WMC: Baseband Corrections for Precision Millimeter-Wave Signal Measurements

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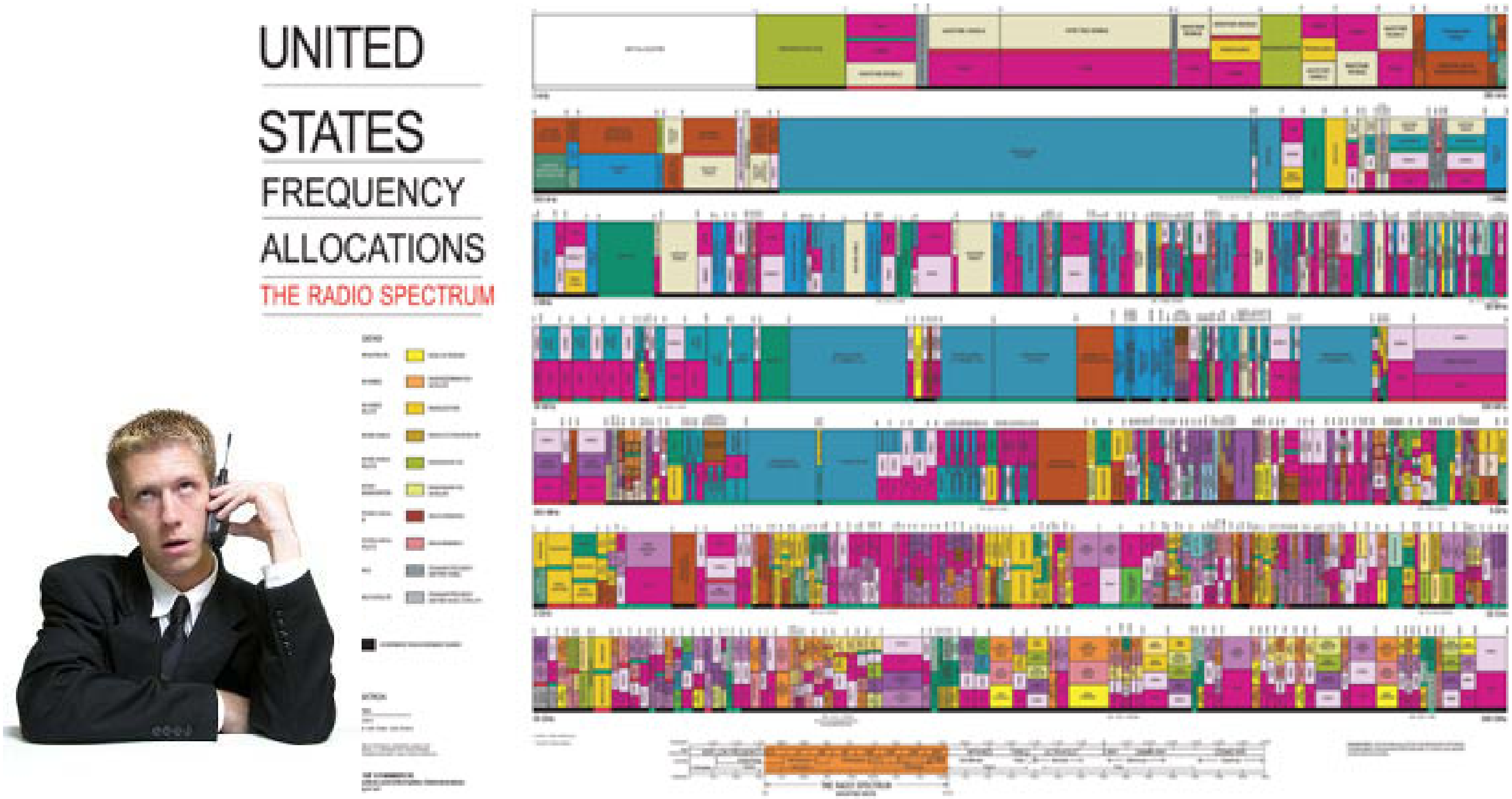
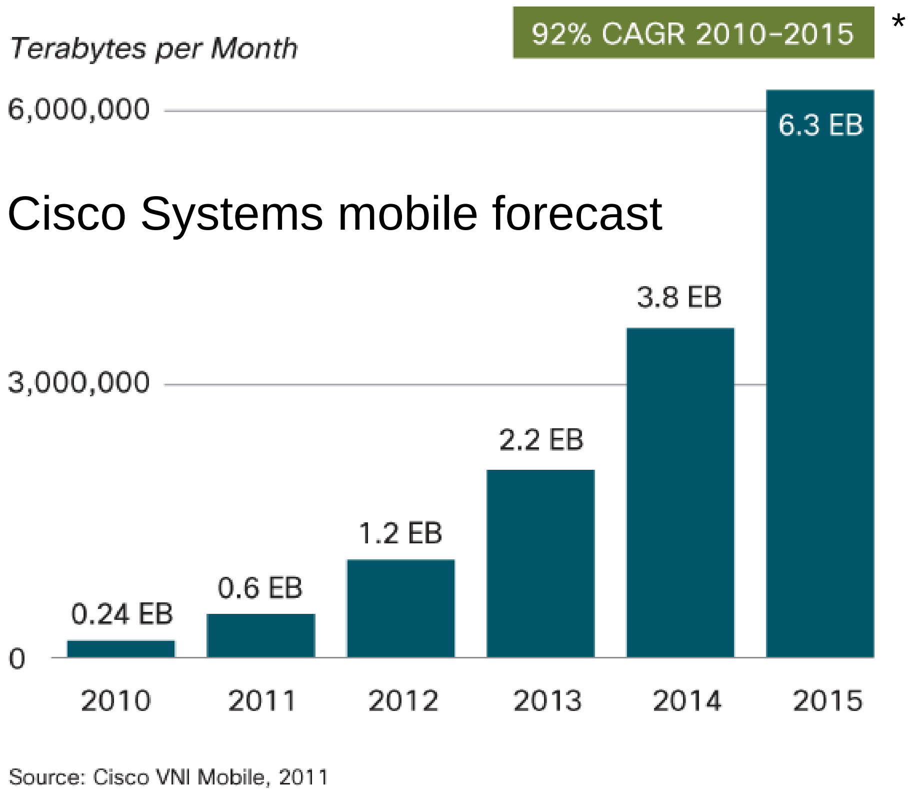
Millimeter-Wave Wireless: Alignment of three critical factors

- Regulatory
  - Millimeter-wave spectrum recently allocated by FCC in the U.S. for commercial use
- Technology
  - Silicon devices now have adequate speed for integrated antennas, transmitters and receivers
- International need
  - Mobile broadband networks are hot
  - "Spectrum crunch": a top telecommunications industry priority

What is the spectrum crunch?



What is the spectrum crunch?



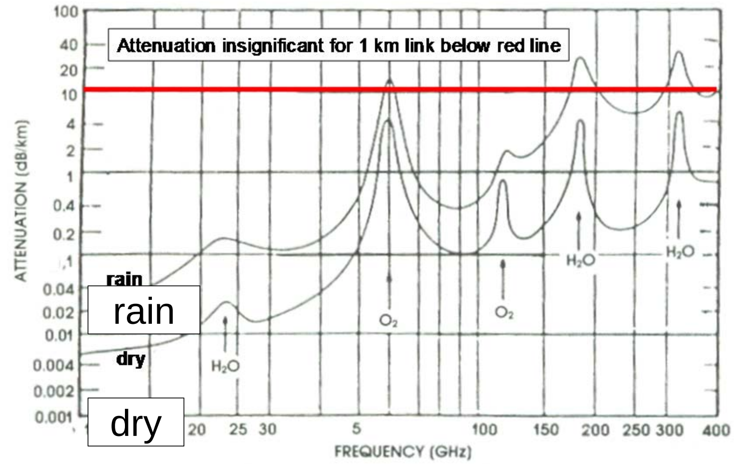
* CAGR: Compound annual growth rate

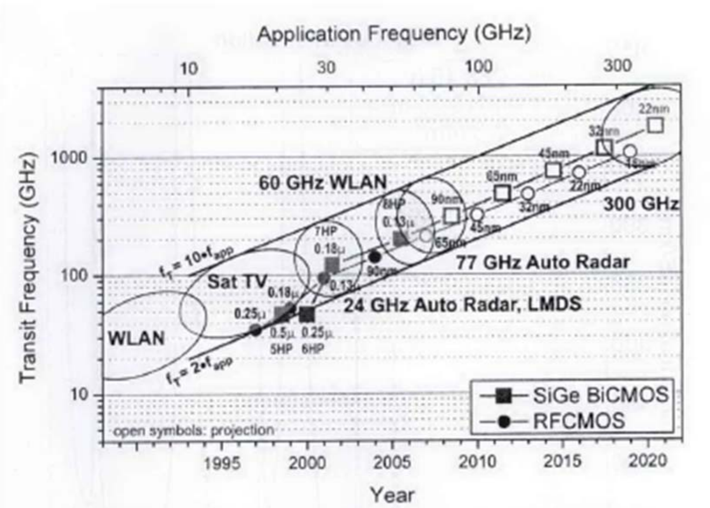
- 3 % of wireless smart-phone customers use 40% of total available wireless bandwidth
- 5000 % growth in demand for wireless internet data in the last three years
- "The biggest threat to the future of mobile in America is the looming spectrum crisis." (Julius Genachowski, Chair of the FCC)

Cellular Telecommunications Industry Association keynote talks, October 2009

Technical enablers

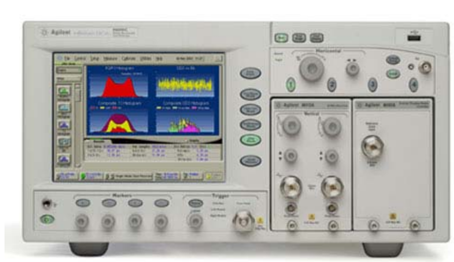
- Attenuation not significant for paths under 1 km
  - Well-suited for cellular and mesh-networked architectures
- Transistor speed
  - Microwave industry ready to exploit its cutting edge high-speed technology
- Short wavelengths enable active, agile, integrated antennas

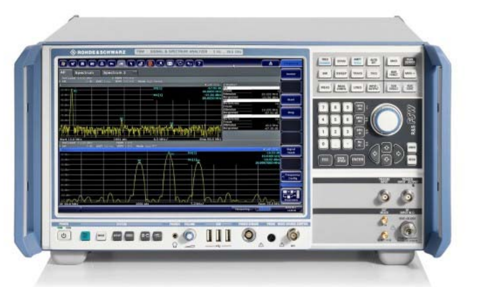




Technical challenge: Hardware verification

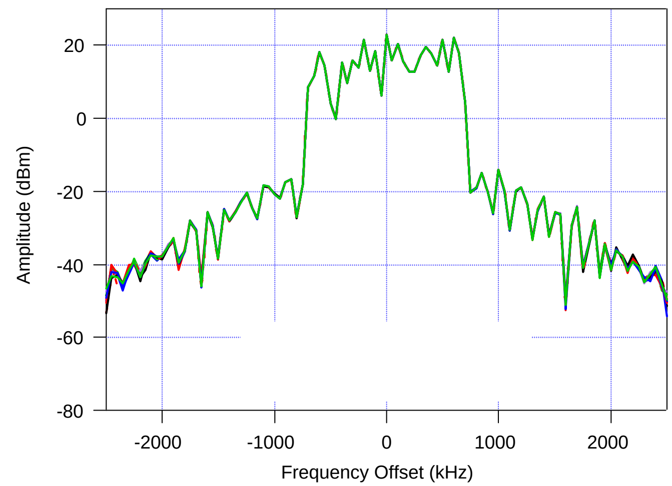
- Verifying sources and receivers of broadband digitally modulated signals at millimeter-wave frequencies
- Required measurement accuracy increases linearly with frequency
- Impedance, timing, nonlinearities: problematic at mm-wave





Lack of traceability for calibrations of commercial instruments inhibits knowledge of measurement accuracy

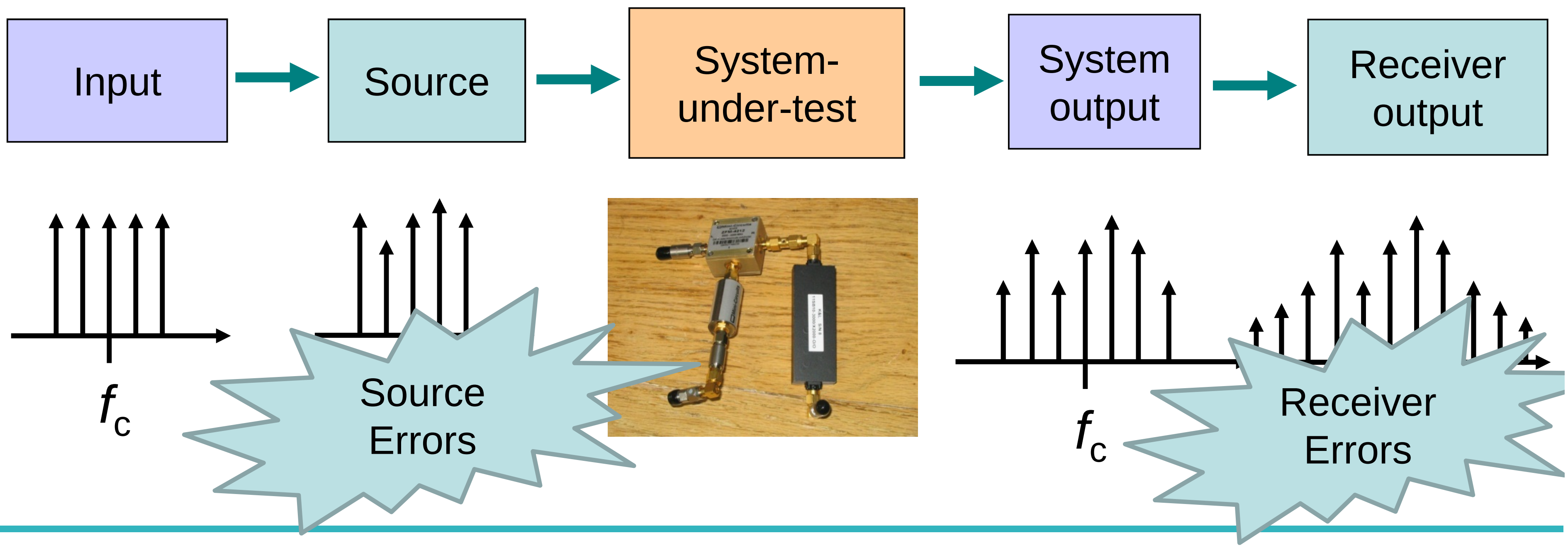
Wireless measurements: hard at RF, harder at mm-wave



- Bandpass signals: Fast sampling for detail around carrier
- Multipath: Channel characterization, system equalization
- Effects of power amplifier: Nonlinear measurements
- Highly integrated systems: Free-field test

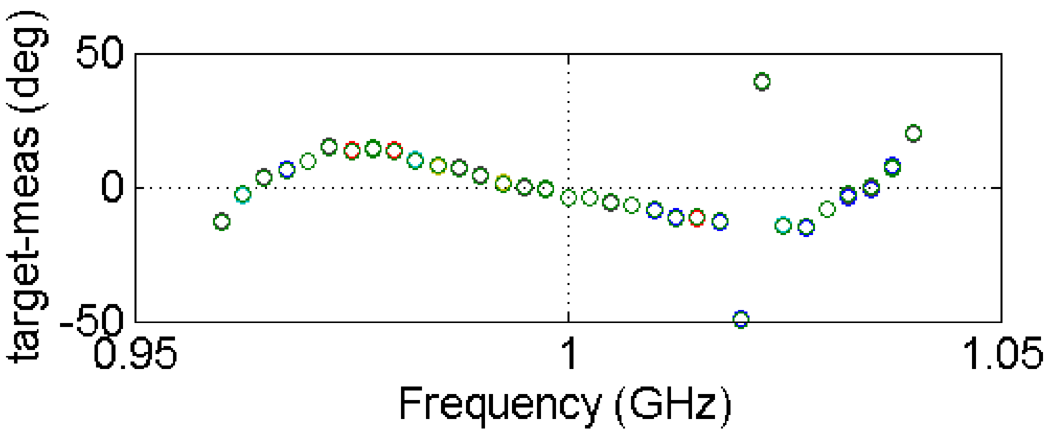
Errors in Sources and Receivers

- Need for accurate test of system response
- Characterized source needed to characterize system-measurement receiver



Vector Response of Sources and Receivers

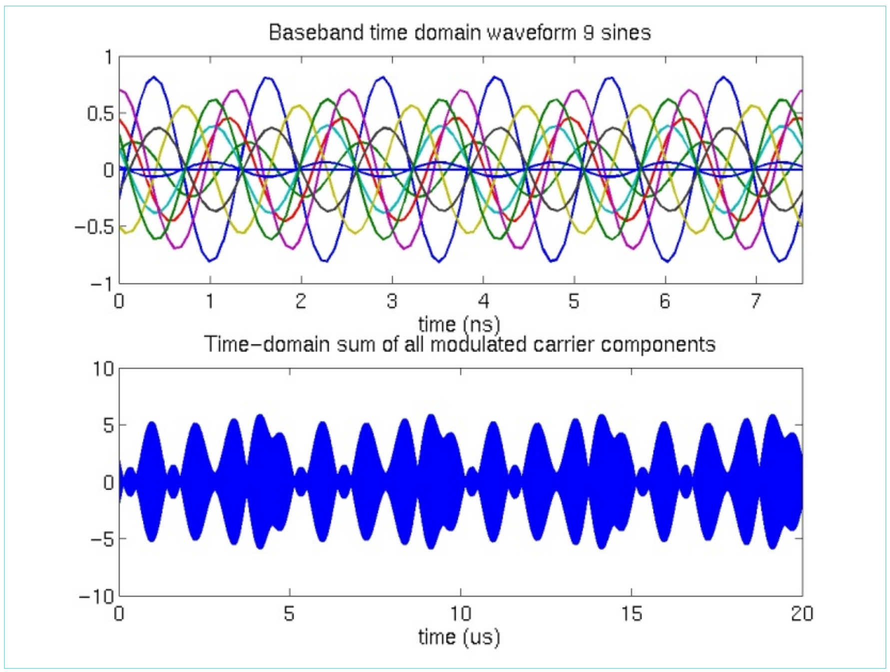
- Characterized source
- Issue: many types of modulated signals
  - Modulation format: peak-to-average power ratio (PAPR) and bandwidth
  - Sources optimized for various formats, bandwidths
  - How to generalize the calibration?



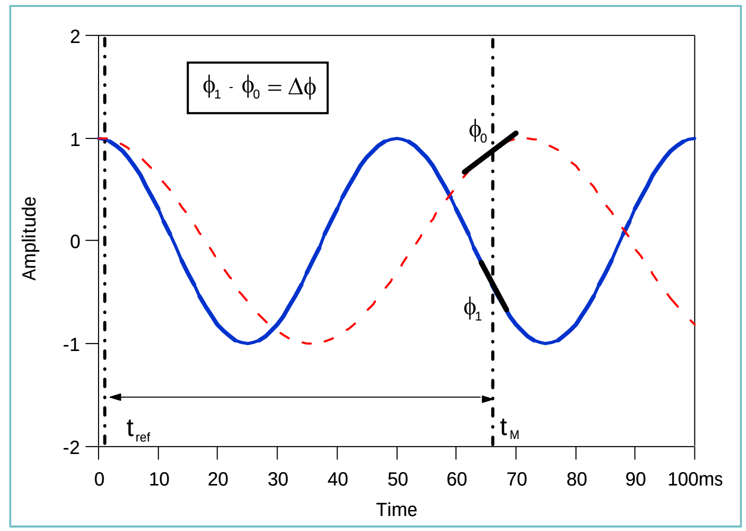
Phase response of vector source: BW = 80 MHz

Calibration signals: Multisines

Multisines replicate various PAPRs, bandwidth, frequency spacing and sampling of digitally modulated signals



Top: 9 frequency-offset sines
Bottom: vector addition of sines

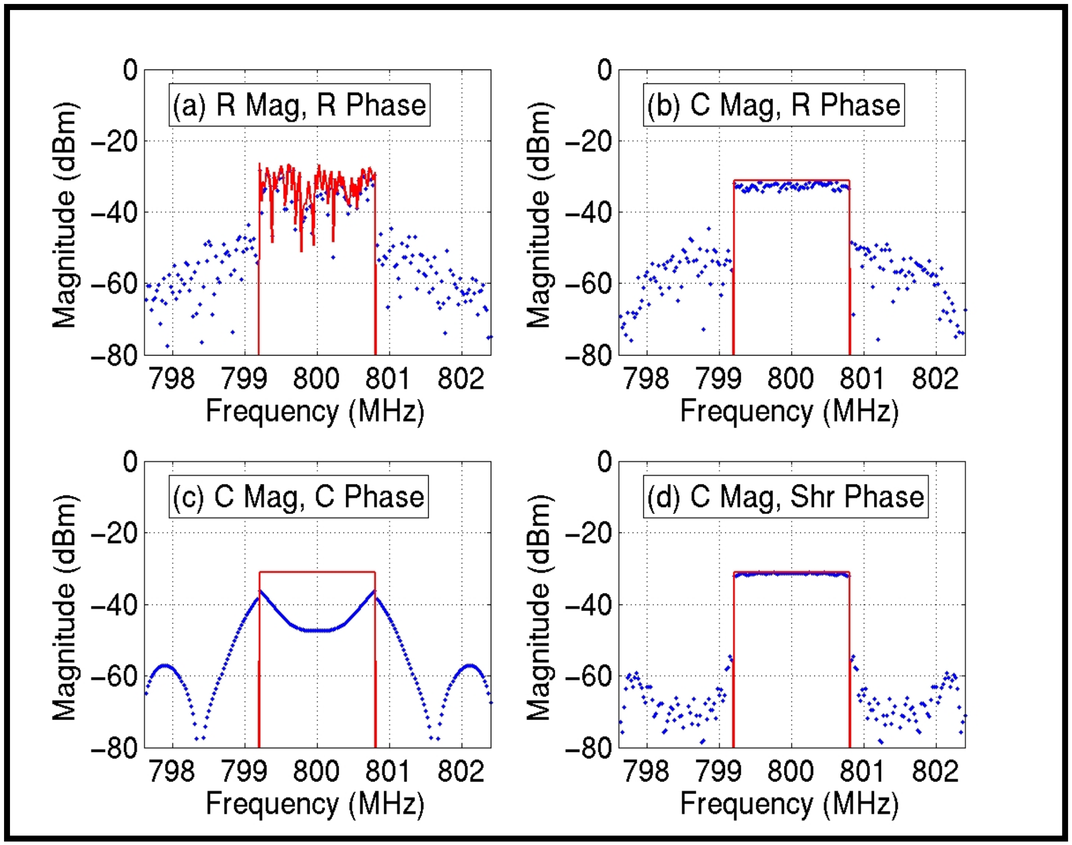


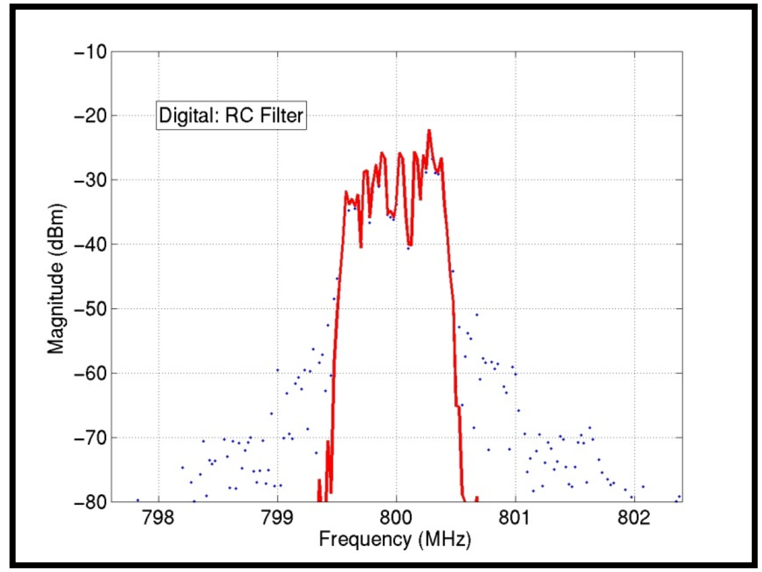
Detrending: Phase alignment based on finding reference time

Low PAPR Schroeder phases:

$$\phi_k = -k(k-1)\pi \; / F_k$$

Replicating waveform features





QPSK signal with raised cosine filtering

Four 65-tone multisines

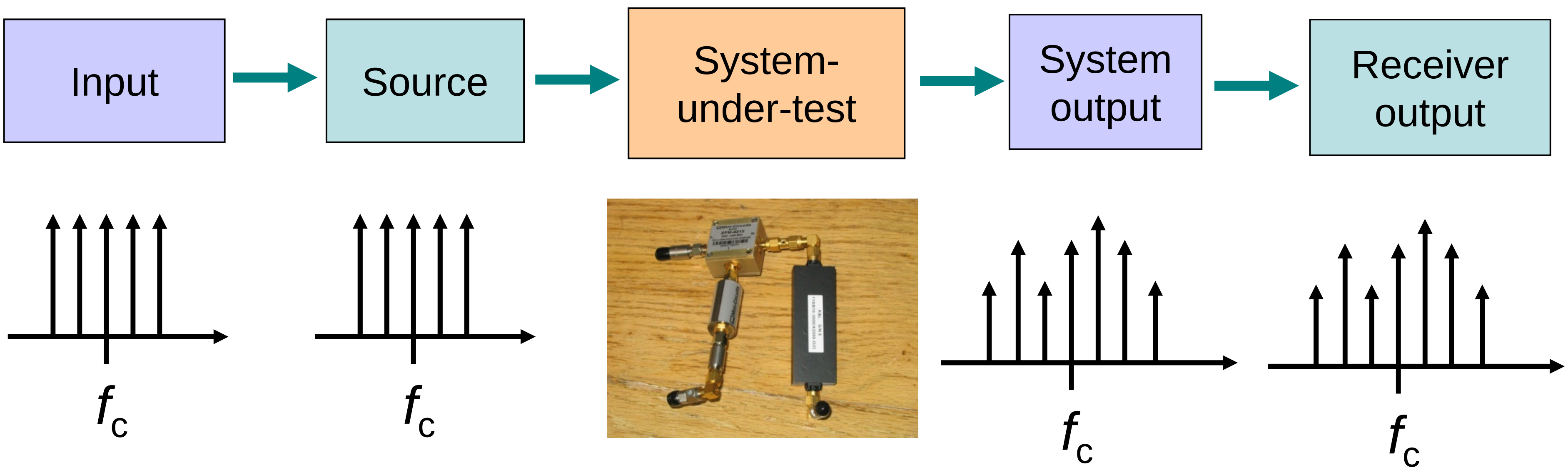
input

output

Relative phase sets signal's spectrum

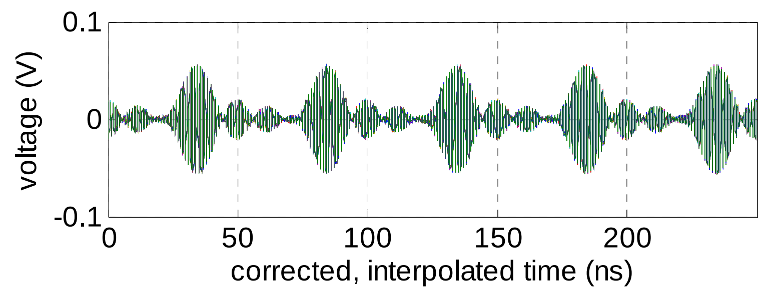
Calibrating source and receiver

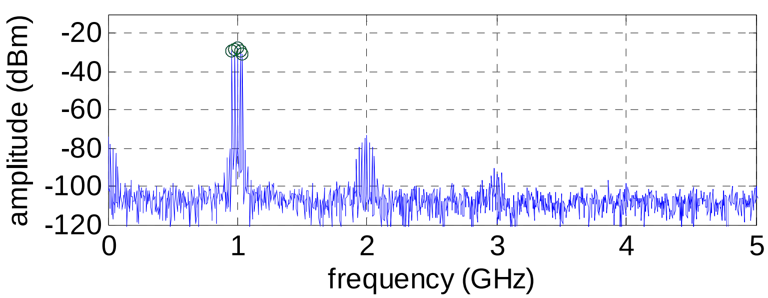
- Excite with multisines, measure imperfections
- Correct for imperfections before measuring system-under-test (with uncertainty)
- Reduce uncertainty with “best” measurement of source



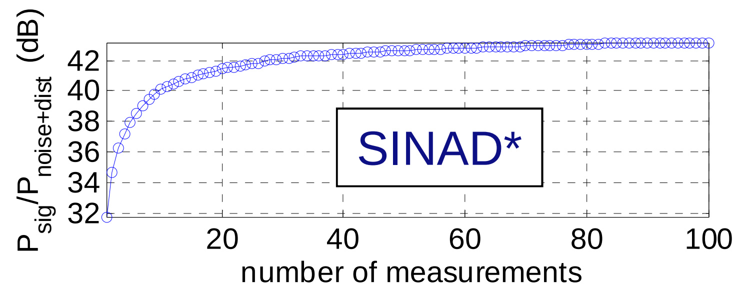
Calibrated vector receiver: sampling oscilloscope

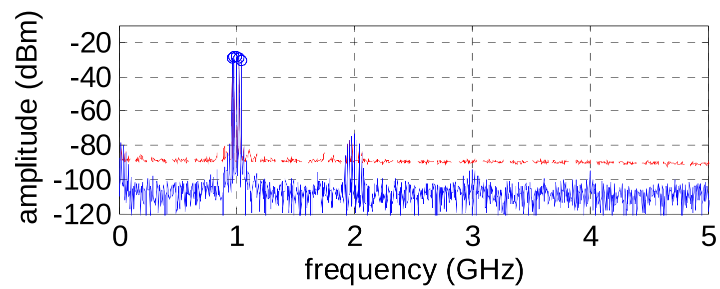
- Traceability: scope response
- Calibrated: time-base correction, mismatch correction
- Broadband: measure signal plus distortion
- Periodic signals: representative communication signals





Time-domain measurement: transform to frequency domain





Time-domain averaging reduces noise floor

* SINAD: Signal-to-interference-and-distortion ratio

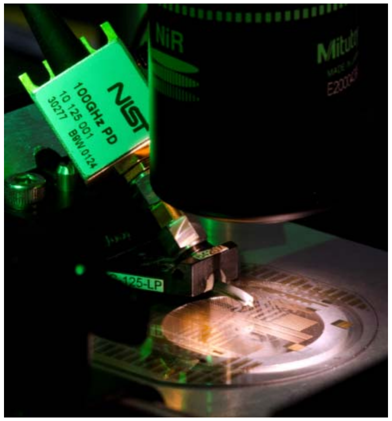
Calibrating the oscilloscope

Calibrate a photodiode impulse source

Mode-locked laser

Photodetector

Electro-Optic Sampling (EOS) system (>1 THz BW)

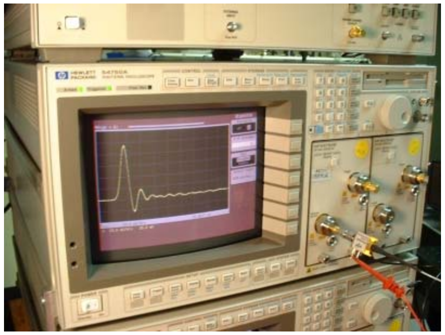


Use calibrated source to correct oscilloscope

Mode-locked laser

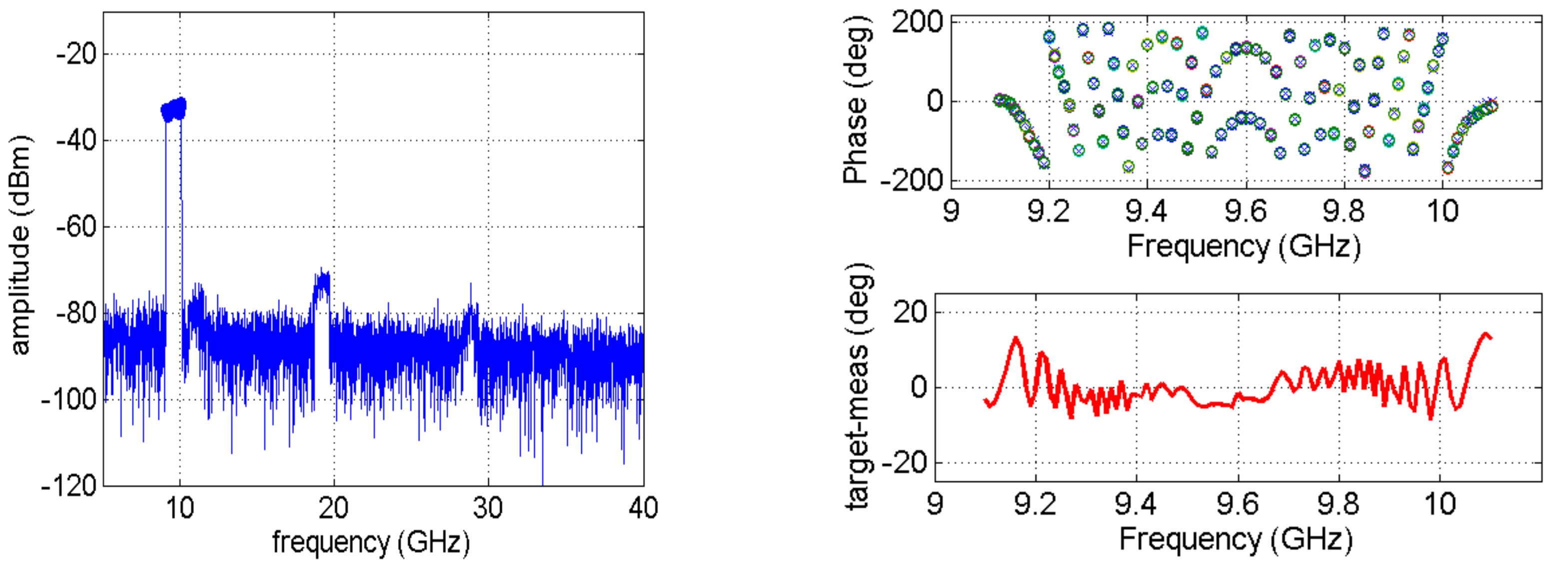
Photodetector

Sampling oscilloscope



Vector sources are not ideal

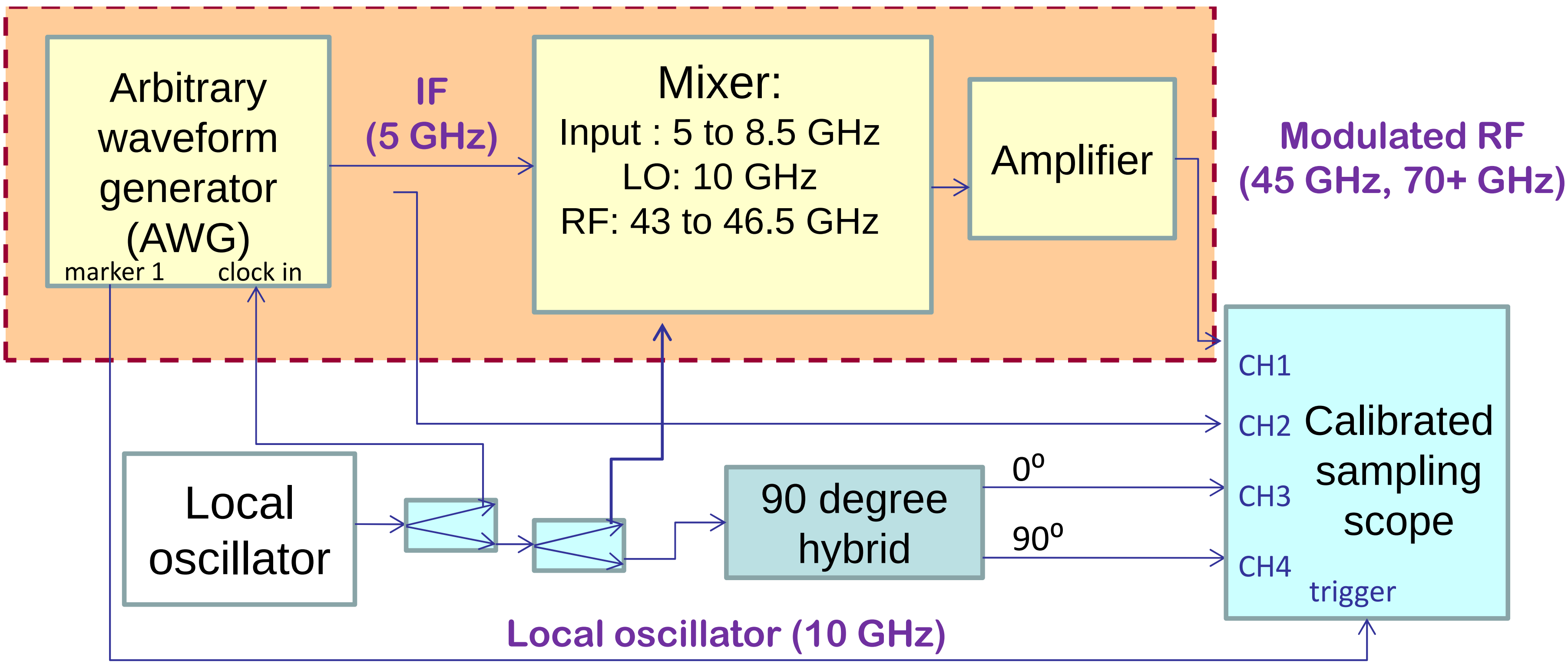
Magnitude and phase distortion can affect error vector magnitude (EVM), bit error rate (BER), other metrics, especially for broadband signals



Scope: 10 GHz Schroeder multisine with 1 GHz modulation bandwidth: Phase error up to 15 degrees

mm-wave sources are less so!

Verify source performance with calibrated sampling oscilloscope



Lab-based mm-wave source

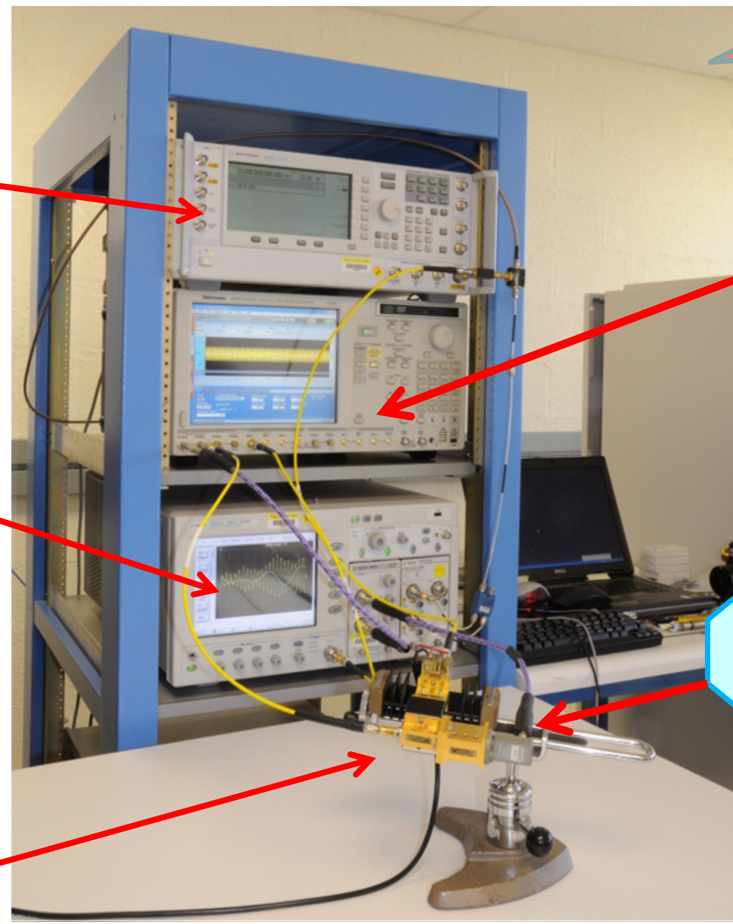
- Mixer LO
- AWG clock
- Scope time-base correction

Baseband effects

Arbitrary waveform generator (IF = 5 GHz)

Calibrated vector receiver (oscilloscope)

Nonideal frequency conversion

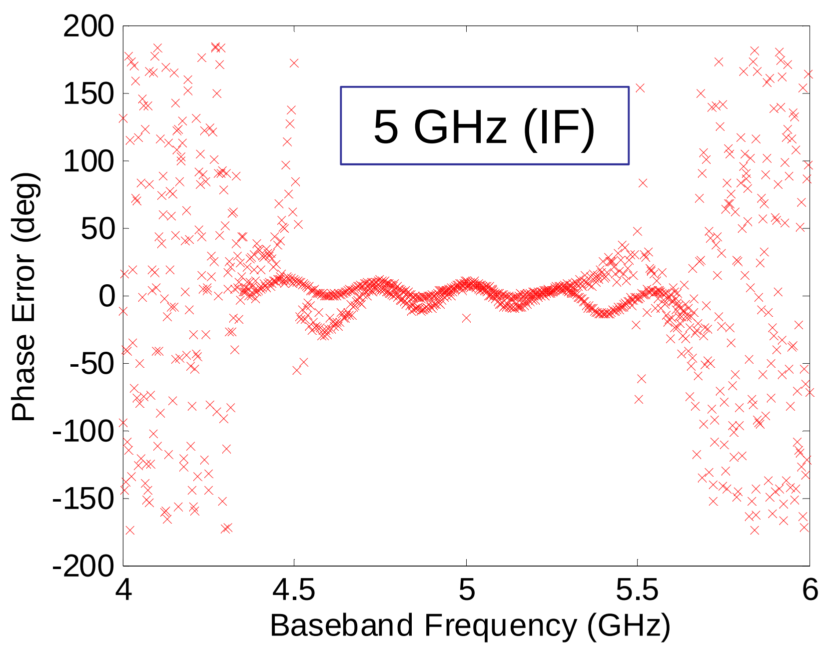


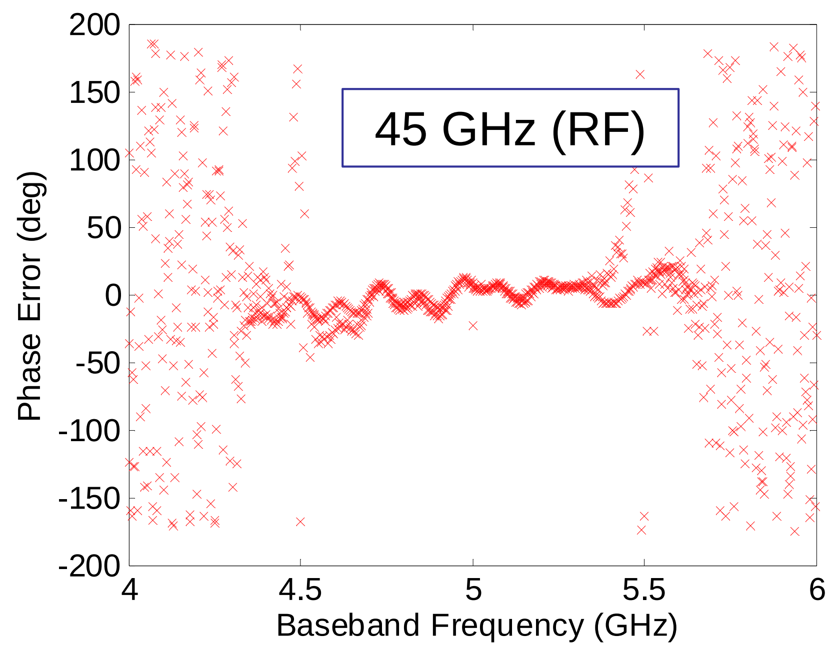
Modulated RF (fc = 45 GHz)

Frequency converter and amplifier

Imperfect source response

Calibrated scope measurement characterizes source



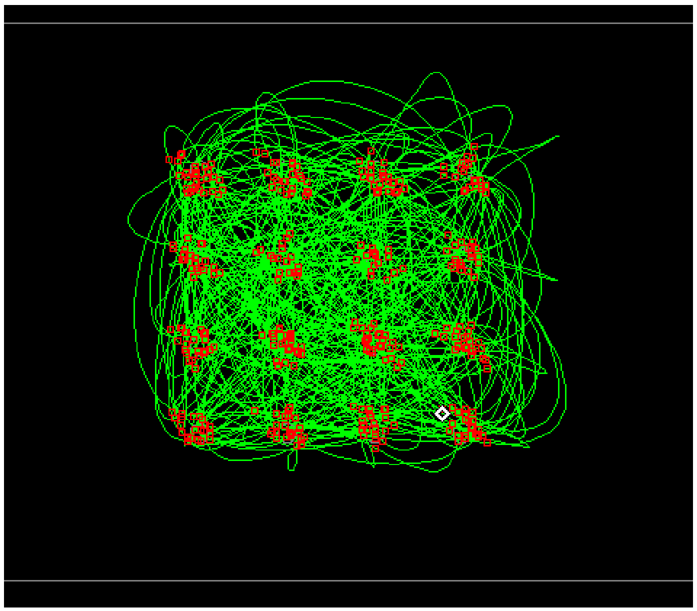


Majority of error introduced at baseband frequency

Imperfect source response

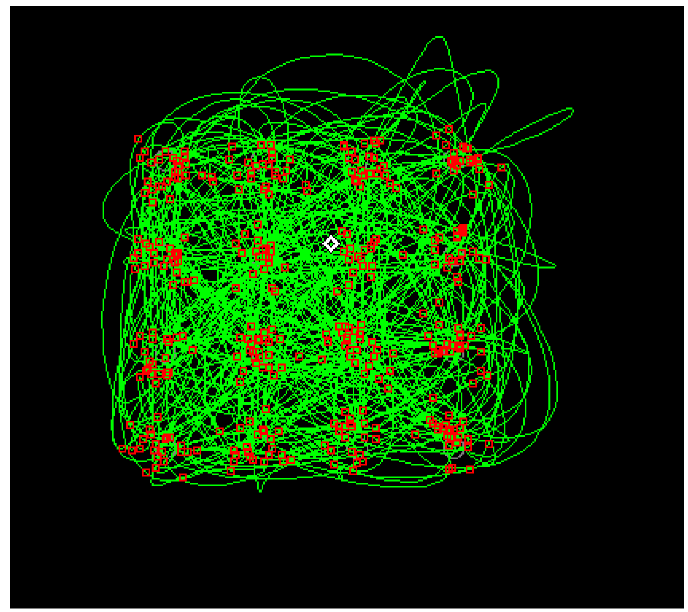
How do baseband errors affect a measurement?

Baseband effects



EVM = 9.5 %

Baseband effects + nonideal frequency conversion

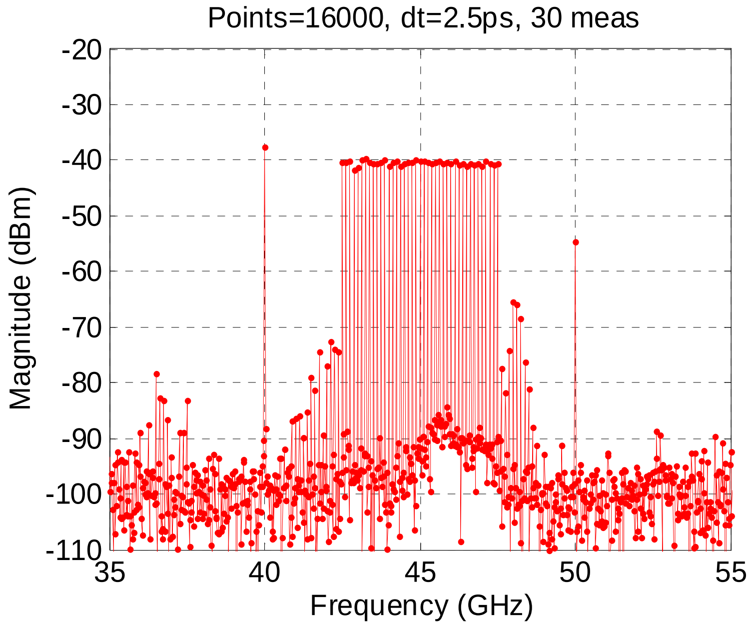


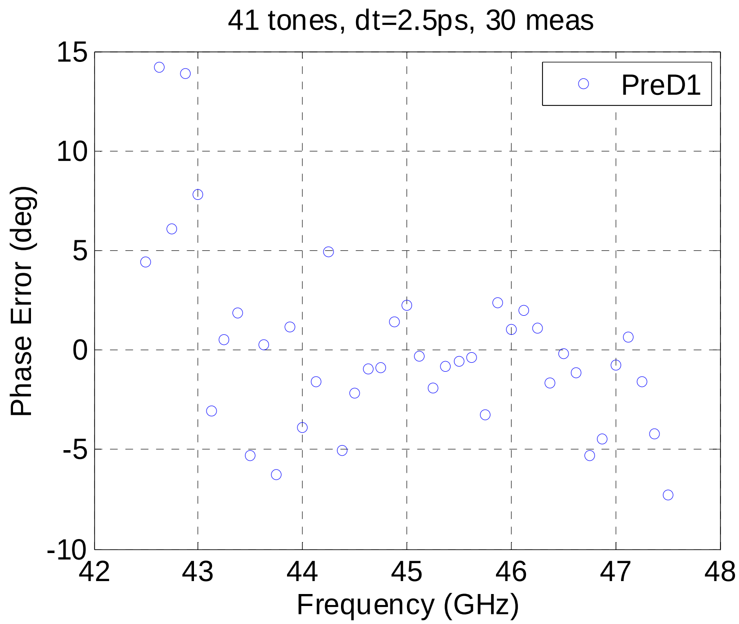
EVM = 11.9 %

16QAM signal with 1 GHz modulation bandwidth

Correct source output

- Predistort AWG-based source input signals
- Iterative predistortion: linear and nonlinear response





In-band magnitude and phase errors are reduced with predistortion

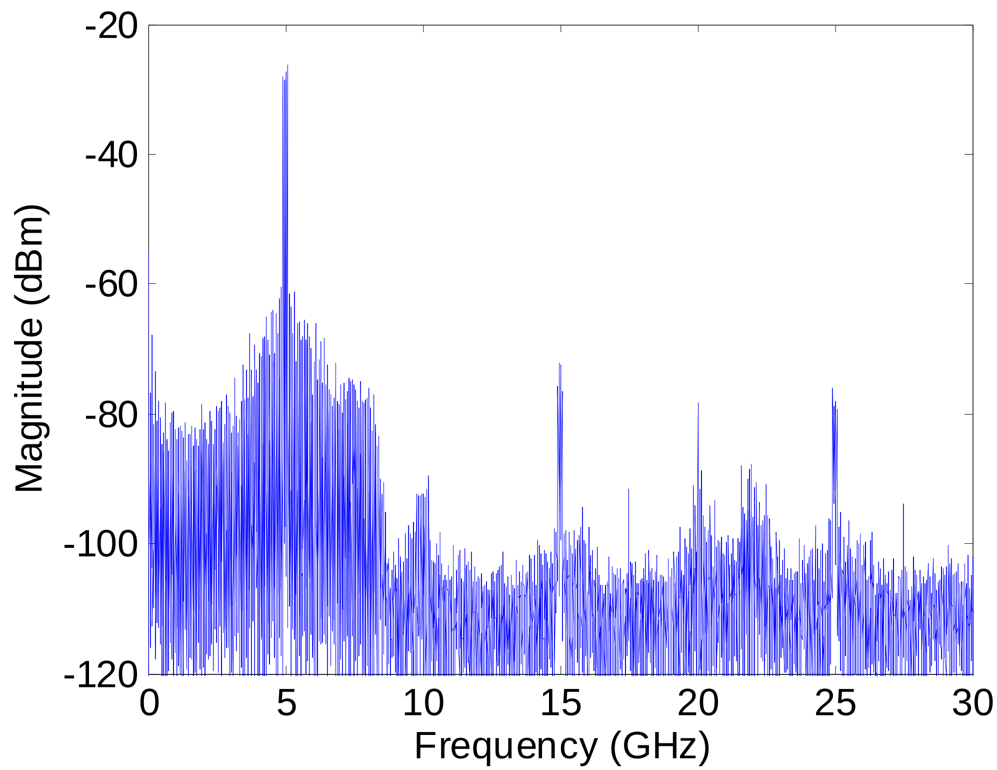
Quantization noise and spurs

Quantization noise

- Nonlinearity of ADC
- Limits effective number of bits of AWG

Spurs

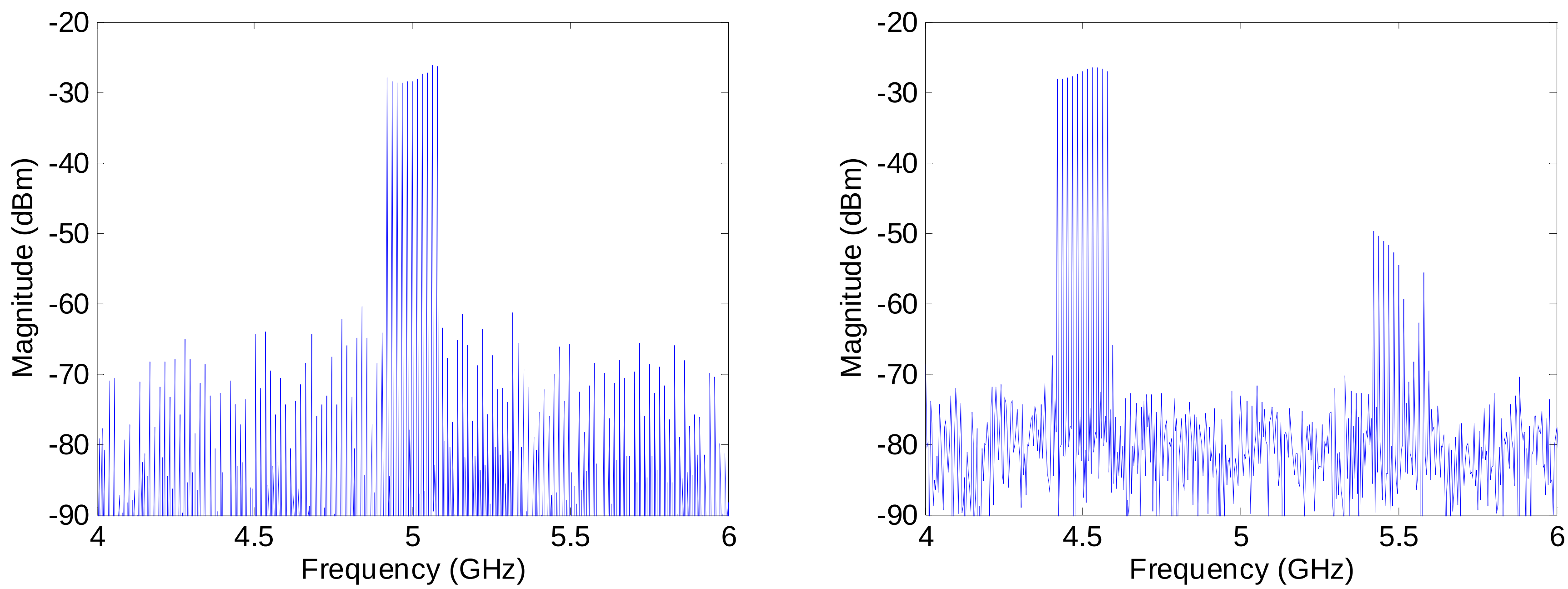
- Harmonics and mixing products caused by sampling
- Dithering improves AWG noise floor as much as 10 dB



11-tone, Schroeder-phase multisine
160 MHz modulation bandwidth

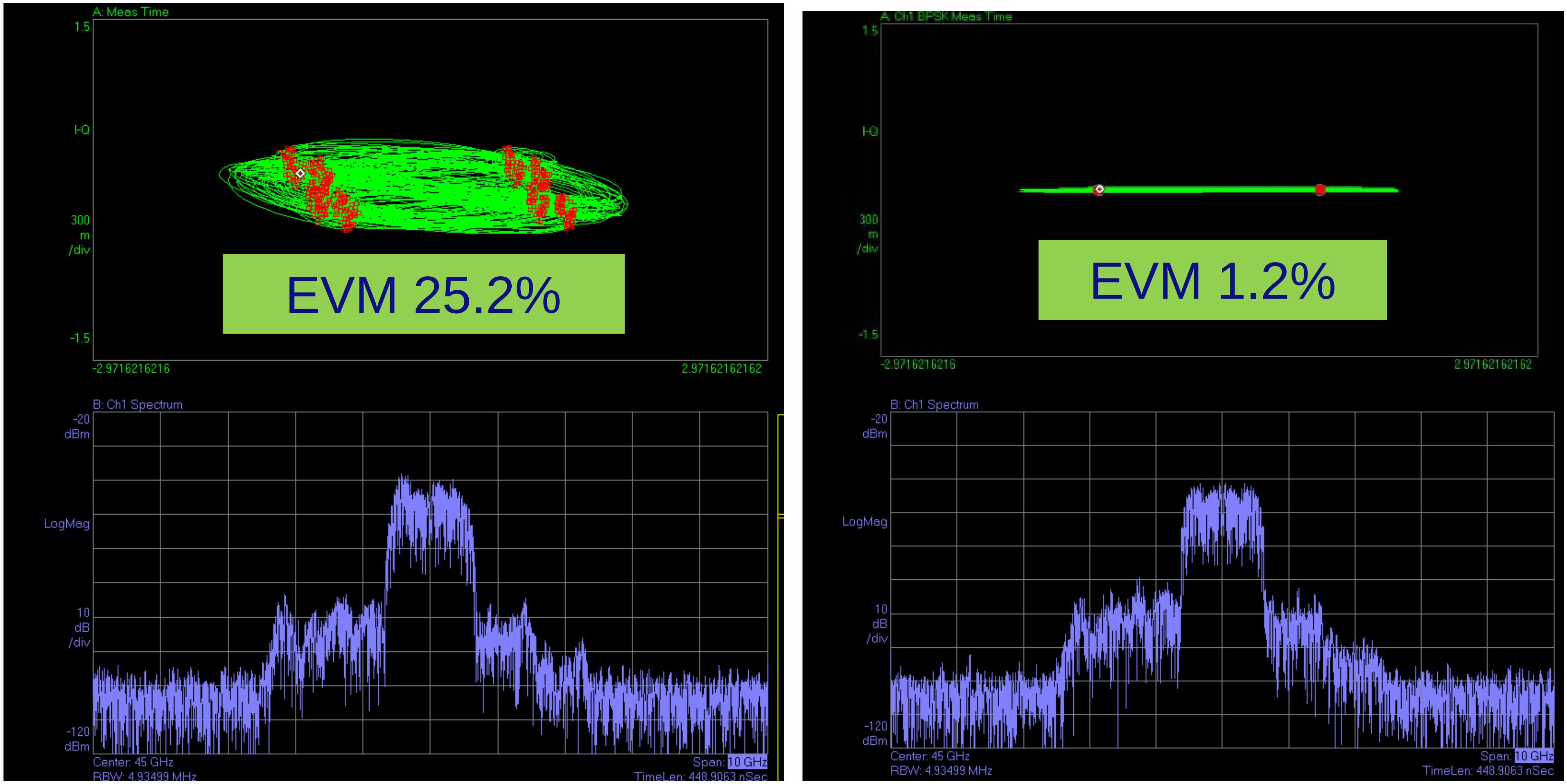
Suppress in-band spurs

In-band spurs degrade generated baseband (IF) signal



Carrier offset moves spurs out of the passband of the signal, reduces in-band distortion and adjacent-channel power ratio

Good baseband signals give good mm-wave measurements

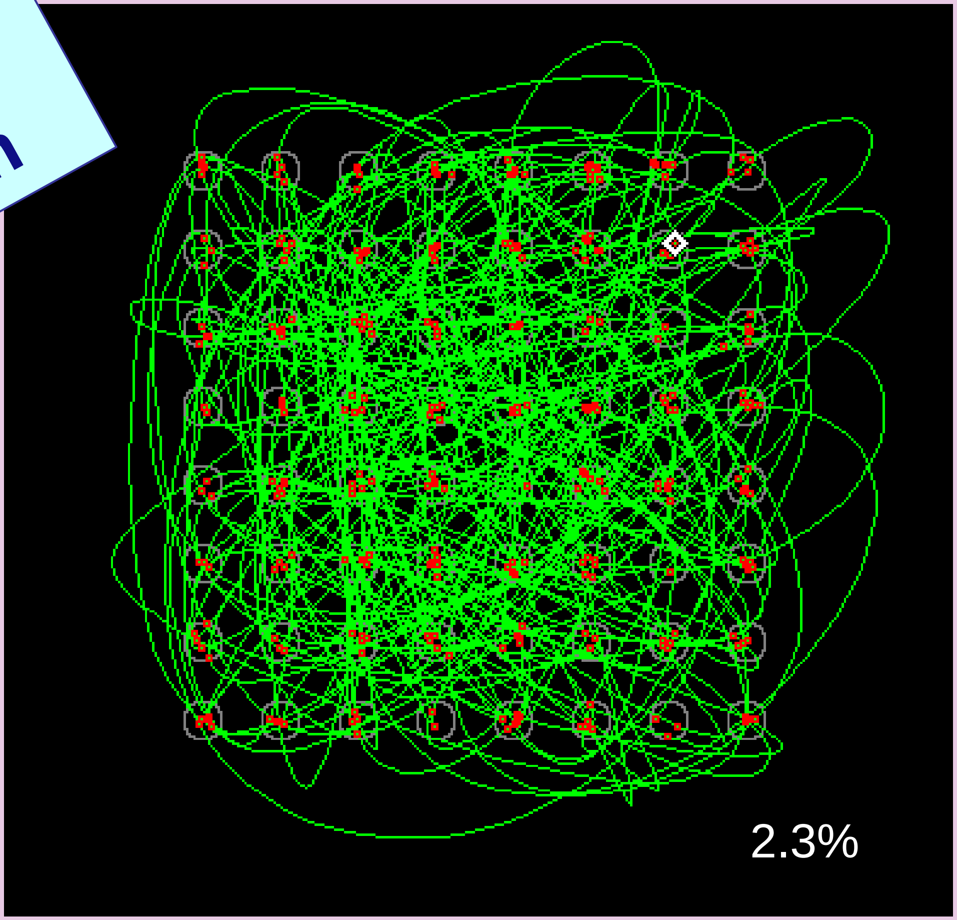


1 GHz bandwidth BPSK signal at 45 GHz

Low-EVM 64 QAM waveform

Allows mm-wave vector receiver calibration, system characterization

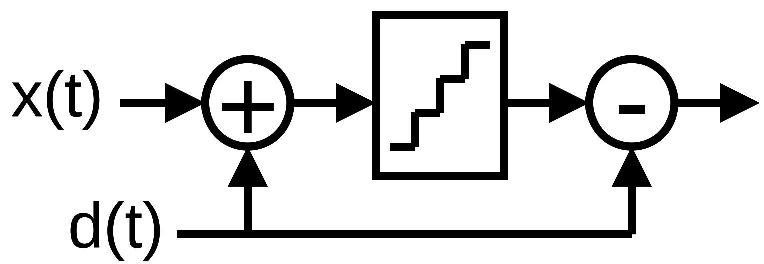
EVM for 64 QAM



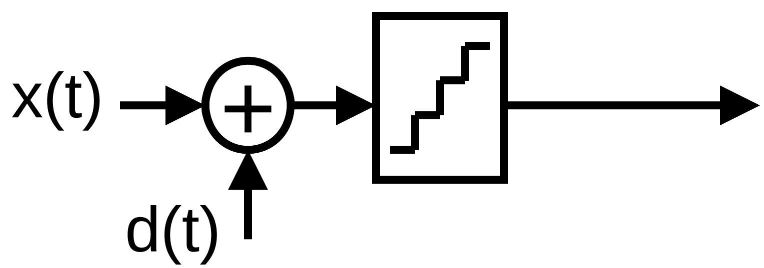
45 GHz center frequency,
1.2 GHz modulation bandwidth,
512 symbols

Dithering to reduce ACPR

- Intentional addition of a special waveform to the input signal prior to the data conversion
  - Makes quantization noise less correlated to signal
  - Spreads quantization noise over frequency range
  - Reduces quantization noise
- Types:
  - Subtractive



  - Non-subtractive

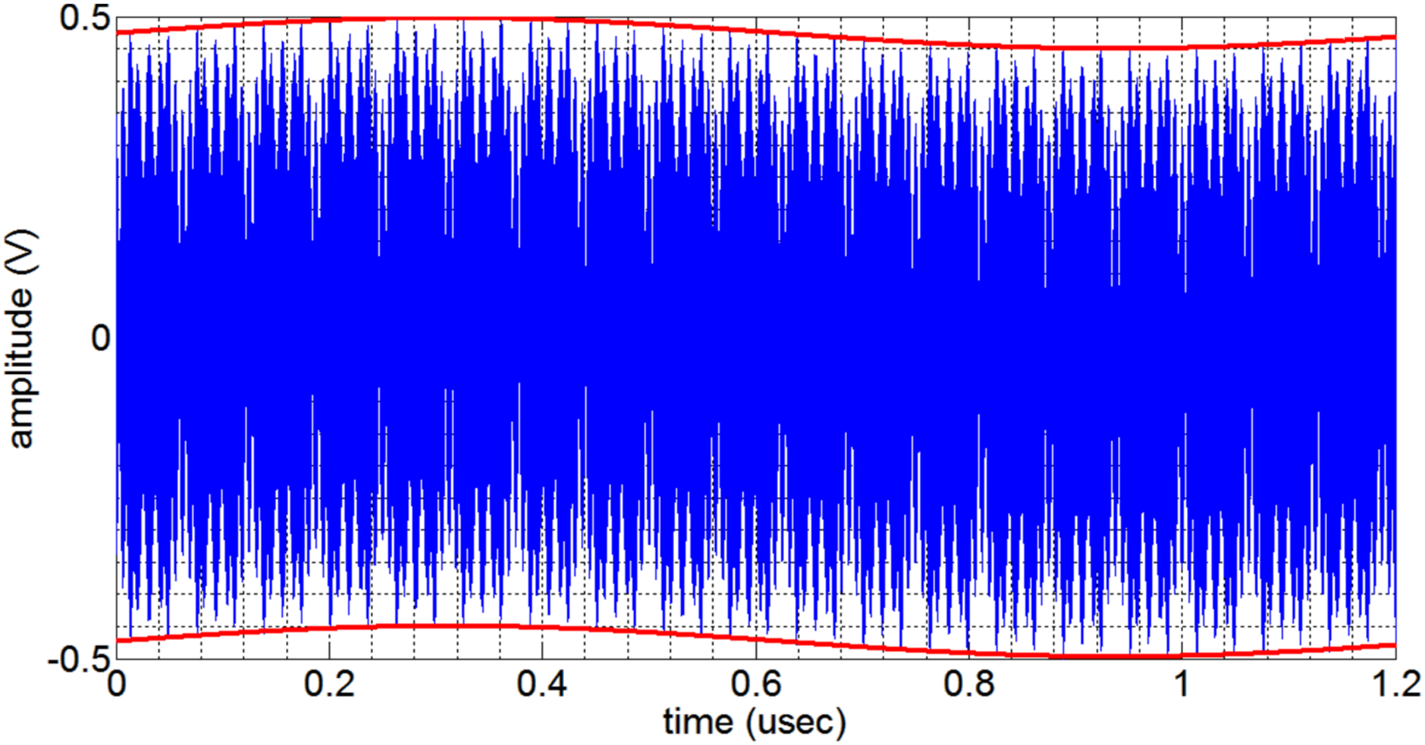


Non-subtractive dithering

- Dithering signals are chosen so that by filtering, they can be efficiently removed after conversion
- Ensemble dithering:
  - Record multiple periods of periodic waveform (multisine)
  - Add different dither to different ensemble member
  - Average over the whole ensemble to remove dither

Time-Domain Ensemble-Averaged Dithering

- Use self-subtractive dither
- Repeat the waveform with time-varying additive dither

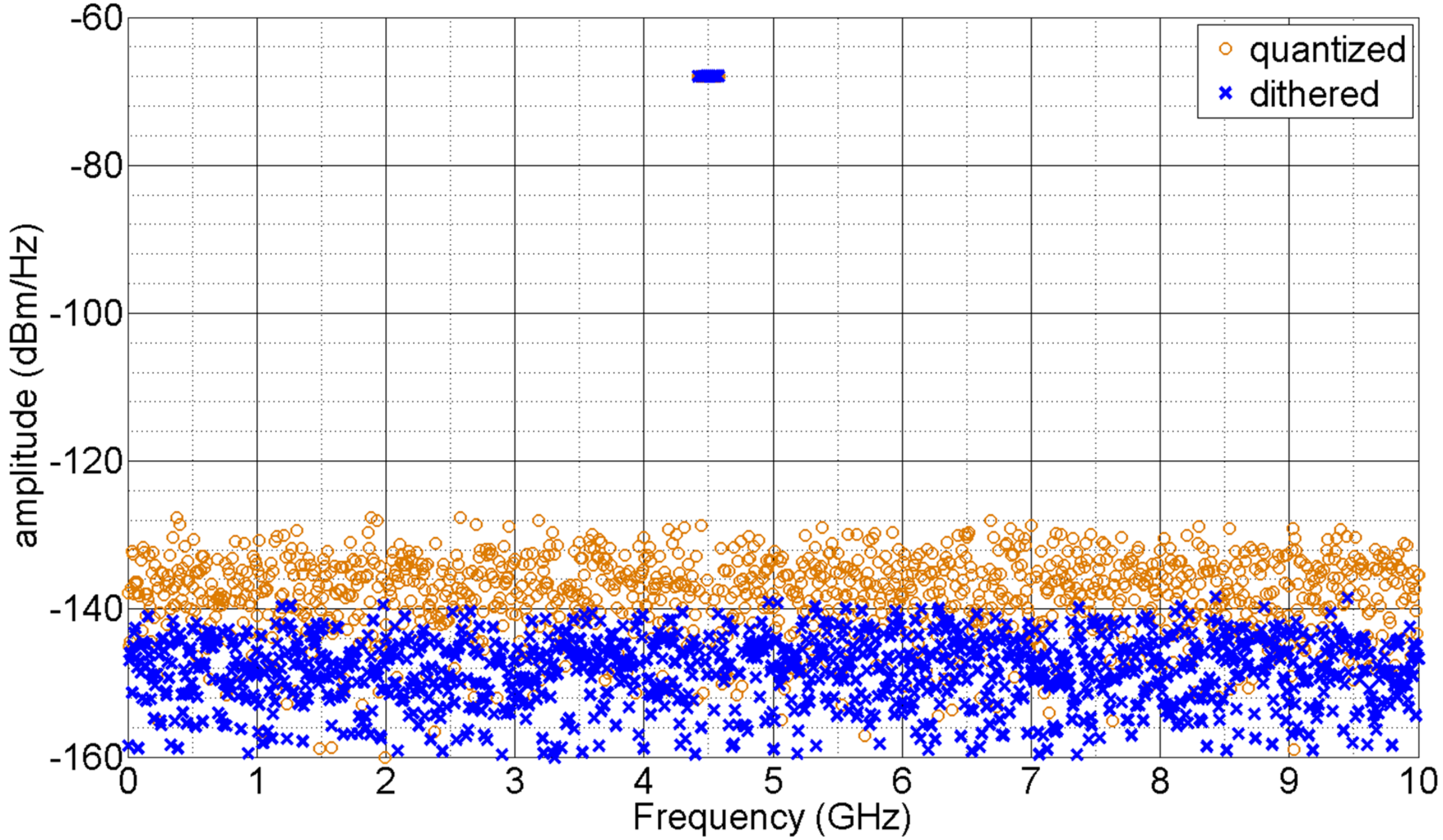


Time-Domain Ensemble-Averaged Dithering

- The averaged waveform effectively lacks the dithering component
- This is a suitable technique for test and characterization with a high-resolution requirement
- The quantization noise is reduced in post-processing

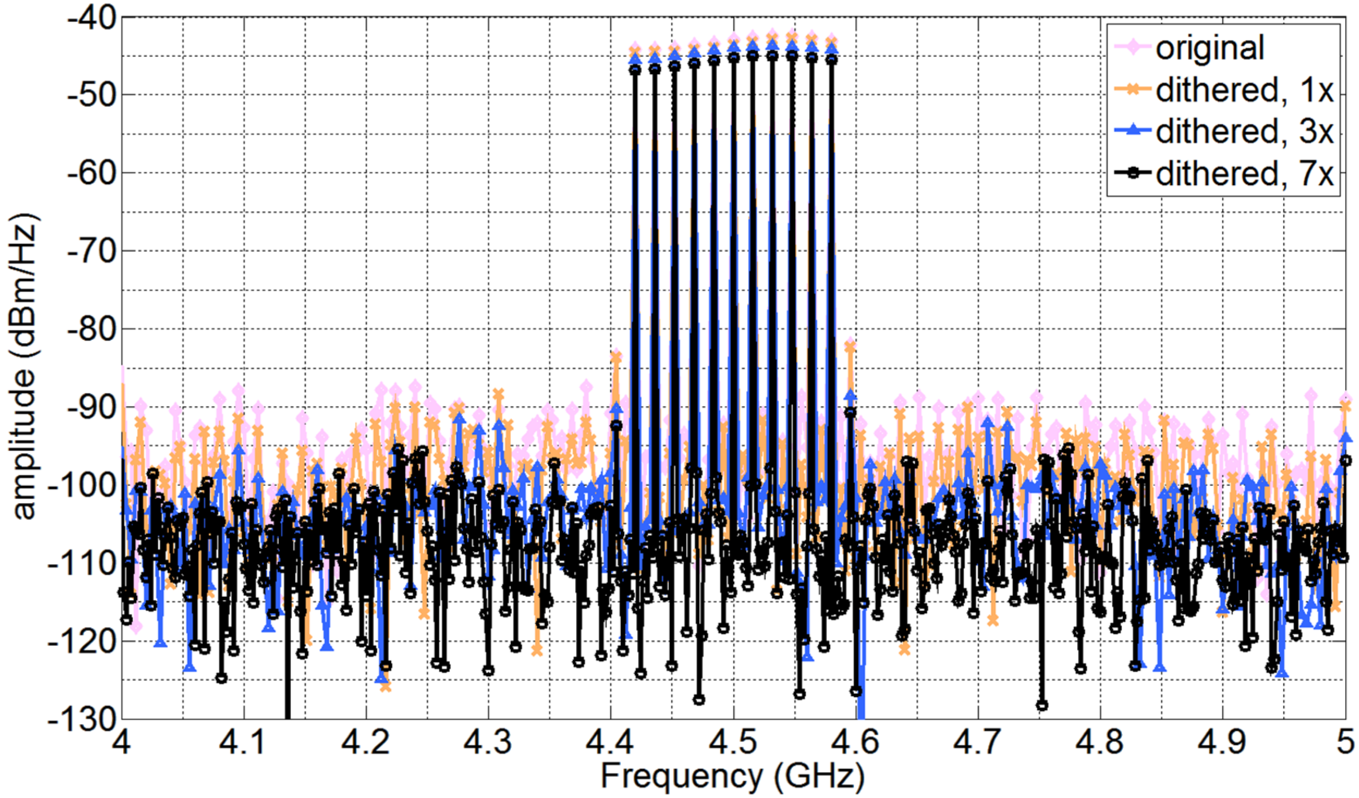
Quantization noise reduced

11-tone multisine, fc = 4.5 GHz, BW = 160 MHz



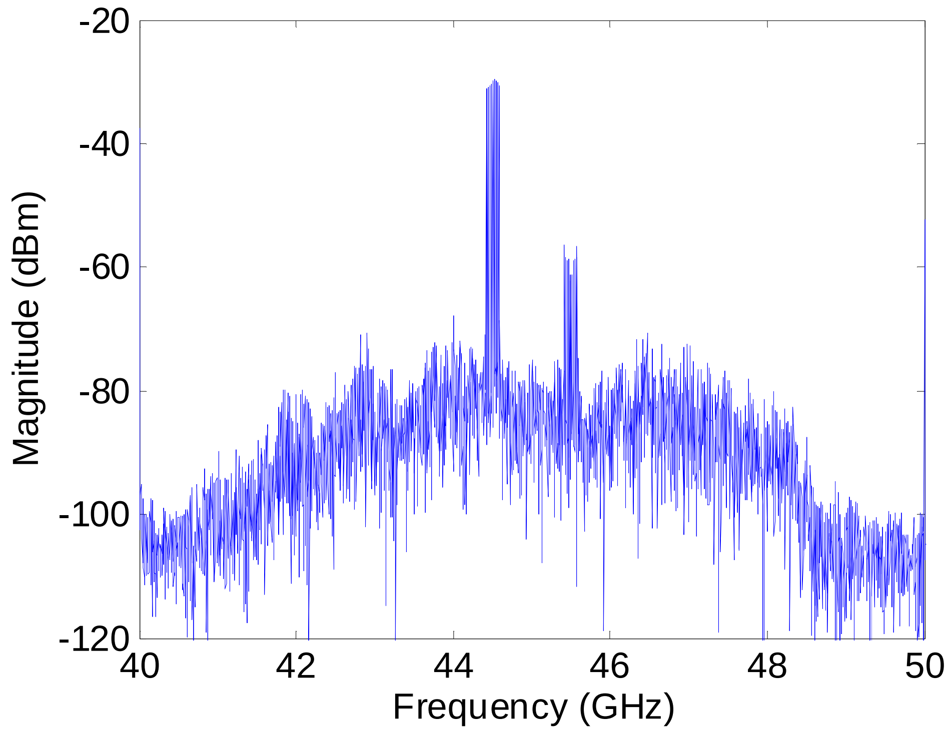
Improved dither signal

Use of larger dither signal to reduce non-idealities of signal generator in post processing



mm-wave ACPR improved

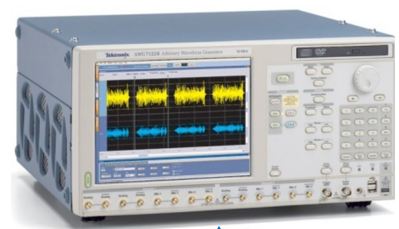
Baseband-frequency offset and dither improve mm-wave signal

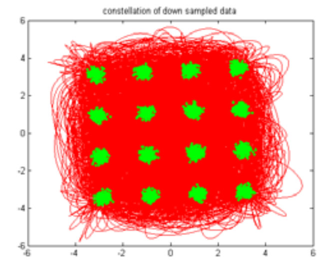


Offset + Dithering
(ACPR 52 dB)

Looking forward

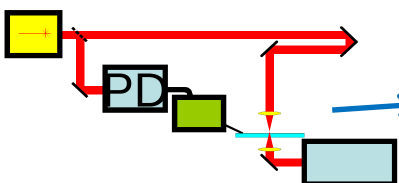
Calibrated vector signal sources



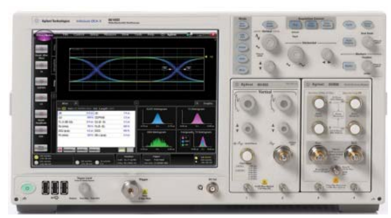


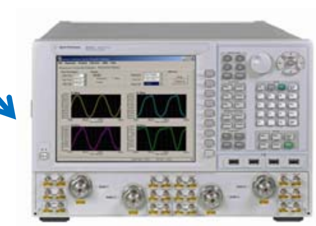
Vector signal analyzers

NIST EOS
On-wafer CPW
~1 THz BW
<< 1 ps FDHM



NIST Photodiode
1.0 mm connector
Calibrated to 110 GHz
100 GHz BW
~4 ps FDHM





Large-signal network analyzers

Impedance metrology, mm-wave power

NIST Oscilloscope
1.0 mm connector
Calibrated to 110 GHz

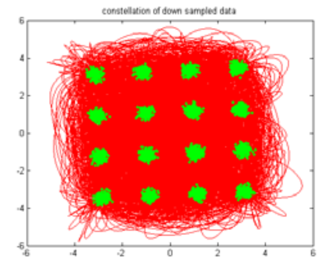
Meter, second, volt

Uncertainties established

Looking forward

Measurements for millimeter-wave wireless

- Baseband and frequency conversion:
  - mixing products, spurs
  - quantization noise
- Calibrated sources and receivers
  - Distortion characterization
  - Known EVM
  - Traceability
- Baseband effects can muddy the waters at millimeter-wave frequencies!



Vector signal analyzers

Large-signal network analyzers