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A software-centric platform that accelerates the development and increases the productivity of test, measurement, and control systems.
NI Alliance Partner Network
Achieving Superior RF Performance
The Quest for -50 dB EVM

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Mikhail Kamenskihs, Staff RF Product Support Engineer
Topics

- Introductions
- What is EVM?
- Determining Dominant Degraders
- Improving Performance Limiters
- 802.11ax Case Study: Achieving -50 dB EVM
- Q&A
Introductions
Chris Elliott
Senior RF Applications Engineering Specialist

- Dual-bachelor’s degrees in physics and computer science

- 5 years WLAN test experience with lead semiconductor companies, targeting RF transceivers, SoCs, and packaged modules

- Recent research focused on RF performance optimization and test methodology for the new 802.11ax standard
Mikhail Kamenskihs
RF Measurement Software Product Support Engineer

- Master’s in Avionics and Control Systems; 5 years RF experience, 3.5 years focused on wireless communications standards (WLAN, LTE, Bluetooth, GPS, etc.).

- WLAN toolkit: contributed to 802.11ax development effort and V&V
What is EVM?
What is EVM? – Definition

- EVM quantifies the quality of a digitally modulated signal
  - Calculation of the delta between an ideal symbol location and the actual symbol location on a transmitter or receiver
- May be expressed in dB or %:

\[
\text{EVM}(\text{dB}) = 10 \log_{10} \left( \frac{P_{\text{error}}}{P_{\text{reference}}} \right)
\]

\[
\text{EVM}(\%) = \sqrt{\frac{P_{\text{error}}}{P_{\text{reference}}}} \times 100\%
\]

Images source: https://en.wikipedia.org/wiki/Error_vector_magnitude
What is EVM? – Common Degraders

- Noise (thermal, pink, flicker, shot)
- Non-linear Distortion (amplitude, IMD, harmonic, group delay)
- Phase Noise (close-in, far-out)
- Spurious signals (harmonic, non-harmonic)
- IQ Impairments (imbalance, quadrature error, skew, INL/DNL)
- Clock Stability (PLL, noise)
What is EVM? – Common Degraders

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- **Non-linear Distortion** *(amplitude, IMD, harmonic, group delay)*
- **Phase Noise** *(far-out, close-in)*
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What is EVM? – Noise and Distortion

- Thermal noise is often assumed to be Gaussian and causes random errors on symbols (174 dBm/Hz @ room temp)

- Distortion
  - Linear terms: $P_{out} = a + b*P_{in}$
    - For linear devices, these coefficients are the largest and dominate the majority of the device’s operating range
  - Non-linear terms: $P_{out} = c*P_{in}^2 + d*P_{in}^3 + \ldots$
    - For linear devices, these coefficients are relatively small
    - Will begin to dominate at higher power levels
What is EVM? – Phase Noise

- Phase noise – random variations in phase of LO or carrier
  - Measured by spectral acquisition of unmodulated carrier
- Close-in phase noise

- Far-out phase noise
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- Far-out phase noise
  - Subcarrier phase noise skirts interfere as noise with adjacent subcarriers
  - Cannot be removed without improving HW phase noise
What is EVM? – Impacts of Noise, Phase Noise, Distortion

- LO Phase Noise Limited
- Improved LO
- Phase Noise Floor

Diagram showing EVM (Error Vector Magnitude) as a function of measured average power, with lines representing different LO configurations and their phase noise floors.
Determining Dominant Degraders
Determining Dominant Degraders – Common Test Setups

- 2-port DUTs (Frequency converter, transceiver, PA, LNA filter, etc.)
- 1-port DUTs (baseband, RF assemblies)
Determining Dominant Degraders – Instrument & DUT Contributions

- DUT and instrument error are always combined
- Rule of thumb, historically: >10 dB instrument performance margin
  - Recommended to obtain reliably accurate measurements
- Newer technology squeezes these margins, <6 dB margins in some cases
- Tips for dealing with tighter margins
  - Understand impact to measurement uncertainty/accuracy, spec verifiability
  - Optimize and focus on one degrader at a time

Simple example
Ideal signal of interest = 1
DUT error \( \leq x \)
Instrument error \( \leq y \)

Measurement = \( 1 +/-( |x| + |y| ) \)
[Phase and amplitude error]
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Determining Dominant Degraders

- System-level
  - Diagnostic Traces
    - Constellation diagram
    - EVM vs time
    - EVM spectrum
  - Scientific method
    - Vary suspect degrader and observe EVM correlation
    - Modulation-specific tracking correlated with EVM

- Component-level
  - Non-modulated (tone-based) measurements
Determining Dominant Degraders – System-level, Diagnostic Traces
- Constellation Diagram (WLAN example)
Determining Dominant Degraders – System-level, Diagnostic Traces

- EVM vs time (WLAN example)

EVM per symbol

EVM per symbol

Ideal

CFO/SCO offset

AM non-linearity

Time tracking OFF

EVM

Symbol

Symbol
Determining Dominant Degraders – System-level, Diagnostic Traces

- EVM spectrum (WLAN example)

Sample clock offset
Time tracking OFF

Ideal
Spur
Determining Dominant Degraders – Component-level Diagnostics

- Go one level deeper to examine component-level performance with non-modulated (tone-based measurements)

Gain and Output Power
Calibrating Power Measurements with a Power Meter
Measuring Gain with a Vector Network Analyzer
Return Loss and Reverse Isolation
Noise Figure
Noise Unit Conversion
Noise Figure Measurements
Y-Factor Method Using a Calibrated Noise Source
Harmonics
Intermodulation Distortion
Determining Dominant Degraders
System-level, Scientific Method

- Test single suspect degrader by varying its contribution and tracking EVM
  - Independent variable: parameter space of all degraders
  - Dependent variable: EVM

- Example independent variables:
  - Non-standard-specific: thermal noise level, distortion, phase noise
  - Standard-specific tracking parameters, e.g. WLAN:
    - Phase – removes close-in phase noise, not far out
    - Amplitude – removes power variance over time (like PA droop) via pilot tracking
    - Time – SCO track from pilots
Determining Dominant Degraders
System-level, Distortion

- EVM vs Distortion
- Experiments
  - Adjust power level
    - Use pad test to decouple Tx and Rx (e.g. instrument and DUT)
  - Insert known, compressed component
  - Intentionally distort VSG waveform

EVM vs Distortion
- Experiments
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External Attenuation
- Experiments
  - Adjust power level
    - Use pad test to decouple Tx and Rx (e.g. instrument and DUT)
  - Insert known, compressed component
  - Intentionally distort VSG waveform

EVM vs External Attenuation
- Experiments
  - Adjust power level
    - Use pad test to decouple Tx and Rx (e.g. instrument and DUT)
  - Insert known, compressed component
  - Intentionally distort VSG waveform

Extra PA with known performance
Determining Dominant Degraders

System-level, Phase Noise

- EVM vs Phase Noise
- Know your modulation scheme
  - Sub-carrier spacing, SNR requirements
- Experiments
  - De-correlate reference level with respect to EVM degradation
  - Change LO
  - Simulate phase noise in waveform
Determining Dominant Degraders System-level, Noise

- EVM vs Noise
- Vector averaging
  - Coherent (time-aligned) averaging that can reduce random noise contributors in the signal, exposing constant distortion contributors (IP3, IQ imb., etc).
- Two approaches
  - Single VSA (Both DUT’s and VSA’s noise is reduced)
  - Dual VSA (Only VSA’s noise is reduced)
Example Experiment: Vector Averaging

- Vector averaging is coherent (time-aligned) averaging that can reduce random noise contributors in the signal, exposing constant distortion contributors (IP3, IQ imb., etc).
  - Dual VSA (Only VSA’s noise is reduced)
  - **Single VSA** (Both DUT’s and VSA’s noise is reduced)

**Vector Ave. Experiment Setup:**
- **HW:** 5840 (VSG DUT) -> 5840 (VSA)
- Impaired Signal: 802.11ax, 80MHz, MCS11
- 20 averages

**Simulation Results:**

- **Before Vector Averaging**
  - Total EVM = -44.19 dB

- **After Vector Averaging**
  - Total EVM = -47.02 dB

**Measurement Results**
- -0.680884 Measured Average Power (dBm)
- -44.1877 RMS EVM Average (dB)
- -47.0475 OFDM RMS EVM Vector Averaged (dB)
Improving Performance Limiters
Improving EVM Performance

- Phase noise
  - Improved LO
- SNR
  - VSA dynamic range, balancing RF cascade, VSA noise compensation
- Distortion
  - DPD
- Spur Cancellation
  - Spur removal, LO nulling
Improving Phase Noise Performance

- Recall: Phase noise – random variations in phase of LO or carrier
- Improved LO performance => Improved Phase Noise Performance of the instrument => Better EVM

Fig 1. VST’s Internal LO Phase Noise

Fig 2. NI 5653 External LO Phase Noise
Improving dynamic range / SNR

- High-Quality component selection (low Noise Figure, etc.): Amplifiers, Filters, Mixer, Attenuators, IQ demodulator, ADC
- Balancing RF cascade to achieve optimal power at the mixer
Digital Predistortion (DPD)

DPD algorithm implementations in base station technology:

1) Simple Memoryless Look-up Table (LUT)
2) More complex algorithms based on the Volterra series
Spur Cancellation Process:
1. VSA measures the spurious frequency components seen by the VSA
2. VSA software calculates I/Q stimulus waveforms for the VSG to cancel the spurious signals
3. After spur cancellation only desired waveform remains at VSG output
802.11ax Case Study: Achieving -50 dB EVM
Demo: Hardware & Software

Hardware setup #1:
• PXIe-8880 (Controller)
• PXIe-1085 (Chassis)
• 2 x PXIe-5840 (VST)
• 2 x PXIe-5653 (LO module)

Software:
• Windows 7 (64-bit)
• LabVIEW 2015 SP1 (64-bit)
• NI-RFSA/G 16.0.2
• NI WLAN Toolkit 17.0
  • 802.11ax, 80MHz, MCS11
Demo: 802.11ax EVM results

EVM vs Average Power (802.11ax, 80MHz, MCS 11, SU PPDU. 16 OFDM symbols)
Demo: Hardware & Software

Hardware setup #2:
- PXIe-8880 (Controller)
- PXIe-1085 (Chassis)
- 1 x PXIe-5840 (VST)
- 2 x PXIe-5653 (LO module)

Software:
- Windows 7 (64-bit)
- LabVIEW 2015 SP1 (64-bit)
- NI-RFSA/G 16.0.2
- NI WLAN Toolkit 17.0
  - 802.11ax, 80MHz, MCS11
Demo: 802.11ax EVM results
Demo EVM Results vs VST nominal performance

EVM vs Average Power (802.11ax, 80MHz, MCS 11, SU PPDU, 16 OFDM symbols)

Figure 17. WLAN 802.11ax Measured RMS EVM (dB) versus Measured Average Power (dBm), External LO

- 5.1 GHz Noise Uncompensated
- 5.1 GHz Noise Compensated
- 5.8 GHz Noise Uncompensated
- 5.8 GHz Noise Compensated

10 Conditions: RF Output loopback to RF Input; waveform bandwidth: 80 MHz, MCS Index: 11; LO Offset: -250 MHz, device instantaneous bandwidth: 1 GHz, External LO: PXIe-5653.
Performance Options (VST 1.0 / 2.0)

- 5 GHz Band
  - The VST nominal EVM performance is limited by the phase noise of the internal synthesizer. An external LO can be used to achieve better EVM performance

- 2.4 GHz Band
  - The VST internal synthesizer provides adequate performance
  - 5653 LO does not support 2.4G band

- For dual-band test configurations, an external LO is not required for the 2.4 GHz band
  - With an external LO, no external connection changes or switching is required for operation in the 2.4 GHz band
Performance Option: 1x1 (VST 1.0 / 2.0)

PXie-5653: -133 dBc/Hz at 10kHz offset
Performance Option: 2x2 / Dual-band / 80+80 (VST 1.0 / 2.0)

Independent LO for each 1x1 segment
Performance Option: 4x4 / Dual-band / 80+80 (VST 1.0 / 2.0)

Independent LO for each 2x2 segment
Performance Option: 8x8 / Dual-band / 80+80 (VST 2.0)

- Independent LO for each 4x4 segment
- LOs placed in separate chassis
- PXI chassis share same controller and software
Standard Option: Up to 8x8 / Dual-band / 80+80 (VST 2.0)
# 11ax Testing Solutions over the DUT Product Life Cycle

## Goals
- Characterization of RF design performance
- Establish optimized gain/setting table
- Validation of RF design performance
- Validation of gain/setting table
- Validation of final product (board, module, device level)
- Validation of assy. process (optimization)

## Focus
- Completeness of Tests:
  - Coverage
  - Flexibility
  - Scalability
- Completeness of Tests:
  - Coverage
  - Test time
  - Closer to “Turn-key”
- Costs of Tests:
  - Throughput
  - Rugged reliability
  - Availability

## Test approach
- **Characterization**
  - Extensive, granular tests using open PXI and WLAN Toolkit
- **DVT**
  - Efficient automated tests using open PXI and WTS IS
- **Production**
  - Automated tests using WTS* and WTS IS

* Open PXI for advanced req.
Check out -50 dB EVM 802.11ax on the Expo Floor!

“WTS + Open PXI 802.11ax”
In the AT Pavilion
Before you go, take the survey.
• 10 a.m. – 12:45 p.m. Morning Sessions 4th Floor Rooms 11-19
• 12:45 p.m. Lunch Keynote/Awards Ceremony Expo Hall 4
• 2:30 – 5:30 p.m. Afternoon Sessions 4th Floor Rooms 11-19
• 5:30 – 7 p.m. NIWeek Welcome Happy Hour/Exhibition Opens

Alliance Day 2017
Schedule At A Glance
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WLAN Measurement Suite

- Programming API in LabVIEW, LabWindows™/CVI, C/C++, and .NET
- Support for IEEE 802.11a/b/g/n/j/p/ac/ah/af/ax
- 5X to 10X faster than traditional box instruments
- Residual (EVM) measurements as low as -51 dB
- Common measurements:
  - EVM
  - Spectrum mask
  - Carrier leakage
  - Frequency offset
WTS Instrument Software (WTS IS)

- WTS Instrument Software with SCPI interface
- Advanced User Interface (UI) for monitoring, configuration, controlling and debugging incl. timing chart
- Support for
  - GSM/EDGE
  - WCDMA, TD-SCDMA, CDMA-2k
  - LTE FDD/TDD
  - WLAN 802.11a/b/g/n/j/p/ac/ax
  - Bluetooth 4.2/5.0
  - LR-WPAN (ZigBee, Thread, WirelessHART, …)
  - Z-Wave
  - GPS
- Residual (EVM) measurements as low as -51dB
- Common measurements:
  - EVM
  - Spectrum mask
  - Carrier leakage
  - Frequency offset
2012: PXIe-5644/45R
- 80 MHz Bandwidth
- 65 MHz to 6 GHz
- Baseband IQ (5645R)

2014: PXIe-5646R
- 200 MHz Bandwidth
- 65 MHz to 6 GHz
- $\leq -48$ dB EVM (ext. LO)

2016: PXIe-5840
- 1 GHz Bandwidth
- 9 kHz to 6 GHz
- $\leq -51$ dB EVM (ext. LO)