What is I/Q Data?

Publish Date: Feb 06, 2014

Overview

This white paper is part of the NI Measurement Fundamentals main page (http://zone.ni.com/devzone/cda/tut/p/id/4523) series. Each page in this series teaches you a specific concept related to common measurement applications by explaining the theory and giving practical examples. This white paper describes the theoretical background of I/Q data as well as practical considerations which make the use of I/Q data in communication so desirable.

Put simply, I/Q data shows the changes in magnitude (or amplitude) and phase of a sine wave. If amplitude and phase changes occur in an orderly, predetermined fashion, you can use these amplitude and phase changes to encode information upon a sine wave, a process known as modulation.

Modulation changes a higher frequency carrier signal in proportion to a lower frequency message, or information, signal. I/Q data is highly prevalent in RF communications systems, and more generally in signal modulation, because it is a convenient way to modulate signals.

Table of Contents

1. Background on Signals

Signal modulation changes a sine wave to encode information. The equation representing a sine wave is as follows:

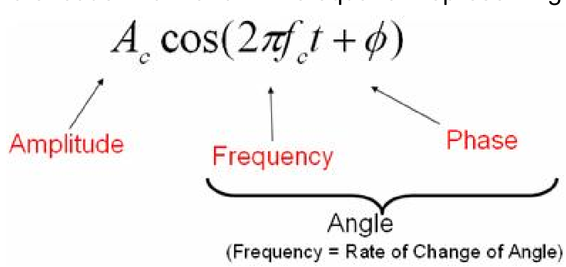


Figure 1: Equation for a Sine Wave

The equation above shows that you are limited to making changes to the amplitude, frequency, and phase of a sine wave to encode information. Frequency is simply the rate of change of the phase of a sine wave (frequency is the first derivative of phase), so frequency and phase of the sine wave equation can be collectively referred to as the phase angle. Therefore, we can represent the instantaneous state of a sine wave with a vector in the complex plane using amplitude (magnitude) and phase coordinates in a polar coordinate system.

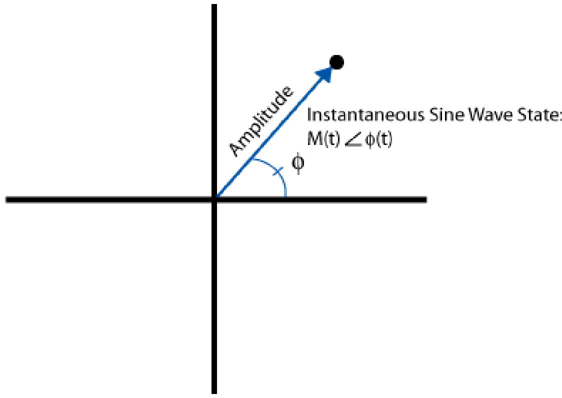


Figure 2. Polar Representation of a Sine Wave

In the graphic above, the distance from the origin to the black point represents the amplitude (magnitude) of the sine wave, and the angle from the horizontal axis to the line represents the phase. Thus, the distance from the origin to the point remains the same as long as the amplitude of the sine wave is not changing (modulating). The phase of the point changes according to the current state of the sine wave. For example, a sine wave with a frequency of 1 Hz (2π radians/second) rotates counter-clockwise around the origin at a rate of one revolution per second. If the amplitude doesn't change during one revolution, the dot maps out a circle around the origin with radius equal to the amplitude along which the point travels at a rate of one cycle per second.

Because phase is a relative measurement, imagine that the phase reference used is a sine wave of frequency equal to the sine wave represented by the amplitude and phase points. If the reference sine wave frequency and the plotted sine wave frequency are the same, the rate of change of the two signals' phase is the same, and the rotation of the sine wave around the origin becomes stationary. In this case, a single amplitude/phase point can represent a sine wave of frequency equal to the reference frequency. Any phase rotation around the origin indicates a frequency difference between the reference sine wave and the sine wave being plotted.

Up to this point, this white paper has described amplitude and phase data in a polar coordinate system. All the concepts discussed above apply to I/Q data. In fact, I/Q data is merely a translation of amplitude and phase data from a polar coordinate system to a Cartesian (X,Y) coordinate system. Using trigonometry, you can convert the polar coordinate sine wave information into Cartesian I/Q sine wave data. These two representations are equivalent and contain the same information, just in different forms. This equivalence is show in Figure 3.

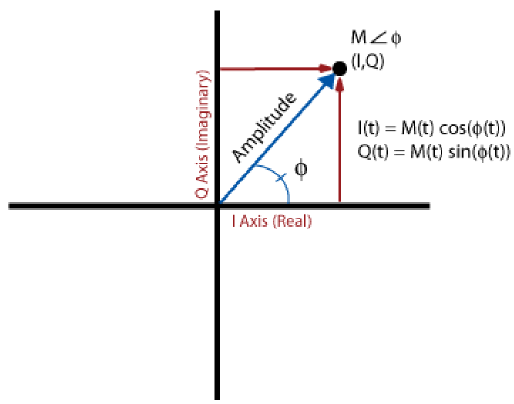


Figure 3. I and Q Represented in Polar Form

The figure below shows a LabVIEW example demonstrating the relationship between polar and Cartesian coordinates.

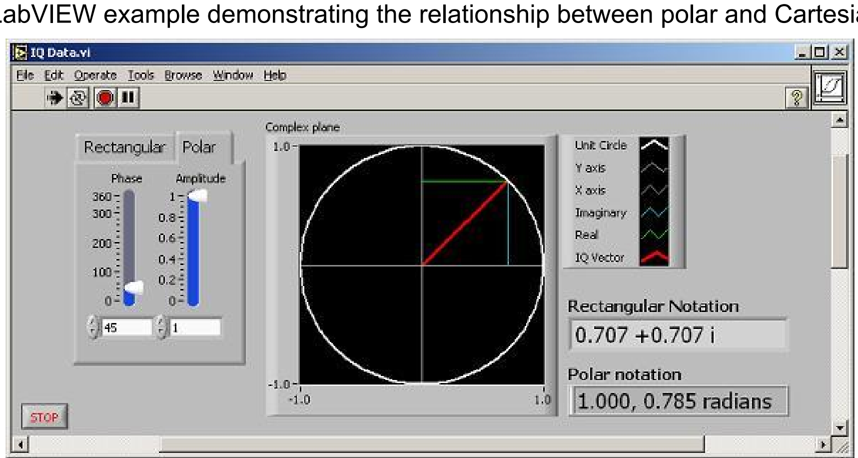


Figure 4: I/Q Data in LabVIEW

2. I/Q Data in Communication Systems

To explain why I/Q data is used in communications systems, you must understand modulation basics.

RF communication systems use advanced forms of modulation to increase the amount of data that can be transmitted in a given amount of frequency spectrum. Signal modulation can be divided into two broad categories: analog modulation and digital modulation. Analog or digital refers to how the data is modulated. If analog audio data is modulated onto a carrier sine wave, this technology is referred to as analog modulation. If analog audio data is sampled by an analog-to-digital converter (ADC) with the resulting digital bits modulated onto a carrier sine wave, this technology is defined as digital modulation because digital data is encoded. Both analog modulation and digital modulation involve changing the carrier wave amplitude, frequency, or phase (or combination of amplitude and phase simultaneously) according to the message data.

Amplitude modulation (AM) (http://zone.ni.com/devzone/cda/tut/p/id/3002), frequency modulation (FM) (http://zone.ni.com/devzone/cda/tut/p/id/3361), or phase modulation (PM) (http://www.ni.com/white-paper/1320/en/) are all examples of analog modulation. With amplitude modulation, the carrier sine wave amplitude is modulated according to the message signal. The same idea holds true for frequency and phase modulation.

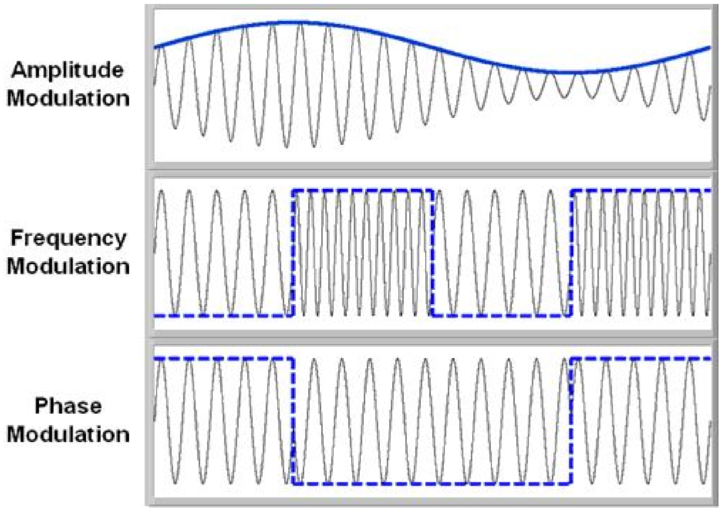


Figure 5. Time Domain of AM, FM, and PM Signals

Figure 5 represents various analog techniques—AM, FM, and PM—applied to a carrier signal. For AM, the message signal is the blue sine wave that forms the "envelope" of the higher frequency carrier sine wave. For FM, the message data is the dashed square wave. As the figure illustrates, the resulting carrier signal changes between two distinct frequency states. Each frequency state represents the high and low state of the message signal. If the message signal were a sine wave in this case, there would be a more gradual change in frequency, which would be more difficult to see. For PM, notice the distinct phase change at the edges of the dashed square wave message signal.

As mentioned earlier, if only the carrier sine wave amplitude changes with respect to time (proportional to the message signal), as is the case with AM modulation, the I/Q plane graph changes only with respect to the distance from the origin to the I/Q points, as shown in the following image:

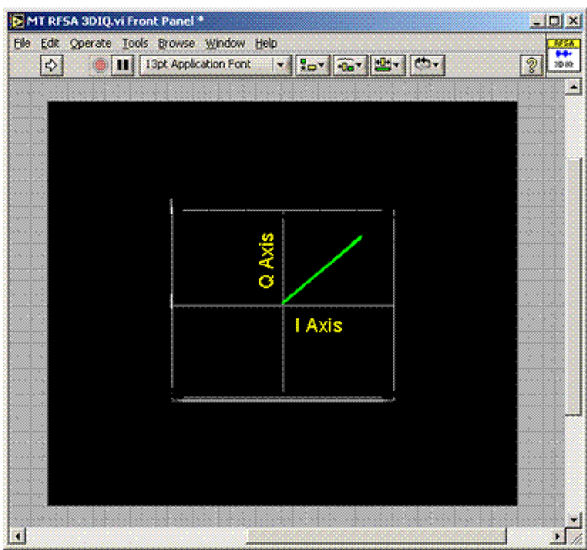


Figure 6. I/Q Data in the Complex Domain

The preceding figure shows the I/Q data points vary in amplitude only, with the phase fixed at 45 degrees. You cannot tell much about the message signal, only that it is amplitude modulated. However, if you watch how the I/Q data points vary in magnitude with respect to time, you can essentially see a representation of the message signal. Using LabVIEW's 3D graph control, we can show the third axis of time to illustrate the message signal.

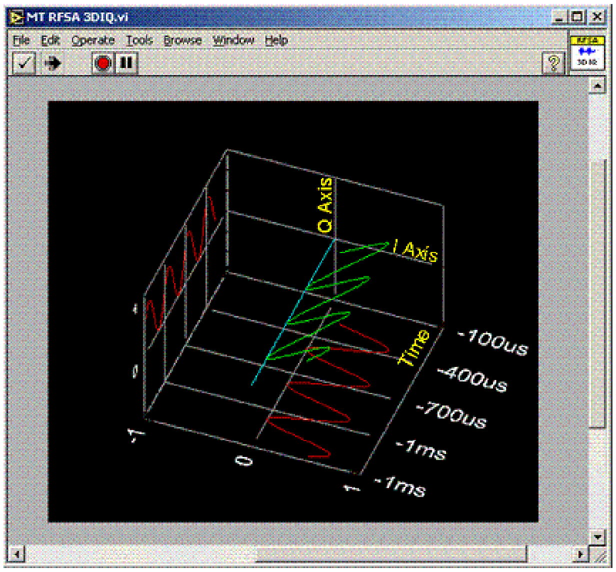


Figure 7. Representation of Magnitude vs. Time

Figure 7 shows the same data as the 2D I vs. Q plot in Figure 6. The magnitude of the signal trace modulates in a sinusoidal pattern, indicating that the message signal is a sine wave. The green trace represents the amplitude and phase data in a polar coordinate system, while the red traces represent the projections of this waveform onto the I and Q axes, representing the individual I and Q waveforms.

We can show the same type of example using PM, as shown in the following figure:

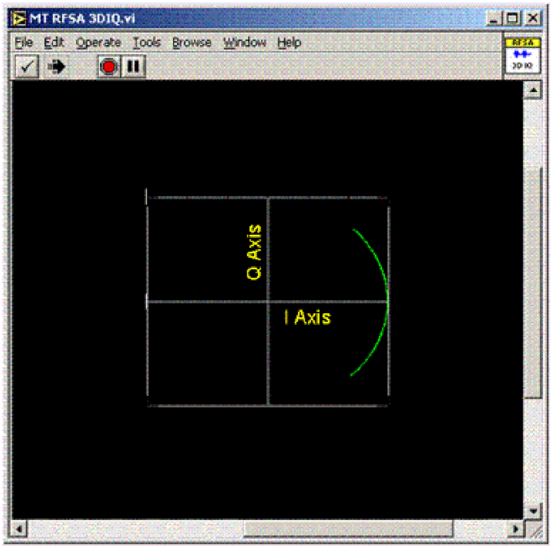


Figure 8. Polar Representation of Phase vs. Time

You can tell that the message signal is phase modulated, as the amplitude is constant but the phase is changing (modulating). You cannot see the shape of the message signal with respect to time, but you can see the minimum and maximum signal levels of the message signal are represented by phase deviations of -45 degrees and +45 degrees respectively.

The time axis can be used to better understand this concept, as shown in the following figure:

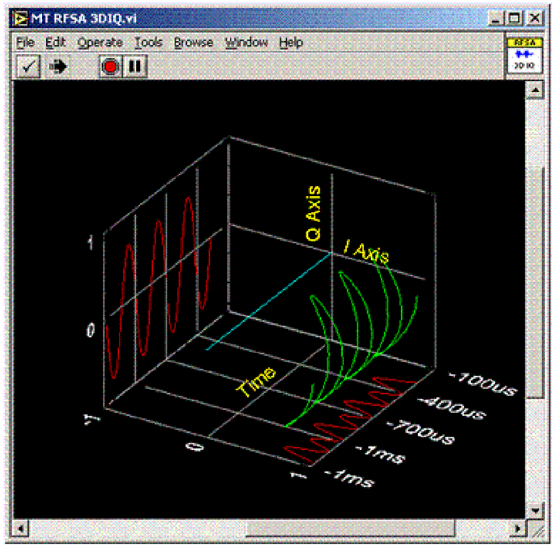


Figure 9. 3D Representation of Phase Modulation

Figure 9, shown in the LabVIEW 3D graph, shows the green trace varying in a sinusoidal fashion with respect to time. The projections onto the I and Q axes represent the individual I and Q waveforms corresponding to the PM sine wave with fixed magnitude and oscillating phase.

In essence, the I/Q data represents the message signal. Because the I/Q data waveforms are Cartesian translations of the polar amplitude and phase waveforms, you may have trouble determining the nature of the message signal. For example, compare the red I and Q traces on the 3D I vs. Q plots in Figure 9 to the green trace in Figure 9. If you plot amplitude vs. time for the AM sine wave, you would see the message signal. If you plot the phase data vs. time for the AM sine wave, you would have a straight line. You would see sine waves for the I vs. time and Q vs. time waveforms as well, but the scale would be off, and this would not necessarily be the case for more complex digital modulation schemes where both amplitude and phase are modulated simultaneously.

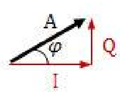
3. So Why Use I/Q Data?

Because amplitude and phase data seem more intuitive, you might assume you should use polar amplitude and phase data instead of Cartesian I and Q data. However, practical hardware design concerns make I and Q data the better choice.

Precisely varying the phase of a high-frequency carrier sine wave in a hardware circuit according to an input message signal is difficult. A hardware signal modulator that manipulates the amplitude and phase of a carrier sine wave would therefore be expensive and difficult to design and build, and, as it turns out, not as flexible as a circuit that uses I and Q waveforms. To understand how to avoid manipulating the phase of an RF carrier directly, refer to the following I/Q modulation equations:

$$\cos(\alpha + \beta) = \cos(\alpha)\cos(\beta) - \sin(\alpha)\sin(\beta)$$

$$A\cos(2\pi f_c t + \varphi) = A\cos(2\pi f_c t)\cos(\varphi) - A\sin(2\pi f_c t)\sin(\varphi)$$



$$I = A\cos(\varphi)$$
$$Q = A\sin(\varphi)$$

$$A\cos(2\pi f_c t + \varphi) = I\cos(2\pi f_c t) - Q\sin(2\pi f_c t)$$

where I is the amplitude of the in-phase carrier
Q is the amplitude of the quadrature-phase carrier

Figure 10. Mathematical Background of I/Q Modulation

According to the trigonometric identity shown in the first line of Figure 10, multiply both sides of the equation by A and substitute $2\pi f_c t$ in place of α and φ in place of β to arrive at the equation shown in line 2. Then substitute I for A cos(φ) and Q for A sin(φ) to represent a sine wave with the equation shown on line 3.

Remember that the difference between a sine wave and a cosine wave of the same frequency is a 90-degree phase offset between them. Essentially, what this fact means is that you can control the amplitude, frequency, and phase of a modulating carrier sine wave by simply manipulating the amplitudes of separate I and Q input signals. With this method, you do not need to directly vary the phase of an RF carrier sine wave. You can achieve the same effect by manipulating the amplitudes of input I and Q signals. Of course, the second half of the equation is a sine wave and the first half is a cosine wave, so you must include a device in the hardware circuit to induce a 90-degree phase shift between the carrier signals used for the I and Q mixers, but this addition is a simpler design issue than the aforementioned direct phase manipulation.

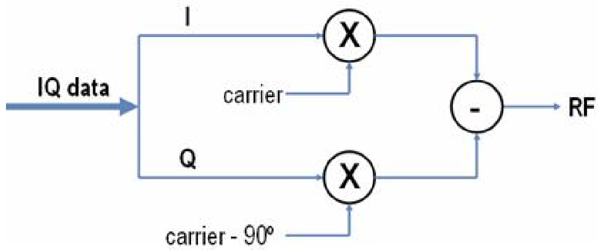


Figure 11. Hardware Diagram of an I/Q Modulator

Figure 11 shows a block diagram of an I/Q modulator. The circles with an 'X' represent mixers—devices that perform frequency multiplication and either upconvert or downconvert signals (upconverting here). The I/Q modulator mixes the I waveform with the RF carrier sine wave, and it mixes the Q signal with the same RF carrier sine wave at a 90-degree phase offset. The Q signal is subtracted from the I signal (just as in the equation shown in line 3 in Figure 10) producing the final RF modulated waveform. In fact, the 90-degree shift of the carrier is the source of the names for the I and Q data—I refers to in-phase data (because the carrier is in phase) and Q refers to quadrature data (because the carrier is offset by 90 degrees). This technique is known as quadrature upconversion, and you can use the same I/Q modulator for any modulation scheme. The I/Q modulator is merely reacting to changes in I and Q waveform amplitudes, and I and Q data can represent any changes in magnitude and phase of a message signal. The flexibility and simplicity (relative to other options) of the design of an I/Q modulator is why it is so widely used and popular.

4. Related NI Products

Refer to ni.com/rf (http://www.ni.com/rf/) for more information about related NI hardware and software products.

5. Conclusions

This document is meant to provide a brief overview and introduction to I/Q data as it relates to RF and wireless systems. For the complete list of tutorials, return to the NI Measurement Fundamentals main page (http://zone.ni.com/devzone/cda/tut/p/id/4523), or for more RF tutorials, refer to the NI RF Fundamentals page (http://zone.ni.com/devzone/cda/tut/p/id/3992). Additional information can also be found with Teaching and Research Resources for RF and Communications (http://ni.com/academic/communication.htm)