Chapter VII
Receiver Optimization Using Error Vector Magnitude Analysis
By Eric Newman

Figure 1 depicts a signal space constellation containing two vectors, a reference vector, R(k), and the actual measured vector, Z(k), which indicates the recorded symbol trajectory. The reference vector defines the coordinates of an ideal error-free symbol trajectory. The difference between the reference vector and the actual measured symbol vector is defined as the error vector.

- **EVM Introduction**
- **Bit-Error-Rate and Probability of Error**
- **SNR and EVM Relationships**
- **Optimization Example: AD8348/AD8362 IF to Baseband Sub-System**
- **Using RSSI to Estimate EVM and BER Performance**

The error vector magnitude represents the Euclidian distance between the ideal symbol coordinate and the actual recorded symbol. In general EVM is averaged over an ensemble of symbol trajectories and can be defined numerically as

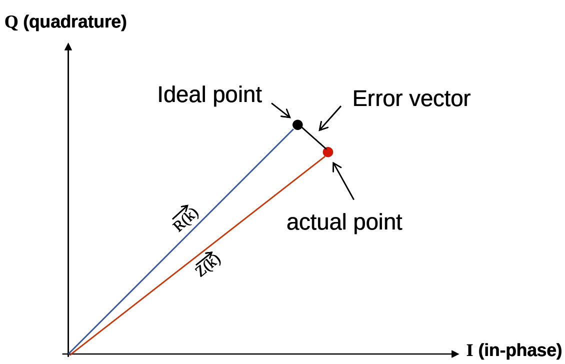


Figure 1. IQ signal space illustrating reference vector, R(k), and measurement vector, Z(k).

$$EVM = \sqrt{\frac{\sum_{k=1}^{M} |Z(k) - R(k)|^2}{\sum_{k=1}^{M} |R(k)|^2}} \qquad (1)$$

EVM provides a measure of the ratio of the error vector to the reference vector. In a perfect system, free of noise and non-linearities that would otherwise create signal distortion, the measured vector and reference vector would be identical, and the EVM would be zero. Consider the signal-to-noise-ratio (SNR) of the symbol trajectory. If the SNR was very good, then the displacement of the measured vector from the reference vector due to noise and distortion effects would be very small, and the resultant EVM would approach zero. Conversely, a large EVM suggests that the measured symbol is significantly displaced from the ideal reference vector, which can only be the result of noise and distortion effects unless the reference vector is somehow in error. This suggests that the SNR and EVM of a modulated signal share an inverse relationship. Numerically this relationship can be expressed as

$$EVM = \frac{1}{\sqrt{SNR \times L}} \qquad (2)$$

where L is the coding gain

Coding gain accounts for any benefits due to signal coding. In general the baseband information may be encoded using a number of techniques. For instance, in a spread-spectrum system the baseband data is spread by multiplying each transmitted bit by a direct sequence. The direct sequence consists of a random series of ones and zeros. The sequence is carefully selected so that it is unique and weakly correlated to other sequences used to encode other data-streams that will share the same carrier frequency. The ratio of the number of 'chips' used to encode each bit is the coding gain. In decibels, it is expressed as 10Log_{10}(chip-rate/data-rate). For example, a UMTS transceiver may be transmitting a 12.2 kbps data stream using a chip-rate of 3.84 Mchips/s, resulting in a coding gain of $3.84\times10^6/12.2\times10^3=314.75$, or 25 dB.

In order to link EVM to BER, it is necessary to determine the dependency of SNR on the probability of a symbol error for a given modulation scheme. For quadrature amplitude modulations (QAM), the probability of a symbol error can be expressed as:

$$P_M = 2\left(1-\frac{1}{\sqrt{M}}\right)erfc\left(\sqrt{\frac{3}{2(M-1)}k\gamma_b}\right)\times\left[1-\frac{1}{2}\left(1-\frac{1}{\sqrt{M}}\right)erfc\left(\sqrt{\frac{3}{2(M-1)}k\gamma_b}\right)\right] \quad (3)$$

where M is the order of the modulation (i.e. 64 for 64-QAM)

γ_b is the average signal to noise ratio per bit

k is the number of bits per symbol (i.e. 6 bits per complex symbol for 64-QAM)

Using equations 2 and 3, the symbol-error-rate (SER) and EVM can be derived for varying SNR. SER versus SNR is presented in figure 2a. This provides the classic waterfall patterns for various order QAM modulation schemes. The EVM versus SNR is presented in figure 2b for the same modulations. This allows designers to predict the bit error rate performance of a given receiver using error vector analysis techniques. For example, if the EVM is measured to be 3% for un-coded 256-QAM modulation, the anticipated symbol error rate would be 600 ppm. In other words, on average 6 symbols could be expected to be erroneous out of a 10,000 symbol sequence, corresponding to a bit error rate of 75 bits in a 1 million bit sequence, or a BER of 7.5×10^{-5}.

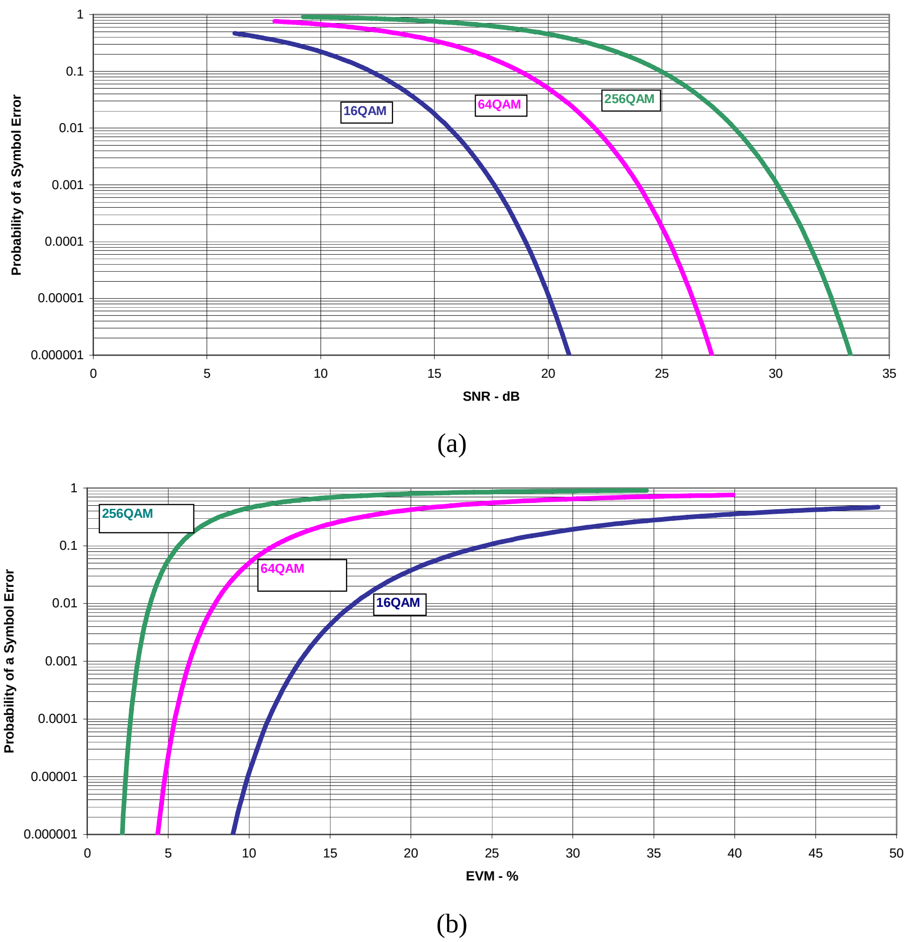


Figure 2 a) The theoretical probability of a symbol error for un-coded 16-, 64-, and 256-QAM modulations versus SNR. b) The corresponding symbol error probability versus measured EVM.

Using the data in figures 2a and 2b along with an appropriate vector signal analyzer, designers can optimize performance in a timely manner. Parameters such as filter selection, inter-stage matching and conversion gain can all be adjusted while observing EVM performance. This allows designers to quickly optimize their signal chains. Figure 3 illustrates some of the possible signal impairments that can occur in a real-world system. By monitoring the signal space it is possible to identify the noise or distortion mechanisms that may be degrading EVM performance.

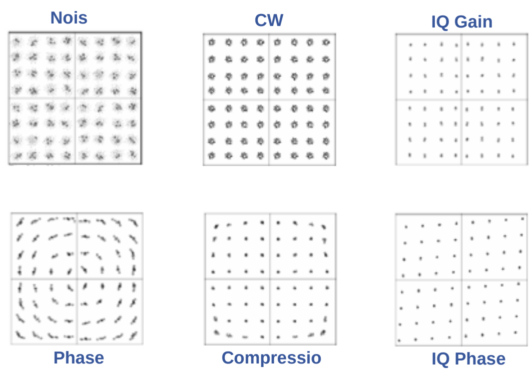


Figure 3. A variety of possible signal pairments. By recognizing the tell-tale signs of different signal impairments, receiver problems can be more easily isolated and debug simplified.

Optimization Example: AD8348/AD8362 IF to Baseband Sub-System

A quadrature demodulator and rms-accurate power detector are presented in Figure 4 as a closed-loop ALC (Automatic Level Control) IF-to-baseband receiver subsystem. The AD8348 provides accurate quadrature demodulation from 50 MHz to 1 GHz. An internal LO frequency divider allows an LO that is twice the desired carrier frequency to be used, easing LO-pulling issues associated with a full duplex transceiver. In the example, the IF input frequency was 190 MHz with an LO drive of –10 dBm at 380 MHz. An integrated front-end variable gain amplifier (VGA) comprised of a resistive variable-attenuator and high intercept-point post amplifier provides variable conversion gain while preserving a constant spurious free dynamic range. The AD8362 is a highly accurate RF power measurement device capable of measuring the rms power of signals from arbitrarily low frequencies out to 2.7 GHz. The device exhibits insensitivity to varying crest factor waveforms, making it an ideal solution for measuring the true rms power of digitally modulated signals.

The circuit in Figure 4 is configured to measure the rms power of the baseband signal present on the in-phase channel. The choice of in-phase or quadrature detection is arbitrary assuming that I and Q vectors are pseudo-random, a valid assumption for most digital modulation schemes. The on-board error amplifier uses the baseband rms power measurement to generate a control signal that drives the gain-control port on the quadrature demodulator. The conversion gain of the demodulator is adaptively adjusted in a closed-loop fashion to maintain a constant baseband rms power level, regardless of wave-shape. The output level is set by applying the appropriate set-point control voltage to the VSET pin. Error vector analysis was used to find the optimum ALC output set-point and to determine a suitable filter for a 256-QAM 1-Msymbol/sec digital modulation.

The demodulator provides a single-ended interface for application of a low pass filter. Fourth-order Bessel filters were employed on both I and Q channels to minimize wideband noise and to help reject unwanted adjacent signals. The Bessel filter was selected for its low group delay characteristics, a necessary attribute to ensure low inter-symbol-interference. Initially Butterworth and Chebyshev filter designs were tested, but the greater group delay in the passband resulted in degraded EVM performance. The subtle differences in receiver performance with the various filter selections would have been difficult to measure using classical methods. The VSA quickly measures the performance, allowing the filter networks to be optimized in a short period of time.

The baseband EVM was measured using an FSQ8 vector signal analyzer from Rohde & Schwarz. While observing the EVM, the set-point control voltage was varied to find the optimum setting. With the appropriate set-point voltage the EVM remains better than 2% over more than a 40 dB input range as indicated in Figure 5. The measured IQ baseband constellation for a 256-QAM modulation scheme is presented in Figure 6. The variable conversion gain of the demodulator allows receiver designs with optimum BER performance over a wider dynamic range than a fixed gain demodulator.

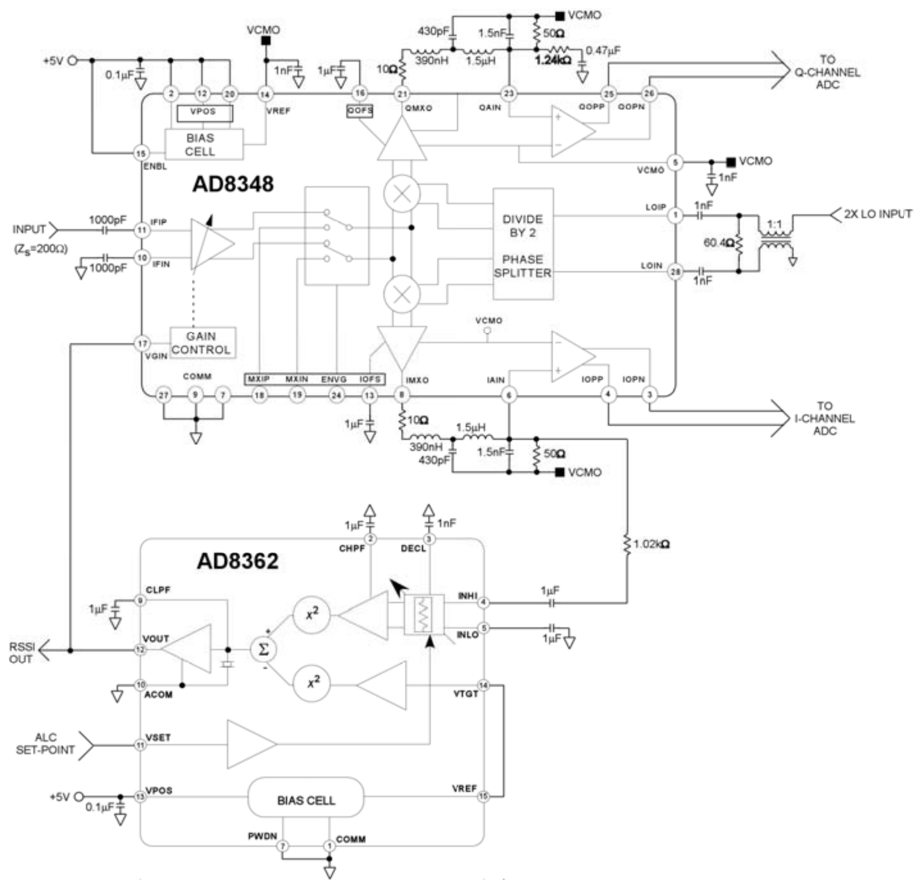


Figure 4. The AD8348 IQ Demodulator in combination with the AD8362 TruPwr™ Detector can be configured to provide highly accurate automatic level control IF-to-baseband receiver subsystem.

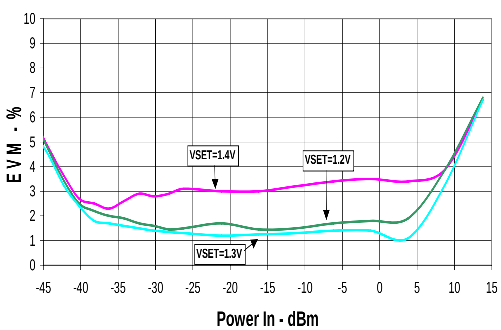
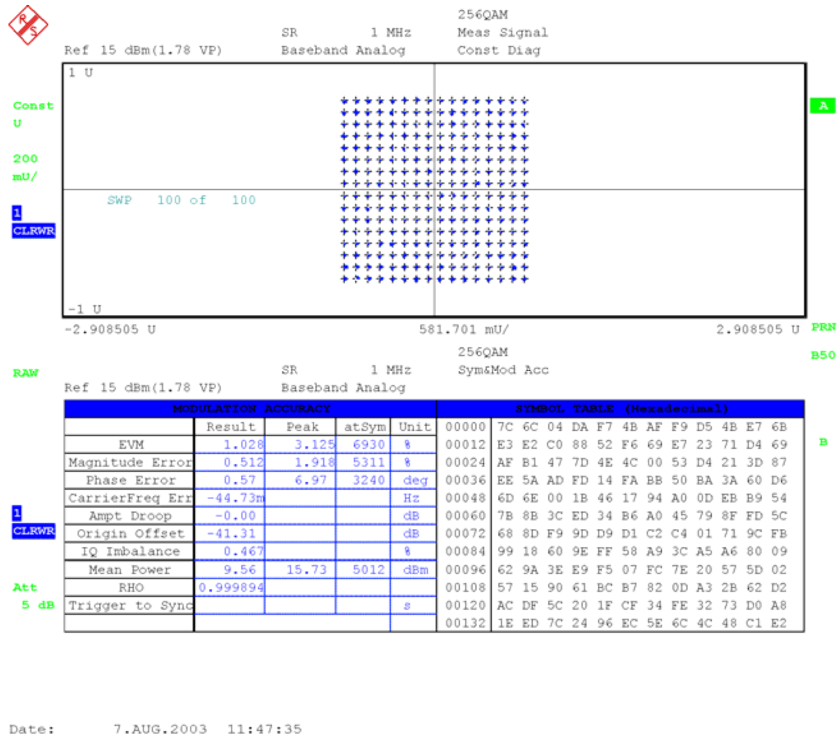


Figure 5. Error Vector Magnitude (EVM) versus input power level for 256-QAM at 1-Msymbol/sec.

Figure 7 illustrates the performance for lower order QAM modulations of the same signal bandwidth. The lower order modulation schemes require less SNR for adequate BER performance. It is no surprise that the lower order modulation schemes result in even better EVM performance over a slightly broader input power range.

By monitoring the RSSI (Received Signal Strength Indication) voltage of the AD8362 it is possible to predict EVM performance. Figure 8 provides the measured RSSI voltage for several modulation schemes. It is possible to use the RSSI voltage to estimate the input power presented at the demodulator input within a reasonable error. The input power estimate can then be used to predict the EVM performance at that input power level.



MODULATION ACCURACY				
	Result	Peak	atSym	Unit
EVM	1.028	3.125	6930	%
Magnitude Error	0.512	1.918	5311	%
Phase Error	0.57	6.97	3240	deg
CarrierFreq Err	-44.73m			Hz
Ampt Droop	-0.00			dB
Origin Offset	-41.31			dB
IQ Imbalance	0.467			%
Mean Power	9.56	15.73	5012	dBm
RHO	0.999894			
Trigger to Sync				s

SYMBOL TABLE (Hexadecimal)												
00000	7C	6C	04	DA	F7	4B	AF	F9	D5	4B	E7	6B
00012	E3	E2	C0	88	52	F6	69	E7	23	71	D4	69
00024	AF	B1	47	7D	4E	4C	00	53	D4	21	3D	87
00036	EE	5A	AD	FD	14	FA	BB	50	BA	3A	60	D6
00048	6D	6E	00	1B	46	17	94	A0	0D	EB	B9	54
00060	7B	8B	3C	ED	34	B6	A0	45	79	8F	FD	5C
00072	68	8D	F9	9D	D9	D1	C2	C4	01	71	9C	FB
00084	99	18	60	9E	FF	58	A9	3C	A5	A6	80	09
00096	62	9A	3E	E9	F5	07	FC	7E	20	57	5D	02
00108	57	15	90	61	BC	B7	82	0D	A3	2B	62	D2
00120	AC	DF	5C	20	1F	CF	34	FE	32	73	D0	A8
00132	1E	ED	7C	24	96	EC	5E	6C	4C	48	C1	E2

Figure 6. IQ constellation of baseband output for 256QAM modulation at 1 Msymbol/sec.

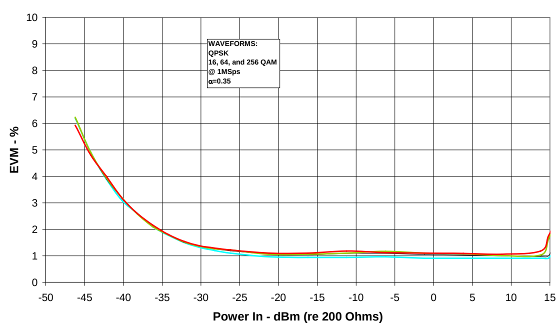


Figure 7. EVM versus input power for 16, 64, and 256QAM.

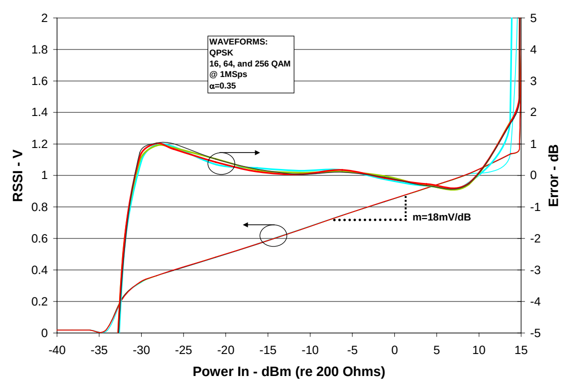


Figure 8. By understanding the EVM versus input power relationships, an rms-accurate RSSI measurement can be used to predict receiver performance.

Summary

By measuring the EVM over the desired input signal range, one can readily estimate symbol error rate performance. Using the measured EVM data in combination with the plots in figure 2, the dynamic performance of the receiver can be predicted. For a 256-QAM modulation the EVM must be better than ~2% to ensure the symbol error rate is less than 10^{-6}. The measured results of the IF-to-baseband receiver subsystem indicates that the receiver could tolerate more than a 40 dB range of input power variation before SER is degraded to an unacceptable level. EVM analysis is a useful tool for signal chain optimization and prediction of dynamic performance.