ANALOG DEVICES

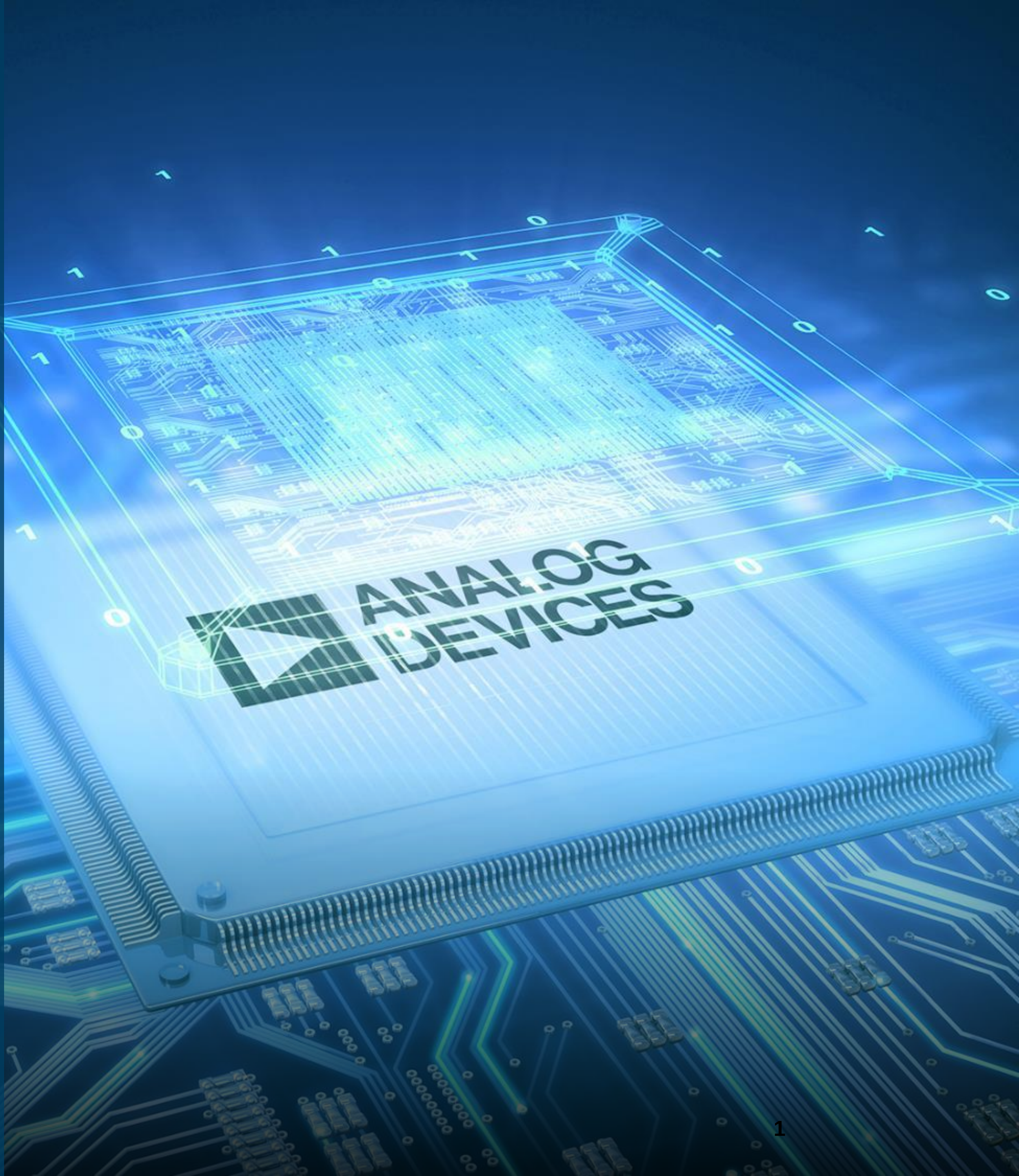
AHEAD OF WHAT'S POSSIBLE™

Does The Radio Even Matter?

- Transceiver Characterization Testing Framework

TRAVIS COLLINS, PHD

ROBIN GETZ



Which cost least?

Which cost least?

$8.95

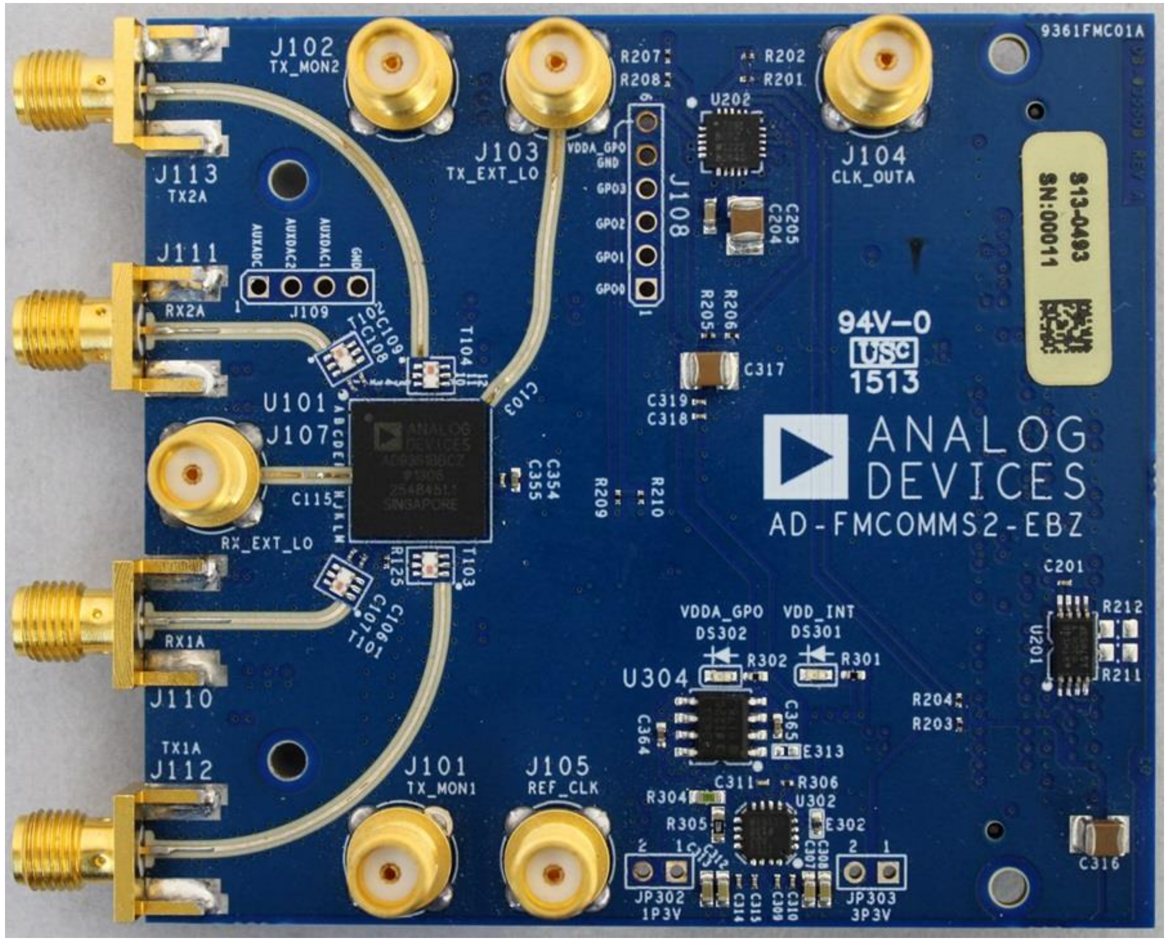
$16.98

$28,000

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Motivation For Common Test Framework (Software perspective)

- Does the radio matter?
  - Pluto vs RTL-SDR vs E310
- Answer questions datasheet doesn't answer
  - Depth of product without burden of datasheet
  - Receiver sensitivity?!?!
  - Application perspectives
- Did my build my radio right?
  - Allow customers to test their own designs again references
  - Applies to companies and individuals
- Receiver development guidance for users



ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Test Framework/Infrastructure

- Purpose:
  - Perform testing that is insightful for communications engineers
  - Compare different SDR platforms in a repeatable and flexible way
  - Limit requirements on test equipment (if possible)

- Requirements
  - Standards compliant waveforms with range of performance modes
    - LTE
  - Instruments
    - Keysight N5182B MXG (6GHz)
    - Agilient N9030A PXA (6GHz)
    - Only used for data capture not measurements

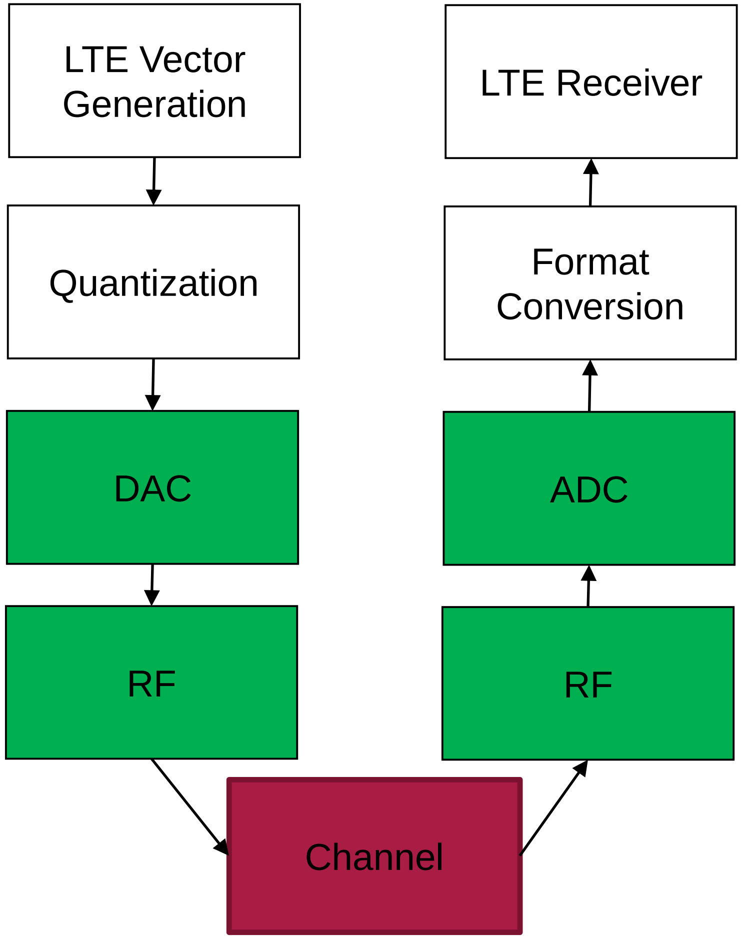
- Platform
  - Built upon MATLAB unit test framework (xUnit-Style)
    - Waveform generation and recovery
    - SDR support
    - Instrumentation support
    - Deep measurement library

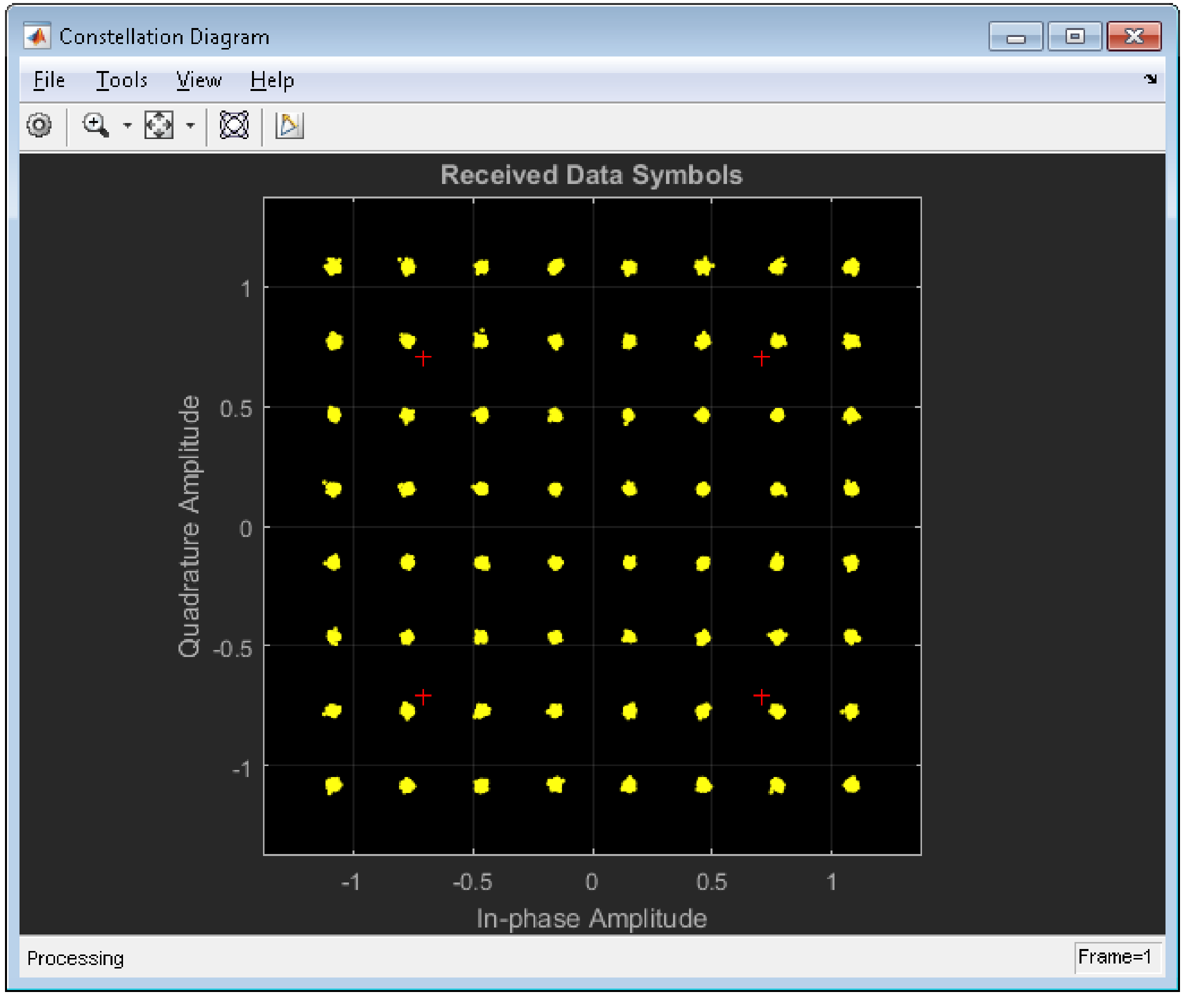
Disclaimer

- These conditions are ideal as possible
- These plots are not a datasheet
- Understand the differences between radios and their designs
  - Pluto has no TX/RX filters (cabling limits possible aliasing products)
  - RTL-SDR was built for DVB
  - Radios like E310 or Matchstiq have necessary additional RF pieces
- We have a lot more expertise with AD9361 and libiio controlled products
- Framework is still under development

Pseudo – device / system specs

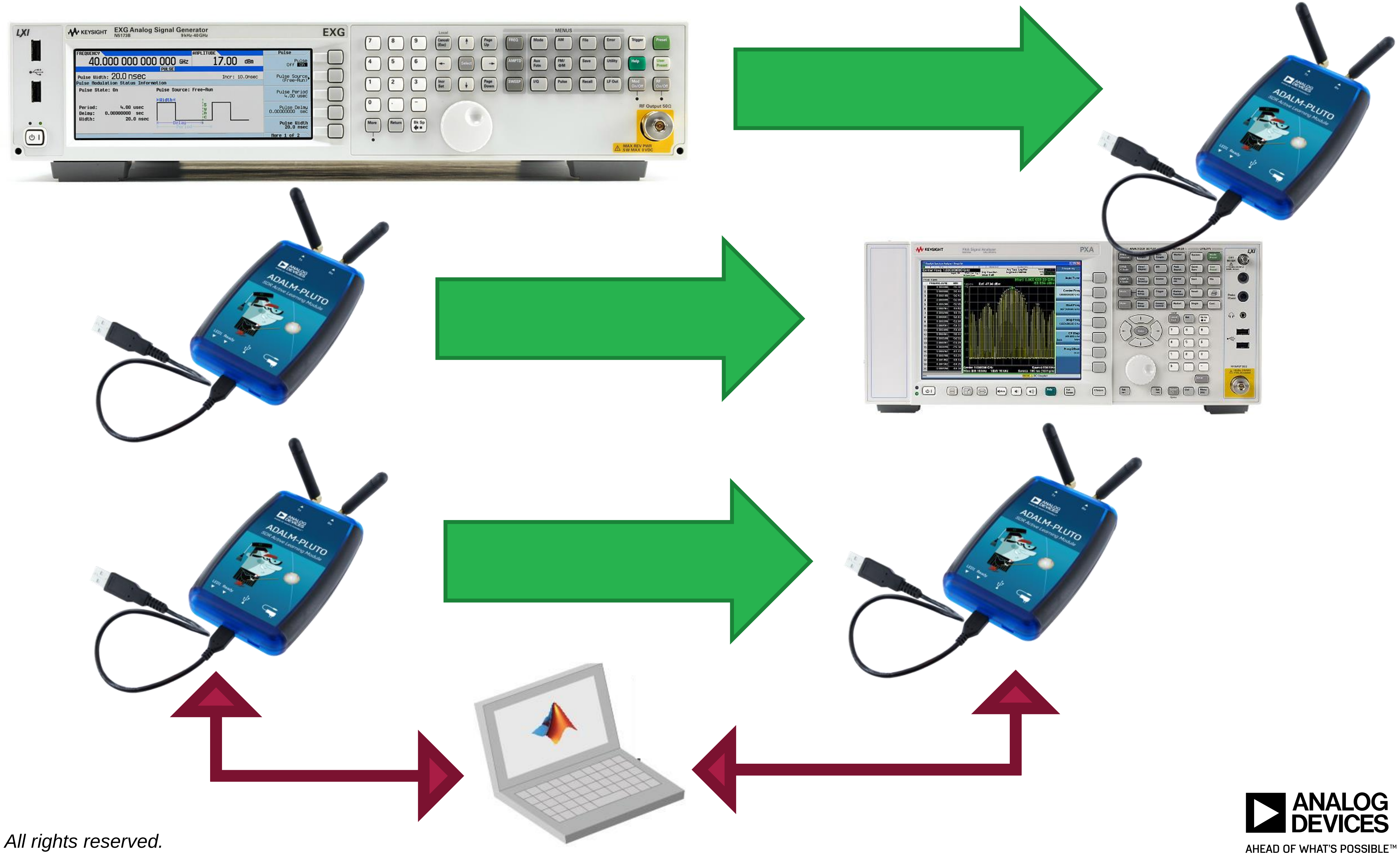
- The error vector magnitude or EVM is a measure used to quantify the analog performance of a complete data link.
- The entire transmitter and receiver is measured.
  - Measured result is the weakest link, but no idea what that is.



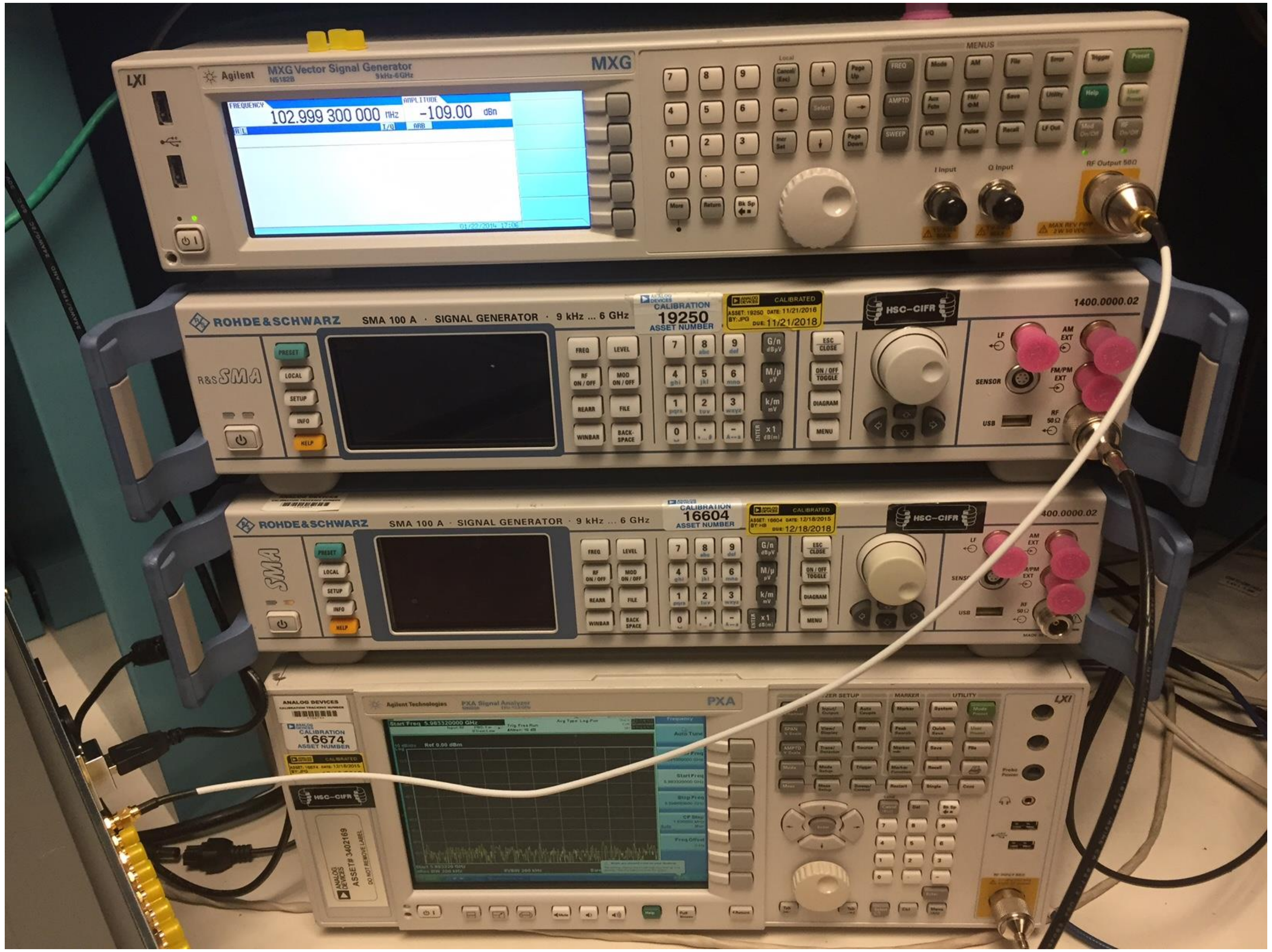


Flexible Test Setups

- *[Instrument To SDR]*
- *[SDR To Instrument]*
- *[SDR To SDR]*

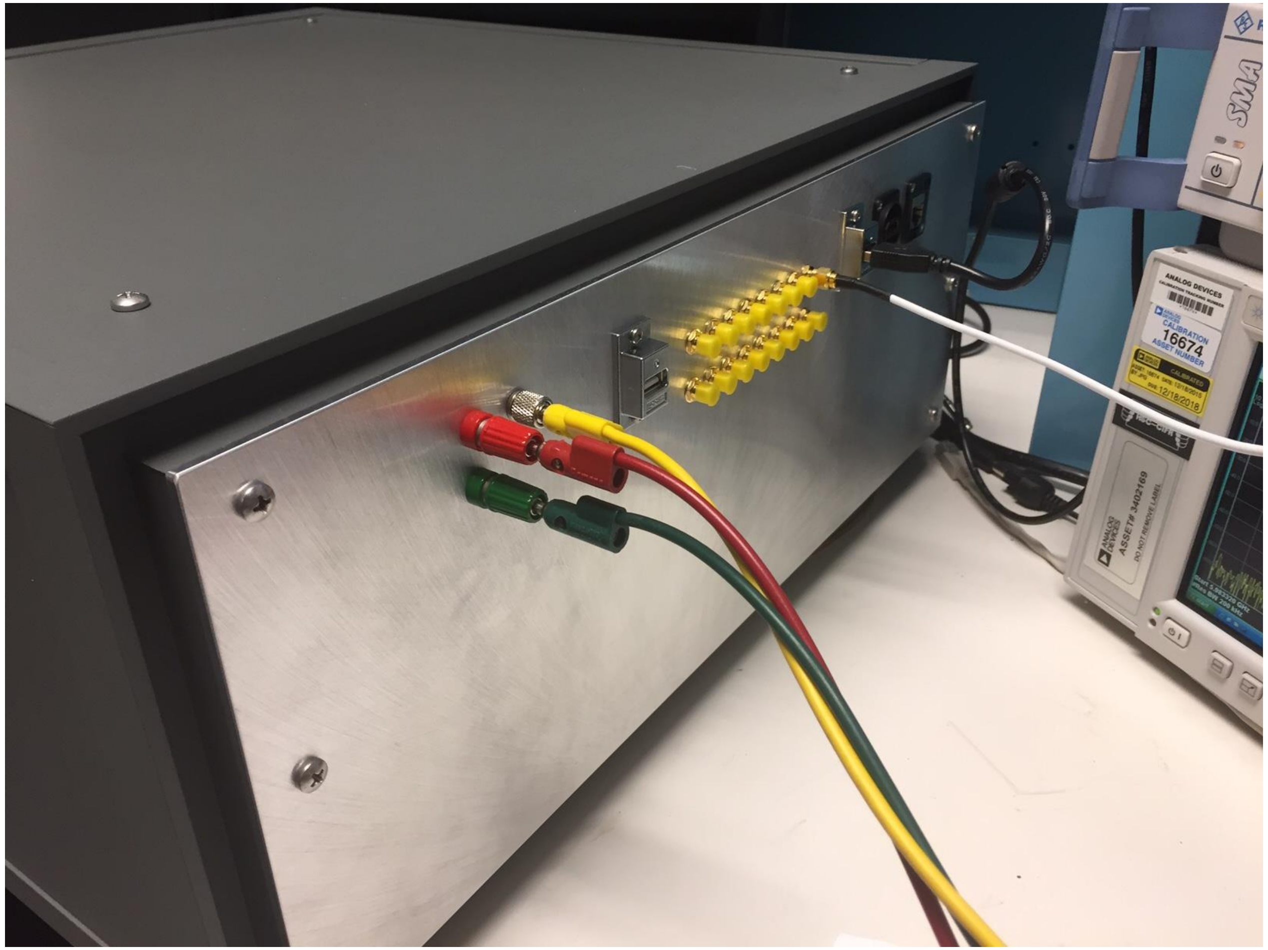


Equipment



ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Shielded Testing (Tin foil isn’t good enough!)



ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Box Inside

Adding SDRs and Instruments

```
classdef iioSDR < matlab.System

    properties...

    properties (Access = private)...

    methods
        % Constructor
        function obj = iioSDR(varargin)...
        % Setup system
        function Setup(obj,varargin)...
        % Generic abstract call to start transmitting data
        function EnableTX(obj,txWaveform)...
        % Generic abstract call to start receiving data
        function [RxIQ, rssi, gain]= EnableRX(obj)...
        % Perform gain calibration for PXA
        function CalibrateRXTXGain(obj, OtherDevice, CenterFrequency)...
        % Perform calibration for XO
        function CalibrateXO(obj, OtherDevice, CenterFrequency)...
        % Cleanup
        function Release(obj)...
```

- SDRs == Instruments
  - Independent view of framework from instrument
- Currently implemented
  - FMComms/Pluto/RF-SoM SDRs
    - Any IIO device should work
  - USRP-E310
  - RTL-SDR
  - Keysight E8267D (Signal Generator)
  - Keysight N9030A (Vector Signal Analyzer)
  - Keysight N5182B (Signal Generator)
- Doesn't necessarily require a MATLAB interface!

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Test Case Example

```
%% SDR Transmitter To PXA Receiver
function testEVMR7_SDRtoPXA(testCase)
    % Set up parameters based on LTE Configuration
    testCase.LTEConfigurationLibrary('LTE5');
    % Set up source
    source = iioSDR('IP','192.168.2.1','Mode','TX','dev_name','pluto');
    % Set up sink
    sink = N9030A('IP','10.66.100.143');
    % Calculate frequencies to evaluate
    startFreq = 70e6+1e6;
    freqStep = 10e6;
    endFreq = 6e9-1e6;
    frequencies = startFreq:freqStep:endFreq;
    % Pick gains to consider
    TXgains = [-4 -6 -8 -10];
    % Enable Visuals
    testCase.EnableVisuals = true;
    % Run
    [evm, pow, rssi, gain, evmVar, rssiVar] = ...
        testCase.testEVMOverGainAndFrequency(RXgains, TXgains,...
        frequencies, source, sink);
    % Create Plot
    testCase.genEVMResultsPlot...
        (evm,pow,gain,rssi,evmVar,rssiVar, frequencies);
end
```

- Select LTE configuration
- Select source and sink devices
- Set parameters and call test method
  - testEVMOverGainAndFrequency
  - testEVMOverGain
  - testEVMOverFrequency
- Tests in development
  - IIP3
  - Noise figure (factor)
  - ACLR

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Framework Extensibility: Parameter Sweeps Get Complex Fast

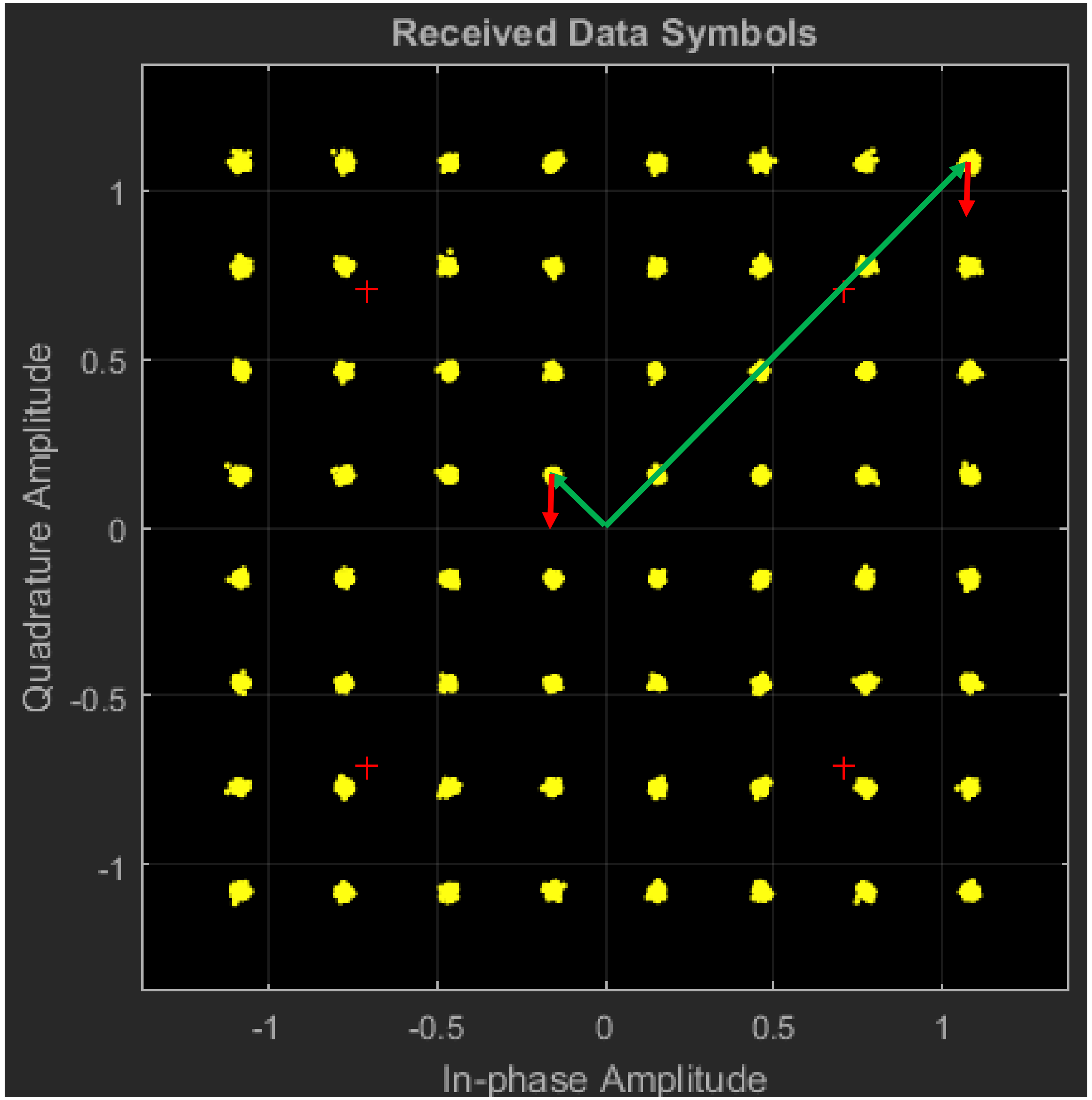
- Sweep over Frequency
  - Over entire tuning range
    - 70 to 6000 MHz in 2.5 Hz steps (Takes a long time!)
- Sweep over Tx Output Amplitude
  - Tx Amplitude +30dBm can damage Rx
- Sweep over Rx Gain settings
  - ACG Modes
  - Manual Settings
- Sweep over Channel
  - Bandwidth
  - Adjacent transmitters
- Don’t sweep (repeatability)
  - Noise is random, are the results?
- Measurements:
  - Analog (SNR, Image, SFDR, etc)
  - Digital (EVM, etc)

- Can’t combine too many things
  - Too many points, too many curves
  - Takes too long to gather input
  - Too difficult to interpret.
  - Results in dB or % - all needs to be the same.
    - Log plots are harder to understand

- Needs to provide insight into the question:
  - What link budget can I use?
  - Receive Power (dB) = Transmit Power (dB) + Gains (dB) − Losses (dB)

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Metric of Merit: EVM



- Single numbers are convenient for people to discuss

$$EVM_{RMS} = 10\log_{10}\left(\frac{\sum_{k=1}^{M}\left|Z(k)-R(k)\right|^{2}}{\sum_{k=1}^{M}\left|R(k)\right|^{2}}\right)$$

- Acceptable peaks at outside constellation points will define min ratio.
- -3dB / 70.7% before bit error

Reference vector
Error vector

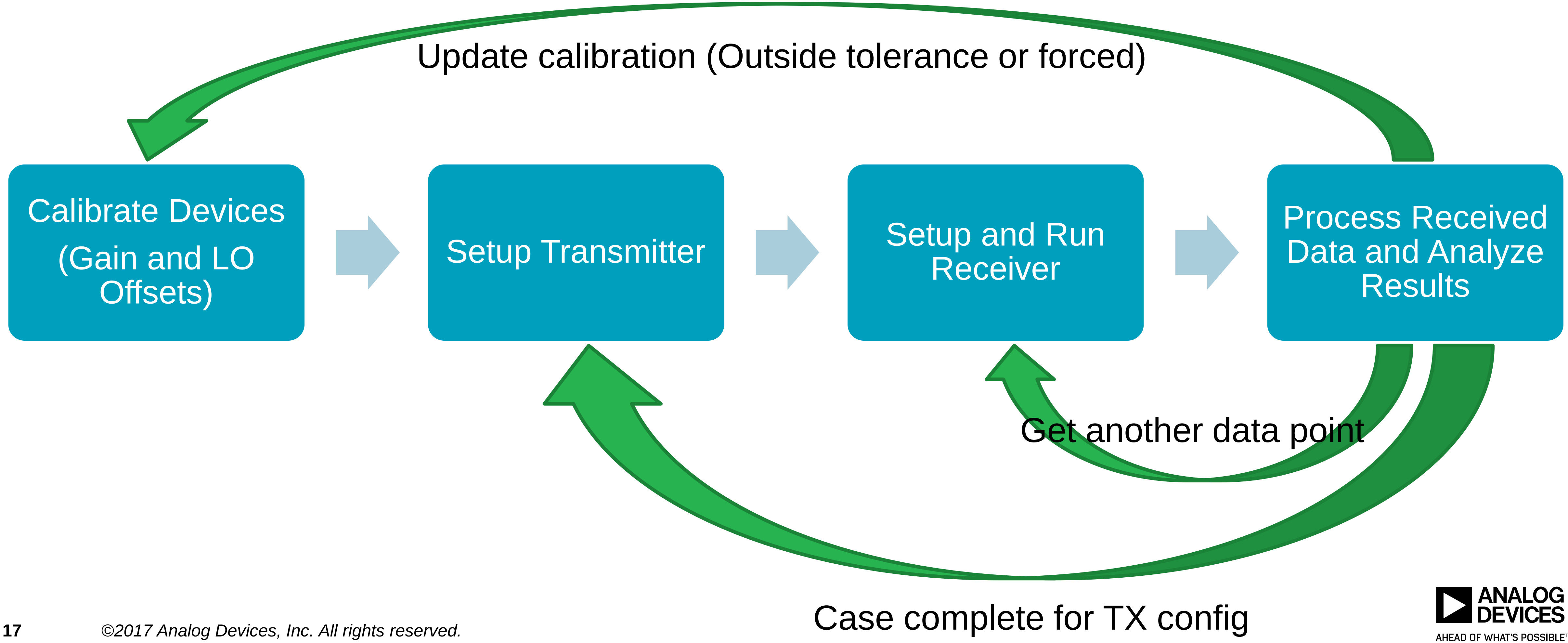
- -19dB / 10.1% before bit error

Reference vector
Error vector

- What this means?
  - Peak EVM measurements are useless without understanding where they are.
  - Large constellations (QAM64) can normalize the measurement to the outside (ring of 28 points).
  - QPSK has less room to hide.

Test Flow

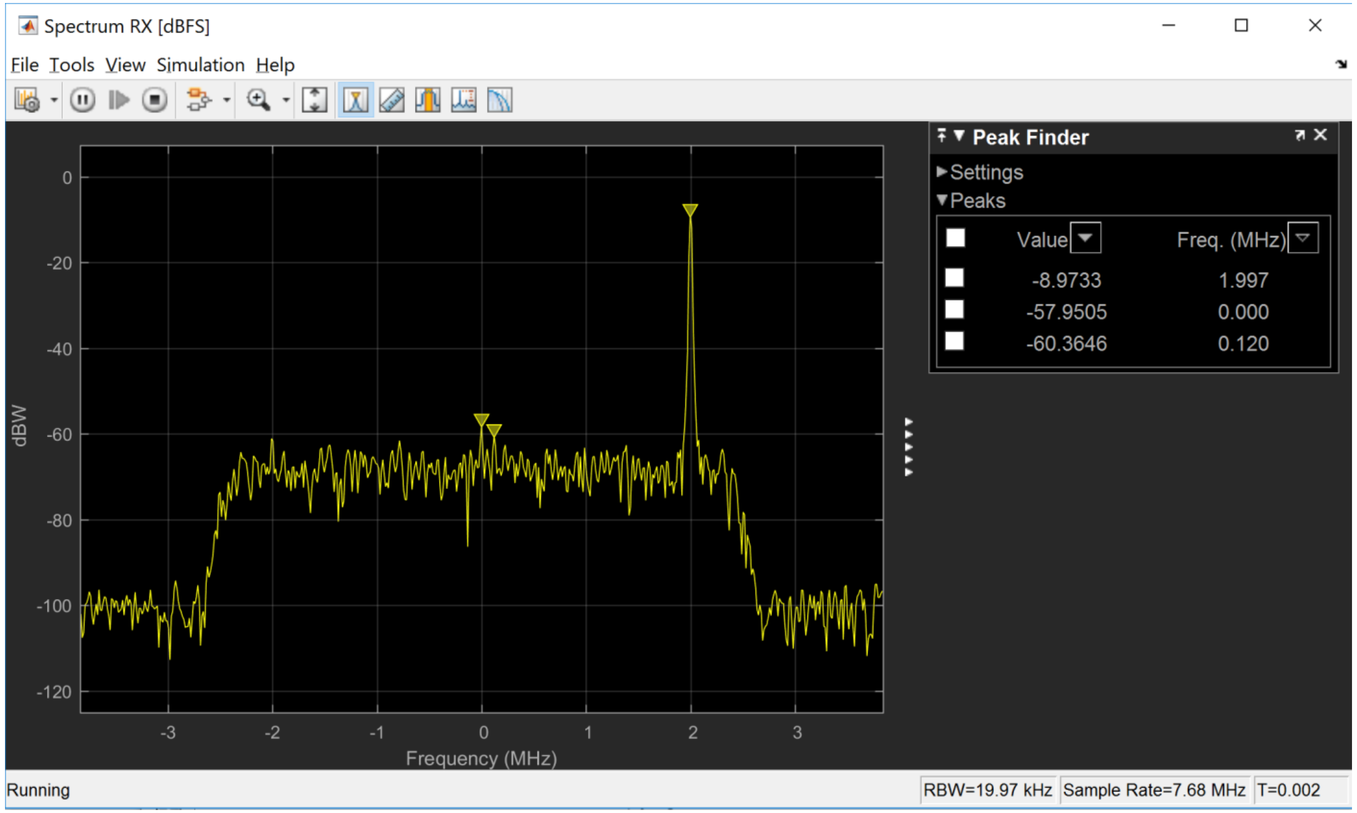
<u>Tests will cycle over parameter sets (Gains, Frequencies, User defined)</u>



ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Automatic Device Tuning

- *Calibration stages are user defined since dependent on radio/instrumentation controls*
- **Pluto**: uses xo_correction tuning to remove timing and carrier phase offsets
- **RTL-SDR**: LO is moved to limit offset (way better than PPM updates!)
- **N5182B** (Signal Generator): IQ calibration at specific frequencies. Usually do the full gamut by hand (aka push a button)



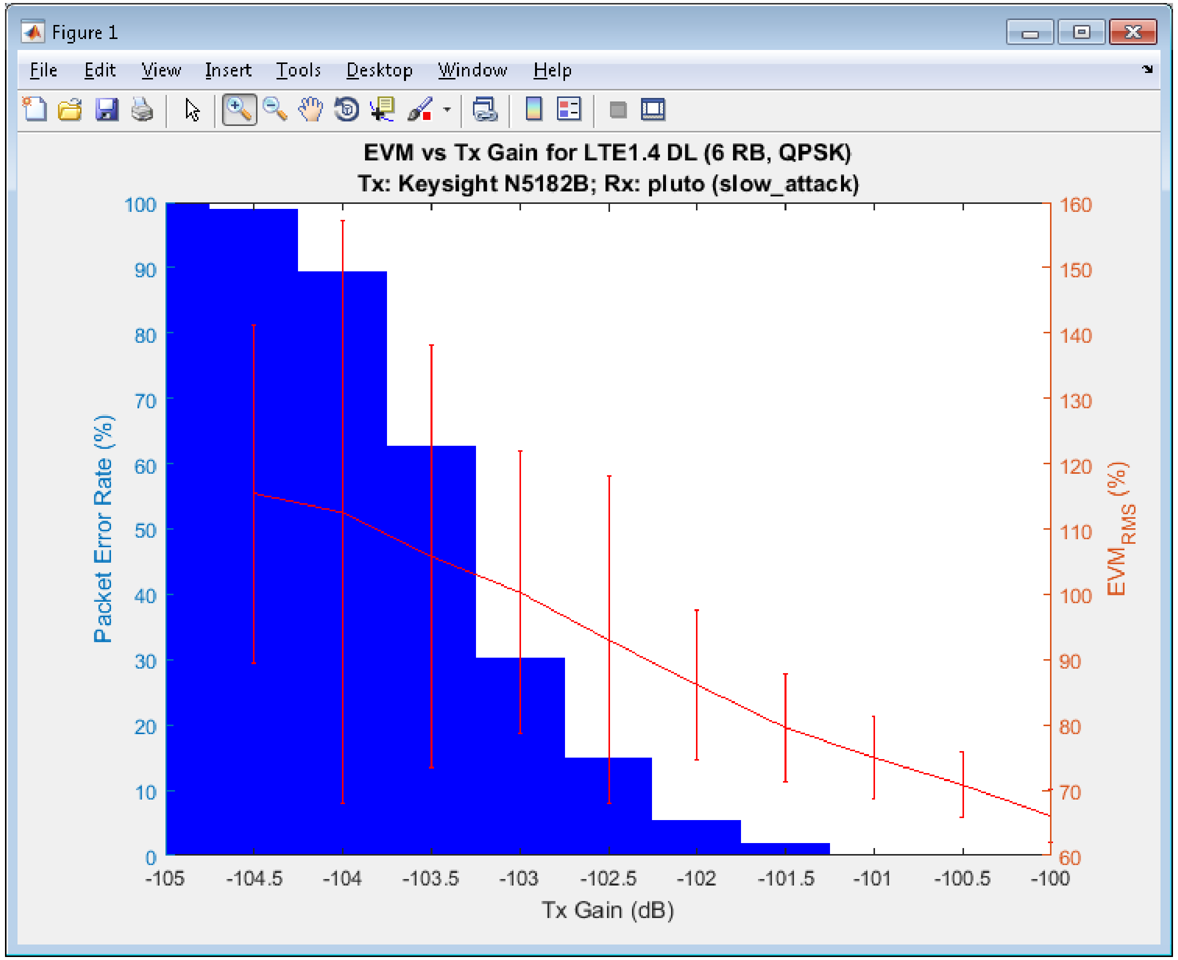
ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Pluto Deep Dive Analysis:

Receiver Sensitivity

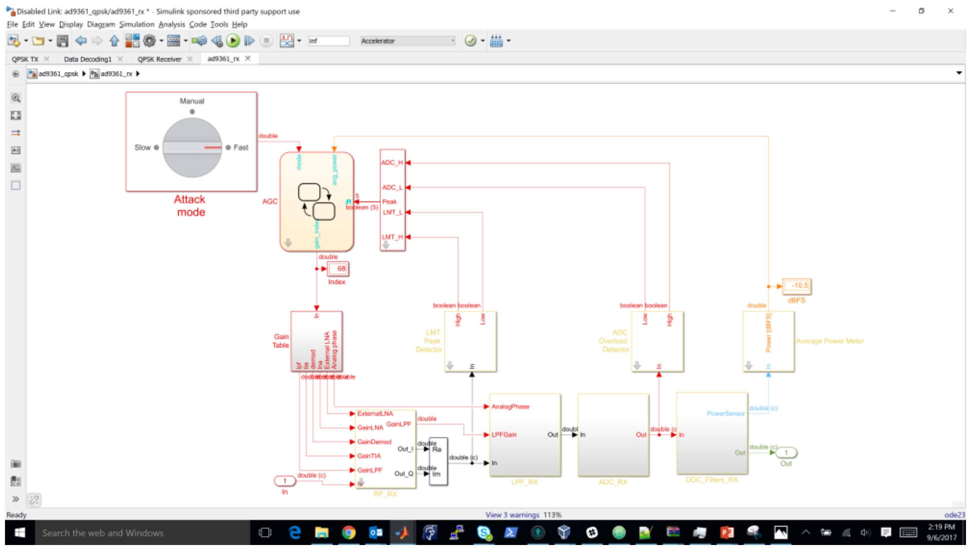
Receiver Sensitivity

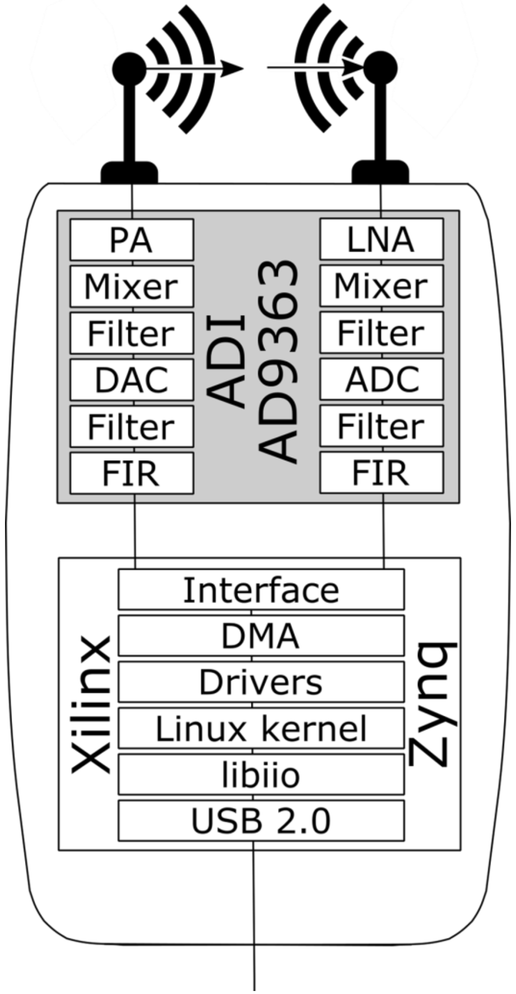
- Definition:
  - *Receiver sensitivity is the lowest power level at which the receiver can detect an RF signal and demodulate data.*
- Unknowns:
  - What modulation scheme?
    - QPSK?, QAM?, FSK?
  - What channel?
    - Additive noise?
    - Adjacent channels?
    - Blockers?
  - What bandwidth?
    - 1.4 LTE, 10 LTE?
  - What Peak to Average Ratio?
    - LTE UpLink?
    - LTE DownLink?
  - What acceptable packet loss (for digital modulation)
    - 10%? Lower? Higher?



Pluto Has Many Knobs

- How do I get the best performance?
  - Frequency range
  - Gain requirements
  - Operational bandwidth
- Example: AGC
  - Modes: Fast Attack, Slow Attack, Manual
  - Gain tables: Full vs Split
  - Thresholding in analog and digital domains





Remaining Tests To Discuss

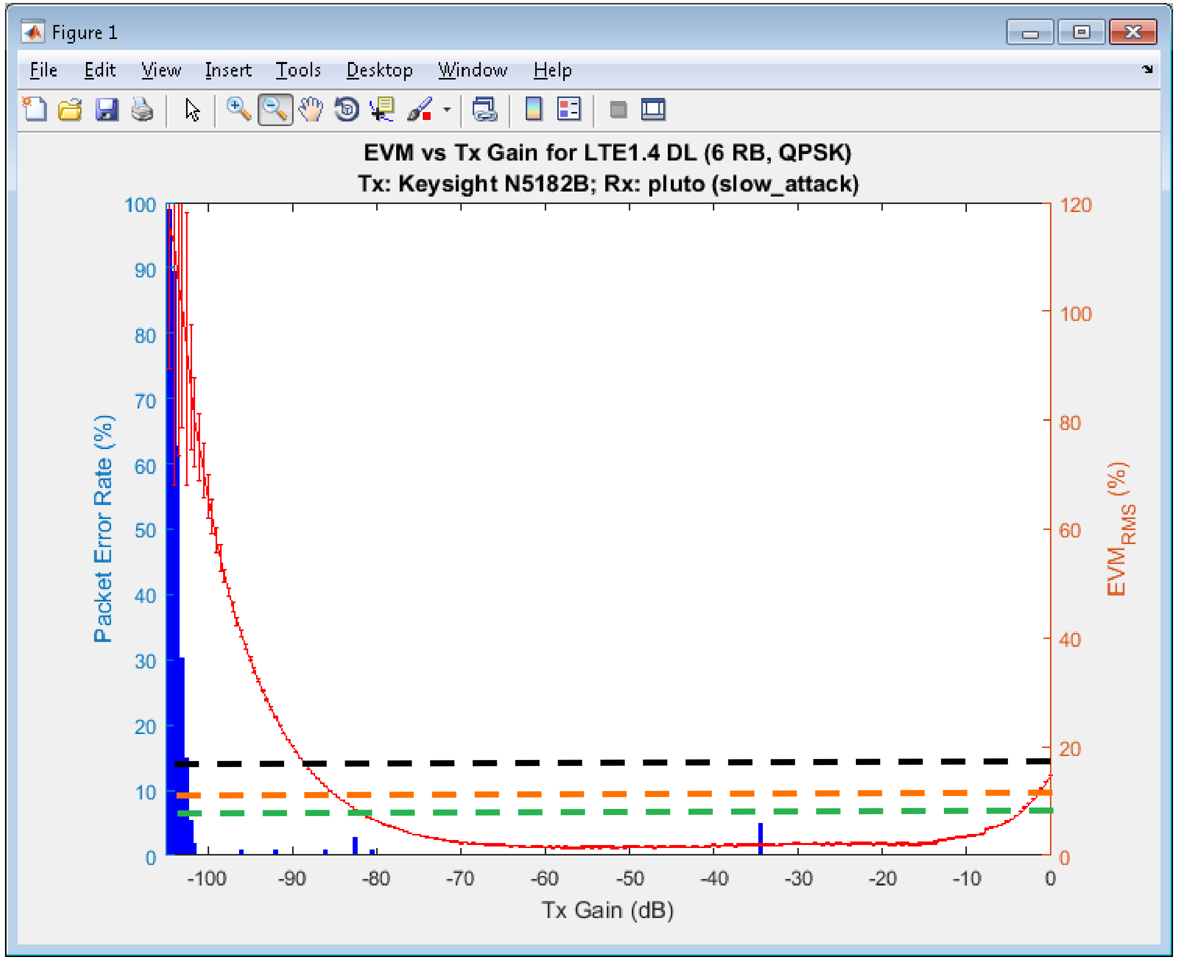
- Receiver only tests (Downlink LTE signals)
  - Pluto/RTL-SDR and N5182B Signal Generator
- Variability introduce by:
  - Frequency
  - Gain
- Pluto will utilize Slow Attack (-10 dBFS target)
  - Data taken after settling

- Sensitivity Tests
  - Pick your requirement from the plot!

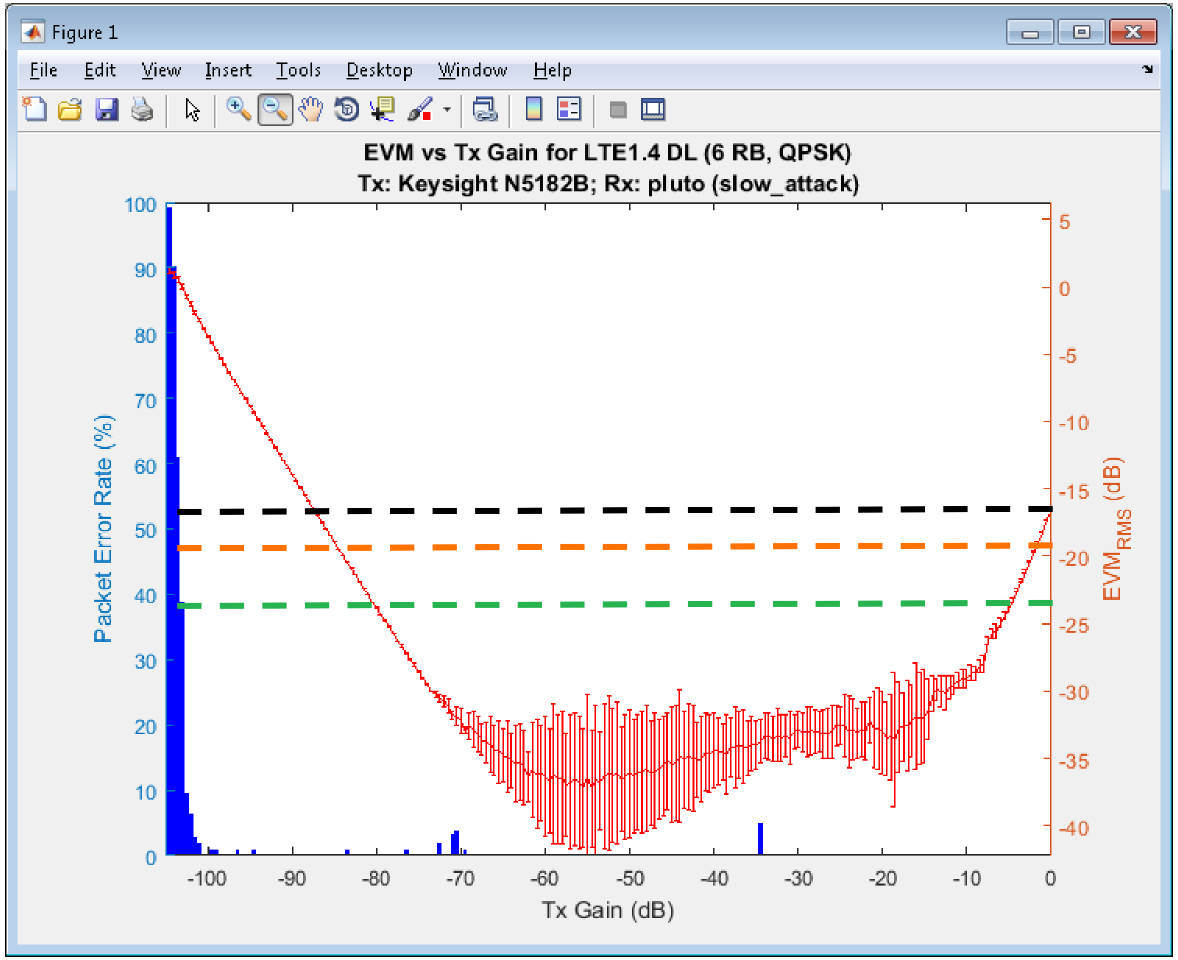
ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Measurement Perspectives

Vertical axis in %



Vertical axis in dB



- QPSK
- 16QAM
- 64QAM

Same Radio!

Just scales are different

- QPSK
- 16QAM
- 64QAM

Understanding amplitude (dBm)
Assuming 50Ω, sin wave (Tx or Rx)

dBm	mVolts (p-p)	mVolts (rms)	μW (10^{-6} W)
0	632.45	223.61	1000
-6	316.97	112.069	251.2
-12	158.86	56.167	63.10
-18	79.621	28.150	15.85
-24	39.905	14.108	3.981
-30	20.000	7.0710	1.000
-36	10.023	3.5439	0.2512
-42	5.0238	1.7761	0.06310
-48	2.51785	0.89019	0.01585
-54	1.26191	0.44615	0.003981
-60	0.63245	0.22361	0.001000

dBm	μVolts (p-p)	μVolts (rms)	pW (10^{-12} W)
-60	632.45	223.61	1000
-66	316.97	112.069	251.2
-72	158.86	56.167	63.10
-78	79.621	28.150	15.85
-84	39.905	14.108	3.981
-90	20.000	7.0710	1.000
-96	10.023	3.5439	0.2512
-102	5.0238	1.7761	0.06310
-108	2.51785	0.89019	0.01585
-114	1.26191	0.44615	0.003981
-120	0.63245	0.22361	0.001000

-102dBm = 63fW (femto = 10^{-15})

@ 100 MHz, that is 2216 electrons per full wave of the carrier

Perspective

Power that comes off an antenna is measured as effective isotropic radiated power (EIRP). EIRP is the value that regulatory agencies, such as the FCC or European Telecommunications Standards Institute (ETSI), use to determine and measure power limits in applications such as 2.4-GHz or 5-GHz wireless equipment.

In order to calculate EIRP, add the transmitter power (in dBm) to the antenna gain (in dBi) and subtract any cable losses (in dB).

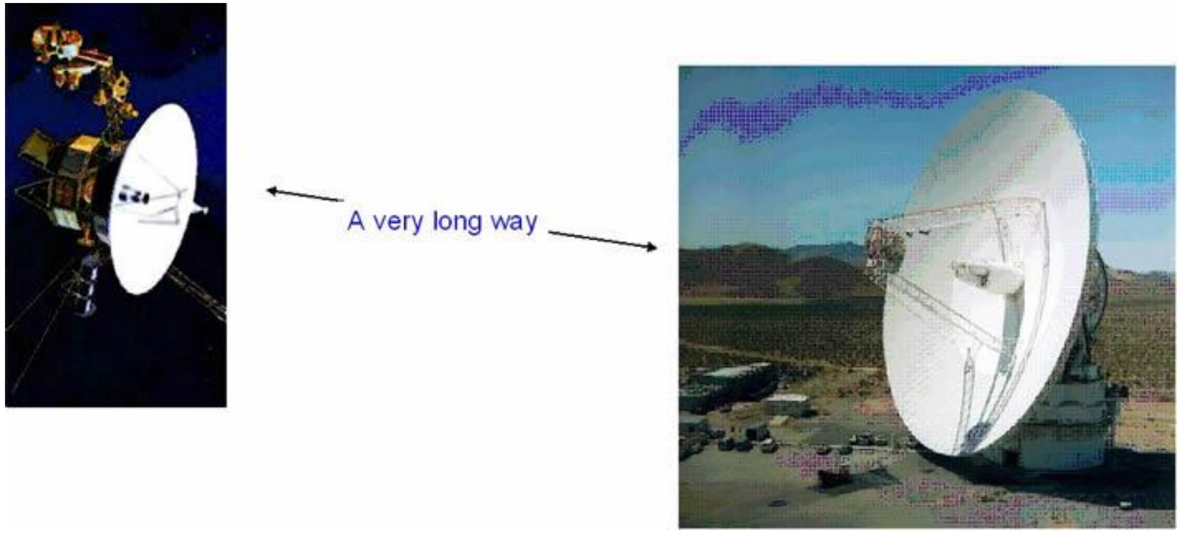
- Maximum transmitter output power, fed into the antenna, is 30 dBm (1 watt).
- Maximum Effective Isotropic Radiated Power (EIRP) is 36 dBm (4 watt).

WiFi

Receive Signal Strength		Required for
-30 dBm	Max achievable signal strength. The client can only be a few feet from the AP to achieve this. Not typical or desirable in the real world.	N/A
-67 dBm	Minimum signal strength for applications that require very reliable, timely packet delivery.	VoIP/VoWiFi, streaming video
-70 dBm	Minimum signal strength for reliable packet delivery.	Email, web
-80 dBm	Minimum signal strength for basic connectivity. Packet delivery may be unreliable.	N/A
-90 dBm	Approaching or drowning in the noise floor. Any functionality is highly unlikely.	N/A

https://support.metageek.com/hc/en-us/articles/201955754-Understanding-WiFi-Signal-Strength

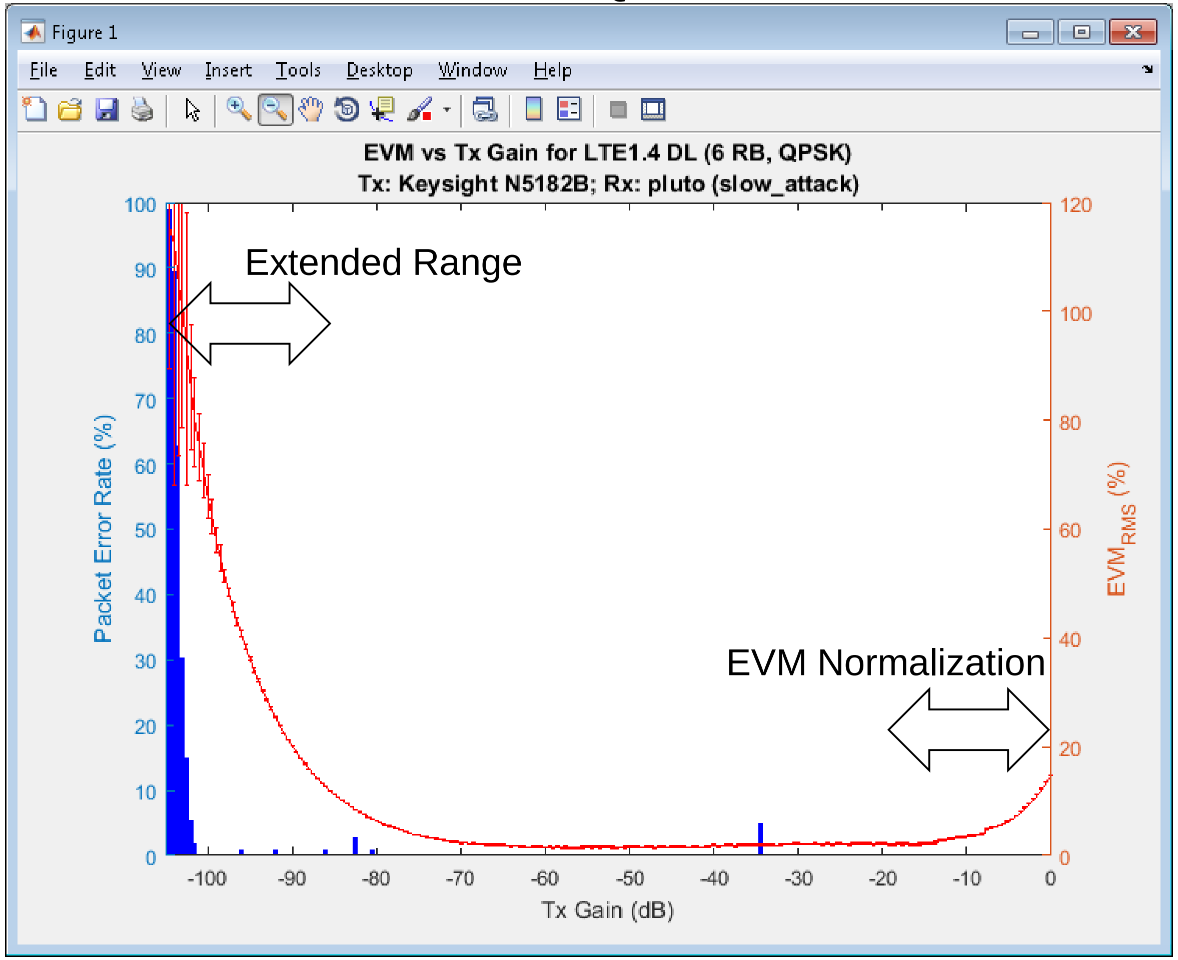
- Voyager 1's main transmitter radiates around 22 watts (+43.42dBm) with 3.7 meters antenna
- -130 dBm with 70m dish from Voyager



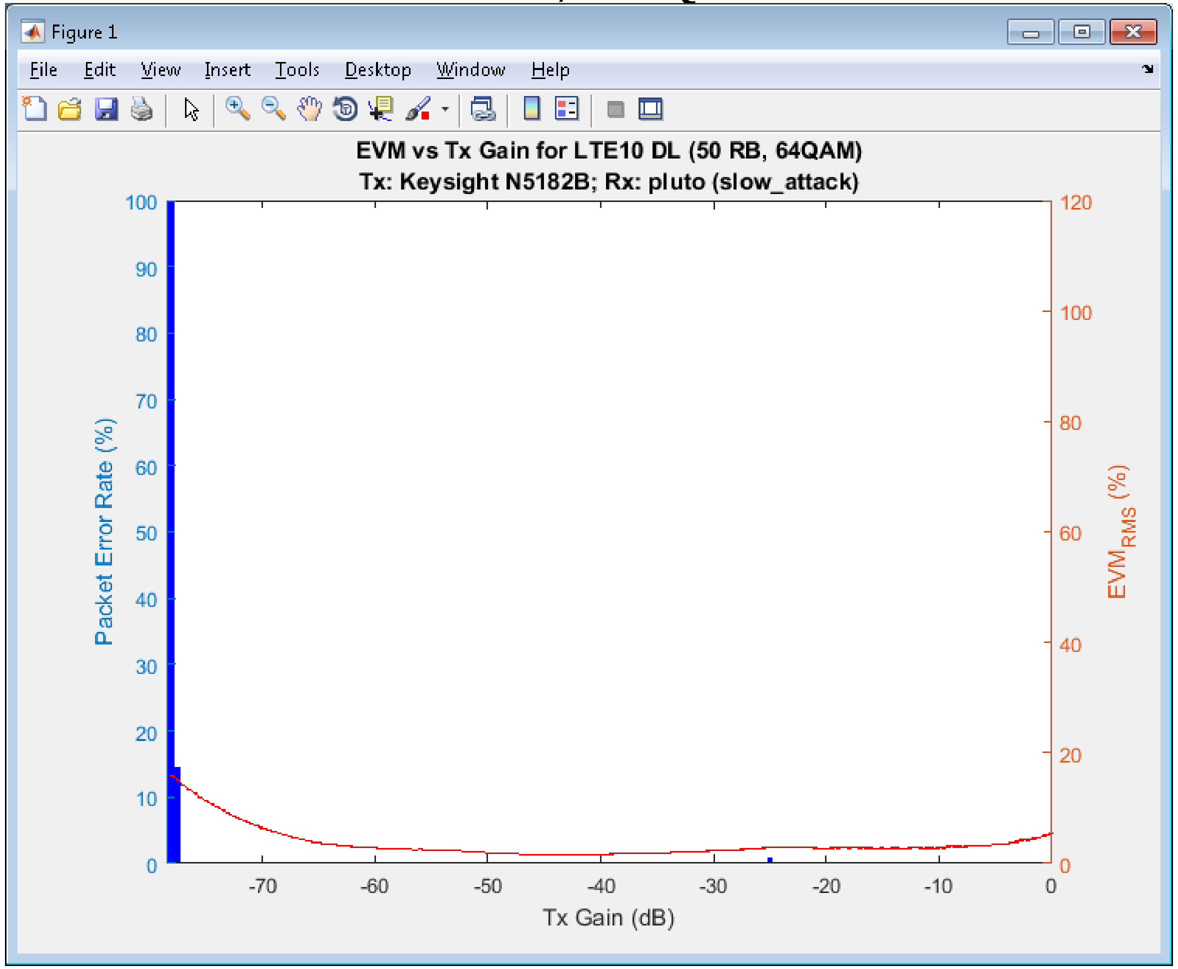
- Transmit from earth to Voyager happens at 20kW (+73dBm)

Bandwidth and Modulation Differences

LTE 1.4, QPSK



LTE 10, 64-QAM

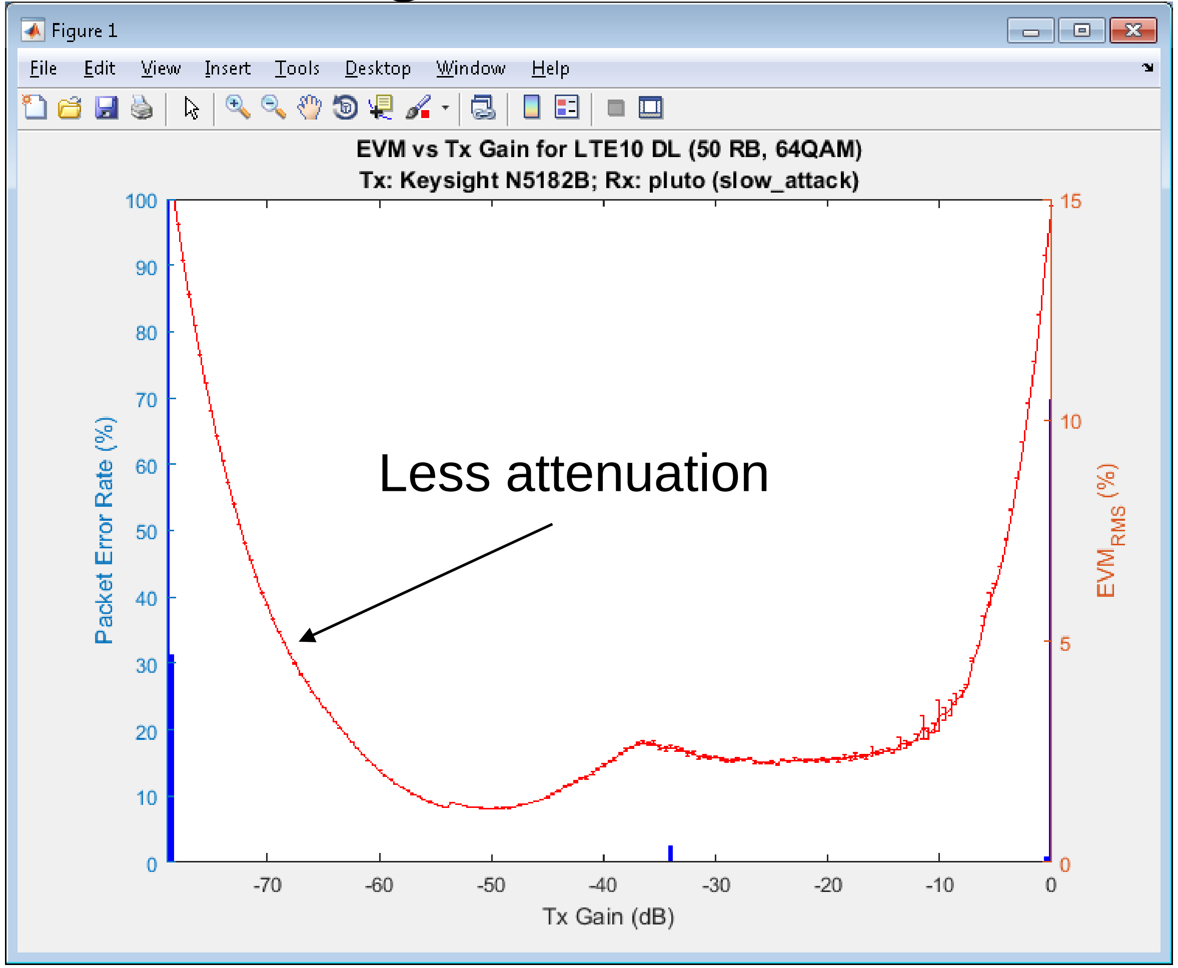


Wider Sensitivity Range VS. EVM performance (Sort of)

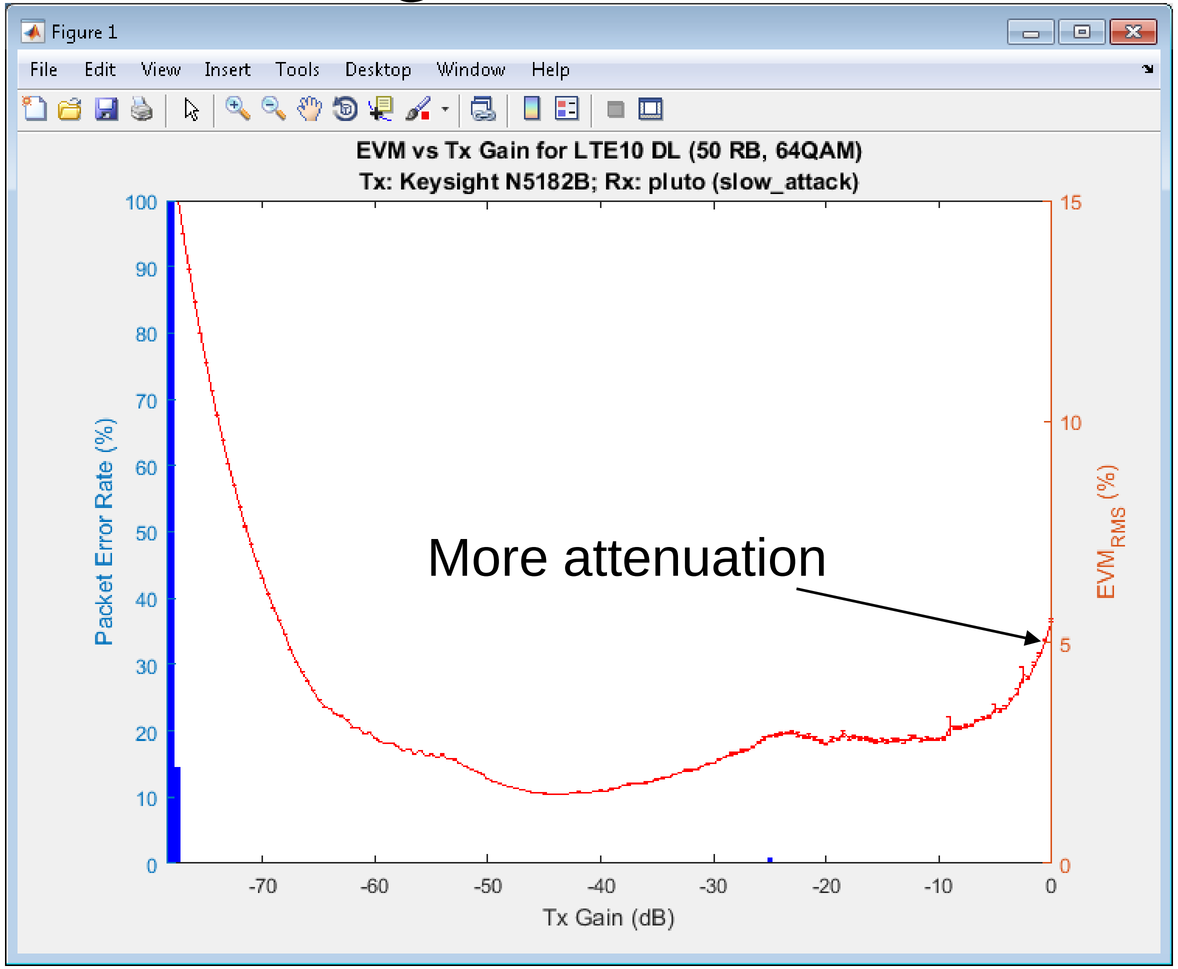
ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Frequency Dependency (LTE10 64QAM)

@ 100 MHz



@ 5.8 GHz



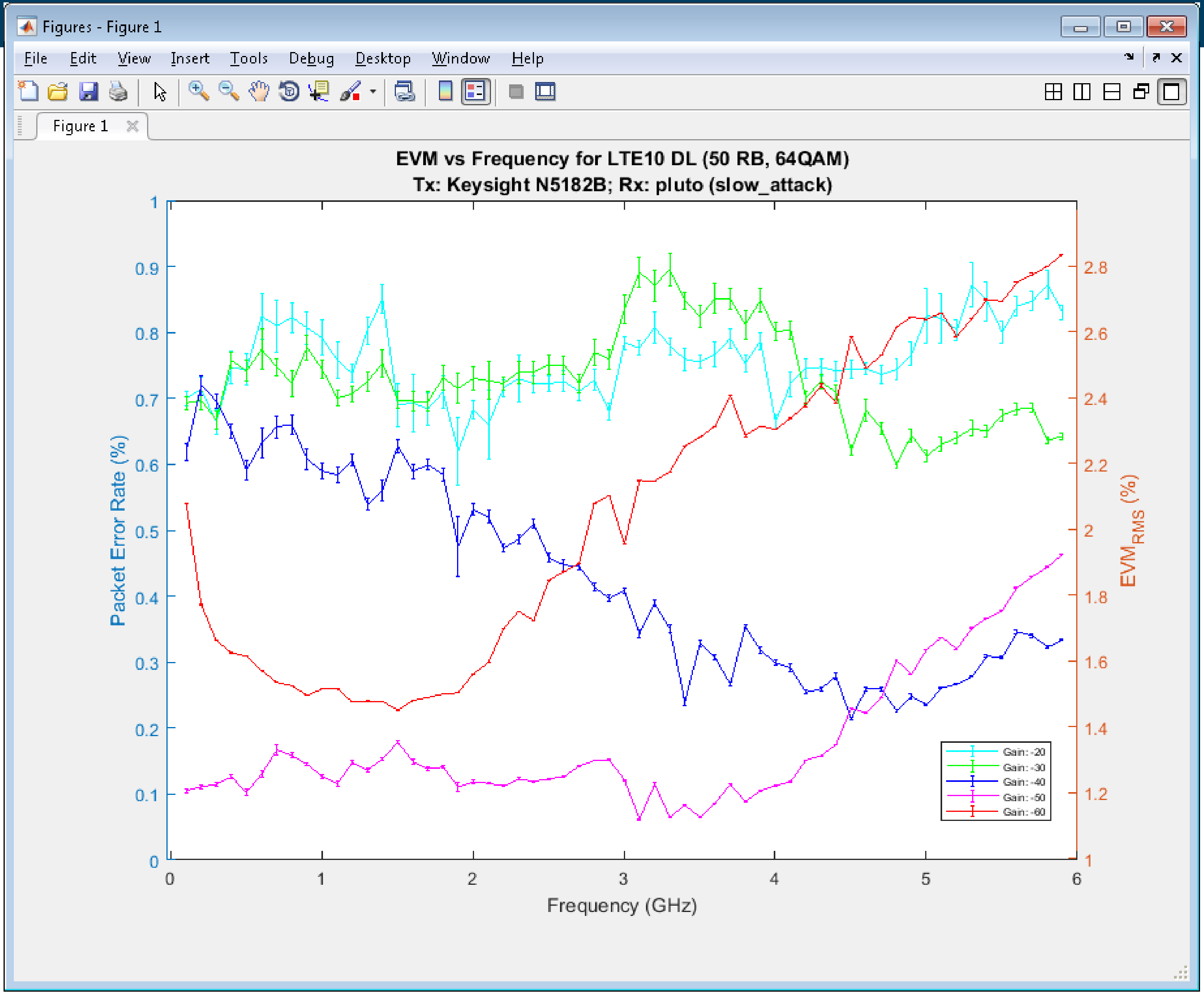
Same Radio!

Just LO frequencies are different

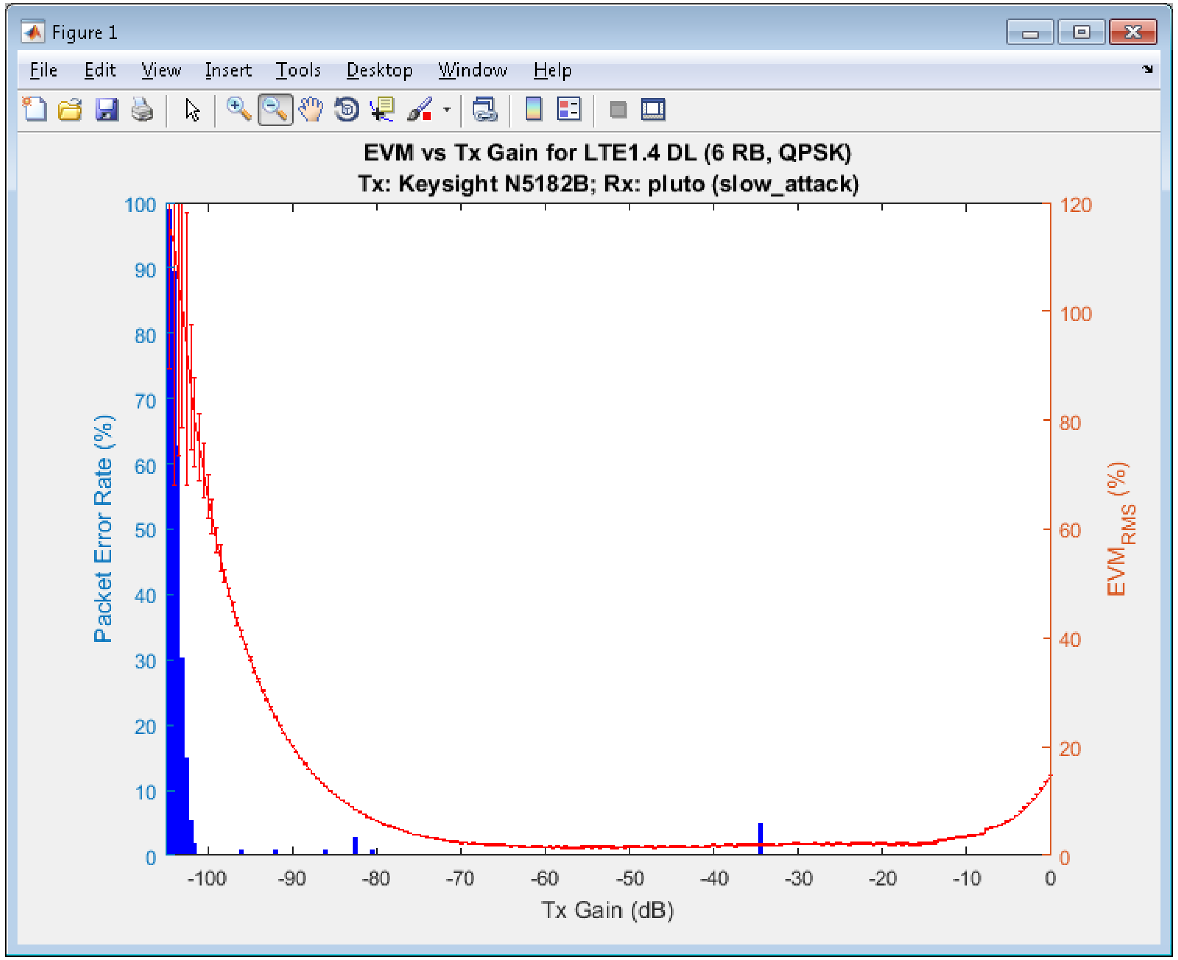
ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

EVM over frequency at different Input Power Levels

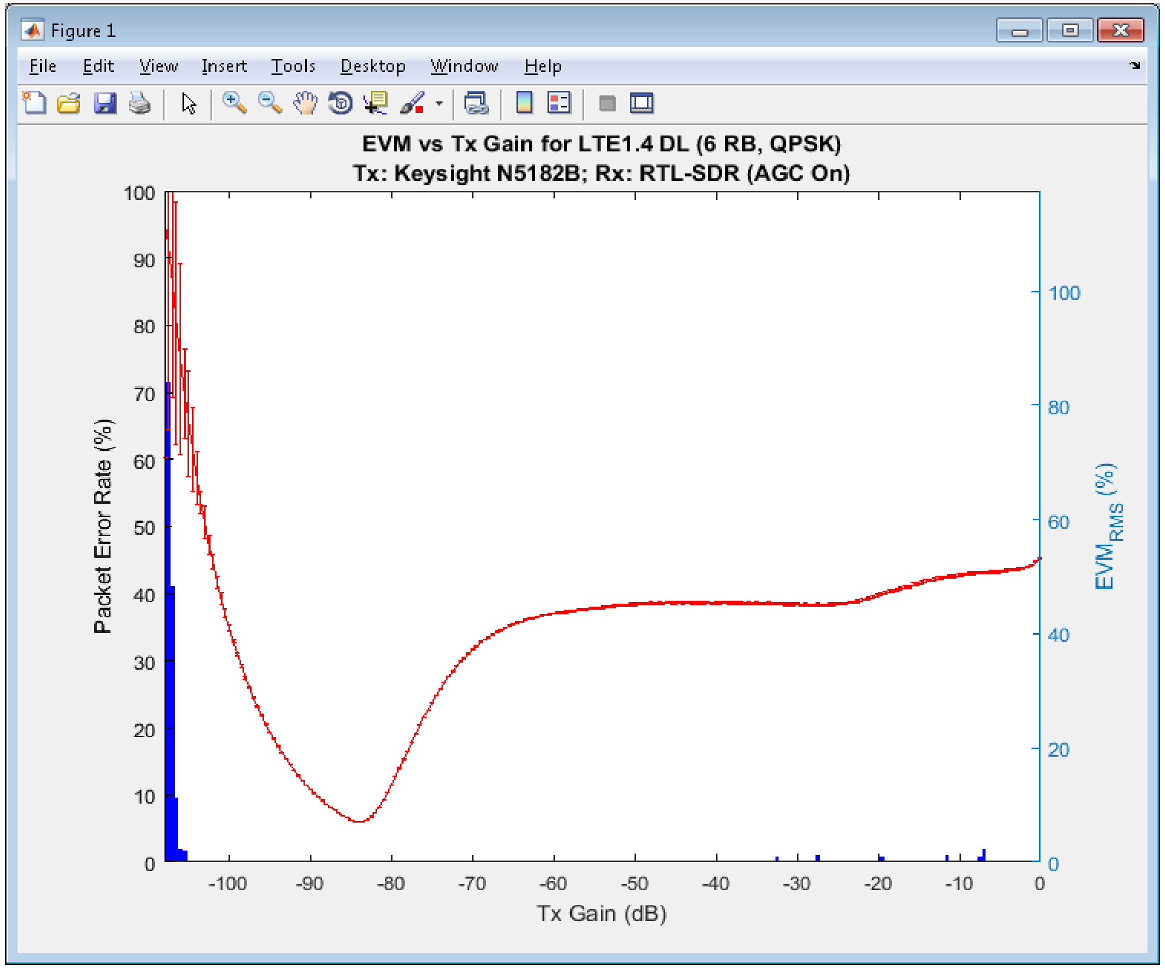
- Received signal strength big factor
- Not a linear relationship between receive power and EVM
- Basically EVM performance has many dependencies
- Test equipment is not perfect either (especially at 4GHz)



Let’s compare Radios



Pluto-SDR

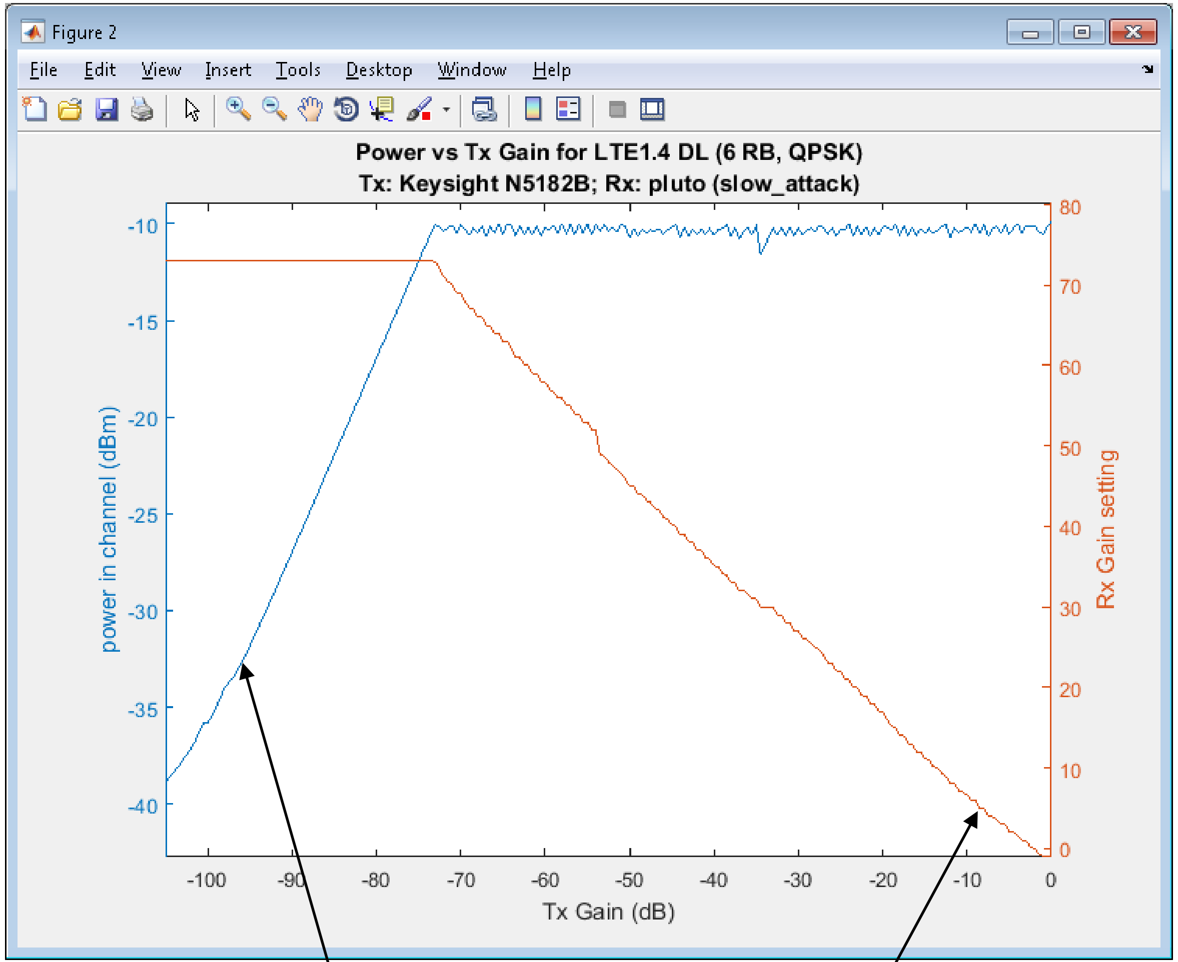


RTL-SDR

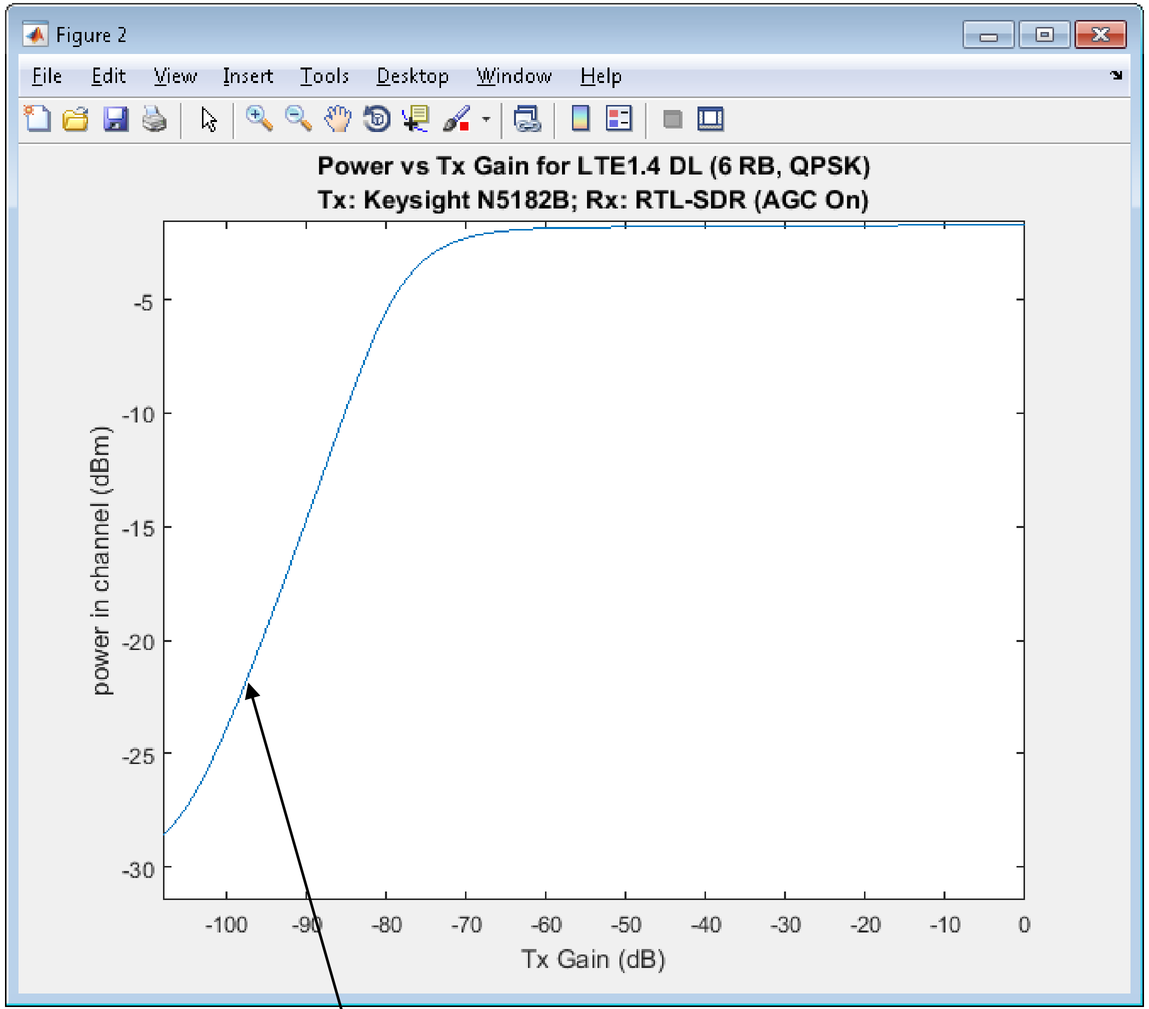
ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

AGC Power Target Comparison

Pluto-SDR



RTL-SDR



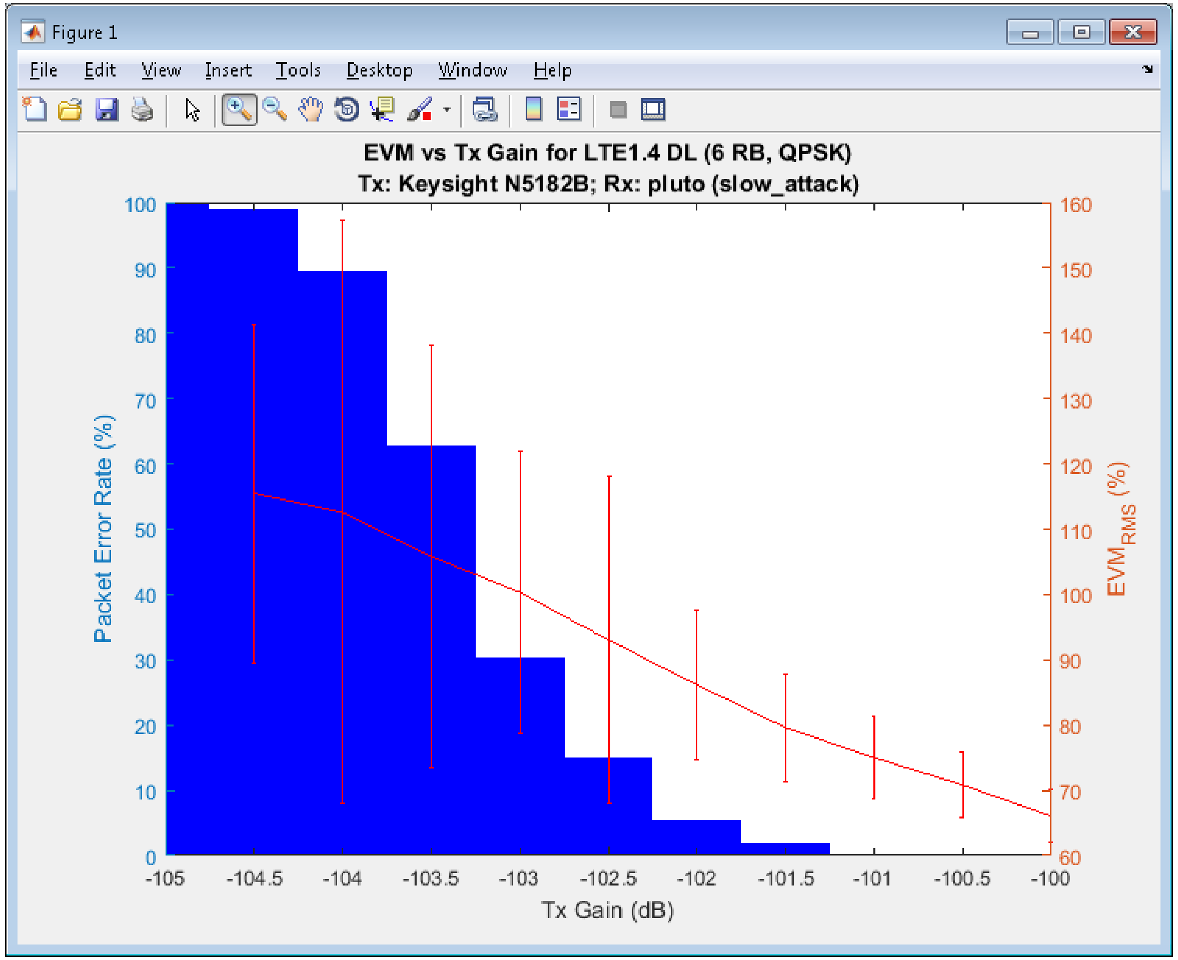
Rx Power in Channel

AGC Gain Setting

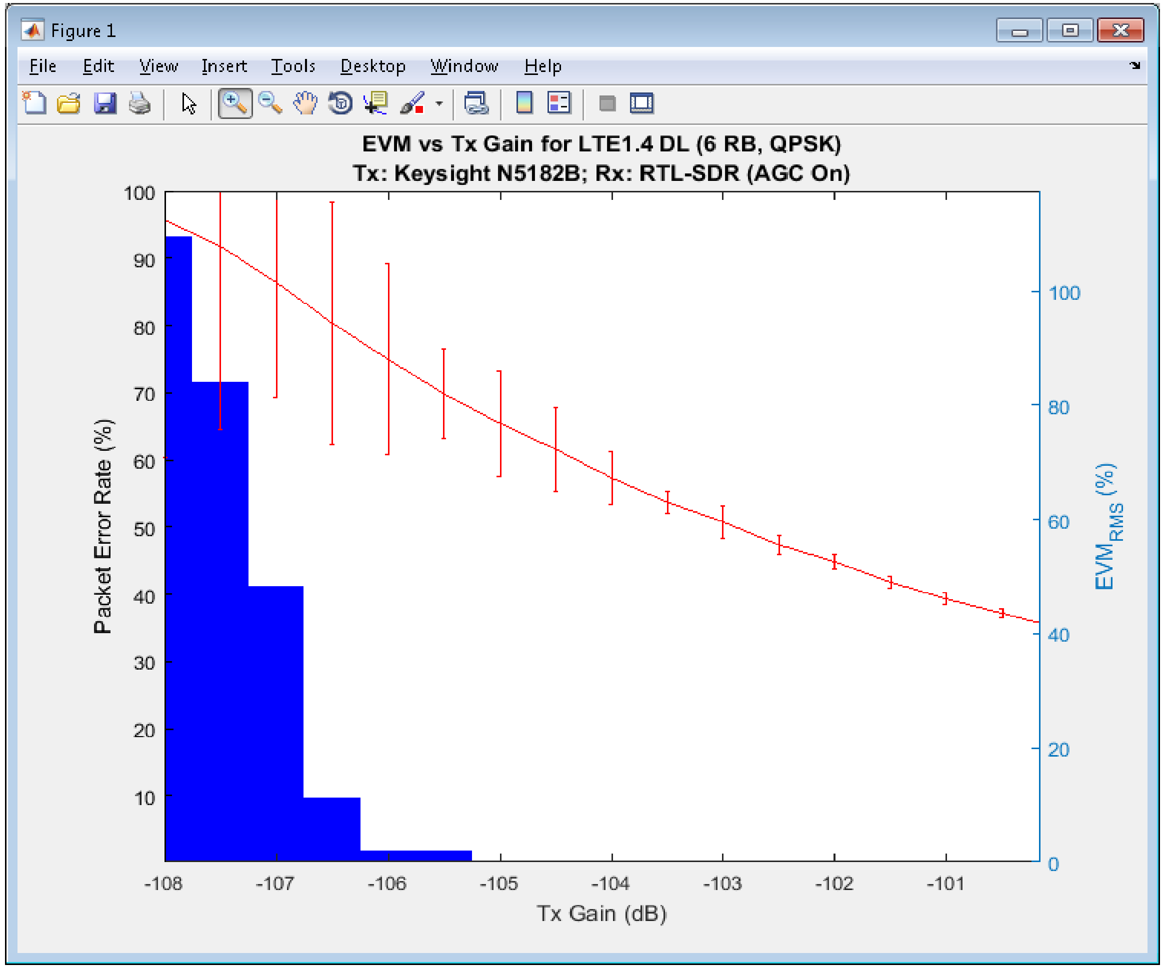
Rx Power in Channel

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Receiver Sensitivity Comparison



Pluto-SDR

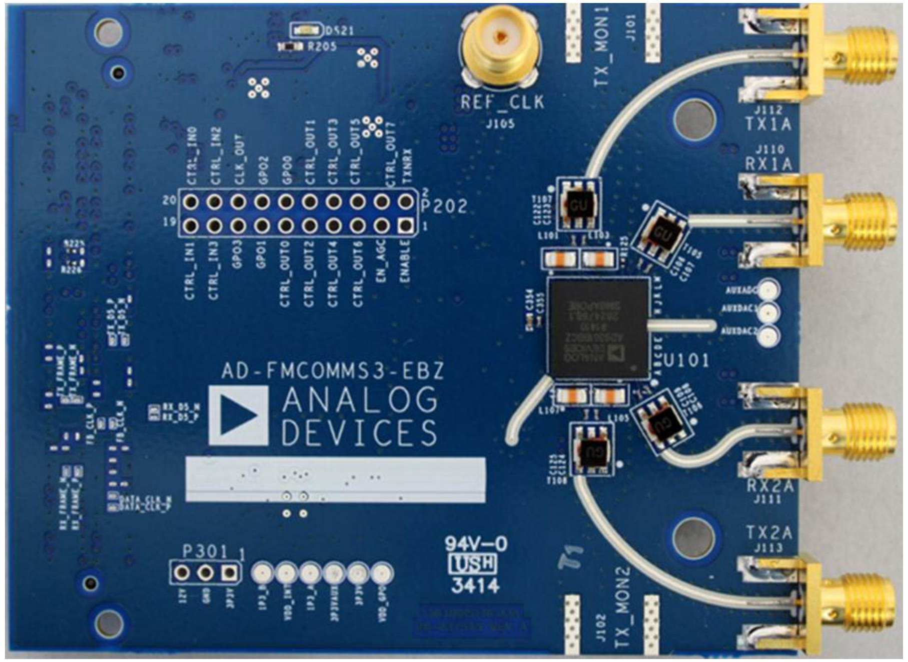


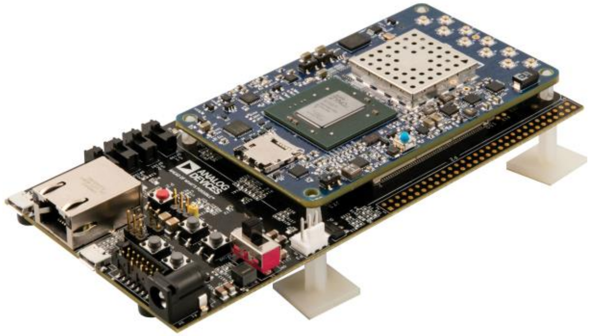
RTL-SDR

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Outcomes and To-dos

- Does the radio matter?
  - <u>*Depends*</u> on the applications and design margin
- Results and testing code will be released
  - github.com/analogdevicesinc
- Send us a radio if you want it tested ;)
  - E310 underway
  - FMComms 2/3/4/5
- Software bugs are in everyone's code
  - libusb on windows
  - Even Keysight hardware





ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™