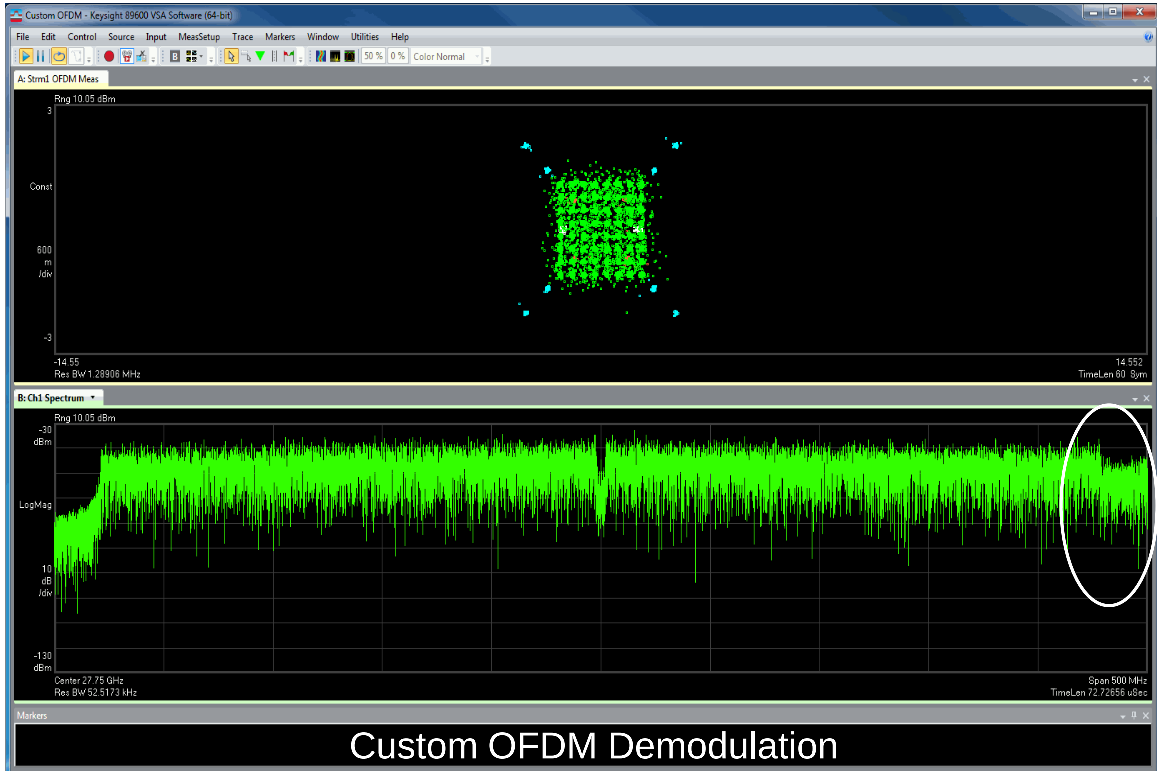




Frequency Band Sharing

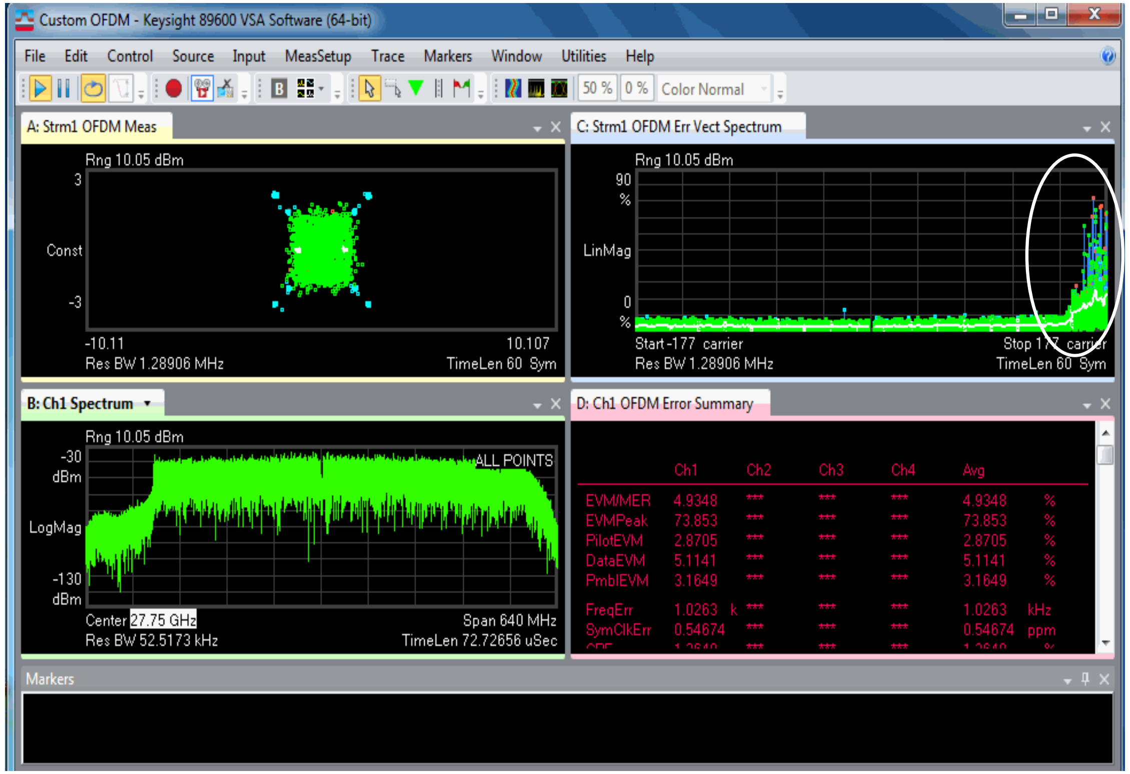
POOR COEXISTENCE WITH SATELLITE AND CUSTOM OFDM

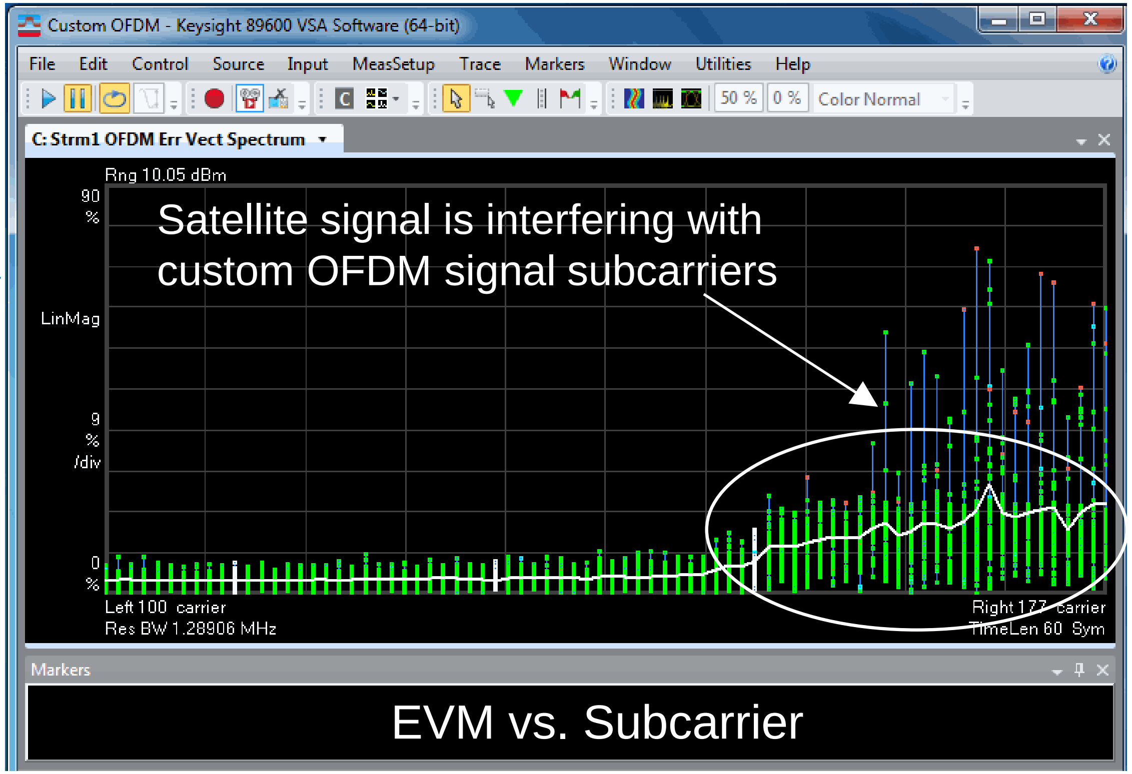




Frequency Band Sharing

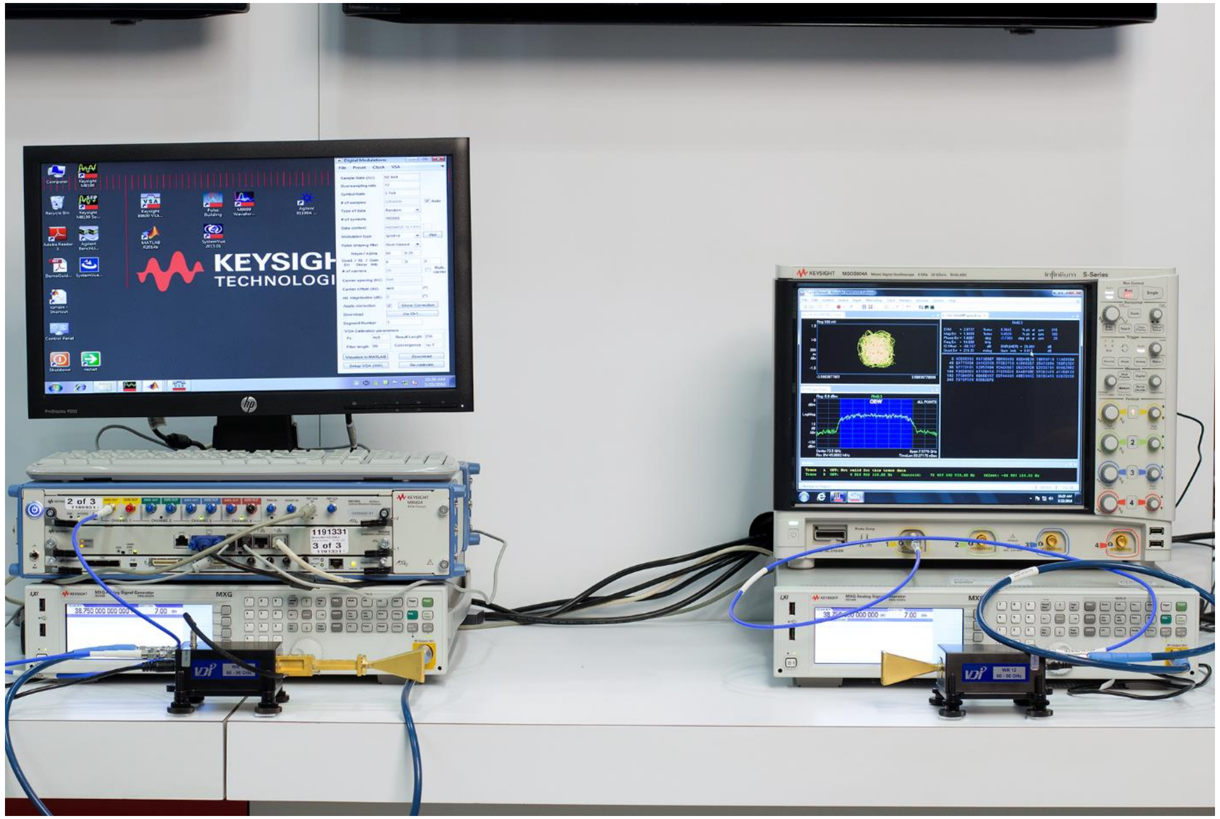
POOR COEXISTENCE LOOK LIKE ?

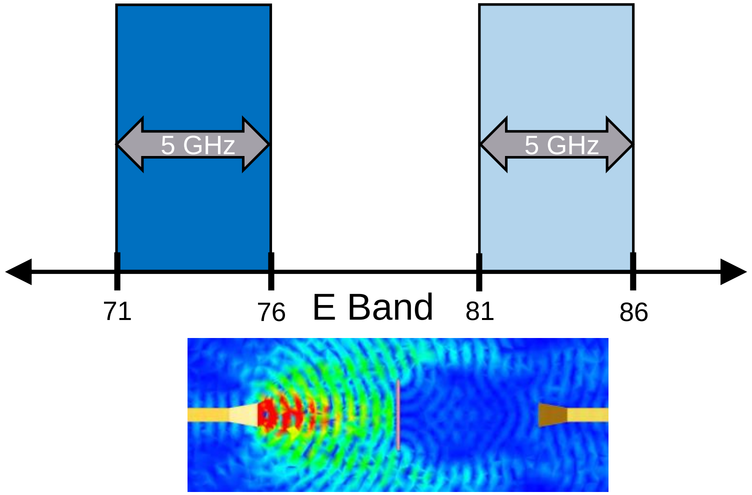




Example 2: E-Band Communication

5GHZ BANDWIDTH COMMUNICATION SYSTEM





- VDI Compact E-Band Upconverter and Downconverter,
- E-Band Amp
- 71-76 GHz Bandpass Filter
- Horn Antennas.

Example 2: Wideband Measurements

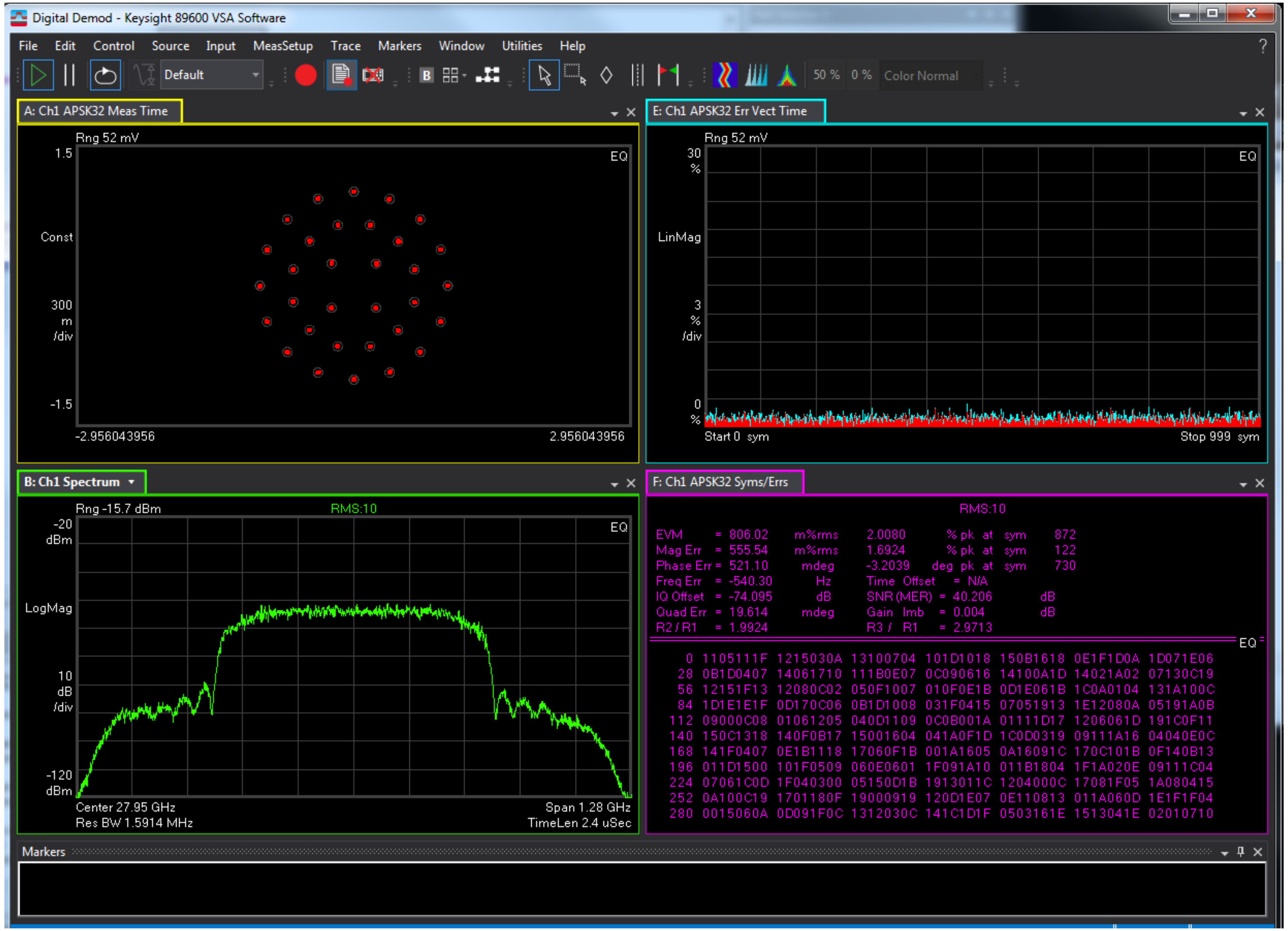
UXR 16QAM MEASUREMENTS IN THE 60- 90 GHZ

Used VDI Compact V-Band Upconverter, V-Band Amp, 57.2-65.9 GHz Bandpass Filter for 61.56 GHz Measurements
Used VDI Compact E-Band Upconverter, E-Band Amp, 71-76 GHz Bandpass Filter for 73.5 GHz Measurements
Used VDI Compact E-Band Upconverter, E-Band Amp, 81-76 GHz Bandpass Filter for 83.5 GHz Measurements

	1 GHz SR (OBW= 1.22 GHz)	2 GHz SR (OBW= 2.44 GHz)	3 GHz SR (OBW=3.66 GHz)	4 GHz SR (OBW=4.88 GHz)
UXR 61.56 GHz	1.18%	1.28%	1.48%	1.71%
UXR 73.5 GHz	1.36%	1.57 %	1.79 %	2.08%
UXR 83.5 GHz	1.45%	1.86 %	2.15%	2.45%

Example 3: Satellite Waveforms Performance

32APSK WIDEBAND DEMODULATION RESULTS AT 27.95 GHZ, 500 MHZ SR

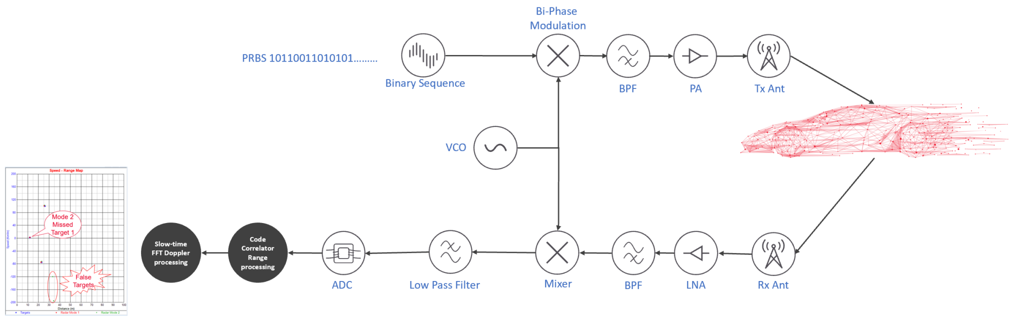


Automotive Measurement Applications

New Automotive Radar Technology Challenges

RADAR TECHNOLOGIES

- **Coded Phase-Modulated Continuous Wave Radar**
  - System design and verification
  - Need to consider compatibility with existing FMCW radar
  - Linear Calibration required for PA
- **New Antenna structure with MIMO/DBF/APA**
  - Combined Antenna Aperture multi-function (Long-, Mid-, and Short-range) Radar
  - Characterizing of various angles and beam distance
  - Verification of MIMO effeteness based on Ant position and location
- **Ultra-high Resolution Image Radar**
  - Requirement of bigger far-field distance comes from bigger Antenna size
  - Required conversion algorithms between near-field and far-field for short distance detection
  - Cascade multiple transceivers for more Antenna array : Phase calibration and time/phase synchronization
- **Requirement for higher Frequency range**
  - New Assignment of next Gen Radar with Wideband Frequency band for higher resolution
  - Emission regulation up to higher Frequency (up to 2nd or 3rd Harmonic of highest Frequency > ~230GHz)

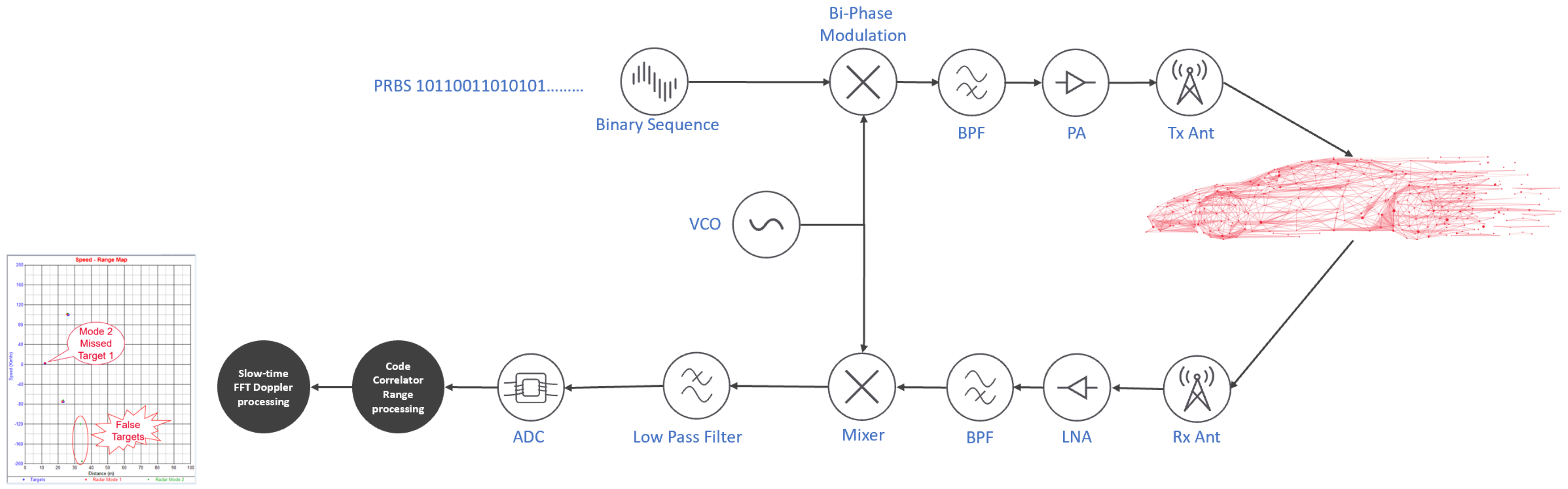


Conventional Radar vs. Coded Radar

PMCW CODED RADAR EVALUATION

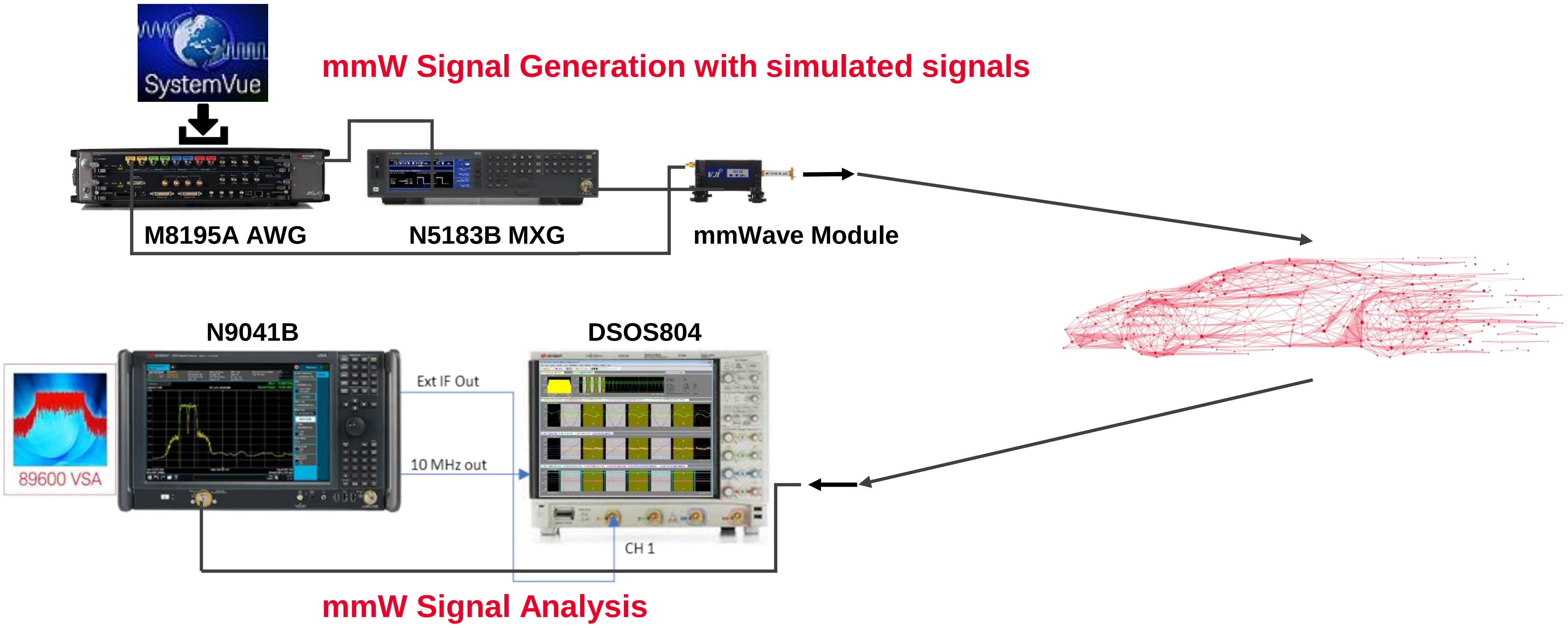
PMCW Coded Radar

- PRBS (ex: 10^{18}) coded to every Tx
- Massive MIMO, high contrast 3D without any constrains on velocity resolution and doppler ambiguity
- Single chip with full support of high # of virtual receivers since cascading of multiple chip is done via code domain down to picosecond precision.
- Ability to detect small differences in range allow precision detection and early tracking.
- Broadband noise increase, lower to FCM/FMCW



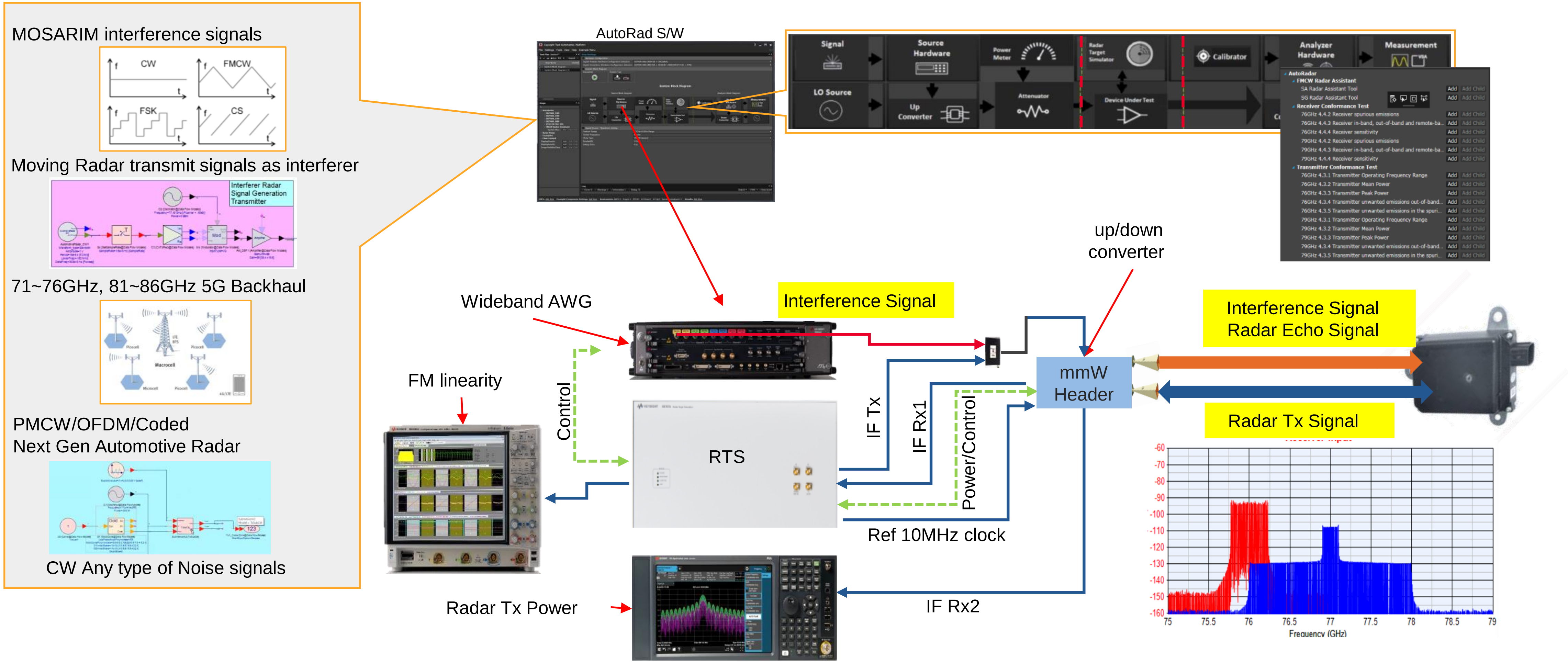
Automotive Radar Development

MILLIMETER WAVE TEST SET UP EXAMPLE



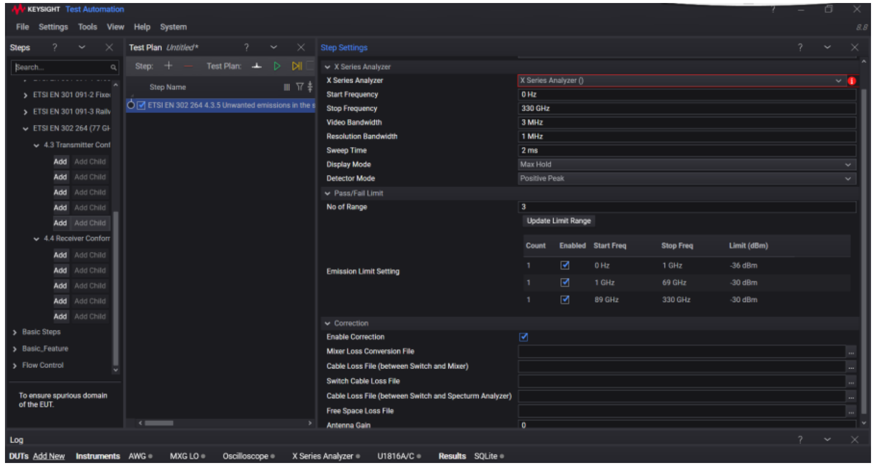
Automotive Radar Rx/Interference Application

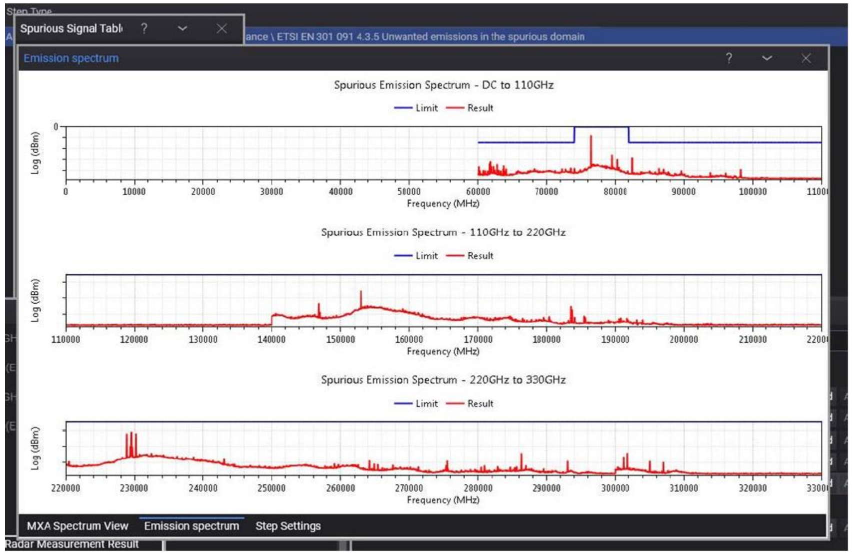
5GHZ BW INTERFERENCE SIGNAL ACROSS E-BAND

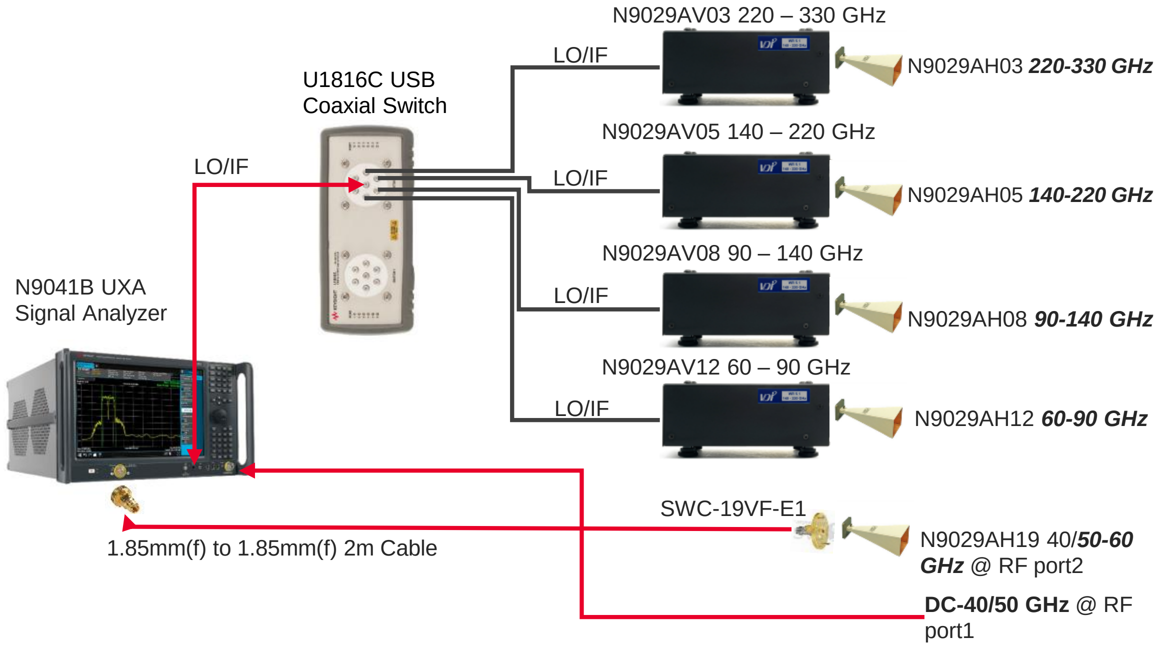


Automotive Emissions Application

TEST UP TO ~330GHZ







Component Measurement Applications

W-Band Amplifier NF Application

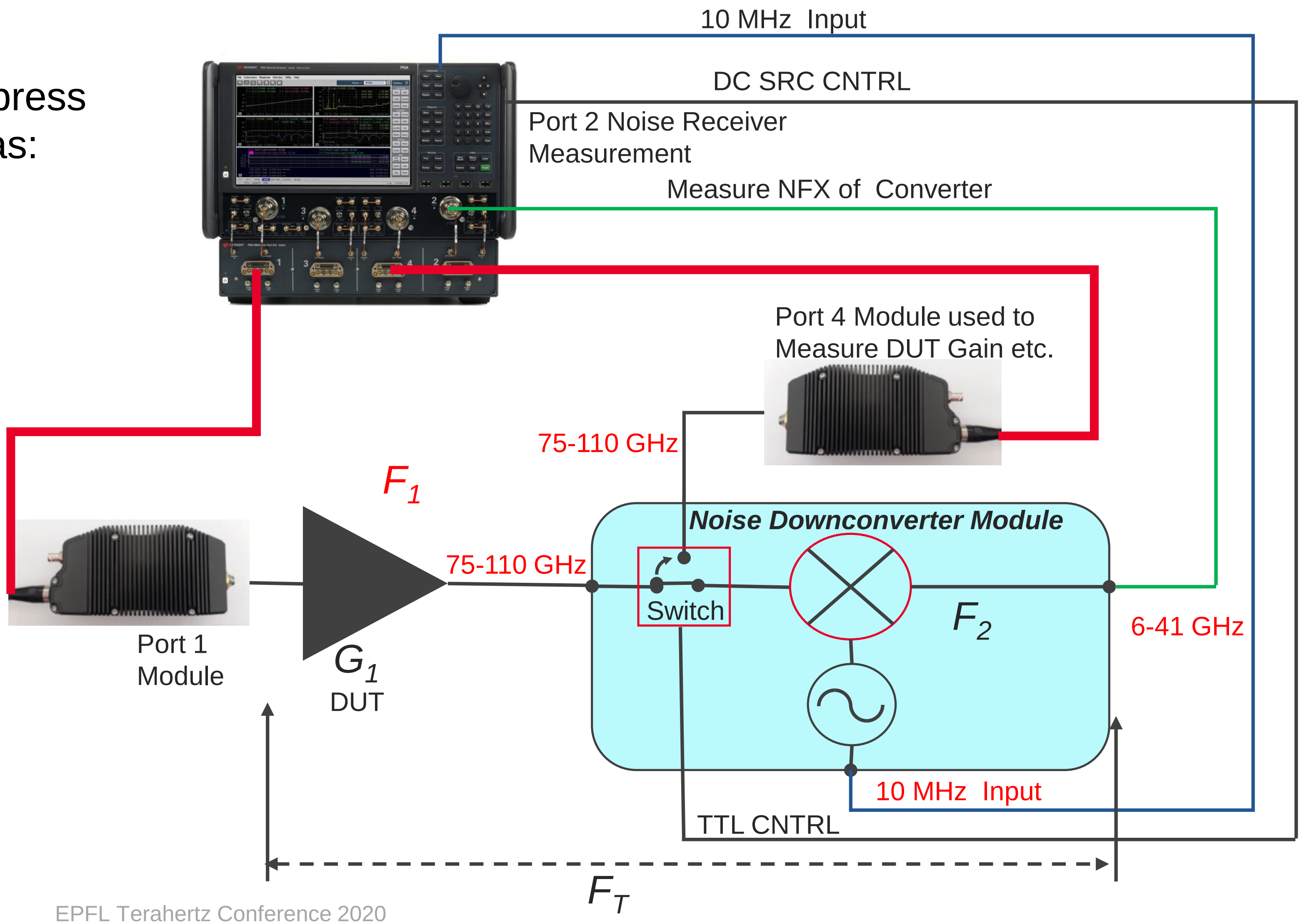
APPLICATION OF COLD NOISE TECHNIQUE

- Using Friis equation we can express the NF of the cascade system as:

$$F_T = F_1 + \frac{F_2 - 1}{G_1}$$

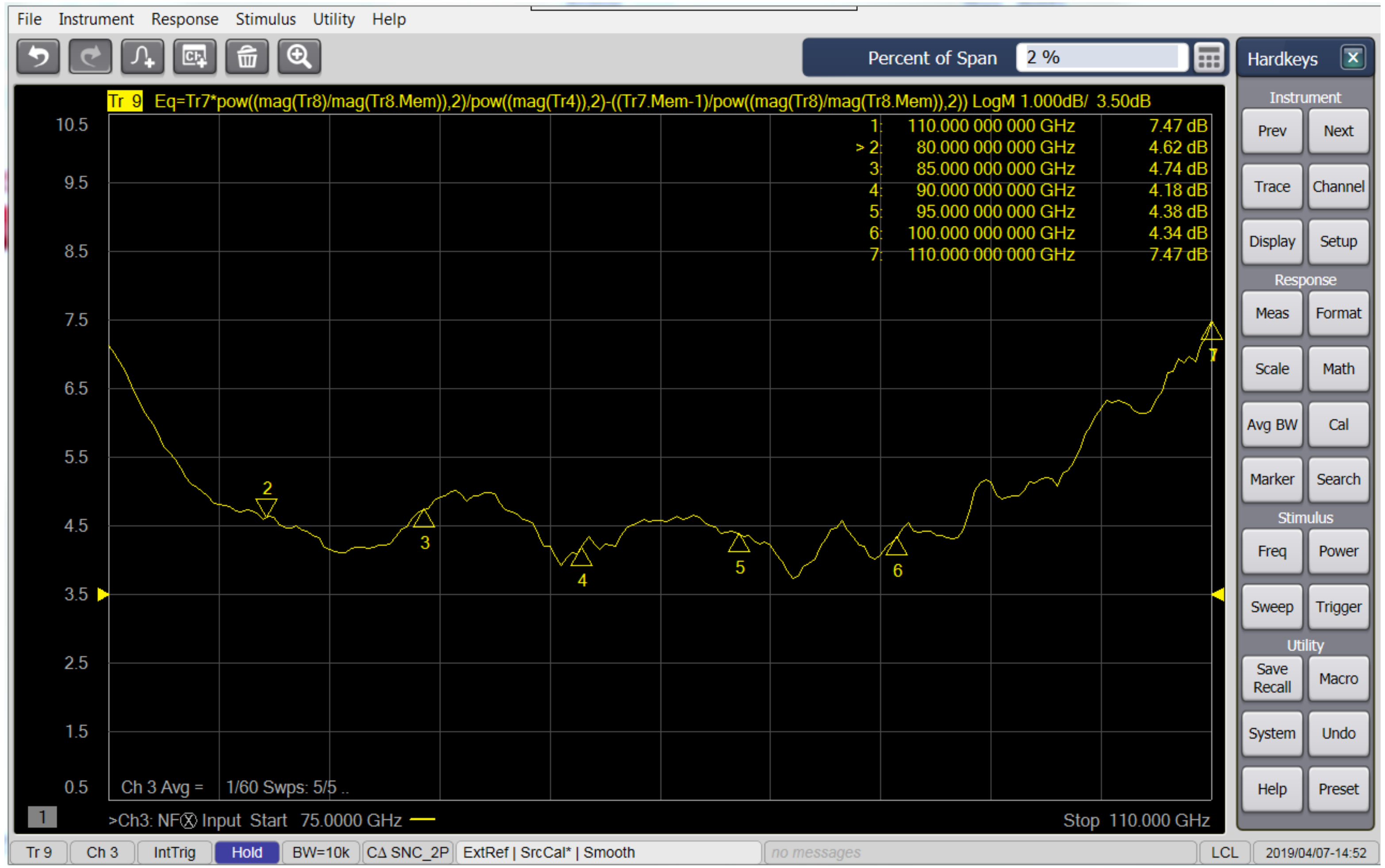
- Since F_1 is the NF of the LNA we can rearrange the above equation.

$$F_1 = F_T - \frac{F_2 - 1}{G_1}$$



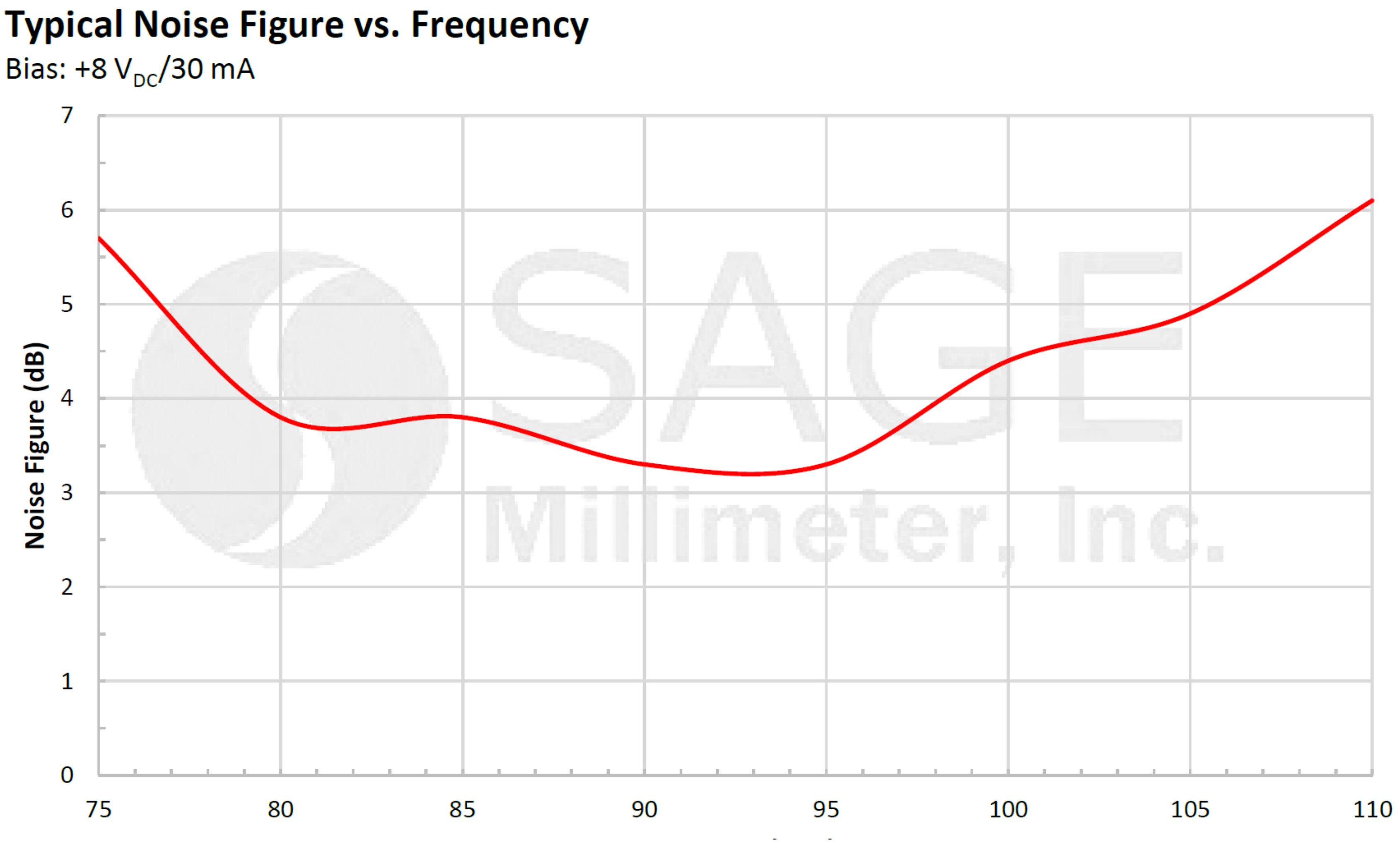
W-Band Amplifier NF Application

COMPUTED NF USING COLD SOURCE METHOD



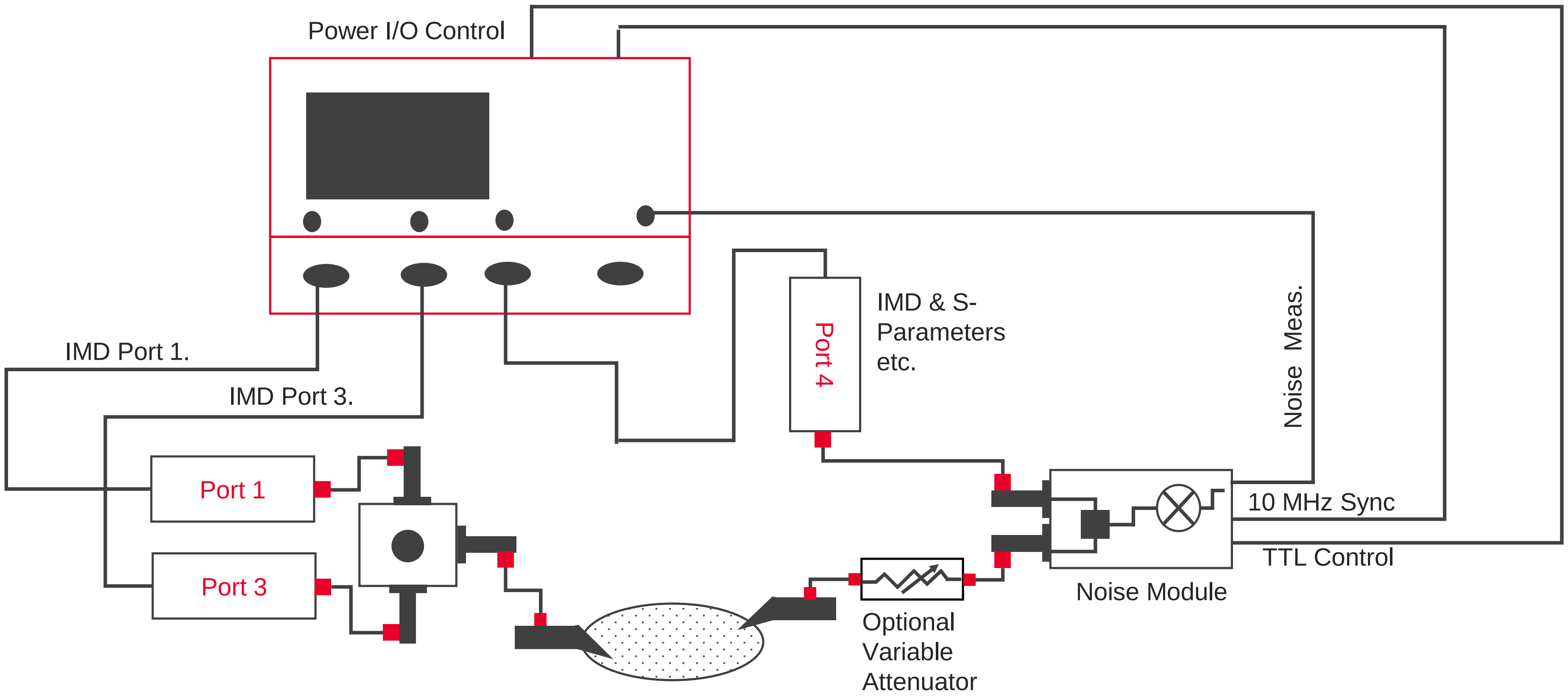
W-Band Amplifier NF Application

MEASUREMENT VERIFIED USING PUBLISHED SPEC



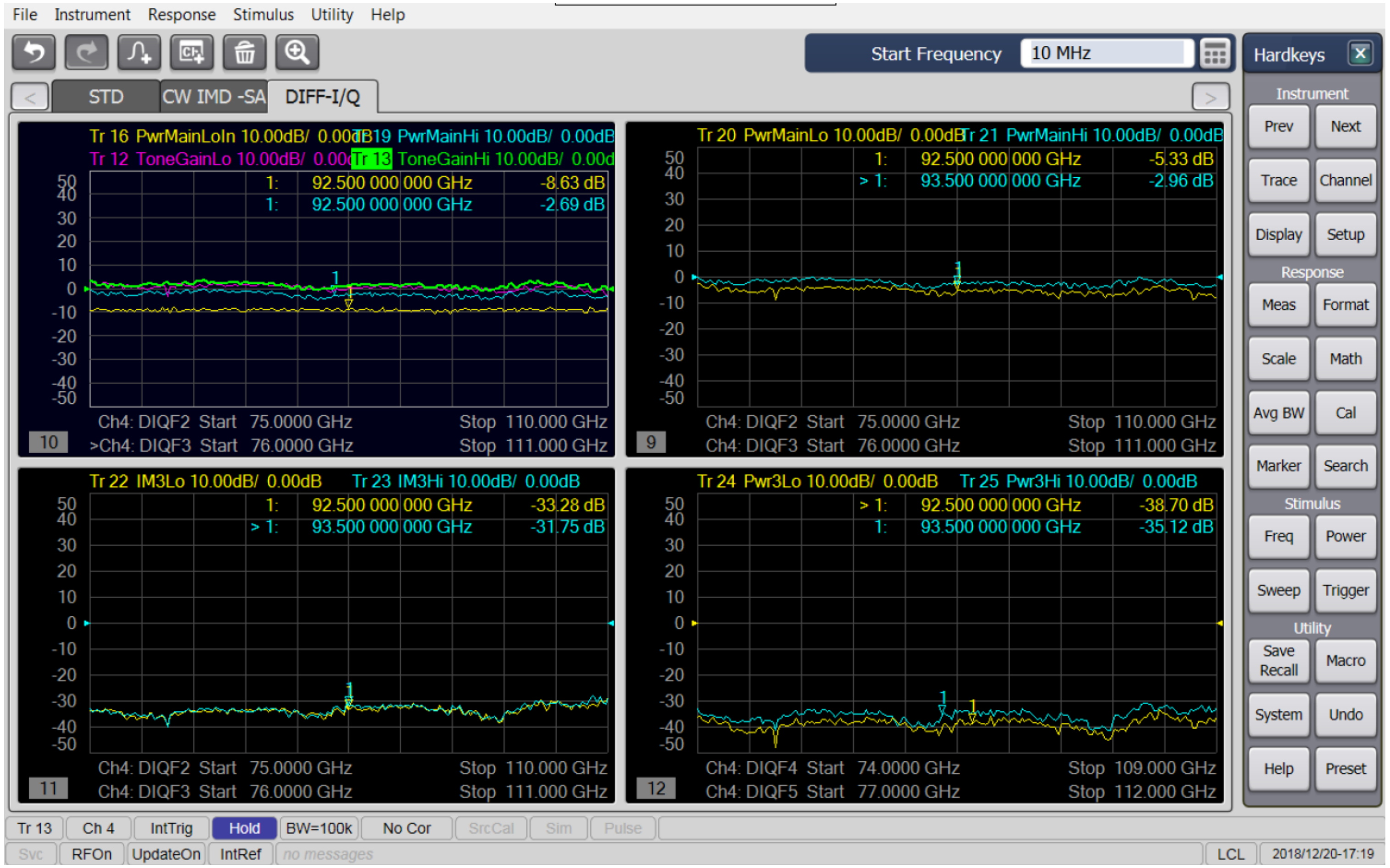
Integrated Millimeter Wave Application

NOISE FIGURE AND IMD MEASUREMENT EXAMPLE



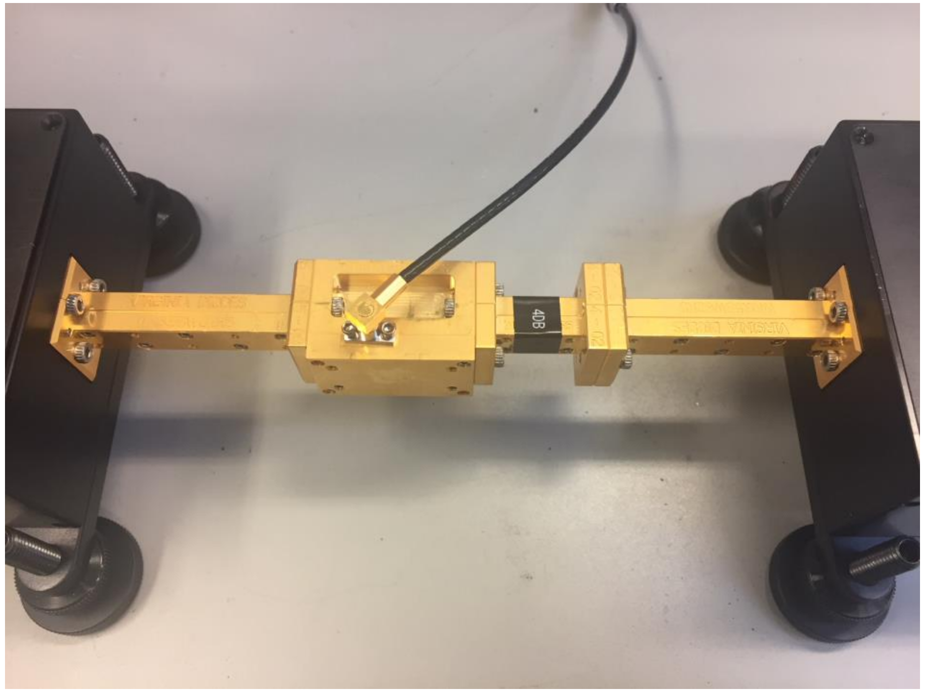
Integrated Millimeter Wave Application

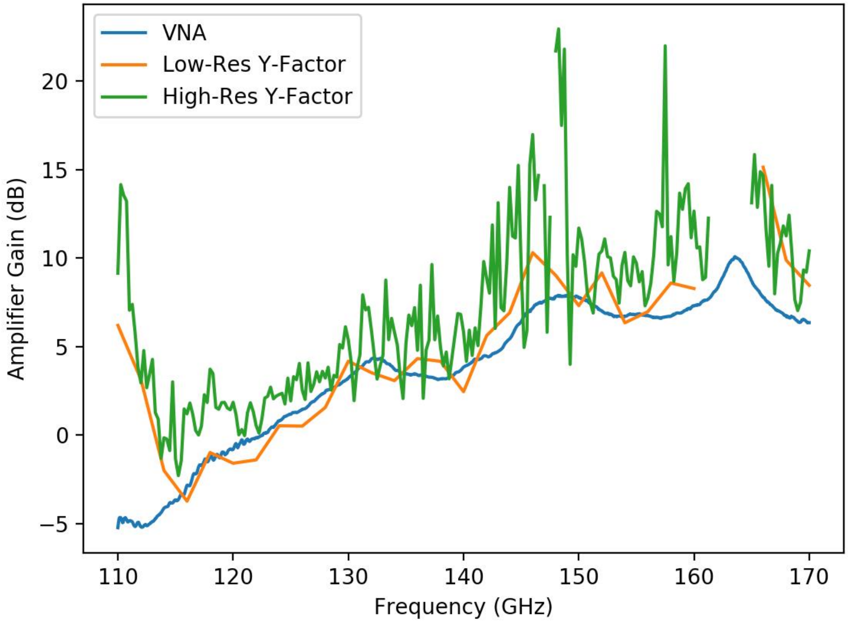
INTERMODULATION AT MM WAVE



Noise Figure in D-Band

APPLICATION OF Y-FACTOR METHOD



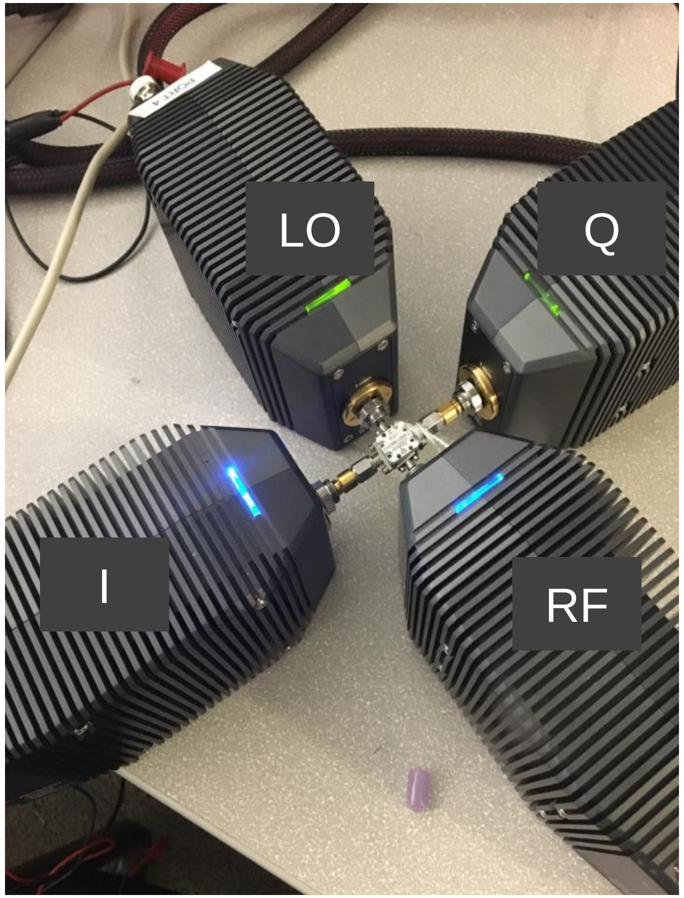


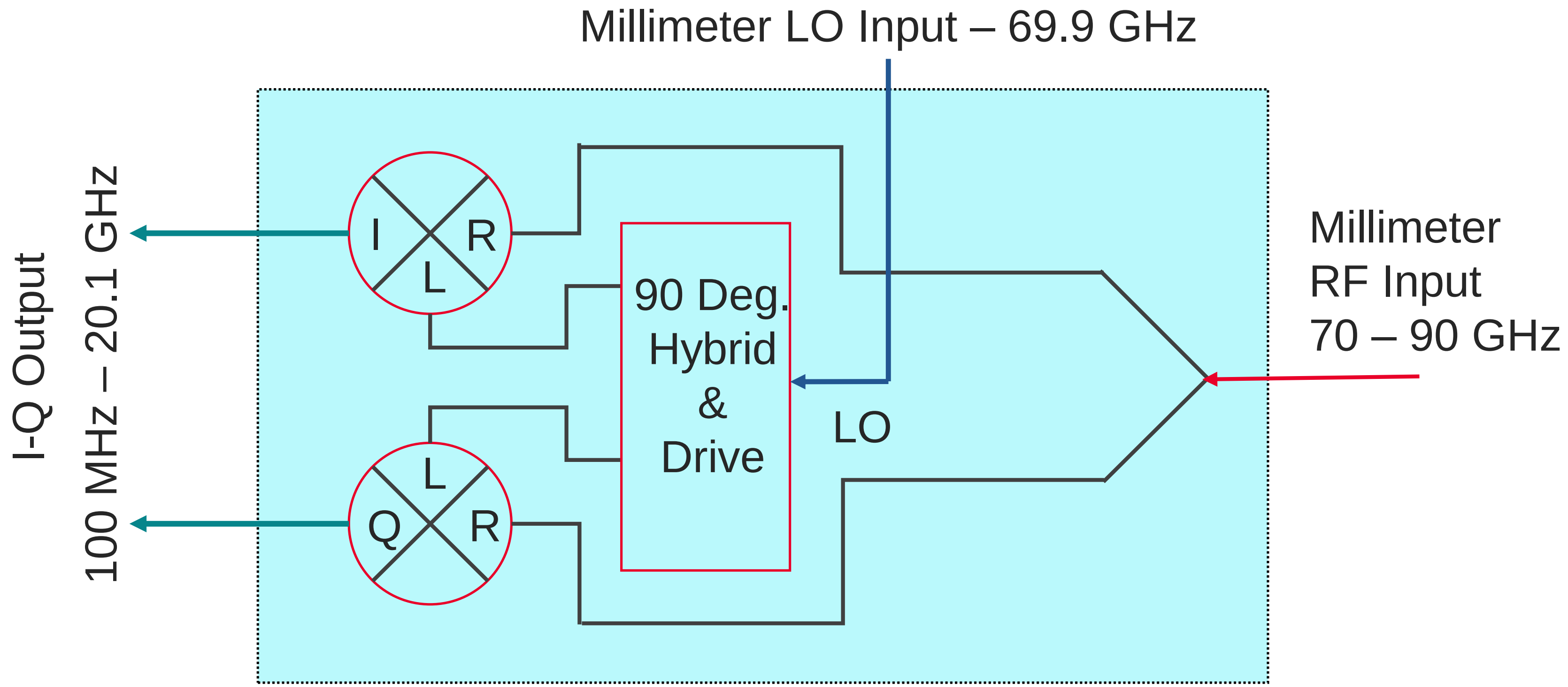
- Standard VNA measurement of amplifier
- Attenuator added to output to ensure receiver is not saturated
- It was also important to let the amplifier thermally stabilize

Reference : Theodore Reck and Jeffrey Hesler VDI

I-Q Mixer Receiver Application

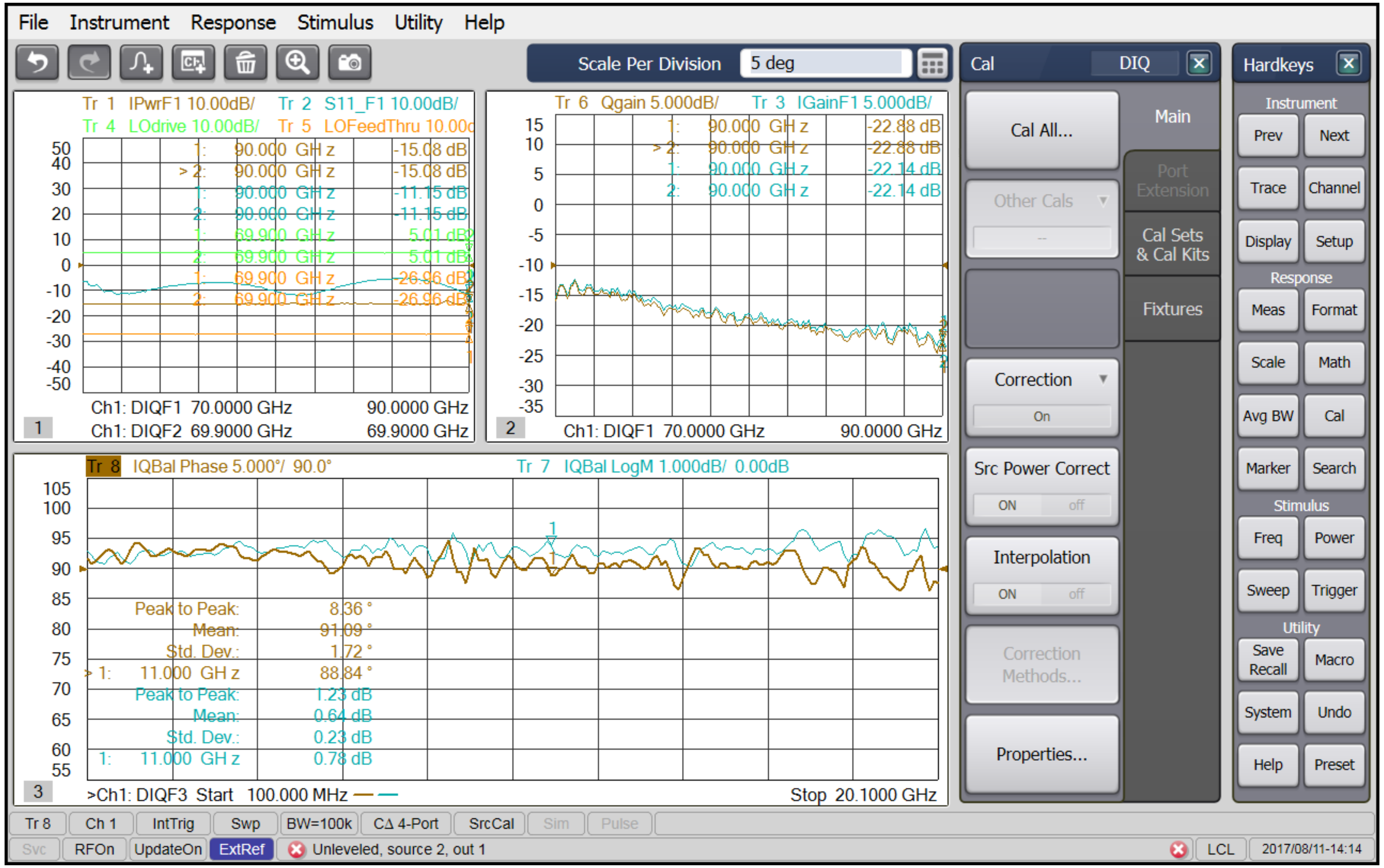
MILLIMETER RF INPUT & BASEBAND I-Q OUTPUT





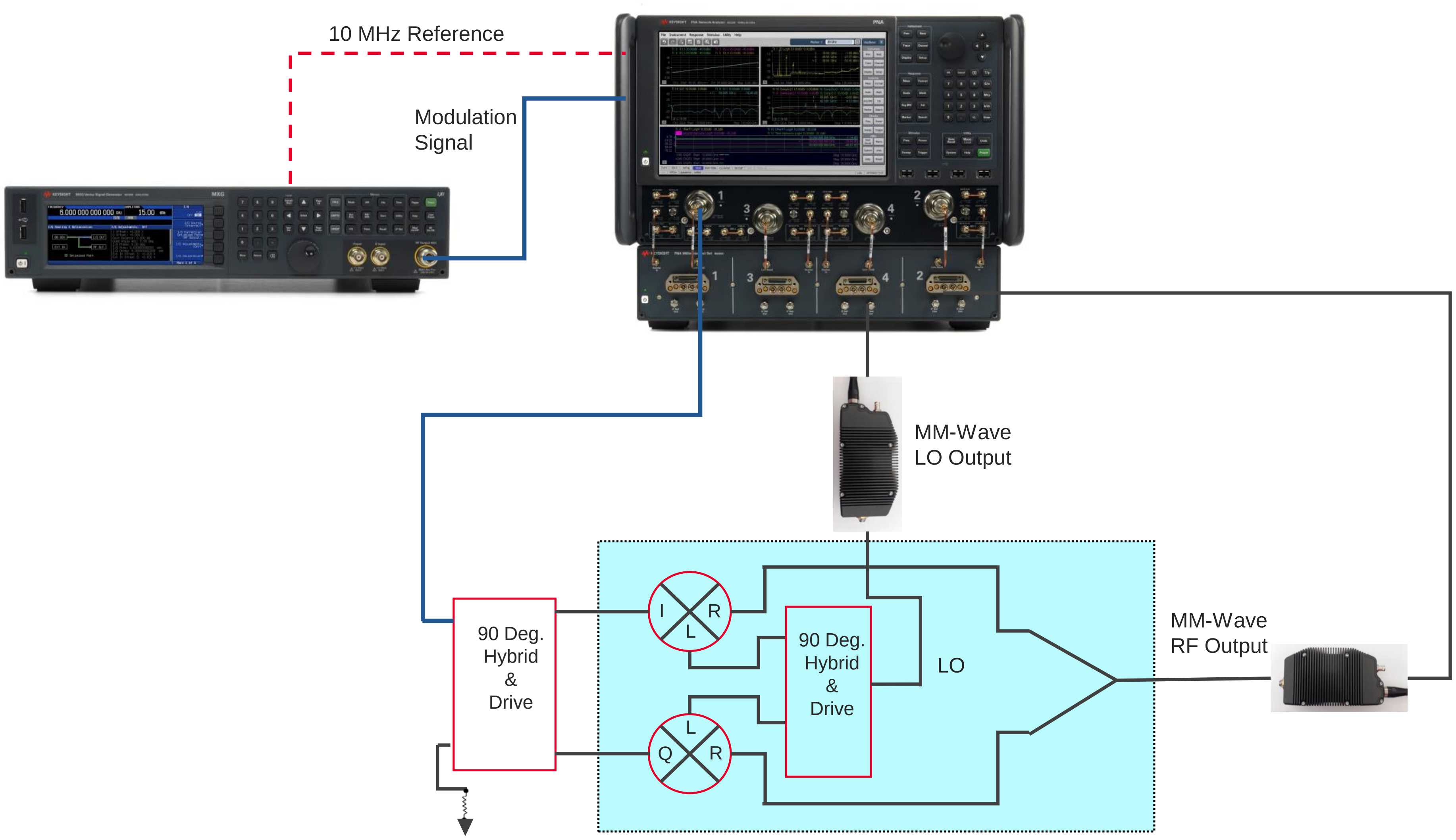
I-Q Mixer Receiver Application

I-Q BALANCE , GAIN & LO FEEDTHROUGH



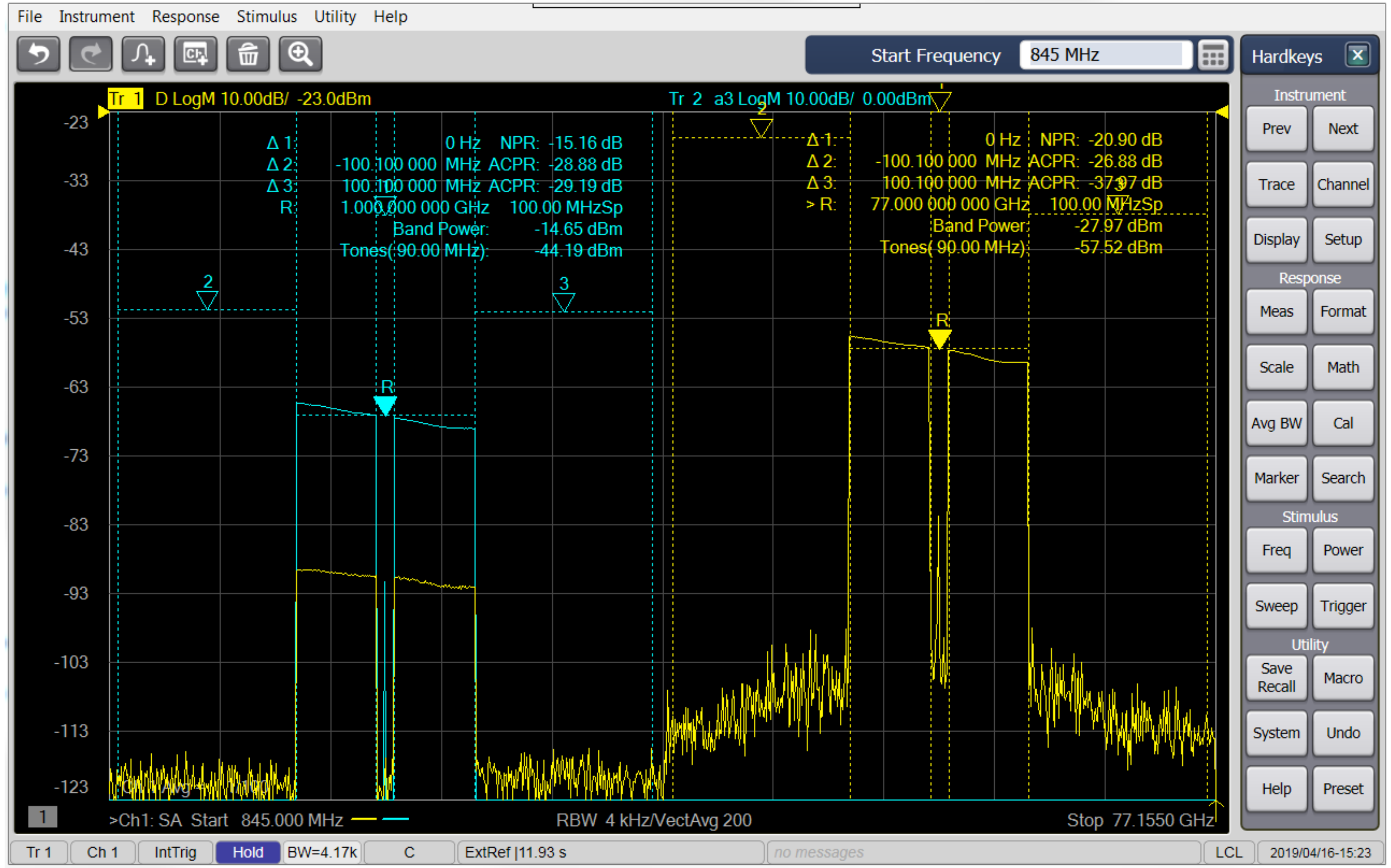
IQ Mixer NPR & ACPR

APPLICATION OF MM-WAVE VNA FOR NPR & ACPR



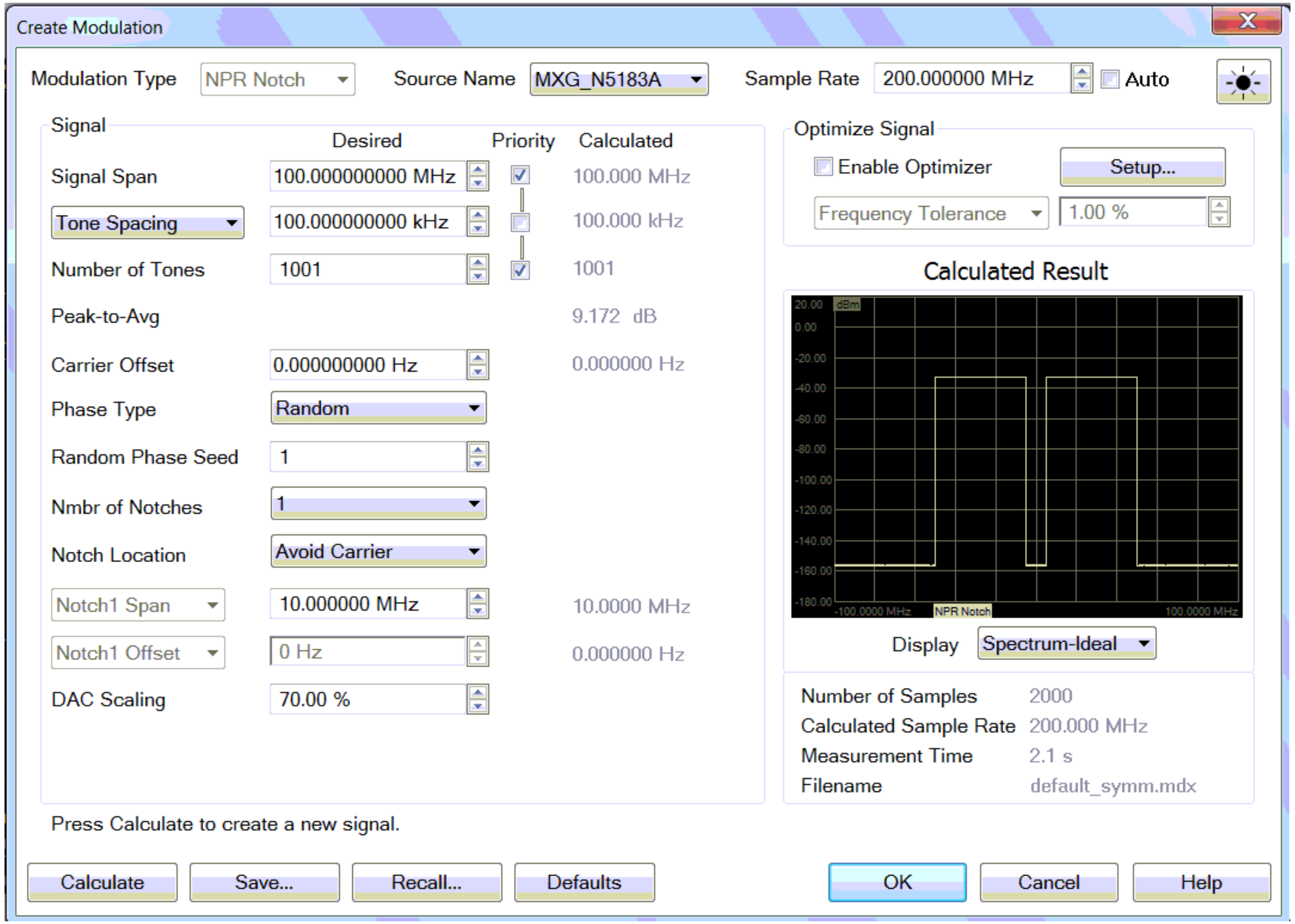
NPR & ACPR 77 GHz IQ Mixer

WITHOUT CARRIER SUPPRESSION



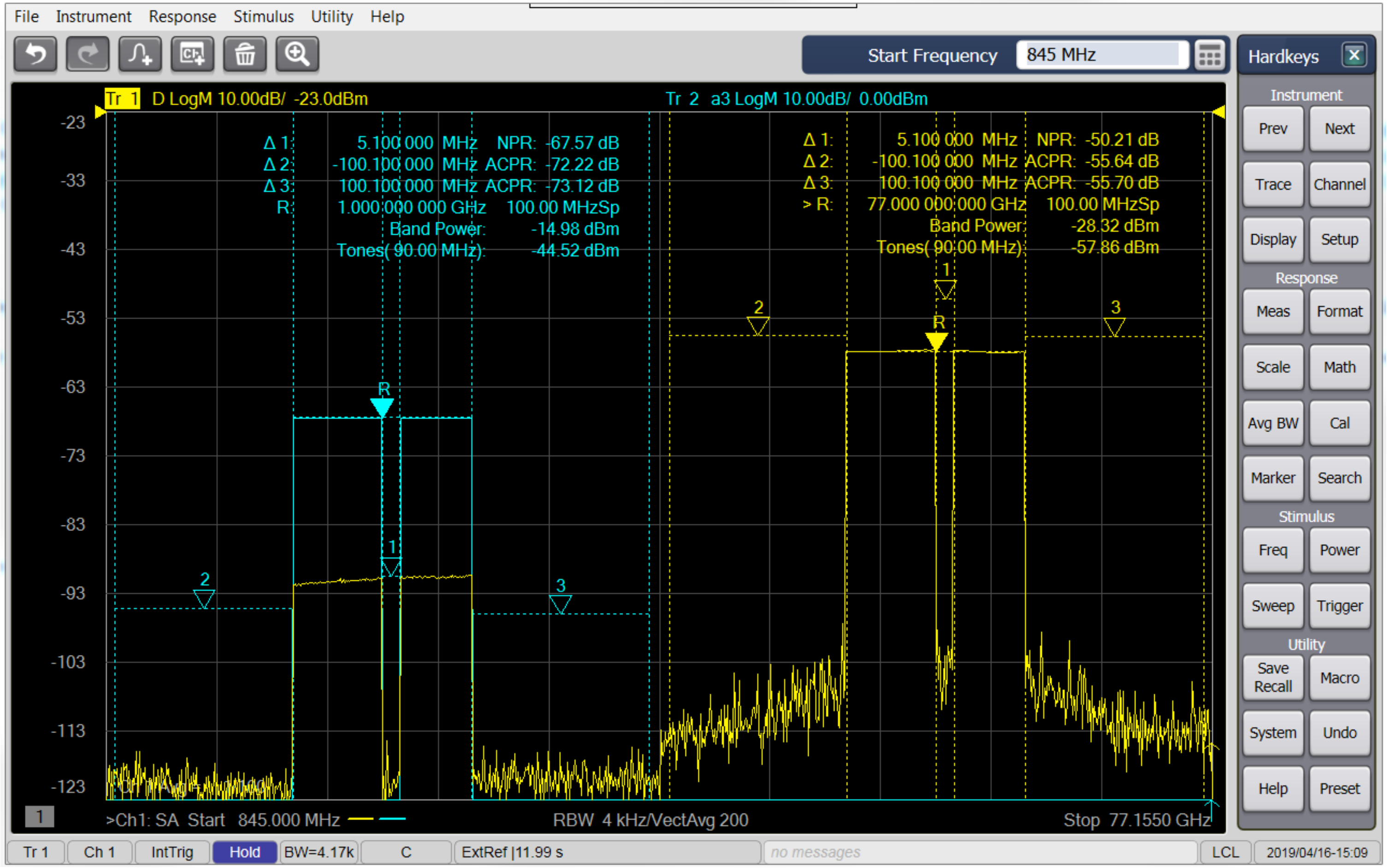
IQ Modulation Definition

CHANGE MODULATION DEFINITION AVOID CARRIER



NPR & ACPR 77 GHz IQ Mixer

WITH CARRIER SUPPRESSION



Advanced Millimeter Wave Applications

SUMMARY

- Introduction
- Wireless communication applications
- Automotive Applications
- Component Measurement Applications

Keysight Technologies in Switzerland

LOCAL ENGINEERING RESOURCES

Keysight Technologies Switzerland S.A.

Rue de la Gare 27, Morges, Vaud

Space and Satellite Industry

Richard Soden B.Eng. Ph.D.
Global Lead: Space and Satellite Market Segment
Aerospace, Defense and Government Solutions

- RF and µWave test systems, Cyber security, Process analysis

Vector Network Analysis

Prof. Andrea Ferrero Ph.D.
VNA Metrology and Software Principal Engineer
Aerospace, Defense and Government Solutions

- Device characterization, calibration techniques and VNA metrology

KEYSIGHT
TECHNOLOGIES