UNDERSTANDING EVM

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CONTENTS

1 INTRODUCTION

The evolution of wireless communications technologies such as Wi-Fi (IEEE 802.11) and cellular (LTE, 5G NR, etc.) has been largely driven by the need for greater data throughput. Increases in achievable data throughput are based primarily on either increased bandwidth and/or on higher modulation orders. Higher order modulation, in which more bits are transmitted with each symbol, require higher modulation accuracy, and therefore quantifying modulation accuracy has become one of the most important tasks in the design, test and debugging of modern radio frequency communications technologies. This paper provides an introduction to error vector magnitude (EVM), which is the primary metric of modulation accuracy.

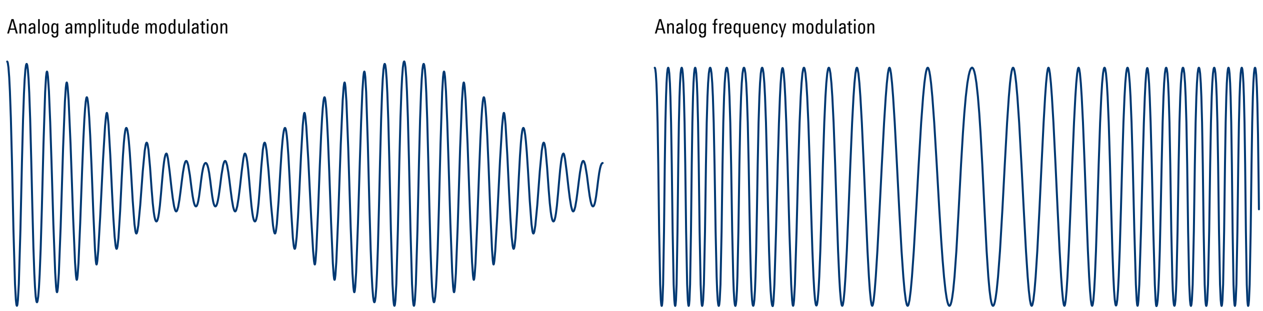
This paper is divided into three sections. The first section discusses the fundamentals of the digital modulation schemes used in modern radio frequency communications systems, in particular, APSK and QAM. Readers already familiar with these modulation types may safely skip or skim over this section. The second section discusses the fundamentals of error vector magnitude. This section not only defines EVM, but also discusses the most common sources of EVM, how EVM is measured, and the effects of EVM. The final section explains the basics of constellation diagrams and how constellation diagrams can often be used to diagnose or troubleshoot the common root causes of EVM.

2 DIGITAL MODULATION FUNDAMENTALS

2.1 About modulation

Modulation can be defined as the process whereby some characteristic of a radio frequency carrier is changed in order to convey information; that is, the carrier's amplitude, frequency, and/or phase. Purely analog modulation, such as amplitude (AM) and frequency (FM) modulation, are typically used to convey purely analog information, such as the human voice or music. Although analog modulation is both efficient and cost-effective for these types of applications, these analog modulation schemes generally are not used to transfer digital information.

Figure 1: Analog amplitude and frequency modulation



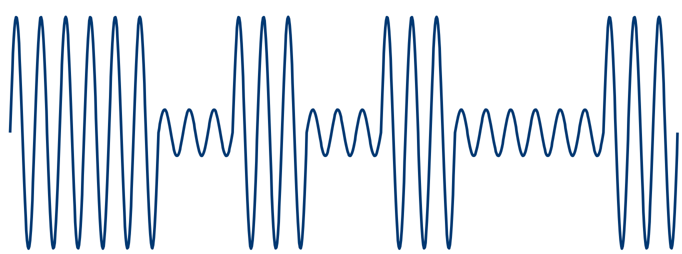
2.2 About digital modulation

Digital (or binary) data is instead transmitted using discrete "states" or "symbols." Each one of these states or symbols corresponds to one or more bits. The radio frequency carrier is "shifted" between these different states depending on the bit pattern that is to be sent. The most basic forms of digital modulation involve changing only a single property of the carrier; that is, the carrier's amplitude, frequency **or** phase. In **amplitude shift keying (ASK)**, the carrier transmits different symbols by shifting between different **amplitude** states. In **frequency shift keying (FSK)**, the carrier shifts between **frequencies** and in **phase shift keying (PSK)**, sudden shifts in the **phase** of the received signal are used to indicate different states. All digital data transmission systems use one or more of these techniques.

2.2.1 Amplitude shift keying (ASK)

With very few exceptions, amplitude shift keying involves shifting the carrier amplitude between only two states. The 1 or "on" state is defined as 100% amplitude, and the 0 or "off" state is defined as a "lower" amplitude. This "lower" amplitude can be either zero or some non-zero amplitude, as shown in Figure 2. Throughput could theoretically be improved by using ASK with more than two levels. For example, if 4 amplitude states were used, then each amplitude state would represent two bits. Using more than two amplitude states is sometimes called "M-ary" ASK. M-ary ASK is, however, rare in practice. As the number of amplitude states increases, noise and other amplitude effects can more easily cause one amplitude state to be mistaken for another.

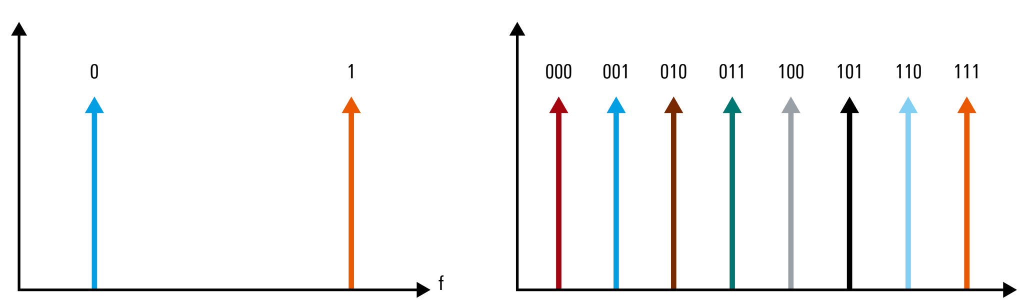
Figure 2: Amplitude shift keying (ASK)



2.2.2 Frequency shift keying (FSK)

In frequency shift keying, different states or symbols are represented by switching or "shifting" the carrier between discrete frequencies. The most basic form of FSK is binary FSK (BFSK) where only two frequencies are used. In BFSK, therefore, each frequency maps to only a single bit. However, FSK is often implemented as M-ary FSK, where more than two frequencies are used. Figure 3 shows 8FSK, where each of the eight frequencies corresponds to a unique pattern of three bits ($8 = 2^3$). As seen in this example, increasing the number of states or the so-called modulation order, also increases the number of bits per symbol.

Figure 3: BFSK and 8FSK

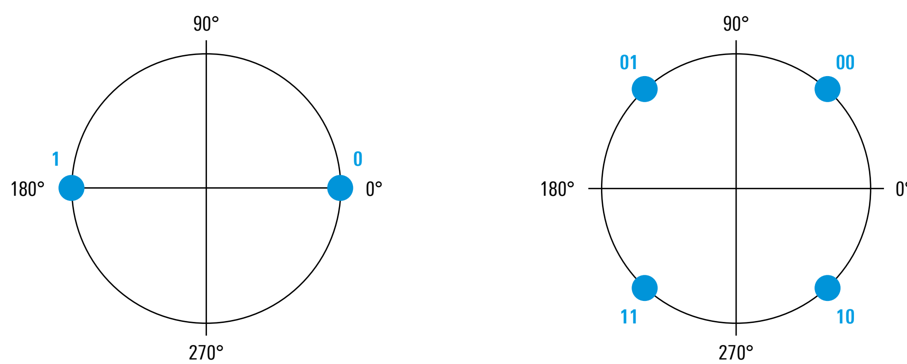


2.2.3 Phase shift keying (PSK)

The third form of basic digital modulation is phase shift keying, in which the phase of the carrier is abruptly shifted in order to indicate different states. When examining or describing PSK modulated signals, the states are usually represented in the form of **constellation diagrams**.

A constellation diagram is a polar plot, in which the phase of the signal is shown as an angle, from 0 to 360 degrees, and amplitude is shown as distance from the origin. In its most basic form, PSK has a constant amplitude, so all of the points in a basic PSK constellation diagram will lie on one circle. As with other forms of digital modulation, PSK can support different modulation orders; that is, different numbers of states or symbols. And as before, higher modulation orders provide higher throughput. For example, binary phase shift keying (BPSK) consists of only two states and therefore can only transmit one bit for every symbol. In M-ary PSK, there are more than two states. Figure 4 shows 4PSK, more commonly called QPSK, which uses four symbols, each corresponding to two bits.

Figure 4: BPSK and QPSK



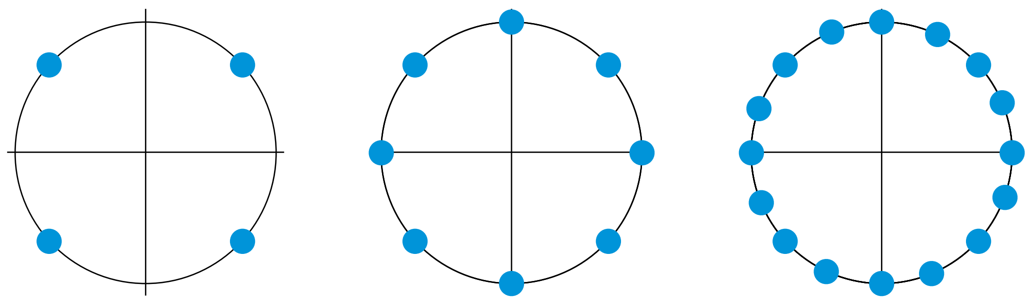
2.2.4 Limitations of ASK and FSK

ASK, FSK, and PSK are widely used, but primarily in applications that do not require high bit rates or throughput. These basic modulation schemes generally are unable to provide the high throughputs needed in Wi-Fi and cellular technologies. The throughput of ASK and FSK can be increased by increasing the modulation order – that is, the number of states or symbols – but there are practical limits. As mentioned previously, ASK is limited by noise. And in the case of FSK, increasing modulation order by increasing the number of discrete frequency states also increases the required bandwidth.

2.2.5 About amplitude and phase shift keying (APSK)

Like ASK and FSK, PSK also has a practical upper bound to modulation order. Because all the symbols in "basic" PSK modulation lie on a single amplitude circle, the distance between the symbols decreases as the modulation order, or the number of states, increases. Compare the distance between symbols in 4PSK, 8PSK and 16PSK, as shown in Figure 5.

Figure 5: 4PSK, 8PSK and 16PSK



When the symbols are very close together, there is a higher probability of one symbol being mistaken for another, and thus errors become more likely. PSK with modulation orders greater than 8PSK or 16PSK are very uncommon. One solution to this problem is to add amplitude states: the constellation diagram in this case would have multiple concentric circles, each with a different but constant amplitude. The symbols are then distributed across these different circles and thus are farther apart – see Figure 6. Using multiple amplitude states reduces the risk of error and allows higher modulation orders, thus increasing throughput. Since the carrier is now shifting between either amplitude and/or phase to send symbols, this form of modulation is called **amplitude and phase shift keying**.

Figure 6: 16PSK and 16APSK (two amplitude levels)

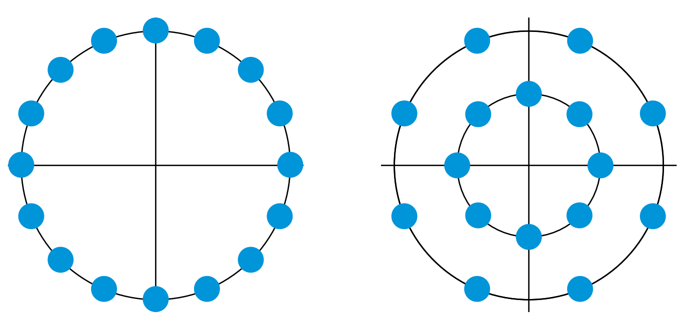
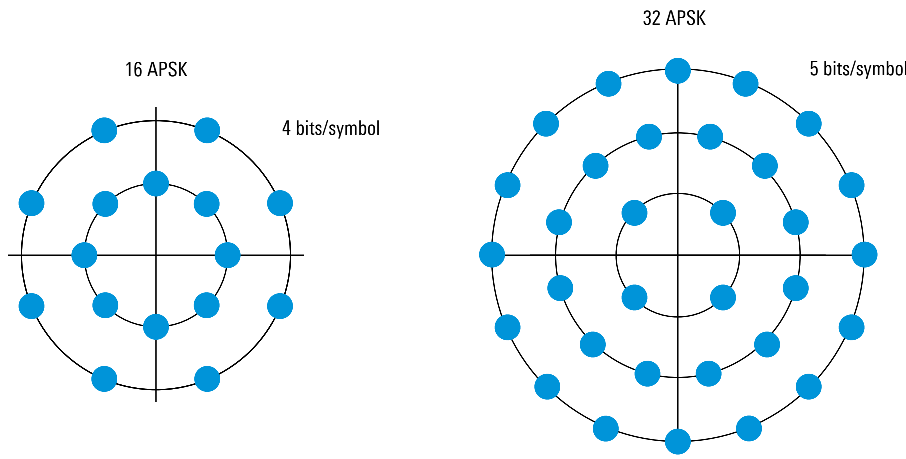


Figure 7 shows two sample APSK constellations. In the 16APSK constellation there are two amplitude states, each with 8 symbols. With 16 states, each state represents 4 bits. The 32APSK constellation has 3 amplitude states. The inner amplitude level has only 4 symbols, the middle amplitude state has 12 symbols, and the remaining 16 symbols are in the outer amplitude state. When 32 states are present, each symbol corresponds to 5 bits. However, other arrangements of the 32 symbols are also possible, such as a 32APSK constellation with 4 amplitude levels.

Figure 7: 16APSK and 32APSK examples



2.2.6 Applications of APSK

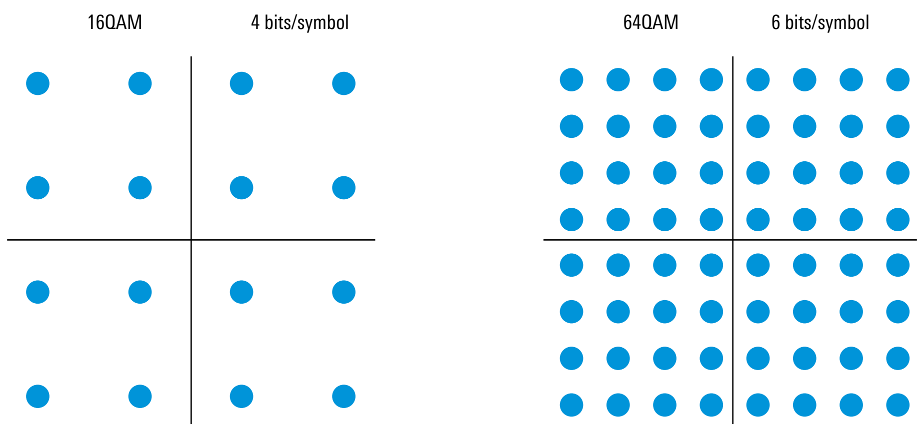
APSK is primarily used in satellite applications. The most recent versions of the DVB-S (digital video broadcast – satellite) standards support modulation orders up to 256APSK, which corresponds to 8 bits per symbol. One reason why APSK is popular in satellite applications is its robustness with regard to various amplitude effects. For example, amplifier non-linearities such as compression may change the relative distances between different amplitude rings in an APSK constellation, but all the points on a given amplitude ring will be equally affected, and this minimizes the impact of non-linearity. Although APSK supports relatively high modulation orders, it is nevertheless uncommon in terrestrial applications.

2.2.7 About quadrature amplitude modulation (QAM)

There is however another form of modulation that combines changes in both amplitude and phase. This modulation is called quadrature amplitude modulation (QAM). QAM derives its name from the fact that QAM symbols are created using something called an I/Q modulator. In an I/Q modulator, an in-phase ("I") component is combined with a quadrature ("Q") component to produce a modulated signal. This will be discussed in more detail below (Section 4.4)

The constellation diagram of a QAM signal typically has the symbols arranged in a square shape. As with APSK, each point in the constellation represents a unique combination of amplitude and phase. Figure 8 shows two QAM constellations. The 16QAM constellation consists of 16 unique combinations of amplitude and phase, and each of these symbols maps to 4 bits. The 64QAM constellation has 64 symbols, meaning each point in constellation maps to 6 bits.

Figure 8: 16QAM and 64QAM constellations

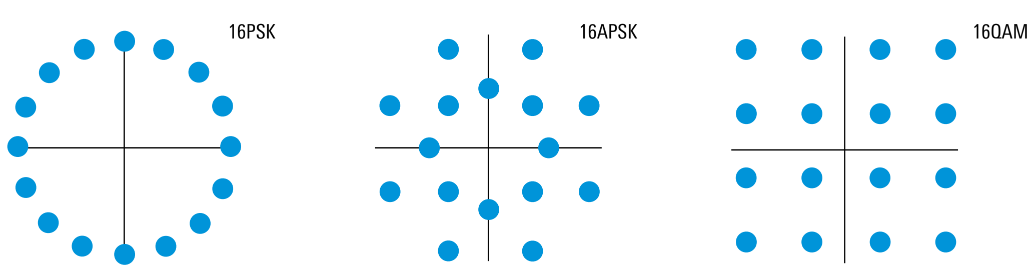


2.2.8 Comparing PSK, APSK and QAM

Figure 9 shows 16PSK, 16APSK and 16QAM constellation diagrams. All three of these constellations have 16 symbols and transmit 4 bits per symbol. Note however that the QAM symbols are spaced further apart and are more evenly distributed than the symbols in PSK or APSK with the same modulation order. As mentioned earlier, more distance between symbols means greater resistance to error.

Another important difference is the number of amplitude states. 16PSK has only a single amplitude state, the 16APSK shown here has two amplitude states and 16QAM has three amplitude states. Recall that increasing the number of amplitude states places higher linearity requirements on amplifiers and transmitters due to higher peak to average power ratios.

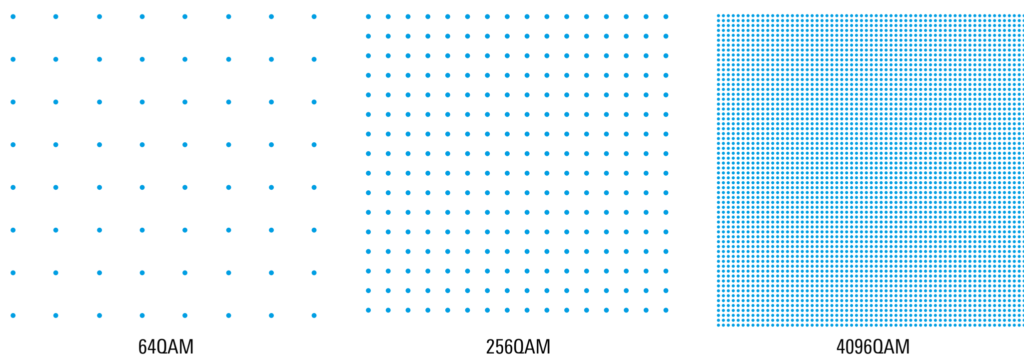
Figure 9: Comparison of 16PSK, 16APSK and 16QAM



2.2.9 QAM modulation order

Similar to other modulation schemes, increasing the modulation order or number of symbols in QAM has two main effects. First, higher numbers of bits per symbol increase the achievable bit rate or throughput. At the same time, higher order modulation also reduces resistance to errors since the states or symbols are closer together. QAM is capable of supporting very high modulation orders: some of the more common QAM variants are 16QAM, 64QAM, 256QAM, 1024QAM and 4096QAM, although other orders are possible. Using 4096QAM as an example, this very high order modulation scheme represents twelve bits with every symbol, so the achievable data rate is very high. But since these points are also very close together, the probability of error – that is, mistaking one point for another – also increases. From Figure 10 it should be clear why higher order modulation requires greater accuracy in modulation and demodulation.

Figure 10: Comparison of QAM modulation orders



2.2.10 Applications of QAM

QAM is the modulation scheme found in almost all high-data rate terrestrial digital transmission systems and is used in the more recent versions of IEEE 802.11 (Wi-Fi) as well as in cellular standards (LTE, 5G NR). In both of these cases, 256QAM is the highest modulation order used. Very high order QAM modulation such as 1024QAM or 4096QAM is normally only found in cable systems, primarily because the transmission environment is less susceptible to noise and interference.

Most systems that use QAM will dynamically adapt modulation order based on the channel conditions, for example, using 256QAM when conditions are good but falling back to 64QAM or 16QAM in the presence of noise, interference, etc. In cellular systems, the decision as to which modulation order to use is based on modulation accuracy, which in turn is specified and measured using something called **error vector magnitude**.

3 EVM FUNDAMENTALS

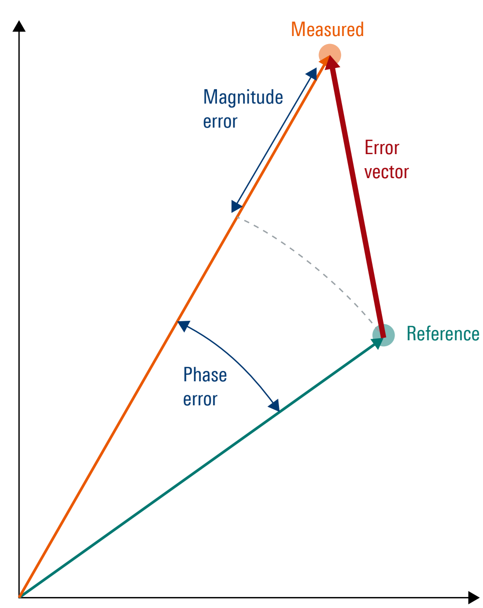
3.1 About error vector magnitude (EVM)

As previously discussed, each symbol in a constellation has an ideal or reference point that corresponds to a defined magnitude and phase, but received or measured points rarely fall exactly on the ideal point. Some of the difference may be due to magnitude error – that is, the received vector is too long or two short. And some of the difference may be due to phase error, in which the angle of the received vector is incorrect. We can quantify these two sources of error by drawing a vector that connects the reference and measured points, and this vector is referred to as the “error vector.” This is illustrated in Figure 11.

Like all vectors, the error vector has both a magnitude and a direction. In digital modulation, the concern is primarily with the **distance** from the ideal point, not the **direction** to the ideal point, so the important measurement is the error vector **magnitude**

EVM is measured at each symbol time, and larger values of EVM indicate greater distance between the measured and ideal points. Greater distance in turn means a higher probability that the receiver will mistake one symbol for another: higher EVM values mean a greater probability of bit errors. Minimizing EVM is therefore one of the most important goals in the design and operation of wireless data transmission systems.

Figure 11: Error vector



3.2 Contributors to EVM

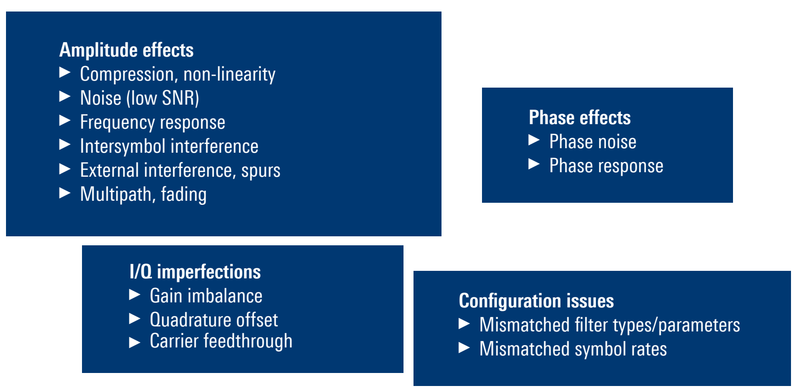
The sources or causes of increased EVM fall into four main categories: **amplitude effects**, **phase effects**, **I/Q imperfections** and **configuration issues**. These are listed in Figure 12.

With regard to amplitude effects, compression or non-linearity is a frequent contributor to EVM, especially at higher power levels. Noise, or more specifically, a low signal-to-noise ratio (SNR), can increase EVM for lower power signals. Any frequency response or frequency-specific attenuation can also lead to higher EVM. Other amplitude related factors are intersymbol interference, external interferers or spurious emissions, and propagation- or channel-related phenomena such as multipath or fading.

The primary phase effect that impacts EVM is phase noise in the transmitter and/or the receiver. The contribution of phase noise to EVM is particularly important in systems using orthogonal frequency division multiplexing (OFDM). Other types of phase response, where phase changes a function of frequency, can also lead to higher levels of EVM.

Imperfections in an I/Q modulator or demodulator (discussed in Section 4.4), such as gain imbalance, quadrature offset, or carrier feed through can be significant contributors to EVM. And finally, some types of configuration issues can impact EVM, for example having mismatched filters or different symbol rates at the transmitter or receiver.

Figure 12: Contributors to EVM



3.3 EVM and modulation order

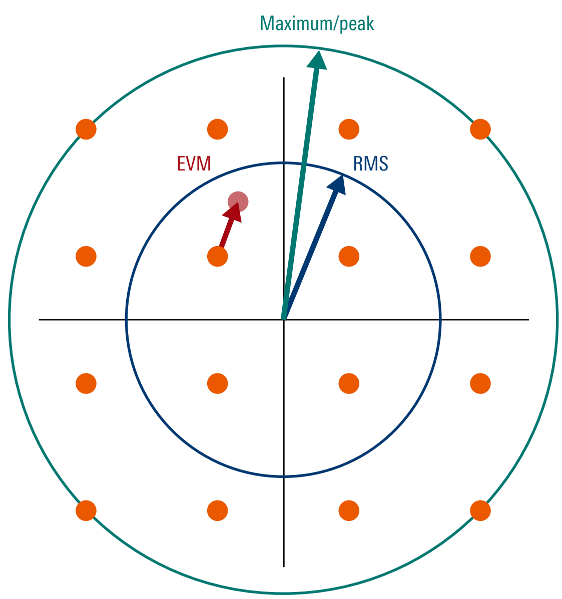
Even relatively minor contributors to overall EVM become important as the modulation order increases. As the number of symbols increases, the symbols become closer together and this increases the chance of mistaking one symbol for another. Another way of saying this is that in very high order modulation, even very small deviations in amplitude and or phase can cause a symbol to be incorrectly decoded. It should therefore be clear that higher modulation orders generally require better or lower EVM values. In fact, the maximum allowable EVM values are often included in various wireless specifications. For example, in cellular or IEEE 802.11 Wi-Fi standards and specifications, maximum EVM is given as a function of modulation order and coding, with the EVM requirements becoming stricter as modulation order increases.

3.4 Calculating EVM

Since most modern cellular and Wi-Fi standards specify certain limits for EVM depending on modulation order, it is important to define a way to measure, quantify or calculate EVM. EVM is the magnitude or length, of a vector that connects the ideal or reference endpoint with the received or measured vector endpoint. In EVM measurements, the magnitude or length of this error vector is a **relative** measurement that can be reported in two different ways. The first of these is relative to the **maximum** or **peak power** in the constellation. The second way is relative to the **RMS** or **root mean square power** of the constellation.

In Figure 13, EVM is calculated by comparing the length of the red error vector either to the length of the green vector (in the case of a peak or maximum power normalization) or to the length of blue vector (for RMS power normalization). When comparing EVM values, it is important to be sure that the same normalization reference is used for each set of measured values. After values are calculated, EVM can be expressed or reported either as a percentage value or in units of decibels.

Figure 13: Peak versus RMS normalization of EVM



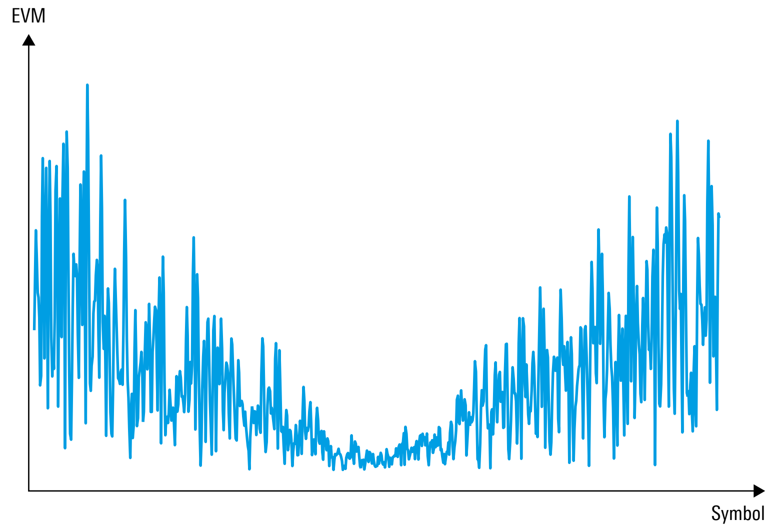
3.5 EVM results

In real-world modulation systems, symbols are constantly changing, and therefore EVM is calculated on a **per-symbol** basis. That is, at each symbol time, the magnitude of the error vector connecting the ideal and actual symbol locations is calculated. EVM is however reported over a number of symbols, often in terms of the maximum value, minimum value, average value, etc. Since EVM is essentially the distance between where the symbols are and where they are supposed to be, lower values of EVM indicate better modulation accuracy. For EVM values that are reported as percentages, smaller percentage values indicate better EVM. When EVM is reported in decibels, the values will always be negative: the more negative the values, the better the EVM.

3.5.1 EVM versus time/symbol

EVM is calculated on a per-symbol basis and EVM values can therefore also be plotted as a function of time; that is, the EVM of successive symbols. Looking at EVM as a function of time can provide very useful diagnostic or troubleshooting information about any sources of error or inaccuracy in the received signal. For example, slight differences between the transmit and receive symbol rate will appear as a “V” shaped curve such as the one in Figure 14. EVM may also be higher at the beginning or end of a bursted or pulsed signal due to various amplifier effects or timing. And if amplitude changes over time, this may increase the EVM of symbols with relatively high (near the edges of the constellation) or relatively low (near the center of the constellation) amplitudes.

Figure 14: EVM versus time/symbol

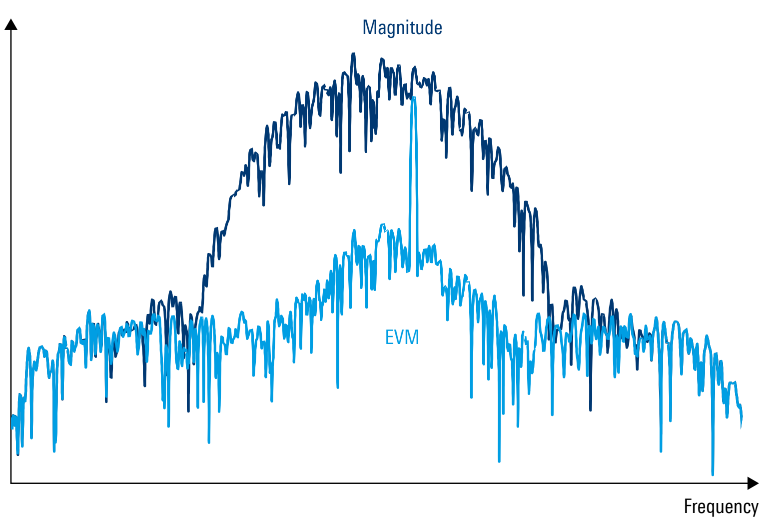


3.5.2 EVM versus frequency

EVM can also be plotted as a function of frequency. This is sometimes called the error vector magnitude **spectrum** and is created by taking the fast Fourier transform of an EVM versus time graph, such as the one in Figure 13 above. One of the more useful applications of plotting EVM versus frequency is finding in-band spurious signals or interferers. In some cases, the presence of a spurious signal may be difficult to detect when looking at a standard power versus frequency trace.

For example, in Figure 15 the magnitude versus frequency trace (blue) does not appear to contain any spurious signals, but the corresponding EVM versus frequency trace (cyan) clearly shows the presence of a narrowband spurious signal. EVM versus frequency can be used to find in-band spurious signals because the combination of the desired and undesired signal will cause increased EVM only at or near the frequency of the spurious signal.

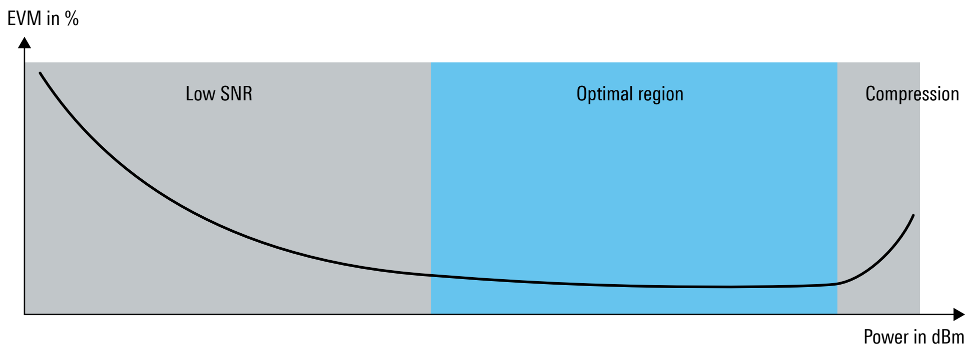
Figure 15: Magnitude and EVM versus frequency



3.5.3 EVM versus power

Another useful way to look at EVM is to plot EVM as a function of input power, and this is normally done when measuring devices such as amplifiers, mixers, etc. Figure 16 shows a typical "bathtub" curve of EVM versus power. At very low input power levels, the signal-to-noise ratio tends to be low, and a low SNR can often lead to high EVM. Conversely, very high input power levels may push the device under test into compression, and this will also increase EVM. There is typically an optimal power region, shown here in cyan, in which the best EVM performance is achieved. Plotting EVM versus power is a convenient way of determining the limits of this region.

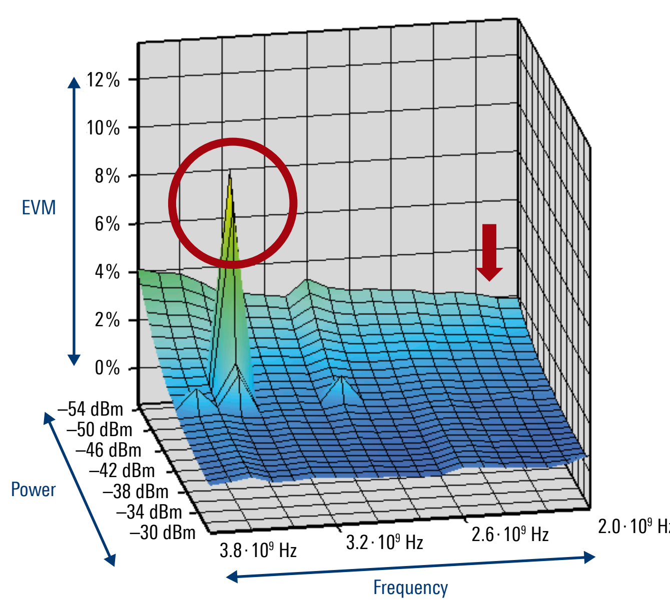
Figure 16: EVM versus power



3.5.4 EVM versus power and frequency

In addition to plotting EVM versus power or frequency, it can also be very beneficial to plot EVM as a function of **both** variables in three dimensions. Using these types of three-dimensional graphs makes it easier to identify trends or problem regions for the device under test. In Figure 17, it can be seen that EVM increases by frequency more rapidly at lower power levels and there is also a particular combination of frequency and power that leads to an unusually high level of EVM.

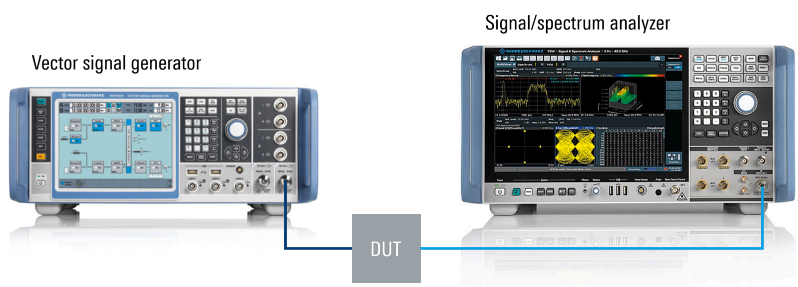
Figure 17: EVM versus power and frequency



3.6 Measuring EVM

EVM is most commonly measured by using a spectrum or signal analyzer connected to the output of the device under test. User-supplied parameters describing the signal properties are used to demodulate the signal and calculate EVM. In some cases, a vector signal generator is used to supply a modulated signal into the DUT input, for example, when testing an amplifier, mixer, etc. In either case, it is important that the instruments used in the measurement setup have better EVM performance than the device under test. A common rule of thumb is a margin of 5 dB to 10 dB, although larger margins are always preferable.

Figure 18: EVM measurement setup



3.7 EVM measurement best practices

There are numerous recommended or "best" practices when measuring EVM. The first of these is to ensure that the reference level is configured correctly in order to have a good signal-to-noise ratio. If the reference level is set too low, the signal may be clipped, leading to distortion. Too high of a reference level will increase the influence of noise and raise EVM as well. In many cases, analyzers may have an "auto EVM" routine that automatically determines the optimum reference level for an EVM measurement.

Another important consideration is the number of EVM measurements that are averaged. EVM is measured and computed at each symbol time, but EVM is normally reported as the average over multiple measurements. The number of measurements taken to obtain the average should be high enough to ensure stable, repeatable results, but too large a number of measurements may lead to an excessively long test time. Enabling equalization and/or frequency response correction is also recommended. And if a vector signal generator is being used to provide a modulated input to the device under test, the generator and the analyzer should share a common frequency reference.

4 CONSTELLATION DIAGRAM FUNDAMENTALS

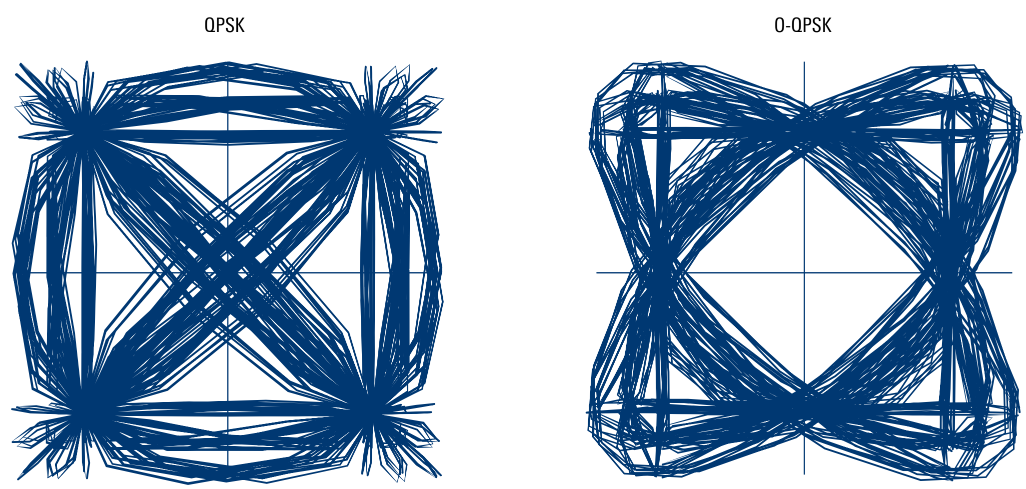
4.1 About constellation diagrams

As shown above, both APSK and QAM symbols can be represented as vectors, in which the magnitude and/or phase of the carrier takes on discrete states. If these vector endpoints are represented using polar coordinates and the endpoints are recorded at each sample or symbol time, this collection of vector endpoints can be used to create a constellation diagram which shows the magnitude and phase of the carrier at each sample or symbol time. Constellation diagrams are useful in visualizing the different states or symbols for a given modulation scheme, but visual inspection of the constellation diagram of a received signal can also be used to diagnose the sources or causes of modulation accuracy impairments.

4.2 Constellation versus vector diagrams

A constellation diagram shows the decision points at each sample time. Vector diagrams show the path taken between the decision points and are therefore made up of lines, rather than points. One application of vector diagrams is differentiating between different modulation variants. For example, using the vector diagrams shown in Figure 19 it is easy to distinguish between standard QPSK modulation and a variant known as offset QPSK. Some sources of errors can be diagnosed using vector diagrams but generally speaking, constellation diagrams are more useful in most cases, particularly with regard to the causes of increased EVM.

Figure 19: Vector diagrams



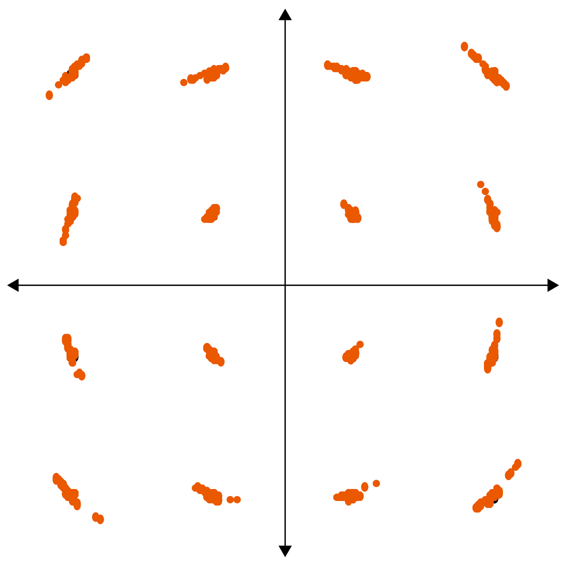
4.3 Diagnosing modulation impairments with constellation diagrams

Errors or impairments in a wireless data transmission system can be caused by the transmitter, the receiver, and/or the channel; that is, the medium through which the signal propagates. Numerical measures of modulation quality, such as EVM, often do not provide much insight into the nature or causes of the errors, but many common types of impairments can be identified by visually inspecting the received constellation diagram. These types of impairments fall into four main categories. First, amplitude linearity issues usually move some of the points towards the origin. Another type of amplitude issue is noise, which causes the received points to spread out around the ideal or reference points. Undesired changes in the phase of the carrier cause the points to rotate with respect to the origin, and imperfections in the I/Q modulator or demodulator can alter the geometry of the constellation.

4.3.1 Phase errors/phase noise

Phase noise (phase error) is very easy to recognize in constellation diagrams. Phase noise is unintentional or undesired variation in the phase of the transmitted carrier. QAM and APSK modulated signals convey information in part by using changes in phase, and therefore random fluctuations in the phase of the signal can lead to incorrect demodulation and increased EVM at the receiver. In Figure 20, variations in the phase causes the points in the constellation to be rotated with respect to the origin, and this affects all of the points in the constellation, creating curved, arc-like segments at each reference point. As the level of phase noise increases, the amount of rotation also increases and the 'arcs' become longer. It is important to remember that phase errors are generally caused by the transmitter or receiver, not by propagation through the channel.

Figure 20: Constellation with phase noise impairments

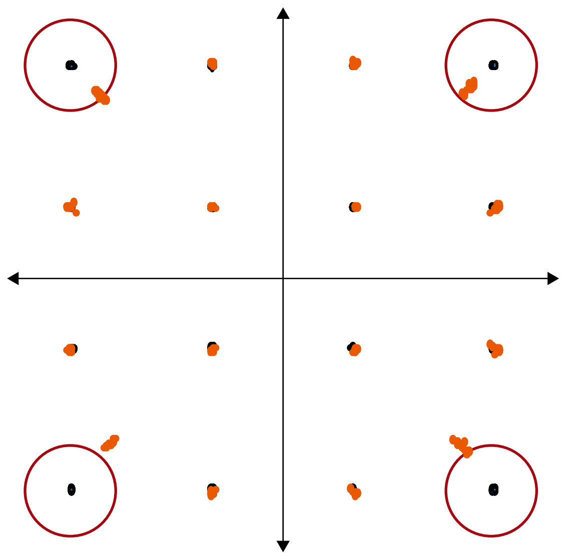


4.3.2 Compression

In additional to phase, both QAM and APSK also convey information using different amplitude states. The most common undesired amplitude effect is compression. Compression is a common characteristic of many amplifiers and refers to the fact that real-world amplifiers may not provide the same amount of amplification at all input levels. In almost all cases, the gain provided by an amplifier will be lower at higher input powers compared to lower input powers.

In constellation diagrams, signal amplitude or magnitude is shown as distance from the origin, and thus the further a point is from the origin, the higher its amplitude. In Figure 21, the four outer corner points are the furthest from the origin and therefore have the highest amplitude. If an amplifier goes into compression, these high-amplitude outer points are amplified less than the lower-amplitude inner points, causing the outer points of the constellation to be "pulled in" towards the origin. This in turn may cause these points to collide with other points or symbols in the constellation, creating higher levels of EVM. Since amplifiers are used in both transmitters as well as receivers, distortion may be caused by compression on one or both ends of the overall signal path.

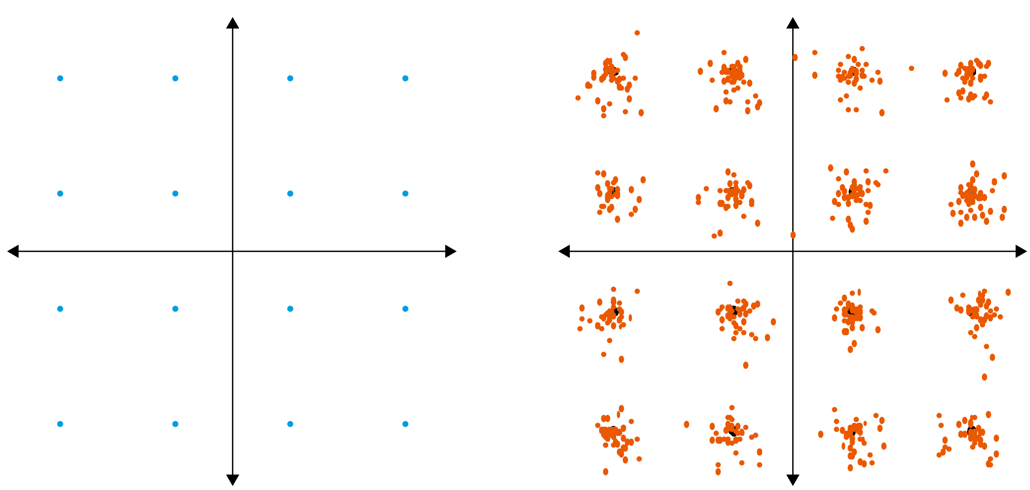
Figure 21: Constellation showing compression effects



4.3.3 Noise

Noise is another form of amplitude impairment in digital transmission systems. As mentioned above, noise is a more serious issue when signal amplitude is low, because increased noise lowers the signal-to-noise ratio (SNR). Low SNR manifests itself in constellation diagrams in the form of the points "spreading out" or away from the ideal or reference points. As the SNR decreases, the points spread further from the ideal point. If noise is wideband or uncorrelated, constellation points will be more or less randomly distributed around the ideal points, leading to a constellation diagram similar to the one on the right in Figure 22.

Figure 22: High versus low SNR constellations

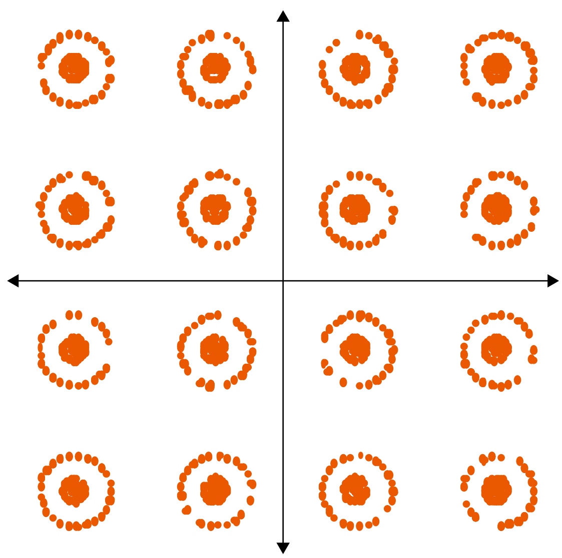


4.3.4 In-band spurious

In-band spurious refers to narrowband interferers or "spurs" which fall within the bandwidth of the modulated signal. Section 3.5.2 showed how plotting EVM versus frequency can be used to detect in-band spurs. In constellation diagrams, these spurs often create circles around the constellation reference points, as seen in Figure 23. The radius of these circles depends on the level or amplitude of the spurious signal. As the level of the spurious signal amplitude increases, the radius of these circles increases. Note however that in the case of low-level spurs, it may be difficult to see these circles without zooming in to the individual constellation points.

The measured EVM for a system with this type of narrowband noise and the measured EVM for a system with wider band noise may be the same or similar, but by observing the constellation diagrams the source or cause of the degraded EVM can be more easily identified.

Figure 23: In-band spurious

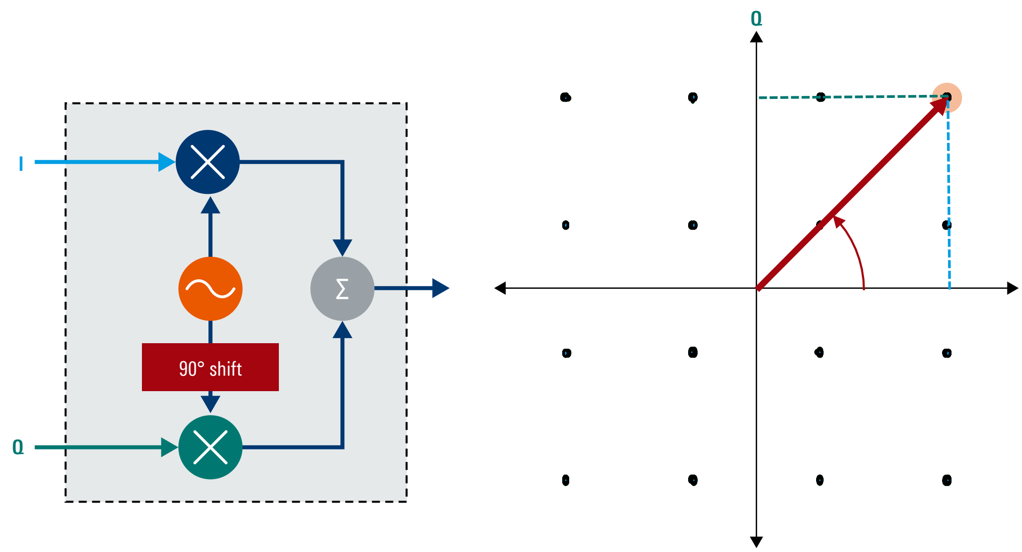


4.4 About I/Q and constellations

Another common source of EVM degradation is the I/Q modulator or demodulator. In most of this paper, symbols have been described as points on constellations representing a magnitude and a phase. These vector endpoints can also be represented in terms of I and Q.

Radio frequency vector signals are often produced using an I/Q modulator, illustrated in Figure 24.

Figure 24: I/Q modulator and constellation diagram



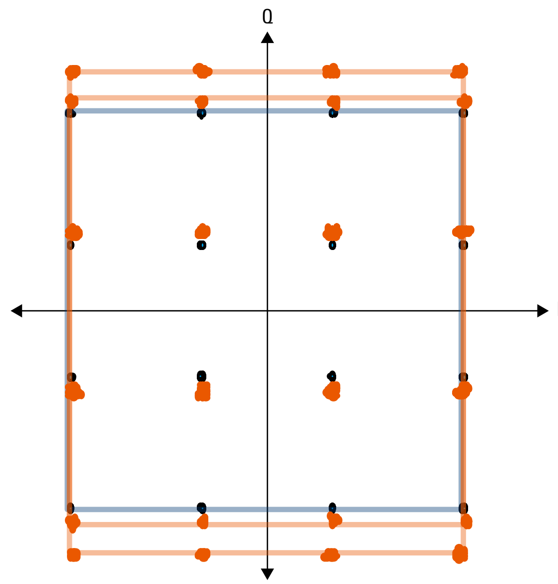
In an I/Q modulator, the in-phase (I) channel and a quadrature (Q) channel are both mixed with a local oscillator. In the Q path the phase of this oscillator should be shifted by precisely 90 degrees. These I and Q components are then combined to produce the modulated vector signal, and the process is reversed on the receive side during demodulation. The two axes on a constellation diagram correspond to the magnitudes of the I and Q channels. Therefore, imperfections in the transmit I/Q modulator or receive I/Q demodulator can cause distortion in the geometry of the constellation and increase EVM.

4.4.1 I/Q gain imbalance

Ideally, the I and Q channels should have equal gain, and this equal gain gives most QAM constellations their characteristic "square shape". I/Q gain imbalance occurs when there is a difference between the gain of the I component and the Q component. I/Q gain imbalance is relatively easy to diagnose in constellation diagrams because it causes the constellation to be "stretched" – that is, it becomes more rectangular than square. This distortion or stretching is proportional to the amount of gain imbalance, and higher levels of gain imbalance lead to increased "stretching" of the overall constellation.

Figure 25 shows both the ideal constellation points, outlined in blue, and a "stretched" constellation, outlined in orange, which is the result of greater gain in the Q channel compared to the I channel.

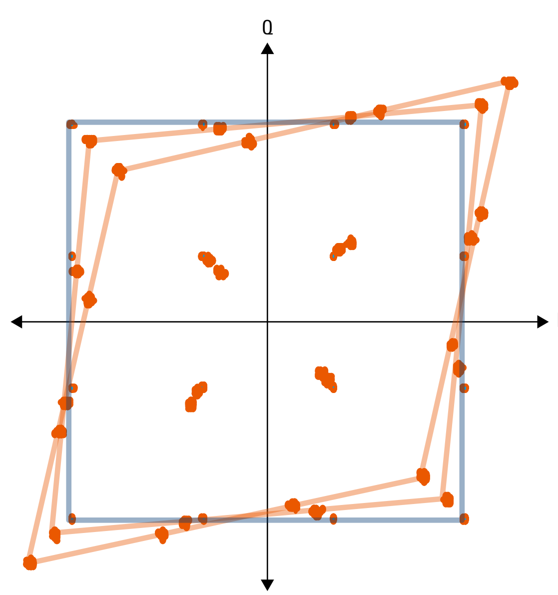
Figure 25: I/Q gain imbalance



4.4.2 I/Q quadrature error

Regardless of modulation order, the points or symbols in most QAM constellations are arranged in a square shape, with the horizontal and vertical "edges" of the constellation normally being perpendicular; that is, at right angles, to each other. Quadrature error, also sometimes called quadrature "offset" or quadrature "skew", occurs when the oscillator signal mixed with the Q signal is not shifted by precisely ninety degrees. ("Quadrature" means "shifted by 90 degrees"). This causes the constellation to become tilted or trapezoidal rather than square. As the amount of deviation from this 90 degree separation increases, the constellation becomes increasingly "tilted," leading to increased EVM and therefore a higher probability of bit errors at the receiver. An example is shown in Figure 26.

Figure 26: I/Q quadrature error



5 SUMMARY

Modern high throughput wireless communications systems normally use a combination of amplitude and phase modulation to transfer digital information. Increasing the number of unique amplitude/phase combinations or symbols – that is, the modulation order – increases the number of bits per symbol and thus increases throughput. However, higher modulation orders cause the symbols to be closer together, which in turn requires higher accuracy in modulation and demodulation in order to avoid bit errors. Error vector magnitude (EVM) is the most common numerical measure of modulation quality and is calculated by determining the magnitude of a vector connecting the ideal and received vector endpoints. EVM is most often measured using signal or spectrum analyzers and can be reported and plotted in various ways. Since EVM is a purely numerical value, it may not provide much insight into the root causes of reduced modulation accuracy, and thus visual inspection of the received signal's constellation diagram can often be used to identify many of the more common causes of degraded EVM.

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