Extending the Useable Range of Error Vector Magnitude (EVM) Testing

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Abstract

This paper discusses practical constraints of Error Vector Magnitude (EVM) measurements for high-coverage Radio Frequency Integrated Circuit (RFIC) device testing. Noise, distortion, spurious signals, and phase noise all degrade EVM, and therefore EVM provides a comprehensive measure of an RFIC's quality of use in digital communications. New wireless standards with large instantaneous bandwidths, such as 802.11ac WLAN and LTE-Advanced, make EVM thresholds more difficult to achieve. This paper describes techniques to optimize test equipment setup and operation to extend the useable range in frequency, power and instantaneous bandwidth of EVM-based testing.

1.   Introduction

The rapidly-increasing prevalence of wireless technology drives the need for new test capabilities for Radio Frequency Integrated Circuit (RFIC) devices. Historically, simple RF testing and characterization has been accomplished using un-modulated single-tone or two-tone RF signals. Un-modulated RF testing involves distortion or noise figure measurements, and requires relatively simple RF test equipment. Unfortunately, single-tone or two-tone testing is inadequate for communication protocols that use many subcarriers. For RFIC devices capable of modern digital communication protocols such as WLAN, WiMAX, and LTE, testing must cover the expected performance using actual digital communication waveforms.

In order to perform high-coverage testing for modern communication systems, modulated-signal analysis is necessary. There is much published research on achieving rapid and extensive test coverage by performing error vector magnitude (EVM) measurements on modulated RF signals [1][2]. For modulated signal analysis, test equipment with vector signal capability is required, including a Vector Signal Generator (VSG) and a Vector Signal Analyzer (VSA). The VSG and VSA instrument setup can noticeably affect the quality of the EVM measurement floor. This is especially conspicuous when testing over a broad range of center frequencies, power levels and instantaneous bandwidths.

In this paper, we use an IEEE 802.11 WLAN test example to illustrate the various modulated signal test scenarios and the effects of test equipment imperfections on the EVM test results. We go on to explain techniques to enhance test equipment setup to extend the useable EVM measurement range in frequency, power, and instantaneous bandwidth.

2.   Overview of Digital Modulation

Most digital communication standards rely upon In-Phase (I) and Quadrature (Q) modulation to encode digital data onto the RF signal. I/Q modulation coding schemes include quadrature amplitude modulation (QAM) and phase shift keying (PSK). Figure 1 shows constellation diagrams for various coding schemes. The density of the constellation defines the number of bits per constellation symbol. For example, each 64-QAM constellation symbol represents 6 bits of digital data.
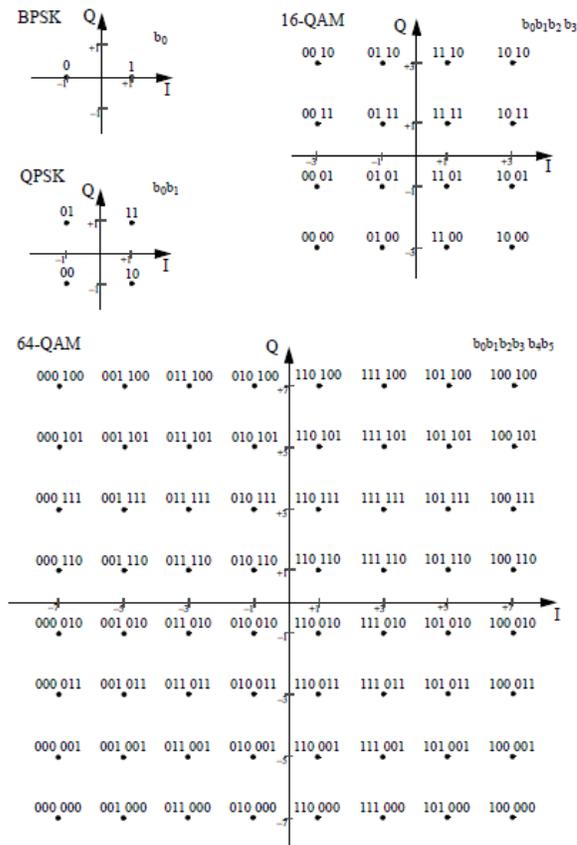

Figure 1) I/Q Constellations

2.1.   Overview of IEEE 802.11 WLAN

The IEEE 802.11a/g/n/ac WLAN standards use orthogonal frequency-division multiplexing (OFDM) modulation. OFDM is a method of encoding digital data simultaneously on multiple subcarrier frequencies. Each

subcarrier is used to transmit QAM or PSK encoded, unique digital data. The number of subcarriers varies by channel bandwidth and IEEE 802.11 standard. For example, 802.11a contains 52 subcarriers (48 data, 4 pilot) in its 20 MHz channel bandwidth, and 802.11ac contains 484 subcarriers (468 data, 16 pilot) in its largest 160 MHz bandwidth. The subcarrier frequencies are divided into data subcarriers and a small percentage of pilot subcarriers used for synchronization.

In the time domain, WLAN signals are transmitted in frames, where each frame consists of a preamble, a header, the data payload, and a frame check sequence (FCS) as shown in Figure 2. The preamble is used to synchronize and equalize the channel. The header contains logical information used to decode the data transmission. The payload contains the variable-length data field of 3.6 μs or 4 μs data symbols. The FCS is the last four bytes in the standard 802.11 frame and is used as a Cyclic Redundancy Check (CRC).

Preamble	Header	Data	FCS

Figure 2) WLAN Frame Format

The newest IEEE 802.11ac WLAN standard, which is still in draft format, will achieve up to 867 Mbps data rate over a single RF channel, and up to 6.93 Gbps using MIMO channels. These data rates for 802.11ac are accomplished by extending the 802.11n standard with more instantaneous bandwidth up to 160 MHz, more MIMO channels, and higher density modulation constellations up to 256-QAM.

3. Modulated Signal Test Overview

For modulated signal testing, test equipment equipped with vector signal capability is required. The two standard pieces of test equipment for modulated signal testing include the Vector Signal Generator (VSG) and the Vector Signal Analyzer (VSA) [3]. The VSG is used for I/Q modulated signal generation and the VSA is used for I/Q demodulated signal analysis. One or both instruments may be necessary depending upon the transmitter and receiver test requirements for a particular RFIC.

Typically, protocol analysis software is required to create the I/Q waveforms used by the VSG, and to analyze the I/Q data captured by the VSA. In all cases, the EVM floor of the test equipment limits the measurement floor for an RFIC device under test (DUT). The test equipment setup and operation needs to be optimized to ensure that the DUT is being accurately measured and not degraded by the residual EVM of the test equipment.

3.1. WLAN Standard Tests

The IEEE 802.11 WLAN specifications define a number of standardized compliance tests [4]. These tests include:

- Spectrum Mask

- Spectral Flatness
- Peak Power
- Center Frequency Error
- Symbol Clock Frequency Error
- Center Frequency Leakage
- EVM

WLAN protocol analysis software creates standard I/Q waveforms used by the VSG to vector modulate the RF signal to produce a standardized WLAN test signal. WLAN protocol analysis software also is used to analyze the I/Q data captured by the VSA and return the various results listed above. Figure 3 shows an example of this type of software analysis tool. Of these measurements, EVM is the most comprehensive and demanding upon the test equipment.

Figure 3) WLAN Analysis Software

4. EVM Measurements

EVM (also called relative constellation error) is a measure used to quantify the performance of a digital communication channel. An ideal digital communication channel would have all constellation points precisely at the ideal locations. Imperfections cause the actual constellation points to deviate from ideal, and EVM is a measure of how far the points are from those ideal locations. The root mean square EVM is a comprehensive measurement and is degraded by any imperfection in the RF channel [5]. Also, EVM is shown to be independent of the coding scheme (i.e. constellation density). EVM is typically expressed in decibels (dB) or a corresponding percentage. For example, -40 dB equates to 1.0% EVM.

The IEEE 802.11 standard defines the EVM test as an average measurement over 20 frames using preamble-only equalization and pilot phase tracking, with a minimum of 16 data symbols per frame. The various EVM thresholds for a WLAN system using the various modulation coding schemes is shown in Figure 4. Note that the EVM requirements for the low-density constellations are very relaxed, and for the highest density 256-QAM an EVM of -32 dB is required. This implies that test equipment EVM floor must be much less than -32 dB to provide measurement margin for 256-QAM signals.

Modulation	Coding rate	Relative constellation error (dB)
BPSK	1/2	-5
QPSK	1/2	-10
QPSK	3/4	-13
16-QAM	1/2	-16
16-QAM	3/4	-19
64-QAM	2/3	-22
64-QAM	3/4	-25
64-QAM	5/6	-27
256-QAM	3/4	-30
256-QAM	5/6	-32

Figure 4) EVM Limits for WLAN Modulation Schemes

4.1. Noise and Distortion Tradeoff

Noise and distortion limit the minimum and maximum power levels at which any device, including the test equipment, can operate with low or negligible contribution to EVM. At low power levels, noise limits the signal to noise ratio and degrades EVM. At high power levels, signal distortion causes inter-carrier interference and degrades EVM.
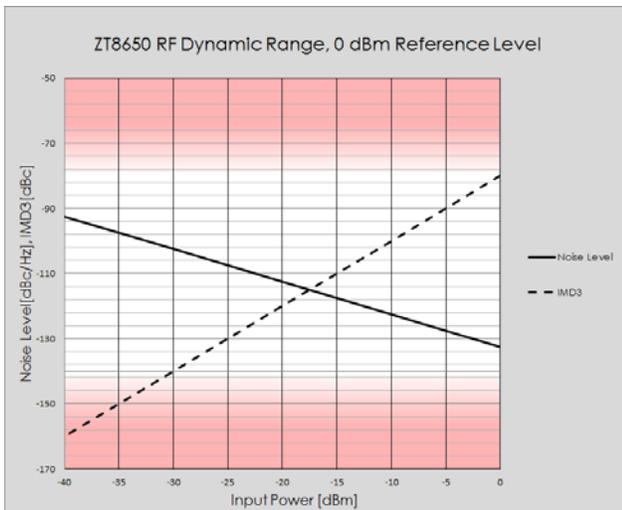

Figure 5) Noise and Distortion Floor in Test Equipment

Figure 5 shows typical VSA noise and distortion tradeoff curves for a selected 0 dBm reference level setting [6]. The reference level setting will define the RF input attenuators and amplifiers paths that correspond to a maximum input of 0 dBm. Note that 0 dBm is used as an example, and testing occurs at many different power level settings. From this plot, the maximum dynamic range can be identified for a 0 dBm reference level setting and 1 Hz instantaneous bandwidth. The point at which the noise and distortion curves cross in Figure 5 shows the optimum dynamic range to occur with an applied RF input power of -17.5 dBm. Note that the noise curve is normalized to dBc/Hz and the total integrated noise will scale with instantaneous bandwidth according to the equation: $10 \log_{10} (B)$, where

B is the instantaneous bandwidth in Hz. The best EVM floor in the VSA occurs where the integrated noise and distortion are balanced for maximum dynamic range.

This implies that in order to minimize EVM limited by VSA noise and distortion, an optimum RF reference level must be set for each power level and instantaneous bandwidth. This process is further complicated by the fact that the RF attenuator and gain path losses vary with center frequency and those losses also shift the curves shown in Figure 5. At higher frequencies, the additional losses through the RF paths will affect the power level going into the mixer(s), and consequently affect the optimum settings for minimum EVM. The effects of noise and distortion cause a complex multi-variable procedure to optimize VSA setup. A multi-dimension EVM optimization algorithm is discussed in section 5.2.

4.2. Phase Noise

Phase noise has significant affects on EVM. Figure 6 shows a phase noise difference in a batch of tested PLL components with 2 outliers having -66 dBc sidelobes as opposed to the batch mean of -68 dBc. The 2 dB difference in sidelobe phase noise performance degraded EVM by 2 dB at 5.66 GHz, from -46 dB (0.5%) to -44 dB (0.6%). As frequency increases, the contributing effect of phase noise on EVM is greater.
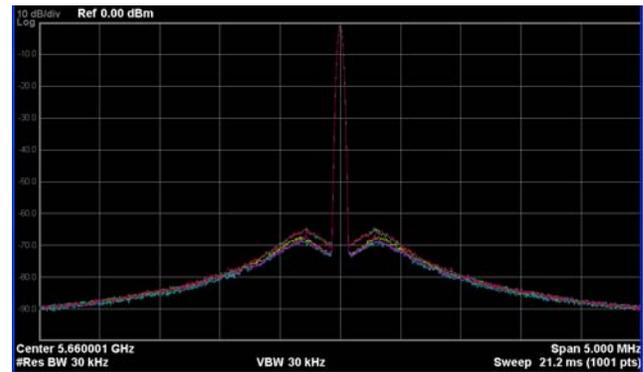

Figure 6) Example of phase noise effects on EVM

For test equipment, there are few techniques that can be used to cancel phase noise degradation on EVM. One technique is to use a common local oscillator (LO). A common LO between the VSA and VSG will remove additional phase noise introduced by the uncorrelated noise in separate oscillators. Testing shows an approximate 1 dB improvement in EVM when using a common LO over separate LOs.

4.3. Spurious Signals

Spurious signals will interfere with any subcarrier at that signal frequency and limit the useable dynamic range. In test equipment, spurious signals are typically low in magnitude, but the dynamic range requirements of an OFDM modulated signal make any interferers

problematic. Spurious signals become more problematic when EVM testing is performed at low RF signal levels. Often, testing can avoid bands where spurious signals reside, but if not, there are cancellation techniques that will be discussed in section 5.4.

4.4. Spectral Shape

The spectral shape of the RF test pattern will affect the measured EVM floor. Windowing and filtering of the I/Q modulation data can dramatically affect EVM. Figure 7 shows the differences in spectrum and the corresponding EVM for two extremes in spectral shaping. Note that EVM is improved at the expense of adjacent channel leakage.
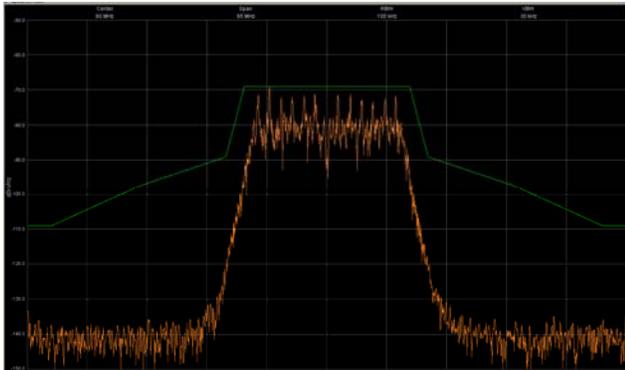

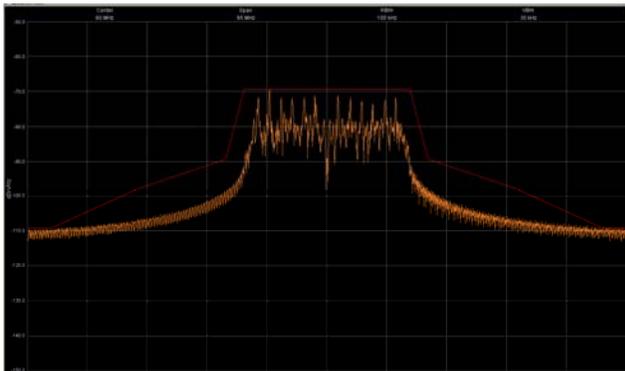**Figure 7a) Shape Optimized for Spectral Mask (-48 dB EVM)**

Figure 7b) Shape Optimized for EVM (-53 dB EVM)

5. EVM Optimization

The goal of any test environment is to minimize the effects of test equipment on the actual DUT measurements. For EVM, this is particularly difficult due to the sensitivity of EVM to imperfections in test equipment. Fortunately, there are techniques that can be employed to extend the useable frequency and power ranges by minimizing the degradation of EVM from those factors discussed above.

5.1. Advanced Equalization Techniques

Although not defined in the IEEE 802.11 standardized tests, there are advanced equalization techniques that are sometimes used to improve EVM measurements. Often these advanced techniques may not be used because the EVM contribution from the test equipment cannot be extracted from the EVM contribution of the DUT. At

times when the error can only be caused by the test equipment, advanced techniques can remove test equipment imperfections. For example, when testing RF power amplifiers, I/Q mismatch compensation can be used because I/Q mismatch can only be caused at baseband within the test equipment.

I/Q mismatch compensation is used to compensate for imbalances in magnitude or phase of the baseband I/Q signals. Many VSA and VSG systems use direct conversion or zero IF systems where I/Q imbalance can be a significant degradation on system EVM performance. Typically, test equipment is calibrated for I/Q imbalance and should not require additional compensation.

As described in section 2.1, the IEEE 802.11 standard defines the channel equalization using the preamble portion of the frame. As an augmentation, some protocol analysis software tools allow the entire frame including the pilot and data to also be used for channel equalization. The additional information yields a better channel estimation and typically results in a 2 dB improvement in EVM. Often, this advanced equalization is not allowed for EVM testing because it is not a valid use case for the actual WLAN system. In essence the test equipment passband flatness cannot be corrected without similarly correcting the DUT passband flatness.

Similar to the preamble, pilot and data equalization technique described above, a thru calibration can be used for equalization prior to insertion of the DUT. The thru calibration performs channel equalization with the VSG connected directly to the VSA. This technique yields the same 2 dB improvement, but applies a fixed passband flatness correction for just the test equipment.

As discussed in section 2.1, pilot subcarrier phase tracking is required for constellation phase alignment. In addition to phase, the pilot subcarriers can be used for time or amplitude tracking also. Neither should improve the EVM floor of the test equipment, but both can be used for diagnostics. In some test scenarios, the DUT will have severely degraded EVM and enabling pilot amplitude or time tracking will fix the problem indicating a root cause of the poor EVM.

5.2 Noise and Distortion Optimization

In section 4.1, we described the complexity involved with manually optimizing the VSA for balanced noise and distortion to minimize EVM. In summary, minimum EVM requires the front-end attenuators and preamplifiers to be adjusted to apply the optimum power level to the mixer(s). The optimum front-end attenuator and preamplifier settings vary with peak envelope power, center frequency, instantaneous bandwidth, and even from instrument to instrument. The only practical solution is for the test equipment manufacturer to perform an EVM-optimized calibration routine during factory calibration. The factory

calibration for best EVM is then applied to automatically setup the RF attenuators and preamplifiers for the optimum EVM at the user-requested RF reference level, center frequency, and protocol instantaneous bandwidth.

With this type of EVM-optimized calibration, EVM can be minimized over a large operating range in power and frequency. Figure 8 shows the "bowl" curves of this type of EVM optimization. Within the bottom, flat portion of the bowl curves, the test equipment EVM floor is minimized. At low power levels, the noise floor ultimately limits the EVM performance, and at high power levels device linearity ultimately limits EVM performance.
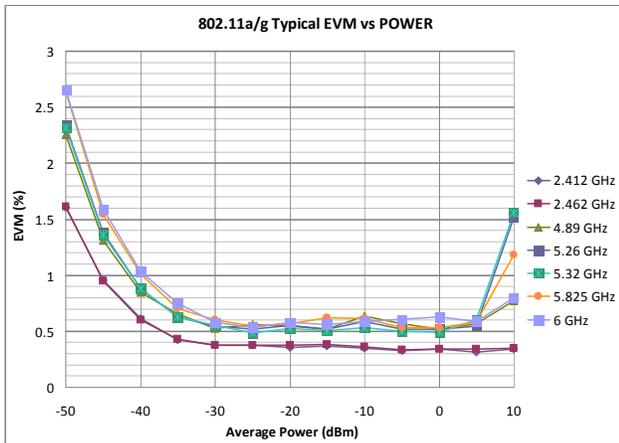

Figure 8) Example of Extended Range of EVM Floor

5.3 Predistortion

Improving linearity within the VSG at high power output is another challenge, and I/Q predistortion is one technique that is used to remove distortion. Software tools simplify and automate predistortion for a combined VSA/VSG test system. With the VSG connected directly to the VSA, software models the nonlinearity of the VSG and creates an inverse operation which effectively linearizes the VSG output. When predistortion compensation is complete, the predistorted VSG signal is then applied to the DUT.

5.4 Spur Cancellation

Similar to predistortion to improve VSG non-linearity, I/Q modulation data can be used to cancel spurious signals within the VSG. With the VSG connected directly to the VSA, software measures the spurious frequency components seen by the VSA. The software then calculates I/Q stimulus waveforms for the VSG to cancel the spurious signals. The spur-cancelling I/Q data includes additional signals at the spurious frequencies of equal magnitude and opposite phase. When spur cancellation is complete, only the desired waveform remains on the VSG output signal.

6. Conclusion

EVM is a powerful measurement technique for comprehensive and efficient RFIC testing. Test equipment selection and setup is critical to achieve the best EVM-based testing performance. This paper defines a number of techniques that assist in the optimization of test equipment setup for minimizing the residual EVM of the test equipment. These techniques allow the test engineer to measure the EVM contribution of just the DUT over a broad range of test conditions.

7. References

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