Low-Cost Alternate EVM Test for Wireless Receiver Systems

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Abstract

In digital radio applications, error-vector-magnitude (EVM) is the primary specification which quantifies the performance of digital modulation implemented in silicon. Production testing of EVM incurs high cost of test instrumentation in automated test equipment (ATE). For EVM testing of wireless receivers, the ATE must include an RF transmitter having (1) the required digital modulation capability, (2) transmitter parameter configurability via test automation software and (3) higher performance and accuracy compared to the receiver-under-test. In this paper, an alternate test methodology for the EVM specification is proposed that eliminates the need for high cost RF sources with digital modulation capability. A sequence of multi-tones generated using low-cost RF sources is used as test stimuli. The EVM specification is computed (predicted) by analyzing the degradation of the test signal by the receiver modules (e.g. LNAs, mixers, filters) by means of the observed waveforms in the baseband. Simulation results are presented.

Keywords: system testing, wireless communication, error-vector-magnitude, RF production tester, digital modulation.

1. Introduction

In wireless communication systems, complex digital modulation schemes are used for meeting stringent spectral and SNR requirements [1][2]. In such systems, the overall quality of the transmission and reception are determined by various baseband and RF system specifications. Among these, the symbol error probability, commonly termed as bit-error-rate, and the *error vector magnitude (EVM)* are two primary specifications that determine the performance of the wireless system in terms of transmitted and received symbols corresponding to a given digital modulation scheme. Direct measurement of these specifications involves capturing the test response signal at the baseband symbol rate. In contrast, no other major specifications that determine the performance of the RF modules in wireless communications, e.g. gain, IIP3, noise figure, receiver sensitivity, transmission spectral mask compliance, are defined in terms of transmitted and receive symbols. The latter specifications are computed using narrowband or broadband spectral measurements with multitones or noise as the input.

EVM is a measure of the digital modulation quality of the wireless system-under-test. The conventional symbol oriented production test measurement method for EVM has the following implications [6][12]:

1. Measurement of EVM requires automated-test-equipment (ATE) that supports digital modulation and hence, simple RF signal source may not be sufficient for EVM measurement. In production testing of RF systems, the requirement for supporting digital modulation capability in a RF signal generator translates into higher cost of test instrumentation for these ATEs and consequently higher test-cost per unit time.
2. For a long test response symbol sequence, measurement of EVM at the corresponding symbol rate incurs prolonged test time.

In this paper, a new specification testing methodology for EVM of wireless receivers is proposed. The proposed framework uses multitone signals at the RF front-end as test stimuli and measures the test response signal, at a higher rate than the baseband symbol rate, in the baseband. Spectral analysis using the alternate test framework [13][14] is performed and the EVM is computed (predicted) using nonlinear regression equations under the alternate test framework (described in Section 3). In alternate testing, the test specifications are not measured directly. They are predicted from measurements of the test response waveforms or spectra, which are strongly related (in a nonlinear manner) with the variations in the test specifications of interest. Simulation result shows that, the EVM of wireless GSM receivers can be predicted within ±3% limits. Consequently, the presented work shows that, using the proposed methodology:

1. a multitone testing scheme for specification testing of EVM of wireless receiver is feasible,
2. the total test time for testing of EVM can be significantly reduced over current EVM test practice.

The paper is organized as follows. Section 2 describes the conventional method of testing EVM and various test issues discussed in the literature. In Section 3, the concept of alternate testing is explained. In Section 4, the test architecture and the system simulation method are described. Simulation results for a GSM receiver are

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presented in Section 5 with conclusions discussed in Section 6.

2. Background: EVM Testing

Error vector magnitude is computed as,

$$EVM = \sqrt{\frac{\frac{1}{N}\sum_{1}^{N}\left\|R - S\right\|^2}{\left\|S_{\max}\right\|^2}} \quad (1)$$

where,

R = the received symbol in vector form (I + jQ),

S = the reference symbol in vector form (I + jQ),

S_{max} = the outermost symbol in the constellation diagram,

N = number of symbols used for EVM computation, where N is sufficiently large.

Figure 1 illustrates the error vector for one symbol due to the received symbol being different in magnitude and phase from the *ideal* or reference symbol. The magnitude of the error vector expressed as the percentage of the reference symbol magnitude determines the EVM value for the received symbol. For multiple symbols, EVM is determined using Eqn. 1.

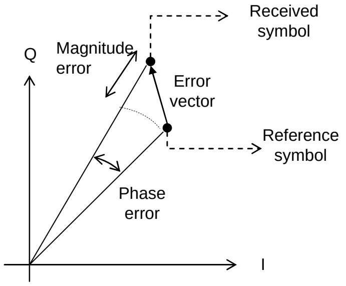

Figure 1. Constellation of a received symbol and its deviation from reference constellation

In theory, for wireless systems, EVM can be measured at any RF, intermediate frequency (IF) or baseband test-point(s) where I-Q modulated signals are present. Figure 2, for example, shows the conventional setup for measuring EVM of an RF device whose behavior may affect the wireless data transmission performance. The EVM measurement setup for this device consists of an RF signal source supporting digital modulation and an internal down-conversion receiver for digital demodulation and symbol reception. The EVM computation block performs the required digital signal processing and computes the EVM value. The digital signal processing involves:

1. Capturing the signal samples comprising the test frame of symbols in the built-in receiver of the ATE. If there are *N* symbols in the test frame, and *m* samples per symbol, ideally *m*N* samples need to be captured. If the baseband sampling clock rate is given by f_{CLK}, the minimum test response capture time is given by,

$$T = m \,.\, N / f_{CLK} \quad (2)$$

2. Sampling of the received symbols at the optimal sampling point (out of *m* possible sampling points within a symbol) by analyzing the eye diagram for the maximum eye opening.
3. Normalization of the received symbols, so that symbol values (volts) are translated into I and Q symbol values of the constellation diagram.
4. Compensating for the constellation rotation due to phase mismatch between receiver and transmitter carrier. This rotational effect of the constellation is constant (outside the limits of phase-noise effect [8][11]) across the symbols of the received frame.
5. Compensating for the constellation rotation due to frequency drift of the receiver. This rotational effect accumulates progressively and the subsequent symbols start moving away from the respective reference symbols following a circle. This is compensated by locking the receiver modulation carrier with the transmitter carrier and/or using an adaptive digital filter in the baseband [8][11][12].
6. Computation of the effective received symbol values using step 1-5 and computing the magnitude of the EVM.

Since EVM is expressed using symbol errors computed at the symbol-rate, it provides a common metric useful for comparison of performance degradation caused by different sub-modules in different stages of the receiver/transmitter and the source of error (gain imbalance, phase imbalance, phase noise, etc) [7][8]. Hence, for cascaded devices, EVM measurement performed on the output(s) of intermediate modules and final output provides useful diagnostic information indicating the amount of signal quality degradation and its sources.

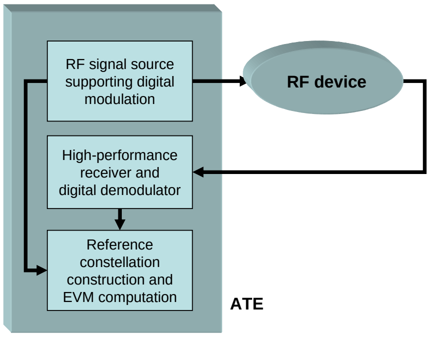

Figure 2. Conventional setup for measuring EVM of an RF (no baseband or IF I/O) device

Although EVM is a useful specification for system performance diagnosis, in a highly integrated wireless system test-point insertion for EVM measurement may not be always possible. Second, the simplicity of the EVM specification, as expressed in Equation 1, translates into long test times and complex test instrumentation setup in the production ATE. For EVM testing of a transmitter, the ATE uses a built-in high-performance receiver, whereas, for EVM testing of a receiver, the ATE uses a built-in high-performance transmitter supporting the digital modulation scheme of interest. Similarly, for RF devices having no baseband I/O, the ATE uses both the transmit and the receive hardware supporting the digital modulation/demodulation scheme of interest. In practice, EVM testing is commonly performed for the entire transmitter or receiver of a wireless transceiver, or is performed for highly nonlinear devices, such as PAs [9][10]. In the proposed work, a wireless receiver is used as the test vehicle for testing of EVM using a multitone test stimulus sequence. The value of EVM is predicted from the baseband test response waveforms using the alternate test framework [13]. The concept of alternate test is explained in the following section.

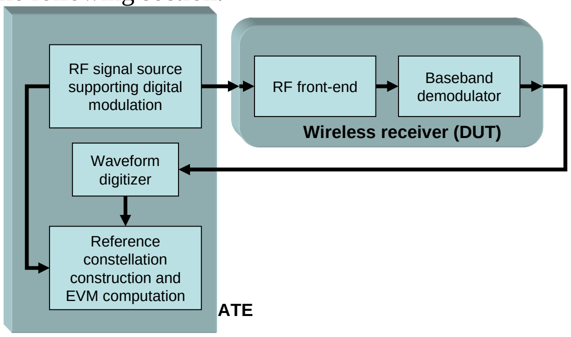

Figure 3. Conventional setup for measuring EVM of a wireless down-conversion receiver

3. Basic Concept of Alternate Test

Past research work [13][14] on automated test generation for specification testing of analog circuits showed that the variation of any circuit parameter, $\boldsymbol{p}$, such as the W/L ratio of MOSFETs, value of a resistor, etc, alters the circuit specifications, $\boldsymbol{S}$, by a corresponding sensitivity factor. The test response measurement data, $\boldsymbol{M}$, sensitive to the circuit parameter perturbation are also affected by a corresponding sensitivity factor. For a region of acceptance (i.e. 'good' circuit) of the circuit specification values $\boldsymbol{S}$, there exists a corresponding allowable range of variation in all the circuit parameters $\boldsymbol{P}$, and this region of acceptance in $\boldsymbol{P}$, in turn, defines an acceptance region in $\boldsymbol{M}$. A circuit can be declared faulty if the measurement data in the measurement space $\boldsymbol{M}$ lies outside the acceptance region. However, defining the region of acceptance in $\boldsymbol{M}$ is often not possible, as the function mapping $\boldsymbol{P}$ onto $\boldsymbol{M}$, i.e. $f:\boldsymbol{P}\rightarrow\boldsymbol{M}$, is of a highly nonlinear nature for analog/RF circuits. In case of EVM of a receiver, though the nonlinearity, noise performance and phase-frequency-gain imbalances of the individual modules affect the EVM performance, a closed form equation for $f:\boldsymbol{P}\rightarrow\boldsymbol{M}$ is not obtainable and, hence, defining acceptance limits on the frequency spectrum of the test response waveforms is by itself a complex problem. Hence, a multitone test framework, which is common for gain and IIP3 testing, is difficult to relate to the EVM specification for an entire receiver or transmitter. However, for amplifiers consisting of simpler RF devices, where frequency translation does not occur, EVM can be estimated as a function of the intermodulation distortion effects [9][10]. However, due to the increased complexity of an entire GSM band receiver system, using these approaches above estimating functions can not be computed from the test response spectra. In this paper, alternate test methodology has been used to accurately compute (predict) the EVM specification of GSM band receiver from a sequence of test response waveforms captured in the baseband corresponding to a sequence of two-tone test stimuli.

On the other hand, as shown in [13] as the basis of 'alternate test', a mapping function $f:\boldsymbol{M}\rightarrow\boldsymbol{S}$ can be computed for the circuit specifications $\boldsymbol{S}$ from all the measurements in the measurement space $\boldsymbol{M}$ using nonlinear statistical multivariate regression. Given the existence of the regression model for $\boldsymbol{S}$, an unknown specification of a CUT can be predicted with a certain accuracy from the measured data $\boldsymbol{M}$. Figure 4 illustrates the concept of specification prediction using test response waveform samples $\{m_1, m_2, m_3, \ldots\}$ under the variation of circuit parameters, e.g. ΔC's, ΔR's, etc. The primary benefits of using the approach of specification prediction are:

1. It is possible to construct a measurement space $\boldsymbol{M}$ corresponding to a specially crafted test stimulus that results in simplification of test instrumentation, viz. test signal source and test response capture hardware.
2. It is possible to reduce the test stimulus application and test response capture time resulting in test time reduction.

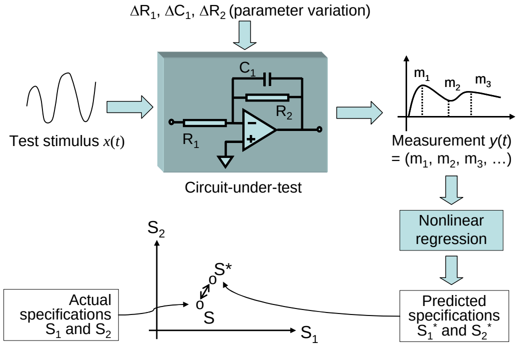

Figure 4. Alternate test framework

In the proposed approach, for testing EVM of a wireless receiver, the use of multitone test stimuli simplifies RF signal generation hardware. Further, in the proposed approach, test time is also reduced by capturing the test response at a higher speed than the baseband symbol rate. Multivariate Adaptive Regression Splines (MARS) [5] are used in the proposed approach to construct the regression model and predict EVM from test response waveforms at the baseband.

4. Test Architecture

The proposed test architecture for testing the EVM specification of wireless receivers uses RF signal sources for applying multitone test stimuli. Different tones at the RF front-end are combined using RF signal couplers. The receiver-under-test consists of an RF band-select filter, LNA, down-conversion mixers, channel-select filter, followed by a digital demodulation circuit. The GMSK demodulation [3] circuit is implemented in the digital domain and performs signal processing at the clock rate f_{CLK}. The signal processing unit consists of a quadrature multiplier and FIR filters for I-Q demodulation followed by a symbol sampler. The symbol sampler samples the signal at the optimal sampling interval and outputs the symbols at the rate of (f_{CLK} / m) symbols/sec, where a symbol comprises of m consecutive samples. In a conventional EVM measurement setup, the sampled symbols available at (f_{CLK} / m) rate are used for EVM computation. On the other hand, in the proposed methodology, the test response waveform at the output of the symbol sampler is sampled at the f_{CLK} rate and the EVM of the receiver is computed (predicted) using the test response waveforms.

4.1. Behavioral Modeling of the Receiver

In the presented work, the concept of using a multitone test framework for EVM testing is proved using behavioral simulation of the receiver system. Repetitive simulation using a transistor-level description of the entire wireless receiver is prohibitive due to the large simulation time needed for transient simulation. All the components of the receiver-under-test, e.g. LNA, mixers, frequency synthesizer, filters, are modeled using existing behavioral models [1][15][16][17]. The modeling principle for the above blocks is described below in brief.

Filters: Analog filters (channel-select and band-select filters) are realized in terms of their s-domain linear transfer function and transformed into discrete time-step filters. Digital filters used in the quadrature demodulator are designed directly in the z-domain.

LNA: The LNA is implemented as a cubic polynomial having the input-output transfer function of the type:

$$y(t) = c_0 + c_1\, x(t) + c_2\, x^2(t) + c_3\, x^3(t) \qquad \textbf{(3)}$$

The coefficients c_0 and c_2 are set to be zero, assuming odd symmetry characteristic of a typical differential signal amplifier. The coefficients c_0 and c_2 are computed from the power gain [dB] and IIP3 [dBm] specifications [1]. Gaussian noise of magnitude V_n corresponding to the noise figure [dB] of the LNA is added to the input of the transient waveform. V_n is given by,

$$\overline{V}_n = \sqrt{4kT \cdot BW \cdot R} \qquad \textbf{(4)}$$

where,
k = Boltzmann constant,
T = 300K,
BW = Sampling-frequency/2 or the Nyquist frequency,
R = 50ohm

Mixer: The mixers are implemented as nonlinear amplifier transfer functions followed by ideal multipliers for the frequency shifting operation [1]. Conversion gain [dB], IIP3 [dB], noise figure [dB] and LO to mix-out leakage [dB] are used to describe the mixer behavioral model.

Local oscillator: Quadrature oscillators are used to synthesize the LO frequency. Peak amplitudes for I and Q outputs, phase imbalance between I and Q outputs, phase-noise [dBc/Hz], which is modeled as the instantaneous frequency deviation of the LO, are used as the behavioral parameters to describe the local oscillators. The local oscillator used within the DSP for GMSK demodulation is implemented in the digital domain and is assumed to be invariant to parameter perturbation. The RF LO is subject to parameter variation.

In the presented work, the entire receiver-under-test is modeled and simulated in the time domain using Matlab.

4.2. Multitone Test Generation for EVM

A multitone test stimulus is applied from the RF signal source. The tones are combined using an RF coupler. For

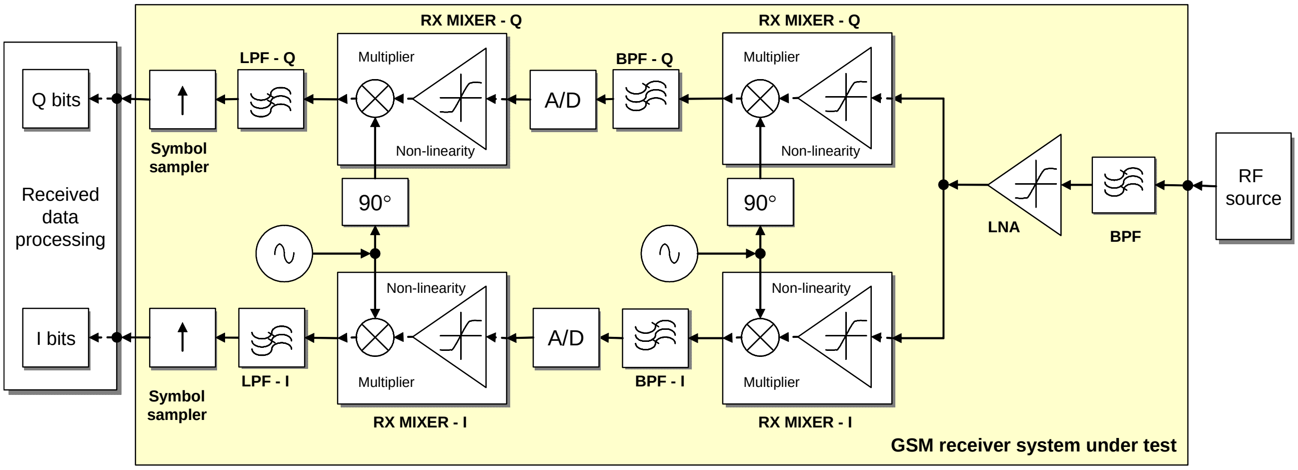

Figure 5. Test architecture for testing EVM of GSM wireless receiver

RF test application, unlike the low frequency analog domain, the use of an arbitrary waveform generator significantly drives up test cost. Hence, the fewer the numbers of tones that are applied simultaneously, the less demanding is the RF signal source requirement. Hence, for test generation, the number of tones that may be used simultaneously is restricted and in this paper we assume that two tones may be used at a time from the RF signal source. Furthermore, this makes the proposed test methodology readily usable within the existing two-tone test framework used for intermodulation performance testing of RF components.

In the proposed test methodology a sequence of two-tones are applied as test stimulus from the RF signal source. The tone-pairs are selected over the channel bandwidth (200kHz for GSM receiver [4]). In the current work, no automated test generation is used and the scope of the paper has been restricted to the showing the feasibility of using the multitone test framework for testing EVM of wireless receivers using alternate test. In the presented work, the frequencies and the amplitudes of the tones are selected at random and the number of tone-pairs is kept small in order to achieve shorter tests.

5. Simulation Results

In this section, simulation results for a 900MHz GSM band wireless receiver are presented. The results of testing for EVM using the proposed alternate test methodology are compared with the results of the conventional EVM testing procedure.

The receiver used as the test vehicle has a direct conversion architecture (Figure 5). A 50ohm RF front-end is assumed. The gain of the band-select filter is -2.7dB. The LNA gain, IIP3 and NF are 10dB, 4.6dBm and 1.6dB, respectively. The mixer conversion gain, IIP3, and NF are 5.8dB, 11dBm and 14dB, respectively. For the frequency synthesizer, f_{LO} is taken to be 900MHz with an instantaneous frequency deviation of 20Hz. The maximum phase imbalance between the I and the Q outputs of the LO is assumed to be 5deg and gaussian random phase is added to the nominal 90deg phase difference. The channel-select bandpass filter center frequency is 100kHz with a Q-factor of 5. In the baseband, a 12bit A/D operating at the speed of 1MSamples/sec is used. Additive noise of 0.5LSB for the input dynamic range of ±2.5V is assumed. The modulating frequency in the baseband is 100kHz and the data rate is 25kbps for each of the I and Q channels, resulting in a symbol rate of 50k symbols/sec. The baseband DSP runs at f_{CLK} = 1MHz. The number of samples per symbol, m = 40. Behavioral simulation is performed in Matlab using time domain analysis with fixed a discrete step of 10^{-10} sec.

It may be noted that the module specifications for the LNA, mixer, filters correspond to the characterization data of different off-the-shelf passive filters, LNA and mixers used to design a GSM receiver on a PCB, which is to be used for hardware experiments in the future. In the hardware prototype, a National instruments' programmable DAQ card represents the A/D and the Matlab program interfacing the DAQ card mimics the digital signal processing unit. The mixers and matched filters in the GMSK demodulation circuit are implemented in software using Matlab.

For the conventional testing procedure, a GMSK modulated pseudo-random bit sequence using BT=0.3 and symbol interval of 3 [3][17] is used. The modulated bit sequence is up-converted to 900MHz and fed into the receiver under test at -45dBm power level, within the -1dB compression point of the LNA input. The test data frame-size for EVM measurement is taken to be 500, i.e. 1000 I and Q symbols. Figure 6 shows the spectrum of the transmitted frame.

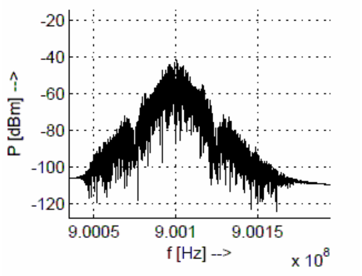

Figure 6. Spectrum of conventional test stimulus for EVM: GMSK modulated test data frame at 900MHz

The received demodulated waveforms (Figure 7) are sampled, normalized, processed for constellation rotation and the EVM value is computed. Figure 8 shows the received symbol distribution in the constellation diagram. The value of EVM is computed to be 0.132 (13.2%) corresponding to the constellation diagram shown in Figure 8. Multiple instances of the receiver-under-test are created by varying the behavioral parameters (i.e. gain, IIP3, NF, filter coefficients) by perturbing them simultaneously around their nominal values. For each receiver instance, the corresponding EVM value is computed and used later for comparison with the results obtained using the proposed methodology.

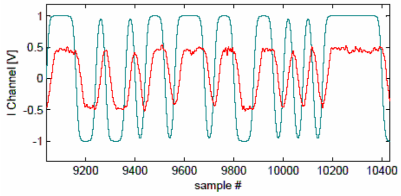

Figure 7. Transmitted and received I channel waveforms (smaller pk-to-pk is the received signal)

In the *alternate test framework*, multitones are applied to the RF front-end and selected as described earlier. Within the channel-bandwidth of 200kHz, a sequence of randomly selected tone-pairs, viz. {900.08MHz, 900.12MHz}, {900.1MHz, 900.14MHz} and {900.1MHz, 900.16MHz} with Vpk of 1mV for each tone, are applied from the RF signal source for 1ms in each case. The experimental results show that for high accuracy of the regression model, the selected tone-pairs need to cover the entire band-width of the receiver under-test. The test response waveforms are captured at the output of the symbol samplers (Figure 5) at 1MHz. The test responses are used for constructing the nonlinear regression model (see Section 3) that maps the test response waveform data onto the EVM specification. Given the existence of this regression model, for different receiver-under-tests (not within the training regression set, i.e. their specification values were not used for computing the regression model), the EVM are predicted. Figure 9 shows the tracking between the predicted values of EVM obtained using the multitone test framework and the measured values of EVM obtained using conventional EVM testing approach using digitally modulated stimulus. A high correlation value (i.e. when all scatter points are close to the straight line of slope +1 in Figure 9) between the predicted EVM and measured EVM shows that the *multitone test framework for EVM testing can replace the conventional EVM test framework without sacrificing test accuracy*. From Figure 9, the maximum prediction error is ±0.03 EVM_{rms}. For the very few outlier DUTs (Figure 9), either conventional test needs to be performed after alternate testing, or these outlier DUTs are designated as 'faulty'.

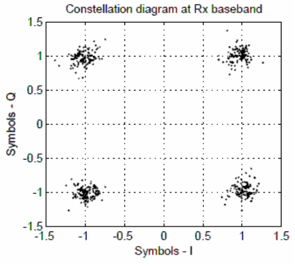

Figure 8. Constellation diagram for the received symbols, EVM (rms) = 0.133

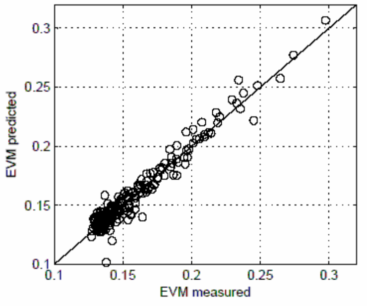

Figure 9. Tracking of predicted rms values (multitone stimulus) of EVM vs. measured rms values (up-converted GMSK bit sequence stimulus) of EVM

Furthermore, significant test time reduction is achieved by using the multitone test framework for testing receiver EVM. In this example, assuming that the basic test time is governed by the time to apply the test stimulus and to capture the test response waveform, for conventional test approach, the total test time for a frame of 500 I-Q bits (1000 symbols) at 25kHz is 20ms. On the other hand, in this example, the total test time for capturing three tone-pairs is 3ms.

6. Conclusion

In this paper, a low-cost test methodology for testing EVM of wireless receiver has been presented. A sequence of multi-tones generated using low-cost RF sources is used as test stimuli. The EVM specification is predicted using the test response waveforms at the baseband. Simulation results using a 900MHz GSM band receiver shows that the EVM at the baseband can be predicted with high accuracy.

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