Application Note AN-005: *Understanding Constellation Diagrams and How They Are Used*

Introduction

Constellation diagrams are an important tool in an engineer's arsenal when determining whether or not a digitally modulated radio-frequency (RF) signal is behaving correctly, and troubleshooting the underlying issues when it is not. However, before delving into constellation diagrams and how they are used, it is important to understand the fundamentals behind digital modulation schemes and why they are used.

Background on Signals and Modulation Types

Transmitting data wirelessly from one point to another, while complex in practice, is simple in concept. In a very broad sense, there are only three main steps in this process: (1) generation of a pure carrier signal (i.e. an unmodulated sine wave) at the transmitter; (2) infusing the carrier signal with information via modulation; and (3) extracting the information from the received signal via demodulation. There are many modulation techniques used today, but all are separated into two broad categories, analog and digital.

Analog Modulation

- AM (Amplitude Modulation)
- FM (Frequency Modulation)
- PM (Phase Modulation)

Digital Modulation

- PSK (Phase Shift Keying)
- FSK (Frequency Shift Keying)
- MSK (Minimum Shift Keying)
- QAM (Quadrature Amplitude Modulation)
- Etc.

Whether a technique is analog or digital is dependent upon how the signal is modulated. In analog techniques, a message signal is modulated directly onto a carrier sine wave. In digital techniques, a message signal is sampled into digital bits by an analog-to-digital converter (ADC) and is then modulated onto a carrier sine wave, thus encoding the information within it.

In any signal modulation scheme, there are three variables by which a carrier signal can be manipulated to convey information: **amplitude**, **frequency**, and **phase**. Amplitude modulation (AM) varies the magnitude (or amplitude) of a signal, while frequency modulation (FM) and phase modulation (PM) both alter the phase angle of a signal. This is because frequency is a measure of the rate of change of the phase, while phase is measured relative to a reference angle (typically 0° relative to carrier signal in digital modulation) [1] [2] [3] [4] [5].

One way to view magnitude and phase is with the use of a polar diagram (Fig. 1). In a polar diagram, magnitude is represented by the distance of the point from the origin, while the phase is represented by the angle from the horizontal axis to the line formed from the origin to the point.

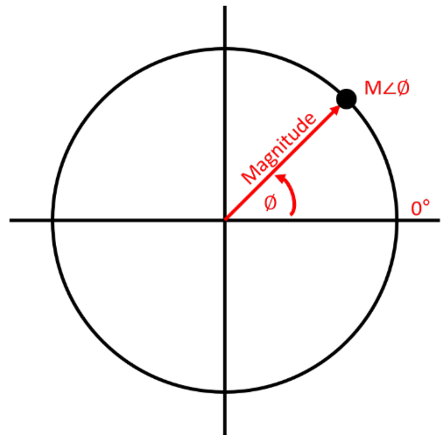

Figure 1. Polar diagram representing amplitude (magnitude) and phase

Conveniently, digital modulation schemes employ the use of an I/Q diagram. An I/Q diagram is simply a diagram using a rectangular coordinate system superimposed on a polar diagram representing the same set of a data (i.e. magnitude and phase). The I/Q values translate magnitude and phase information of a signal into a simple rectangular, linear set of values which simplify the associated signal processing. This is easier visualized, as represented in Fig. 2 [1] [3] [5].

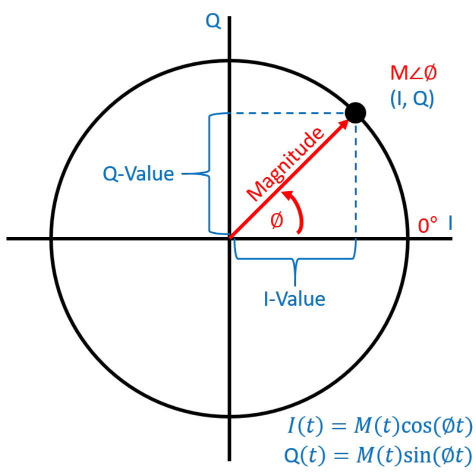

Figure 2. I/Q diagram superimposed on polar diagram

The benefits of viewing digitally modulated signals in the rectangular I/Q format are quickly realized when it is understood that nearly all digitally modulated signals rely on I/Q signals created by an I/Q modulator.

Background on I/Q Modulation

Two signals are said to be in "quadrature" when they are separated in phase by exactly 90°. Signals in quadrature are orthogonal and do not interfere with one another. Quadrature modulation takes advantage of this principal by combining two signals which are in quadrature for a combined output signal. The advantage of this is that the amplitude and phase of the combined output signal can be modulated independently or simultaneously, and can be accomplished digitally without adding unnecessarily complex RF hardware circuitry.

Rather, the two carrier signals, referred to as the **in-phase (I)** and **quadrature (Q)** components, are created using an I/Q modulator. In the transmitter, the I/Q signals are mixed with a single local oscillator (LO) with the "Q" component having a subsequent 90° phase shifter in its signal pathway. The I/Q signals are then summed to form a combined output signal (Fig. 3). The summation of the I/Q signals result in attaining the desired amplitude and phase of the combined output signal. When the combined signal is acquired at the receiver, the reverse process occurs. The combined signal is again mixed with a single LO and split into two I/Q signals, with the quadrature signal again having a 90° phase shifter in its signal pathway (Fig. 3). The separation into I/Q signals at the receiver allows for them to be easily mapped on to an I/Q plane and analyzed, which is the basis for constellation diagrams [1] [3] [5].

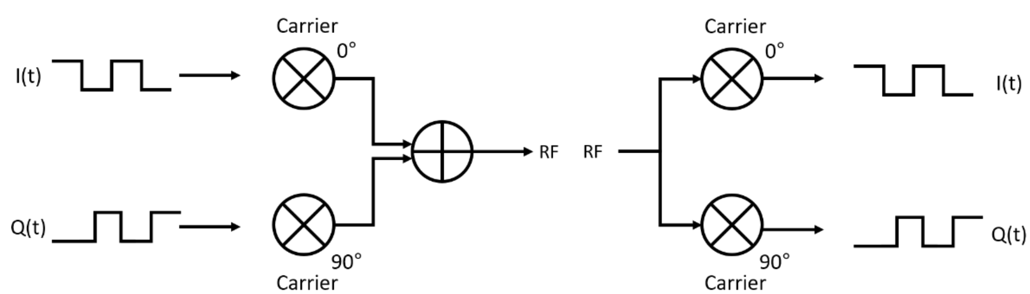

Figure 3. Block diagram of an I/Q transmitter (left) and I/Q receiver (right)

I/Q Data and Constellation Diagrams

Most digital modulation schemes involve a discrete number of symbols which are used to convey information. These symbols are mapped to a discrete set of magnitude and phase values on the I/Q plane, which are referred to as **constellation points**. Modulation schemes with greater numbers of constellation points are able to transmit more information per symbol, as the more symbols there are in a given modulation scheme, the greater number of bits a single symbol can represent [1]. For example, in binary phase-shift keying (BPSK) each symbol can only represent a 0 or a 1 because it has just two constellation points, therefore transmitting just one bit per symbol. Quadrature phase-shift keying (QPSK), which has four constellation points, can represent 00, 01, 10, or 11, and can therefore transmit 2 bits per symbol. This relationship can be expressed by the following equation:

$$M = 2^n, \text{ where } M = \text{\# of constellation points}$$
$$n = \text{bits/symbol}$$
$$\text{or } n = \log_2(M)$$

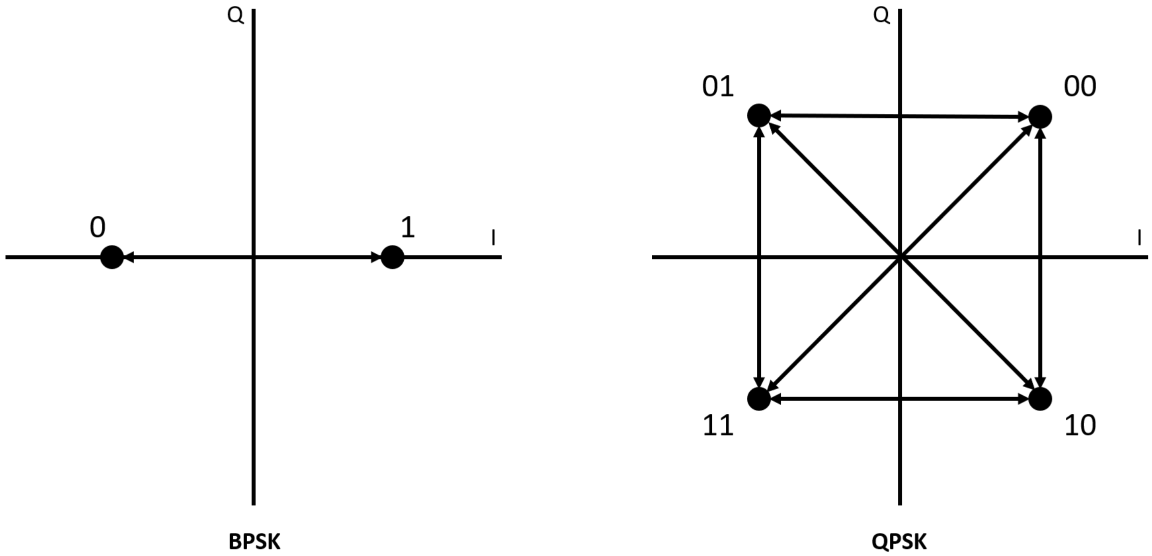

Figure 4. State diagrams for BPSK (left) and QPSK (right)

Therefore, theoretically QPSK can transmit twice as much data using the same amount of bandwidth as BPSK, or it could transmit the same amount of data using half the bandwidth. The tradeoff, however, is that there is less tolerance in the system for error (in terms of magnitude and phase) [1]. To better understand this, recall that in BPSK there are only two constellation points, meaning that the entire I/Q plane is separated into just two sections with the decision boundary located on the Q-axis. This means that a received I/Q value could be 89° out-of-phase, but the intended symbol could still be correctly interpreted because the received symbol falls within the correct decision boundary (represented in Fig. 5). However, in QPSK, the I/Q plane is separated into four sections, with decision boundaries at both the I- and Q-axes, leaving less margin for error. In QPSK, a symbol that is received 89° out-of-phase would be incorrectly interpreted by the receiver and would result in a symbol error.

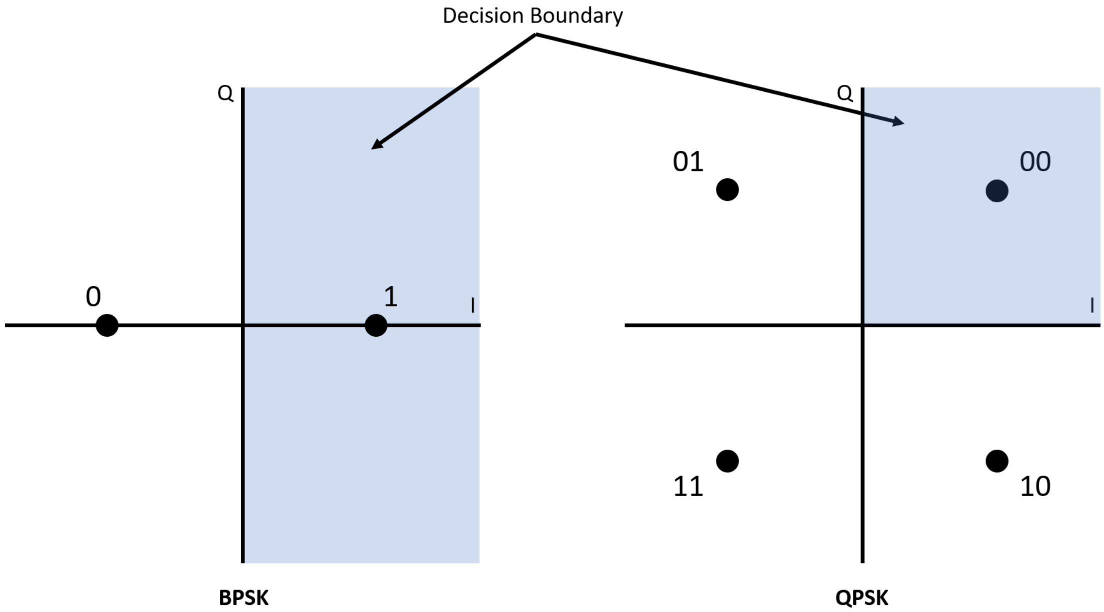

Figure 5. Decision boundaries for BPSK (left) and QPSK (right)

Polar diagrams are used to display the instantaneous value of the carrier signal at any point in time. This includes the values recorded at each symbol-clock transition, as well as the transition pathways between each decision point. In practice, a signal's instantaneous value is typically unimportant unless the transition pathways between decision points are required to better understand the root cause of a dominant error mode. Instead, what is generally of importance are key decision points which are aligned with the symbol clock. With each cycle of the symbol clock, it is expected that the signal's I/Q or magnitude/phase values will be aligned with a corresponding constellation point for the given modulation scheme. The amplitude and phase values captured at these decision points are what is displayed on a **constellation diagram** [1].

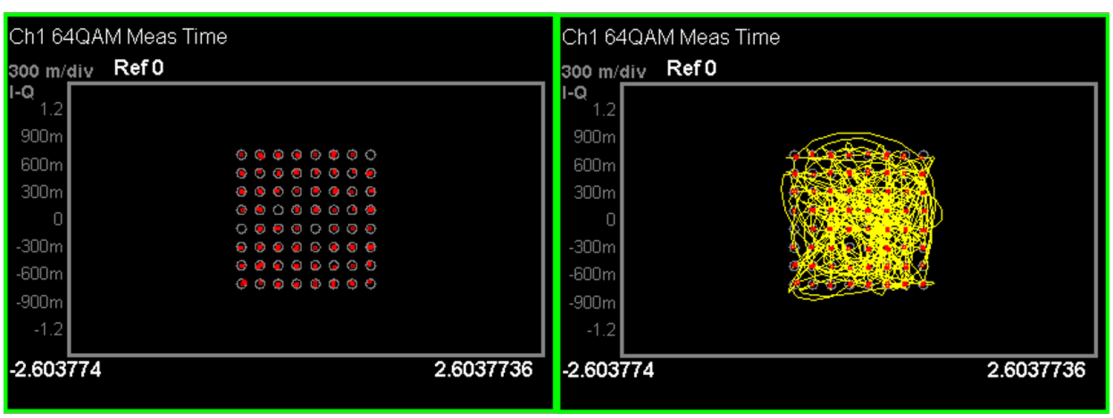

Figure 6. Constellation diagram (left) and polar diagram (right) for 64QAM with an input signal of -30 dBm

The constellation diagram is useful because it displays both the ideal (reference) signal and the actual measured signal on the same plot. The ideal signal locations of a constellation diagram are pre-defined generically depending on the modulation format chosen. In Fig. 6, the 64 white circles represent the ideal magnitude and phase for each of the 64 symbols used in 64QAM. The red dots represent the measured signal's magnitude and phase for each of the 64 symbols. Using constellation diagrams in this context, it is easy to visualize when a signal is performing well and when it is not. When a digital communication system is functioning as it should, the red dots should be tightly clustered within each white circle. When there is excess noise, distortion, spurious signals, or other problematic contributions degrading a signal's integrity, magnitude and phase errors occur, causing the red dots to deviate outside the circles defining the ideal signal locations (Fig. 7).

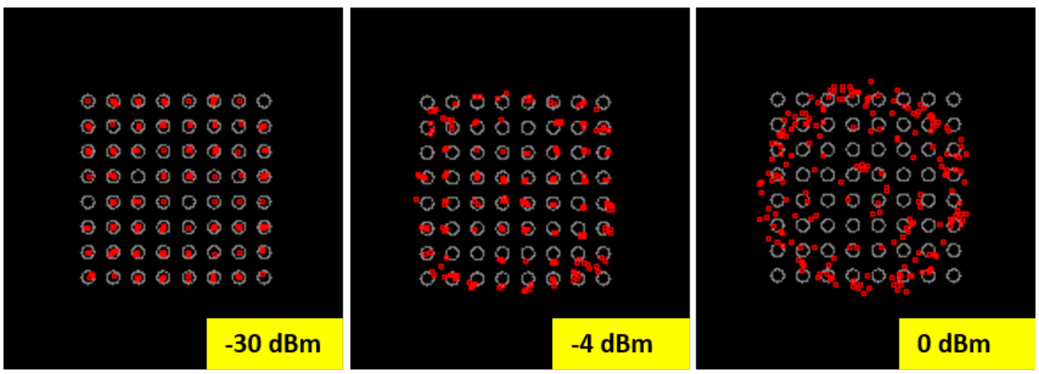

Figure 7. Measured signal symbols (red dots) increasingly misaligned with ideal signal constellation points (white circles) due to greater signal distortion as input drive level increased from -30 dBm to 0 dBm

While constellation diagrams are useful for graphically visualizing signal data to quickly identify problems, it is also useful to quantify the disparity between measured and ideal signals as well by calculating the error vector magnitude (EVM). EVM is the scalar distance between the end points of the measured and ideal phasors, and is a measure of how well a digital communications system is performing. EVM can be defined in both percentage and dB [1].

Magnitude error is the difference in magnitude between the actual and ideal signals, while phase error is the angle between the measured and ideal phasors (Fig. 8). Breaking EVM down into these two components is typically the first step when troubleshooting a problematic system. When one type of error is significantly larger than the other, it is referred to as the dominant error mode and can be used to isolate the problem. For example, when average magnitude error is the dominant error mode, the undesired amplitude modulation could be a result of AM-AM distortion, transistor biasing effects, thermal effects, memory effects, etc. Conversely, if the average phase error is the dominant error mode, the undesired phase modulation could be the result of AM-PM distortion, noise, spurious and/or cross-coupling problems in frequency, or other frequency generating stages [1].

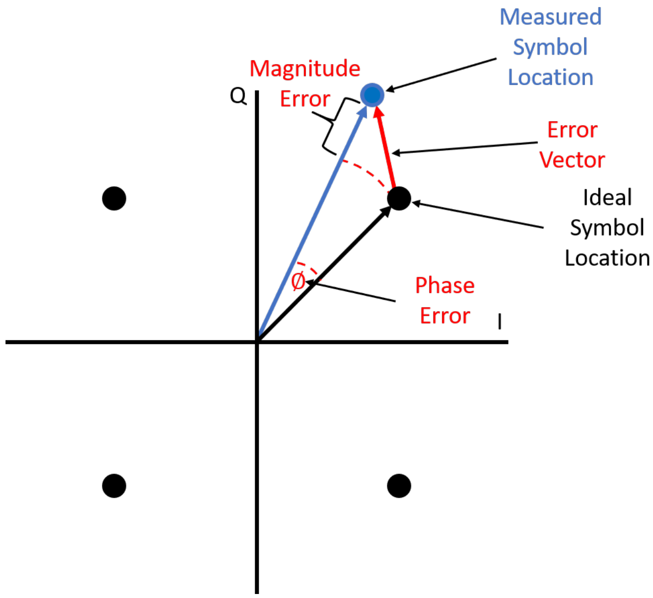

Figure 8. EVM example for QPSK

Summary

Constellation diagrams are an invaluable tool for evaluating a digital communication system's performance. These graphical representations of a digitally modulated signal can be used to troubleshoot and isolate various types of signal distortion and interference in order to determine their root cause. This representation is particularly effective in identifying the dominant error mode reducing a signal's integrity when viewed in the context of I/Q magnitude and phase error.

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